Referee 1 response:

We are very grateful to our colleague Jeremy Caves for his constructive review of the manuscript. We tried to address all his comments and suggestions as highlighted hereunder. A reviewed manuscript with highlighted changes is appended to this submission.

#1 Comment: “I am somewhat confused as to precisely where these cation exchange fluxes occur. On page 2, 2nd paragraph, the authors explain that these fluxes occur in estuaries as river water is transferred to the ocean. However, should not these exchange fluxes be potentially occurring along the entire length of the river system, as tributaries with somewhat different dissolved and adsorbed chemistries contribute water and sediment to the main trunk? Or is the chemical difference between river water and seawater so substantial that this is where the largest cation exchange fluxes are expected? I understand that the authors sampled between the mouths of the Ganges and Brahmaputra and also in the Lower Meghna; however, is the Lower Meghna considered an estuary or still primarily freshwater? A more specific explanation, linked to the hydrology of the GB and Lower Meghna, would greatly help the reader follow the precise mechanism and setting in which these exchange fluxes occur.”

#1 Answer: Cation exchange is supposedly occurring over the entire length of the river network but also in the landscape and soils that are being eroded. Any change in surrounding water chemistry will lead to a change in the adsorbed cation composition load. However, these changes within the river network are likely small and limited. The best argument to support this is given by the observation that the fraction of cations that are absorbed (Figure 4) does not change significantly between rivers and date of sampling even though the chemical composition of the water at the time of sampling was likely slightly different. The most drastic change in water chemistry occurs during transfer of the sediments to seawater as the concentration of dissolved cations (mainly Na+) changes by several orders of magnitude. This occurs several tenth of km of the sampling site on the Lower Meghna which is still in the fresh water zone.

#1 Changes in the manuscript: We have modified the manuscript so as to make it clearer that the major cation exchange occurs across the salinity gradient in the estuary and that all river samples are considered as purely riverine:

- §1 p2: Sediments in an aqueous solution such as river or oceanic water reversibly adsorb cations in equilibrium with the surrounding environment. The nature of these adsorbed cations evolves with changes in the chemical composition of the surrounding solution. The most radical change in the surrounding water chemical composition that the suspended sediment undergoes in a fluvial system occurs in estuaries across the salinity gradient.
- §2.1 p3: These sampling locations are also located upstream of the Ganga-Brahmaputra estuary and can therefore be considered as true riverine samples.

#2 Comment: “I do not follow how the probable exchange fluxes are calculated. I understand that the authors used Eq. 2 to show that KV is approximately constant across sampling locations (and similar to the Amazon); however, I can only see how Eq. 2 applies to the exchange of Ca2+ for Mg2+. Is this same equation (or a similar one) used to calculate the probable fluxes for Na+ and K+? Or is the fact that the proportion of adsorbed cations is constant across Al/Si ratios somehow used to then calculate probable Na+ and K+ exchange fluxes? Regardless, I think the authors should spell C2 out this calculation (particularly as it applies to Na+ and K+) more clearly since these probable fluxes are the primary point of the paper.”

#2 Answer: The CEC measurements on the sediments allow us to constrain the amount of cations that are bound to the sediments within the riverine environment. However, it is known (Sayles and Mangelsdorf, 1977; 1979) that not all Ca2+ is desorbed in seawater. The most probable exchange fluxes are therefore simply calculated assuming that the same proportion of Ca2+ as observed in the Amazon is exchanged in the case of the G&B. We think this is a reasonable assumption as the exchange characteristics of G&B and Amazon sediments are very similar. This similarity of exchange characteristics is derived from the calculation of the exchange coefficient K, for both the Amazon and the G&B. The calculation of K, using eq. 2 is done for the equilibrium between Ca2+ and Mg2+ because these are the dominant species adsorbed in the riverine environment and hence the deduced K, is more robust.

#2 Changes in the manuscript: The calculation has been clarified and table 3 is now more explicit.

- §3.3 p6: For the estimation of the most probable flux of cations exchanged by Ganga-Brahmaputra sediments upon entry in the Indian ocean, we assume that the exchanged proportion measured by Sayles and Mangelsdorf (1979; 1977) on Amazon sediments also applies here. This is a reasonable assumption as the aforementioned studies highlight that the nature of exchange reactions (i.e. the relative proportions of cations exchanged during transfer to the ocean) is very similar among the different samples studied, irrespective of sampling location within the Amazon basin, composition or grain-size. Furthermore, we showed in the previous section that the equilibrium constant K, between different cations in solution and adsorbed to the sediments sampled in the Ganga, Brahmaputra and lower Meghna is in the same range as the equilibrium constant found on Amazon sediments suggesting a similar behavior of these two river systems with respect to cation exchange. A reasonable estimate of the effective exchanged flux in the G&B estuary can therefore be made assuming that 82% of the total Ca2+ exchangeable flux is effectively exchanged for Na+, Mg2+ and K+. This estimation suggests that ca. 23 (±4) × 10^9 mol of Ca2+ are desorbed from the sediments in the Bay of Bengal while 27 (±8) × 10^9 mol Na+, 5 (±2) × 10^9 mol K+, and 8 (±5) × 10^9 mol Mg2+ are reabsorbed (Table 3).
it appears as if the methodology presented here is widely applicable and could be more widely implemented. Though measurements such as presented here should be more widely made as part of river sampling campaigns. For example, note whether this method should be more broadly applied, given that many other corrections to weathering data are being made that are similar in magnitude to the one presented here. Perhaps globally the effect of cation exchange negates the correction for atmospheric inputs of divalent cations?"

**Comment:** “One change that might make this manuscript more widely accessible would be to address whether measurements such as presented here should be more widely made as part of river sampling campaigns. For example, it appears as if the methodology presented here is widely applicable and could be more widely implemented. Though the authors conclude that these exchange fluxes have a relatively limited importance when compared with the long-term carbon cycle, some of the corrections here (i.e., 5% of the Ca$^{2+}$ flux) are of a similar magnitude to corrections for precipitation and cyclic salts (see, for example, Appendix Tables in Torres et al. (2015)). Thus, it would be helpful to note whether this method should be more broadly applied, given that many other corrections to weathering data are being made that are similar in magnitude to the one presented here. Perhaps globally the effect of cation exchange negates the correction for atmospheric inputs of divalent cations?”

**Answer:** This is a good point and we have tried to incorporate these comments in a paragraph and also expanding on the global significance of CEC fluxes:

**Changes in the manuscript:**

- §4.1 p8: …Accordingly, the relative importance of CEC fluxes compared to dissolved fluxes is probably limited for most large fluvial systems. Notable exceptions that would require a more precise quantification of CEC fluxes include rivers draining volcanic areas, as these areas are known to export high surface area and smectite-rich sediments (e.g., Chen, 1978). Organic-rich rivers should also be considered, as the presence of organic matter may yield a high overall CEC (e.g., Thompson et al., 1989; Turpault et al., 1996) susceptible of altering the dissolved fluxes more significantly. In any case it is important to stress that these future evaluations should take into account the variable CEC of sediments with sampling depth so as to correctly evaluate the integrated CEC of a river system. The evaluation of estuarine exchange processes may also be important to better understand the delivery of trace elements to the ocean (e.g., von Blanckenburg and Bouchez, 2014) or for possible isotopic fractionation of light elements during exchange.

- §4.1 p8: Table 3 shows that only less than 1% of the dissolved riverine Na$^+$ load but ca. 8% of K$^+$, 6% of the Ca$^{2+}$ and 3% of the Mg$^{2+}$ are carried by sediments as exchangeable cations in the river system. These related fluxes are therefore typically not accounted for when the major elemental composition or river water is used in the context of determining upstream chemical weathering rates (Guillarret et al., 1999). Although overall small, these “missing” fluxes are of a similar order of magnitude as cyclic salt corrections commonly applied to river water compositions for K$^+$, Ca$^{2+}$ and Mg$^{2+}$ (e.g., Galy et al., 1999)."
Referee 2 response:

We thank the anonymous second referee for his insightful comments and tried to answer all of them appropriately:

#1 Comment: “My major suggestion for the authors would be to add a paragraph to discuss in what extent the adsorption of the major cations on G-B sediments can influence the accuracy of the method for determining silicate weathering flux, which is based on dissolved Ca/Na and Mg/Na ratio (e.g. Gaillardet et al., 1999). Indeed, it has been recently suggested (e.g. Tipper E., 2015 AGU conference abstract) that the selective adsorption of the major cations to river sediments can significantly fractionate the Ca/Na and Mg/Na ratio of the “measured” dissolved load relative to the Ca/Na and Mg/Na of the initially dissolved cations. In that case, using the measured Ca/Na and Mg/Na ratio to calculate silicate weathering rates can lead to underestimated or overestimated silicate weathering flux calculations. Considering the low proportion of adsorbed cations relative to the total dissolved cations, the answer is probably going to be that the adsorption processes in the G-B do not fractionate significantly the Ca/Na and Mg/Na dissolved ratio, but I think that this would be a good addition to the current manuscript.”

#1 Answer: That’s an interesting point that didn’t occur to us. We have tried to address it in a separate paragraph, refereeing to AGU abstract. However, it is not clear to us where the statement found in the abstract “However, it has been proposed that Na-Ca exchange reactions with clay on mineral surfaces could account for 80% of the Na in rivers waters.” comes from and if it applies to the riverine environment only or the river plus the ocean. In the case of the G&B, adsorbed Na+ on river sediments (and in the riverine environment) accounts for less than 1% of the total dissolved river load. The importance of exchange reactions for the Na budget is more important once in the oceanic environments, where sediments can re-absorb up to 15% of the riverine dissolved load by releasing adsorbed Ca2+. It is nevertheless true that the greater portion of adsorbed Ca2+ (about 6% of the dissolved load) compared to Na+ may bias the measured dissolved Ca/Na ratios and hence impact the apportionment of silicate and carbonate weathering fluxes. However, as discussed in the manuscript, we think that in the case of the G&B this bias is limited

#1 Changes in the manuscript:
- §4.1 p8: Table 3 shows that only less than 1% of the dissolved riverine Na+ load but ca. 8% of K+, 6% of the Ca2+ and 3% of the Mg2+ are carried by sediments as exchangeable cations in the river system. These related fluxes are therefore typically not accounted for when the major elemental composition or river water is used in the context of determining upstream chemical weathering rates (Gaillardet et al., 1999). Although overall small, these “missing” fluxes are of a similar order of magnitude as cyclic salt corrections commonly applied to river water compositions for K+, Ca2+ and Mg2+ (e.g. Galy et al., 1999). Riverine dissolved compositions are also largely used to apportion the contribution of silicate and carbonate weathering to the total riverine Ca2+ flux. This is generally based on the total Na+ and K+ fluxes (as these are assumed to be predominantly released by silicate weathering) and estimates of the Ca/Na and Ca/K composition of weathered source rocks (Gaillardet et al., 1999). The preferential uptake of Ca2+ and K+ compared to Na+ by cation exchange in the riverine environment will affect the measured dissolved Ca/Na ratios (Ca/K being less affected as these two cations are taken up in very similar proportions). It has been suggested that these effects could be significant (Tipper, 2015). However, in the case of the Ganga-Brahmaputra the change in the measured dissolved Ca/Na ratio due to the differential uptake of Ca and Na is about 5%, which is most presumably well within the overall uncertainty of the carbonate and silicate weathering apportionment.

#2 Comment: “Page 3 Line 17: what about dolomite dissolution? G-B sediments contain more dolomite than calcite (Lupker et al., 2012) and the CoHex solution is only saturated with calcite. Would you expect any dolomite dissolution during the CEC determination experiment?”

#2 Answer: The dissolution of dolomite cannot totally be excluded. However, the fact that the total CEC determined using Co absorption measurements and determined using the sum of major cations after exchange agree (Figure 1) suggests that dolomite dissolution is negligible and does not significantly affect our measurements. We specified this in the manuscript:

#2 Changes in the manuscript:
- §2.2 p3: The CoHex solution is slightly acidic and may lead to the dissolution of sedimentary carbonates during exchange. To avoid this carbonate dissolution, the CoHex solution was saturated with pure calcite before exchange (Dohrmann and Kaufhold, 2009).
- §2.2 p3: which underlines that no significant amounts of other cations are released during exchange or through mineral dissolutions such as dolomite.

#3 Comment: Page 3 Line 24: did you try to make a second leaching step with CoHex, on at least one sample, in order to check whether all exchangeable cations have actually been exchanged with Cobalt ions during the experiment?

#3 Answer: No this was not tested. The exchange reactions have been made using a large excess of CoHex with respect to exchangeable sites (i.e. CEC value). CoHex is also known to have a very high affinity towards exchange sites (Ciesielski et al., 1997). We therefore assumed that the conditions lead to complete exchange. As reported by Ciesielski et al. (1997) repeated extractions only marginally increased the CEC of some soils and also increased undesirable secondary effects such as dissolutions.
The other remarks have been implemented as well.
Editor’s response:

We’d like to thank the editor for considering our manuscript and spend the time to provide additional comments.

We have implemented all minor comments and these are not detailed here. We appended a revised manuscript to this revised submission so that changes that were made to the manuscript can be tracked and evaluated.

#1 Comment: “3.18: do you have to monitor potential addition of Ca\(^{2+}\) to the solution as a result of adding the calcite?”

#1 Answer: Non-reacted (non-exchanged) CoHex solution was used as base line or reference for the measurement of exchanged cations so that the initial concentration in Ca\(^{2+}\) is accounted for.

#1 Changes in the manuscript:

- §2.2 p3: Additionally, major cations (Ca\(^{2+}\), Mg\(^{2+}\), Na\(^{+}\), K\(^{+}\)) released by the sediments during exchange were determined by atomic absorption spectrometry at SARM-CRPG on the same solution, using a non-reacted CoHex solution as reference.

#2 Comment: 6.30-34: This seems like a very important finding. Higher solid:dissolved ratio (i.e. more turbidity) does not necessarily mean more CE. You make this point in the next paragraph too, but I wonder if it could be more clearly drawn out (and worthy of pointing out in the abstract).

#2 Answer: It has been added to the abstract.

#2 Changes in the manuscript:

- Abstract p1: The limited exchange fluxes of the Ganges-Brahmaputra relates to the lower than average CEC of its sediment load that do not counterbalance the high sediment flux to the oceans. This can be attributed to the nature of Himalayan river sediment such as low proportion of clays and organic matter.
Impact of sediment-seawater cation exchange on Himalayan chemical weathering fluxes

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Abstract. Continental scale chemical weathering budgets are commonly assessed based on the flux of dissolved elements carried by large rivers to the oceans. However, the interaction between sediments and seawater in estuaries can lead to additional cation exchange fluxes that have been very poorly constrained so far. We constrained the magnitude of cation exchange fluxes from the Ganges-Brahmaputra River system based on cation exchange capacity (CEC) measurements of riverine sediments. CEC values of sediments are variable throughout the river water column as a result of hydrological sorting of minerals with depth that control grain-sizes and surface area. The average CEC of the integrated sediment load of the Ganges-Brahmaputra is estimated ca. 6.5 meq/100g. The cationic charge of sediments in the river is dominated by bivalent ions Ca2+ (76%) and Mg2+ (16%) followed by monovalent K+ (6%) and Na+ (2%) and the relative proportion of these ions is constant among all samples and both rivers. Assuming a total exchange of exchangeable Ca2+ for marine Na+ yields a maximal additional Ca2+ flux of 28 x 10^9 mol/yr of calcium to the ocean, which represents an increase of ca. 6 % of the actual river dissolved Ca2+ flux. In the more likely event that only a fraction of the adsorbed riverine Ca2+ is exchanged, not only for marine Na+ but also Mg2+ and K+, estuarine cation exchange for the Ganga-Brahmaputra is responsible for an additional Ca2+ flux of 23 x 10^9 mol/yr, while ca. 27 x 10^9 mol/yr of Na+, 8 x 10^9 mol/yr of Mg2+ and 4 x 10^9 mol/yr of K+ are re-absorbed in the estuaries. This represents an additional riverine Ca2+ flux to the ocean of 5% compared to the measured dissolved flux. About 15% of the dissolved Na+ flux, 8% of the dissolved K+ flux and 4% of the Mg2+ are reabsorbed by the sediments in the estuaries. The impact of estuarine sediment-seawater cation exchange appears to be limited when evaluated in the context of the long-term carbon cycle and its main effect is the sequestration of a significant fraction of the riverine Na flux to the oceans. The limited exchange fluxes of the Ganges-Brahmaputra relates to the lower than average CEC of its sediment load that do not counterbalance the high sediment flux to the oceans. This can be attributed to the nature of Himalayan river sediment such as low proportion of clays and organic matter.

1 Introduction

Chemical weathering on the continents is a primary source of dissolved elements delivered to the oceans. The flux of weathering products, mainly exported through the world rivers, exerts a first order control on oceanic biogeochemical cycles. On geological time scales, silicate weathering also represents a carbon sink that balances mantle and metamorphic CO2 input to the atmosphere thereby affecting the global climate (Walker et al., 1981). During silicate weathering by acid derived from atmospheric CO2, Ca ions are released and are transported along
with bicarbonate ions to the oceans, where they are eventually precipitated as carbonates. This mechanism transfers carbon from the atmospheric to the geologic reservoir following the Ebelman-Urey reaction (Ebelmen, 1845; Urey, 1952):

\[
\text{CaSiO}_3 + 2\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- + \text{SiO}_3^{2-}
\]

\[
\text{Ca}^{2+} + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O}(\text{aq})
\]

Quantifying the weathering flux exported to the oceans is therefore crucial to assess the role of weathering in the global carbon cycle and further compare it to other mechanisms that control atmospheric CO$_2$ content on geological time scales. It is further highly relevant to a broader understanding of oceanic geochemical cycles.

Modern continental weathering fluxes have largely been derived from the study of dissolved elements exported by rivers (Gaillardet et al., 1999). However, most of these fluxes do not account for elements delivered to the oceans through cation exchange, when river sediments are transferred through estuaries and towards the ocean.

Sediments in an aqueous solution such as river or oceanic water reversibly adsorb cations in equilibrium with the surrounding environment. The nature of these adsorbed cations evolves with changes in the chemical composition of the surrounding solution. The most radical change in surrounding water chemical composition that the suspended sediment undergoes in a fluvial system occurs in estuaries across the salinity gradient. In the riverine environment, sediment surfaces are mainly occupied by adsorbed Ca$^{2+}$ species, which is the dominant dissolved cation in rivers. When transferred to the oceans, the Ca$^{2+}$ adsorbed on sediment surfaces is partially exchanged for Na$^+$, Mg$^{2+}$ and K$^+$ (Sayles and Mangelsdorf, 1977) that are more abundant in ocean waters. These exchange reactions represent an additional source of Ca to the oceans and a potential sink for Na, Mg and K. These estuarine exchange reactions cannot be directly compared to additional weathering fluxes from the chemical weathering of sediments in seawater that has recently been suggested (Jones et al., 2012) as the processes are different. Chemical weathering in the presence of seawater involves the formation of secondary minerals (Jones et al., 2012), which is not the case of exchange reactions.

For the Amazon, Sayles and Mangelsdorf (1979) estimated that cation exchange fluxes remained under 10% of the dissolved flux for the major elements Na, Mg, Ca and K. On a global scale, first order estimates suggest that cation exchange can account for an extra Ca$^{2+}$ flux to the ocean ranging from 5 to 20% of the riverine dissolved flux (Berner and Berner, 2012; Berner et al., 1983; Holland, 1978). Nevertheless, these exchange fluxes to the oceans have received little attention and are currently poorly constrained. Global estimates mainly rely on the upscaling of the Amazon data from Sayles and Mangelsdorf (1979) and the magnitude of these fluxes has so far not been assessed for other major river systems.

In an effort to refine the weathering budget of the Himalayan range and its implications for the long-term carbon cycle, we evaluate the exchange flux delivered to the oceans by the Ganga and Brahmaputra (G&B) Rivers. The G&B is the largest river in terms of sediment export, with a total suspended and bedload sediment flux of ca. 10$^8$ t yr$^{-1}$ transported from the Himalayan range to the Bay of Bengal (RSP, 1996). The high sediment to dissolved load ratio of the G&B of ca. 11 (Galy and France-Lanord, 2001), more than double the world average...
(ca. 5, Milliman and Farnsworth (2011)), could potentially yield significant cation exchange fluxes that need to be properly quantified. Raymo and Ruddiman (1992) proposed that Himalayan weathering generated a major uptake of atmospheric carbon during Neogene potentially triggering the Cenozoic climate cooling. This suggestion was moderated based on the observation that Himalayan silicates are mostly alkaline and therefore generate a flux of alkalinity linked to Na and K ions that cannot lead to precipitation of carbonate in the marine environment (France-Lanord and Derry, 1997; Galy and France-Lanord, 1999). Nevertheless, cation exchange on sediment surfaces at the river-ocean transition can potentially exchange Na⁺ for Ca²⁺, strengthening the subsequent carbonate precipitation. Earlier studies on the carbon budget of Himalayan weathering used a rough approximation of this process (France-Lanord and Derry, 1997), and in order to better evaluate the carbon budget of Himalayan silicate weathering, it is necessary to assess the importance of cation exchange fluxes based on the specific physico-chemical properties of G&B suspended sediments.

2 Samples and Methods

2.1 Sampling

Sediments used in this work were sampled at the mouth of the Ganga and Brahmaputra Rivers as well as their confluence in Lower Meghna in Bangladesh during monsoon seasons between 2002 and 2010 (Figure 1). These sample locations integrate all Himalayan tributaries and therefore cover the entire sediment flux exported by the G&B basin. These sampling locations are also located upstream of the Ganga-Brahmaputra estuary and can therefore be considered as true riverine samples. Suspended sediments were sampled along depth profiles in the center of the active channel in order to capture the full variability of transported sediments (Lupker et al., 2011). Bedload samples were dredged from the channel as well. Sediments were filtered at 0.2 µm within 24h of sampling and freeze dried back in the lab. Sediment contact with anything else than river water was prevented to avoid biases in the composition of bound cations due to so called “rinsing effects” (Sayles and Mangelsdorf, 1977). The major element composition of sediments was determined by ICP-OES after LiBO₂ fusion at SARM-CRPG (Nancy, France).

2.2 Cation Exchange Capacity determination

The cation exchange capacity (CEC) is defined as the amount of cations bound to mineral surface charges that can be reversibly exchanged. In this work, cation exchange capacity was measured by displacing the adsorbed ions with Cobalt-Hexammine ("CoHex", Co(NH₃)₆³⁺). CoHex is a stable organometallic compound that effectively displaced major cations while maintaining the pH of the sample constant (Ciesielski et al., 1997; Orsini and Remy, 1976). The CoHex solution is slightly acidic and may lead to the dissolution of sedimentary carbonates during exchange. To avoid this carbonate dissolution, the CoHex solution was saturated with pure calcite before exchange (Dohrmann and Kaufhold, 2009). Between 1 and 2g of sediments were reacted with 30 ml of a calcite-saturated CoHex solution for 2 hours. After centrifugation, the remaining cobalt concentration in the supernatant was determined by spectrometric UV absorbance measurements (Aran et al., 2008), which by difference with the initial cobalt concentration of the solution, yields a first estimate of the total CEC of the sediments (CECₚ). Additionally, major cations (Ca²⁺, Mg²⁺, Na⁺, K⁺) released by the sediments during exchange were determined by atomic absorption spectrometry at SARM-CRPG on the same solution, using a non-reacted CoHex solution as
The sum of the released cations provides a second determination of the total CEC of the sediments (CEC$_{\text{Σ cat}}$). No systematic differences between CEC$_{\text{UV}}$ and CEC$_{\text{Σ cat}}$ are observed (Figure 2), which underlines that no significant amounts of other cations are released during exchange or through mineral dissolutions such as dolomite. Repeated measurements showed that the reproducibility of both measurements is better than 10%.

Freeze-drying the sediment samples prior to CEC analyses did not affect their CEC behaviour since different splits of sediments conserved in river water until exchange and splits subsequently freeze-dried showed similar CEC values within uncertainty.

3 Cation Exchange Capacity of Himalayan sediments

3.1 Total cation exchange capacity

The CEC of river sediments in the Ganga, Brahmaputra and lower Meghna are reported in Table 1. The CEC of sediments is correlated to the sediment sampling depth. Surface sediments have generally a higher CEC than coarse bedload sediments. This is further illustrated by the positive correlation between CEC and the Al/Si ratio of sediments (Figure 3). Al/Si is well correlated to grain size, which is controlled by hydraulic mineral sorting of sediments within the water column (Bouchez et al., 2011; Lupker et al., 2012; Lupker et al., 2011). The variable Al/Si ratio of sediments in the water column is to a first order the result of binary mixing between Si-rich, coarse-grained quartz bottom sediments and Al-rich phyllosilicates and clays that are relatively enriched in surface sediments. Surface sediments also have a higher surface area favouring adsorption compared to bedload samples (Galy et al., 2008). Sediments from the Ganga show higher CECs for a given Al/Si ratio compared to sediments from the Brahmaputra. Ganga sediments also have a higher surface area (Galy et al., 2008), which can be attributed to a higher abundance of mixed layer and smectite clays of Ganga sediments relative to the Brahmaputra (Heroy et al., 2003; Huyghe et al., 2011). Additionally, the CEC of surface sediments may also be enhanced because of the higher organic matter content of river surface samples (Galy et al., 2008) that can provide additional exchange capacity (e.g. Thompson et al., 1989; Turpault et al., 1996). The variable CEC of sediments in the water column and amongst river reaches can therefore be tentatively summarized as resulting from the mineralogical and grain-size control on the surface area and organic matter loading of the sediments (Malcolm and Kennedy, 1970).

3.2 Nature of adsorbed cations

Figure 4 shows the molar fraction of each major cation adsorbed onto the sediments delivered to the Bay of Bengal. Ca$^{2+}$ and Mg$^{2+}$ are the dominant adsorbed cations in river water with 76 % and 16 % of the total exchangeable cations, respectively. Na$^+$ and K$^+$ account respectively for 1 % and 7 % of the total adsorbed species. However, in contrast to total CEC, the nature of the exchangeable cations is not dependent on the Al/Si ratio of the sediments and is constant amongst all samples. The partitioning of exchangeable cations bound to the riverine sediments is therefore not controlled by grain-size or mineralogical sorting in the water column. These exchangeable compositions are also very similar for Ganga, Brahmaputra and Lower-Meghna sediments and for samples collected over different years.

The composition of sediment exchangeable cations is to a first order imposed by the dissolved composition of the river water transporting these sediments. For the two most abundant adsorbed cations, the binary Ca/Mg exchange
is commonly described as an exchange isotherm with an equilibrium constant $K_v$ (Sayles and Mangelsdorf, 1979), such that:

$$\frac{X_{Ca}}{X_{Mg}} = K_v \left( \frac{a_{Ca}}{a_{Mg}} \right)^p$$

where $X_{Ca}$ and $X_{Mg}$ are the fraction of adsorbed cations, $a_{Ca}$ and $a_{Mg}$ the cation activity in the river water and $p$ a constant. The chemical composition of the river water directly in contact with the sampled sediments has not been systematically measured. However, the constant composition of exchangeable cations for sediments sampled at different seasons suggests that a first order determination of $K_v$ can be made using the average dissolved composition of the Ganga, Brahmaputra and Lower Meghna (Galy and France-Lanord, 1999). The equilibrium constant, $K_v$, for sediments of the Ganga, Brahmaputra and lower Meghna is relatively similar (between 1.7 and 2 for $p \approx 1$) despite the use of average dissolved river water compositions that do not take into account for the compositional variability of these rivers (Galy and France-Lanord, 1999; Singh et al., 2005). Using a $p$ value of 0.76 as found in Amazon sediments (Sayles and Mangelsdorf, 1979), the calculated $K_v$ ranges from 2.1 to 2.5, also in agreement with the equilibrium constants found on the Amazon (Table 1). These very similar constants show that the behaviour of Himalayan sediments with respect to the cation exchange composition is very similar to the sediments transported by the Amazon. These similarities most probably stem from the first order resemblance of the mineralogical composition of both rivers (Garzanti et al., 2011; Martinelli et al., 1993).

### 3.3 Exchangeable flux to the Bay of Bengal

In order to derive the flux of exchangeable cations that can be delivered to the Bay of Bengal by Himalayan sediments it is necessary to take into account the variability of the CEC of sediments with the water depth. The average CEC of sediments exported to the BoB can be constrained using the average Al/Si ratio of the sediments owing to the linear correlation between CEC and Al/Si (Figure 3). Lupker et al. (2011) constrained the average Al/Si of Ganga sediments in Bangladesh to 0.23. Changes in the Al/Si ratio of sediments during transport are mainly the result of sequestration of quartz rich sediments in the subsiding floodplain. In the case of the Ganga, the sequestrated flux is limited and the Al/Si ratio of sediments in Bangladesh is close to that inferred for the Himalayan crust. The major immobile element content (Al, Si and Fe) of Brahmaputra sediments is very similar to that of Ganga sediments (Lupker, 2011) suggesting that the parent material has a very similar composition.

Furthermore, the constricted morphology of the Brahmaputra floodplain does not favour high sedimentation fluxes in the floodplain. We therefore suppose here that the average Al/Si of the Brahmaputra is very similar to that of Ganga sediments.

Using an Al/Si ratio of 0.23 (±0.01) yields an average total CEC of 8.0 (±0.9), 4.2 (±1.2) and 6.5 (±1.3) meq/100g for Ganga, Brahmaputra and lower Meghna sediments respectively. The average lower Meghna CEC deduced from the regression through the analysed sediments is very similar to the ca. 6.0 (±1.1) meq/100g CEC that would be expected from the mixing of 550 $\times$ 10^6 t/yr of Ganga sediments and 590 $\times$ 10^6 t/yr of Brahmaputra sediments.
For a combined Ganga and Brahmaputra sediment flux of $1.14 \times 10^3 \text{ t/yr}$, the total exchange capacity of the sediments amounts to $74.1 \pm 14.8$ meq/yr. The maximum exchangeable flux is reported in Table 2.

During exchange with seawater, river sediments mainly lose Ca$^{2+}$ to the ocean while adsorbing Mg$^{2+}$, Na$^+$ and K$^+$ (Sayles and Mangelsdorf, 1979, 1977). Assuming a total exchange of Ca$^{2+}$ (the dominant cation in riverine water) for Na$^+$ (the dominant cation in seawater) during the transfer of sediments to the ocean yields a maximum exchange flux of $28 \pm 6 \times 10^3 \text{ mol/yr Ca}^{2+}$ to the Indian Ocean, while $56 \pm 12 \times 10^3 \text{ mol/yr Na}^+$ are adsorbed onto the sediments. These additional Ca, and lower Na fluxes to the ocean are not accounted for by modern dissolved riverine fluxes.

However, Sayles and Mangelsdorf (1979; 1977) showed that only a fraction of adsorbed Ca$^{2+}$ is exchanged during prolonged contact of sediments and clays with seawater and that these cations are not only exchanged for Na$^+$ but also partially for Mg$^{2+}$ and K$^+$. In their experiments, the authors found that ca. 82% of the adsorbed riverine Ca$^{2+}$ is exchanged for Na$^+$, Mg$^{2+}$ and K$^+$ in respective molar proportions of 58%, 32% and 10%. For the estimation of the most probable flux of cations exchanged by Ganga-Brahmaputra sediments upon entry in the Indian Ocean, we assume that the exchanged proportion measured by Sayles and Mangelsdorf (1979; 1977) on Amazon sediments also applies here. This is a reasonable assumption as the aforementioned studies highlight that the nature of exchange reactions i.e. the relative proportions of cations exchanged during transfer to the ocean is very similar among the different river systems studied, irrespective of sampling location within the Amazon basin, composition or grain-size. Furthermore, we showed in the previous section that the equilibrium constant $K_e$ between different cations in solution and adsorbed to the sediments sampled in the Ganga, Brahmaputra and lower Meghna is in the same range as the equilibrium constant found on Amazon sediments suggesting a similar behavior of these two river systems with respect to cation exchange. A reasonable estimate of the effective exchange flux in the G&B estuary can therefore be made assuming that 82% of the total Ca$^{2+}$ exchangeable flux is effectively exchanged for Na$^+$, Mg$^{2+}$ and K$^+$. This estimation suggests that ca. $23 \pm 4 \times 10^3 \text{ mol of Ca}^{2+}$ are desorbed from the sediments in the Bay of Bengal white $27 \pm 8 \times 10^3 \text{ mol Na}^+$, $5 \pm 2 \times 10^3 \text{ mol K}^+$, and $8 \pm 3 \times 10^3 \text{ mol Mg}^{2+}$ are reabsorbed (Table 3). The main exchange reaction is therefore still the exchange of riverine Ca$^{2+}$ for marine Na$^+$, but non-negligible amounts of K$^+$ and Mg$^{2+}$ are fixed in the marine environment by the sediments.

### 3.4 Comparison with Ganga-Brahmaputra dissolved fluxes

To evaluate the importance of cation exchange fluxes to the ocean we compare the maximum and probable exchange fluxes derived above to the dissolved flux exported by the G&B. Galy and France-Lanord (1999) estimated that the G&B export an annual molar flux of $183 \pm 10^3 \text{ Na}^+$, $59 \pm 10^3 \text{ K}^+$, $462 \pm 10^3 \text{ Ca}^{2+}$ and $187 \pm 10^3 \text{ Mg}^{2+}$. These estimates are close to the fluxes estimated from the GEMS / Water program (UNESCO) and show the dominance of the Ca$^{2+}$ flux, largely derived from carbonate dissolution. Assuming a total replacement of adsorbed Ca$^{2+}$ with seawater Na$^+$, the maximum cation exchange flux would be $28 \pm 6 \times 10^3 \text{ mol/yr Ca}^{2+}$ and $46 \pm 12 \times 10^3 \text{ mol/yr Na}^+$ to the dissolved flux. This would increase by ca. 6% the riverine Ca$^{2+}$ flux and decrease by 32% the Na$^+$ flux (Figure 5). However as discussed earlier, total cation exchange is not expected and a more probable exchange flux can be determined from Sayles and Mangelsdorf (1979) work on the Amazon. This more probable estimate suggests that the cation exchange flux represents an addition of ca. 5% of the dissolved Ca$^{2+}$.
flux and a subtraction of 16% of the dissolved Na\(^+\) flux, 8% of the dissolved K\(^+\) flux and 4% of the dissolved Mg\(^{2+}\) flux (Table 3, Figure 5). The main effect of estuarine cation exchange for the Himalayan weathering budget is therefore a moderate but significant decrease of the overall Na\(^+\) flux to the Indian Ocean since about one sixth of the riverine flux is reabsorbed. The increase in riverine Ca\(^{2+}\) and decrease in K\(^+\), Mg\(^{2+}\) fluxes remain limited.

5 Discussion

4.1 Magnitude of cation exchange fluxes

The exchange fluxes of G&B sediments are in the order of few percent of the riverine dissolved fluxes exported to the Bay of Bengal. Despite the fact that the G&B sediment flux is of the same order of magnitude as that of the Amazon River (Milliman and Farnsworth, 2011), the cation exchange flux of the G&B appears lower by a factor 3 to 5 depending on the element, compared to that determined for the Amazon by Sayles and Mangelsdorf (1979). This difference can be attributed to the lower average CEC value of ca. 6 meq/100g of the G&B sediments compared to the ca. 22 meq/100g of Amazon sediments, (Sayles and Mangelsdorf, 1979) that compensates for the high sediment yield of the Himalayan system. The overall low CEC of G&B sediments also limits the relative importance of cation exchange on the dissolved fluxes. Even though the suspended to dissolved load ratio of the G&B is almost 3 times higher than that of the Amazon River (ca. 4, Milliman and Farnsworth (2011)) the effect of cation exchange are comparable with an increase of ca. 4 to 5% of the Ca\(^{2+}\) dissolved flux and a decrease of 4 to 8 % of the Mg\(^{2+}\) and 6 to 8% of the K\(^+\) dissolved fluxes (Sayles and Mangelsdorf, 1979). The effect of riverine Na\(^+\) re-adsorption is more substantial with a decrease of ca. 16% for the G&B compared to the 6% determined for the Amazon, but this can mainly be attributed to the high dissolved Na flux of the Amazon. If a CEC value of world average river sediments of 18 meq/100g is retained (Berner and Berner, 1996; Holland, 1978), the total riverine cation exchangeable flux would also be higher by a factor of ca. 3 and yield an additional Ca\(^{2+}\) flux in excess of 15 to 18 % compared to the actual dissolved Ca\(^{2+}\) flux. This difference highlights the importance of assessing the average CEC on a river-by-river basis.

The relatively low CEC values of G&B sediments can be linked to the dominance of physical erosion in the Himalayan system that does not favour the formation of high area clay minerals (smectite) and leads to the export of clays dominated by illite and overall coarse-grained material with low surface areas (Galy et al. 2008). CEC exchange fluxes can be expected to scale with the magnitude of sediment fluxes, which means that the underestimation of modern dissolved chemical weathering fluxes is greatest in the most active areas with highest dissolved fluxes (West et al., 2005). However, it seems unlikely that this scaling is linear since active erosion processes do not necessarily favour high surface area mineral formations and hence limit the overall CEC of exported sediments. We would therefore expect the CEC flux over dissolved flux ratio to decrease with increasing erosion or sediment yield. Accordingly, the relative importance of CEC fluxes compared to dissolved fluxes is probably limited for most large fluvial systems. Notable exceptions that would require a more precise quantification of CEC fluxes include rivers draining volcanic areas, as these areas are known to export high surface area and amethyst-rich sediments (e.g., Chen, 1978). Organic-rich rivers should also be considered, as the presence of organic matter may yield a high overall CEC (e.g., Thompson et al., 1989; Turpault et al., 1996) susceptible of altering the dissolved fluxes more significantly. In any case it is important to stress that these future evaluations...
should take into account the variable CEC of sediments with sampling depth so as to correctly evaluate the integrated CEC of a river system. The evaluation of estuarine exchange processes may also be important to better understand the delivery of trace elements to the ocean (e.g. von Blanckenburg and Boucher, 2014) or for possible isotopic fractionation of light elements during exchange.

Table 3 shows that only less than 1% of the dissolved riverine Na\(^+\) load but ca. 8% of K\(^+\), 6% of the Ca\(^{2+}\) and 3% of the Mg\(^{2+}\) are carried by sediments as exchangeable cations in the river system. These related fluxes are therefore typically not accounted for when the major elemental composition or river water is used in the context of determining upstream chemical weathering rates (Gaillardet et al., 1999). Although overall small, these “missing” fluxes are of a similar order of magnitude as cyclic salt corrections commonly applied to river water compositions for K\(^+\), Ca\(^{2+}\) and Mg\(^{2+}\) (e.g. Gały et al., 1999). Riverine dissolved compositions are also largely used to apportion the contribution of silicate and carbonate weathering to the total riverine Ca\(^{2+}\) flux. This is generally based on the total Na\(^+\) and K\(^+\) fluxes as these are assumed to be unambiguously released by silicate weathering and estimates of the Ca/Na and Ca/K composition of weathered source rocks (Gaillardet et al., 1999). The preferential uptake of Ca\(^{2+}\) and K\(^+\) compared to Na\(^+\), by cation exchange in the riverine environment will affect the measured dissolved Ca/Na ratios (Ca/K being less affected as both cations are taken up in very similar proportions). It has been suggested that these effects could be significant (Tipper, 2015). However, in the case of the Ganga-Brahmaputra, the change in the measured dissolved Ca/Na ratio due to the differential uptake of Ca and Na is about 5%, which is most presumably well within the overall uncertainty of the carbonate and silicate weathering apportionment.

### 4.2 Effect of cation exchange on the long-term carbon budget of Himalayan erosion

The effect of continental weathering on the long-term carbon cycle is mainly dictated by dissolved fluxes derived from Ca-silicate weathering following the Ehrlenmeyer-Urey reaction (eq. 1) because it can directly lead to precipitation of carbonate. This reaction stabilizes half of the alkalinity flux used to dissolve the initial silicates and release the other half as CO\(_2\) to the ocean and atmosphere. Silicate-derived Mg fluxes are also similarly efficient as they are exchanged for Ca during oceanic crust alteration or consumed during Mg-rich calcite precipitation (Berner and Berner, 2012). In contrast, it is generally assumed that on the long-term, the uptake of CO\(_2\) by Na\(^+\) or K\(^+\) silicate weathering (eq. 3) is balanced by the CO\(_2\) release during the formation of new Na and K silicates on the seafloor during reverse weathering reactions (eq. 4) (MacKenzie and Garrels, 1966).

\[
2(Na, K)AlSi_2O_8 + 2CO_2 + 11H_2O \rightarrow 2(Na^+, K^+) + 2H_2SiO_3 + 4H_2SiO_3 + Al_2Si_2O_5(OH)_4 (clay mineral)
\]  
(eq. 3)

\[
\text{climate \ mineral} + HCO_3^- + H_2SiO_3 + (Na^+, K^+) \rightarrow (Na, K)\text{silicate} + CO_2 + H_2O
\]  
(eq. 4)

In such case, Na and K silicate weathering do not participate in the long-term carbon budget of continental erosion. Alternatively, cation exchange reaction allows exchange of Na\(^+\) or K\(^+\) for Ca\(^{2+}\) and may subsequently lead to CaCO\(_3\) precipitation and long-term carbon sequestration (eq. 5) (Berner, 2004; Berner et al., 1983; MacKenzie and Garrels, 1966; Michalopoulos and Aller, 1995).

\[
(Na, K)\text{silicate} \rightarrow CaCO_3 + CO_2 + H_2O
\]  
(eq. 5)
Assuming annual exchange fluxes as discussed above (Table 3), 27 ± 10^9 mol/yr Na\(^+\) and 5 ± 10^9 mol/yr K\(^+\) would be exchanged for 16 ± 10^9 mol/yr Ca\(^{2+}\) which can ultimately precipitate as CaCO\(_3\). This is substantial but remains relatively marginal compared to the total flux of silicate derived alkalinity of the Ganga-Brahmaputra that is estimated to be around 270 ± 10^9 mol/yr (Galy and France-Lanord, 1999). 60 to 65% of this silicate alkalinity is balanced by Na\(^+\) and K\(^+\), which corresponds to 160 to 175 ± 10^9 mol/yr of HCO\(_3^-\). Therefore, about 10% of the alkalinity linked to Na-K silicate weathering could finally lead to carbonate precipitation through cation exchange. Hence the total flux of silicate weathering derived alkalinity that can precipitate as CaCO\(_3\) is 55 to 62 ± 10^9 mol/yr. This estimate remains highly speculative since the extent and magnitude of reverse weathering reactions are currently poorly quantified. These fluxes may be substantial but are still limited when compared to the ca. 300 ± 10^9 mol/yr C storage associated with the organic carbon burial fluxes of the modern Himalayan system (Galy et al., 2007), which remains the main forcing of the carbon cycle from Himalayan erosion. It should nevertheless be kept in mind that our estimates are formulated based on the Himalayan system at present. On longer time scales, the variability in both sediment (Goodbred and Kuehl, 2000) and weathering fluxes (Lupker et al., 2013) mean that the relative importance of cation exchange fluxes in the global weathering budget has likely varied and hence should be treated carefully. Finally, it's worth mentioning that these estimates of weathering impact on the carbon cycle do not take into account the role of chemical weathering through sulfuric acid (Galy and France-Lanord, 1999; Turchyn et al., 2013) that is known to also contribute to the weathering budget of Himalayan erosion and does counteract long-term carbon sequestration (Calmels et al., 2007).

5 Conclusions

The Ganga-Brahmaputra is the highest sediment point source of sediment to the oceans with an export of about 1 billion tons of sediments every year. The high average sediment concentration suggests that the cation exchange fluxes of this system may be significant or at least need to be quantified in order to derive robust weathering flux estimates. The flux of exchangeable cations has been quantified in this study based on CEC measurements of riverine sediments. These measurements show that the CEC of sediments is strongly variable within the water column, which is linked to sediment sorting effects and variable mineralogical composition with depth. Contrary to the total CEC, the nature of adsorbed cations is remarkably constant amongst all samples with the dominance of divalent cations Ca\(^{2+}\) and Mg\(^{2+}\). The equilibrium constants between adsorbed cations and river water composition of the Ganga-Brahmaputra are also very close to the ones derived for sediments from the Amazon in a previous study.

Based on the sediment flux of the Ganga-Brahmaputra and assuming a total exchange of adsorbed riverine Ca\(^{2+}\) for marine Na\(^+\) we estimated that estuarine cation exchange could increase the dissolved Ca\(^{2+}\) flux to the ocean by 6 % at most. Taking more realistic estimations based on a partial exchange of riverine Ca\(^{2+}\) for marine Na\(^+\),
Mg$^{2+}$ and K$^+$ yields an increased Ca$^{2+}$ flux of ca. 5%, while the equivalent of 15% of the dissolved Na$^+$ flux, 8% of the dissolved K$^+$ flux and 4% of the Mg$^{2+}$ are reabsorbed by the sediments in the estuaries. Estuarine sediment-seawater cation exchange is therefore mainly a riverine Na$^+$ sink. In the context of the long-term carbon budget of Himalayan erosion, cation exchange increases the pool of Ca$^{2+}$ that can participate to CaCO$_3$ storage. This additional flux is however limited to ca. 10% of the Ca-Mg silicate derived flux. In spite of the very intense particle flux associated to physical erosion of the Himalaya, the cation exchange process occurring in the estuarine zone does not change significantly the estimate of the impact of silicate weathering on long term carbon sequestration. It is likely limited by the relatively coarse nature and low surface area of Himalayan sediments that lead to an overall low CEC.

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Lupker, M.: Dynamique sédimentaire; érosion physique et altération chimique dans le système himalayen, PhD, Centre de Recherches Pétrographiques et Géochimiques, Institut Polytechnique de Lorraine, 2011.


Figure 1: Map of the Ganga and Brahmaputra basins (respectively delimited in red and blue) and sampling locations of sediments used in this study on the Ganga River, the Brahmaputra River and the lower Meghna River, which is the confluence of both rivers.

Figure 2: Total CEC determined by the sum of cations (Ca$^{2+}$ + Mg$^{2+}$ + Na$^+$ + K$^+$) released after sediment exchange with a CoHex solution (CEC$_{\Sigma cat}$) as a function of the total CEC determined based on the absorption of cobalt ions from the CoHex solution after exchange (CEC$_{UV}$). For each sample CEC$_{\Sigma cat}$ and CEC$_{UV}$ were determined on the same CoHex solution.
Figure 3: CEC of sediment samples from the Ganga, Brahmaputra and lower Meghna Rivers as a function of Al/Si that is used here as a proxy for grain size and sediment sorting in the river channel.
Figure 4: Molar fraction of major cations absorbed to sediments in the Ganga, Brahmaputra and lower Meghna Rivers as a function of Al/Si.

Figure 5: Maximum cation exchange fluxes (for a complete exchange of riverine Ca\(^{2+}\) for Na\(^+\)) and more probable exchange fluxes (partial exchange of riverine Ca\(^{2+}\) for Mg\(^{2+}\), K\(^+\) and Na\(^+\)) based on exchange data of Sayles and Mangelsdorf (1977; 1979) of G&B sediments. These exchange fluxes are compared to the total dissolved fluxes exported by the G&B as estimated by Galy and France-Lanord (1999).
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<td>1.48</td>
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<td>0.76</td>
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<td>11.51</td>
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</table>

The table presents the results of water sampling in the Ganges and Brahmaputra rivers. The data includes the sampling date, latitude, longitude, and various chemical parameters such as CEC (cmol/100g), Na, K, Cs, and Mg. The CEC (cmol/100g) is determined from the sum of major cations. The suspended fraction is given along with total CEC determined from the sum of major cations along with the total CEC K, CEC Ca, Na, K, Cs, and Mg.
The exchange coefficient for a binary Ca-Mg exchange in an average Ganga, Brahmaputra and lower Meghna river water composition is given for a p-exponent value of 1 and 0.76 as in Sayles and Mangelsdorf (1979), see test for more details. Samples BR1027 and BR207 are average values of n = 7 replicates each.

Table 2: Sediment fluxes (RSP, 1996), average CEC of the sediments and exchangeable flux of major cations bound to the river sediments.

| River                  | Average CEC meq/100g | Sediment flux Mt/yr | Total exchangeable Na meq/100g | Exchangeable Na 1e12 meq/yr | Probable exchange Na x10^8 mol/yr | Total exchangeable K meq/100g | Exchangeable K 1e12 meq/yr | Probable exchange K x10^8 mol/yr | Total exchangeable Ca meq/100g | Exchangeable Ca 1e12 meq/yr | Probable exchange Ca x10^8 mol/yr | Total exchangeable Mg meq/100g | Exchangeable Mg 1e12 meq/yr | Probable exchange Mg x10^8 mol/yr | Exchangeable Na | Exchangeable K | Exchangeable Ca | Exchangeable Mg |
|------------------------|----------------------|---------------------|-----------------------------|-----------------------------|----------------------------------|-----------------------------|-----------------------------|----------------------------------|-----------------------------|-------------------------------|---------------------------------|-----------------------------|-----------------------------|----------------|----------------|----------------|----------------|
| Ganga                  | 8.0 (±0.9)           | 550                | 44.0 (±50.0)                | 0.7 (±0.7)                  | -15.8 (±4.4)                    | 16.7 (±2.1)                 | 2.9 (±0.6)                  | -2.7 (±0.7)                    | 3.6 (±0.6)                  | 3.0 (±0.7)                  | -4.5 (±1.2)                    | 5.6 (±1.1)                 | 1.1 (±1.1)                  | 56.1 (±11.6)               | 1140           | 1140           | 1140           | 1140           |
| Brahmaputra            | 4.2 (±1.2)           | 590                | 24.8 (±7.1)                 | 0.4 (±0.4)                  | -1.6 (±0.5)                    | 2.9 (±0.6)                  | 1.6 (±1.5)                  | -1.5 (±0.4)                    | 2.0 (±0.7)                  | 2.5 (±0.7)                  | -2.5 (±1.2)                    | 4.9 (±1.3)                 | 1.1 (±1.1)                  | 56.1 (±11.6)               | 1140           | 1140           | 1140           | 1140           |
| lower Meghna           | 6.5 (±1.3)           | 1140               | 74.1 (±14.8)                | 1.1 (±1.1)                  | -2.9 (±2.5)                    | 29 (±2.9)                   | 1.6 (±1.5)                  | -1.5 (±1.4)                    | 4.0 (±1.3)                  | 4.0 (±1.3)                  | -2.7 (±13.0)                   | 4.9 (±1.3)                 | 1.1 (±1.1)                  | 56.1 (±11.6)               | 1140           | 1140           | 1140           | 1140           |

Table 3: Total exchangeable flux of major cations bound to the sediment in river water and most probable exchange fluxes taking place during interaction of G&B sediments with seawater based on the measured total exchangeable cations and the effective exchange proportions of Sayles and Mangelsdorf (1977; 1979). These fluxes are compared to the riverine dissolved fluxes as given by Galy and France-Lanord (1999).