Erosion and weathering fluxes in the granitic Strengbach catchment (Vosges massif, eastern France)

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Erosions- und Verwitterungs-Flüsse im granitischen Strengbach-Einzugsgebiet (Vogesen, Ost-Frankreich)

1 Introduction

Understanding the relationship between chemical weathering and physical erosion rates is an important issue for surface and environmental science; both processes affect studies of soil and landscape evolution and water quality. The determination of these relationships and the parameters controlling chemical weathering and physical erosion can be achieved by comparing weathering and erosion fluxes measured at the outlet of small watersheds (e.g., GABET, 2007; MILLOT et al., 2002). If numerous studies of chemical weathering fluxes exist, only a few of them focus on erosion fluxes. This is the case, for instance, for the Strengbach catchment, for which geochemical budgets have been established since the mid 1980s (e.g., PROBST et al., 1992) but for which physical erosion rates have been available only very recently.

The aim of the present study was to assess the physical erosion rate of the granitic Strengbach catchment along with the dissolved flux carried by the streamlet. The data, associated with the previously published weathering and erosion rates of other basins, are used to discuss the reliability of the relationships that have been determined between weathering and erosion rates. For the Strengbach catch-

Zusammenfassung

Am Auslass des granitischen Strengbach-Einzugsgebiets wurden zwischen 2004 und 2010 regelmäßige Beobachtungen des Schwebstoff- und Geschiebetriebs sowie der gelösten Stoffe analysiert. Die Erosionsrate beträgt im Gebiet 5 $t \cdot km^{-2} \cdot yr^{-1}$, wobei zwei Drittel der physikalischen Erosion zugeordnet sind und ein Drittel dem Geschiebetrieb entspricht. Die berechnete jährliche Netto-Verwitterungsrate für das Einzugsgebiet variiert zwischen dem Kationentransport (4,76 $t \cdot km^{-2} \cdot yr^{-1}$) und dem athmosphärenkorrigierten Transport (2 $t \cdot km^{-2} \cdot yr^{-1}$) um den Faktor 2. Verglichen mit anderen granitischen Einzugsgebieten liegen die Anteile der Verwitterungsprozesse (Verwitterung und Erosion) im Trend der Beobachtungen.

Schlagworte: Schwebstoffe, physikalische Erosion, chemische Verwitterung, granitische Einzugsgebiete, Strengbach.

Summary

Regular observations of the suspended sediment and bedload flux and also analysis of the dissolved load have been realized at the outlet of the granitic Strengbach catchment over the period 2004–2010. The physical erosion flux exported out of the catchment is of 3.3 $t \cdot km^{-2} \cdot yr^{-1}$ and the erosion rate carried by the bedload (1.7 $t \cdot km^{-2} \cdot yr^{-1}$) can reach one third of the total erosion rate (5 $t \cdot km^{-2} \cdot yr^{-1}$). The net annual weathering flux calculated for the watershed can differ by a factor of two or more (from a weathering flux of basic cations of 4.76 $t \cdot km^{-2} \cdot yr^{-1}$ to an atmosphere-corrected flux of 2 $t \cdot km^{-2} \cdot yr^{-1}$). Compared to other granitic catchments, the weathering budgets fit the general trend defined between the weathering rate and runoff, and the relationship between weathering and erosion rates does not differ significantly.

Key words: Suspended sediment load, physical erosion rate, chemical weathering rate, granitic catchments, Strengbach.

ment, the weathering rate is to be estimated from the flux of basic cations exported from the watershed and is therefore labelled in the text as CW. The erosion rate is assessed from the solid load carried by the stream, which consists of the suspended sediment load (SSL) and the bedload.

2 Study area and methods

The small Strengbach (0.8 km²) catchment is located on the eastern side of the Vosges massif (eastern France) at altitudes between 883 m and 1,146 m a.s.l. (PROBST et al., 1990). The up to 1-m-thick acidic soils overlay a < 10 m thick saprolite and a Ca-poor granitic bedrock. Norway spruce covers 65 % and mixed beech and silver fir 35 % of the catchment. The climate is temperate oceanic-mountainous; the mean annual precipitation is 1,400 mm, and the mean annual runoff is 814 mm, with high flow rates during the cold season. The site is well suited for multidisciplinary studies in hydrological, geochemical and forest research. The sampling, the analytical techniques and the fluxes determination are described in VIVILLE et al. (2012).

3 Results

3.1 Fluxes of suspended and bedload sediments

The mean SSL concentration is of 3.69 mg·L^{-1} (n = 213 samples, SD = 3.62 mg·L^{-1}). An important part of the SSL is exported during the major flood events in the snowmelt periods; for example, during March and April 2006, the flux was approximately half of the yearly flux out of the catchment (Fig. 1). Expressed in specific flux, the mean annual value is 3.3 t·km^{-2}·yr^{-1} and varies between 2.6 and 4.2 t·km^{-2}·yr^{-1}. This value is intermediate between the lowest values associated with low runoff observed in boreal zones and the highest values associated with the great amount of runoff in tropical zones (MILLOT et al., 2002). In addition to the suspended sediment fluxes, a yearly bedload deposit has been estimated for the period between October 2009 and September 2010 and correspond to a bedload mass flux of 1.4 t·yr^{-1} (1.7 t·km^{-2}·yr^{-1}). Meanwhile, further bedload determinations are necessary to constrain this value, which is usually characterised by a great inter annual variability.

3.2 Dissolved fluxes

Similar to the estimations of the SSL fluxes, the mean annual output fluxes of basic cations (Na, Ca, Mg and K) are 1.56, 2.14, 0.44 and 0.62 t·km^{-2}·yr^{-1}, respectively. The sum of these basic cations, which is used to estimate the CW flux, is 4.76 t·km^{-2}·yr^{-1}. This value is in the range of the values yet observed for the Strengbach catchment (PROBST et al., 1992; PROBST & VIVILLE, 2001). The output of the basic cation flux from the Strengbach watershed appears to be quite well correlated to the water fluxes.

The comparison of these new data of the Strengbach stream with those previously obtained by PROBST et al. (1992) point to a strong decrease in SO_4 concentration (110 to 60 µmol·L^{-1}) along with Ca (93 vs. 66 µmol·L^{-1}) and Mg (30 vs. 23 µmol·L^{-1}) concentrations over the last 20 years, while the Na concentration has been stable (85 µmol·L^{-1}). The variation observed for the past 20 years could be related to the release of sulphate that accumulated in the catchments during decades due to an acidic atmos-

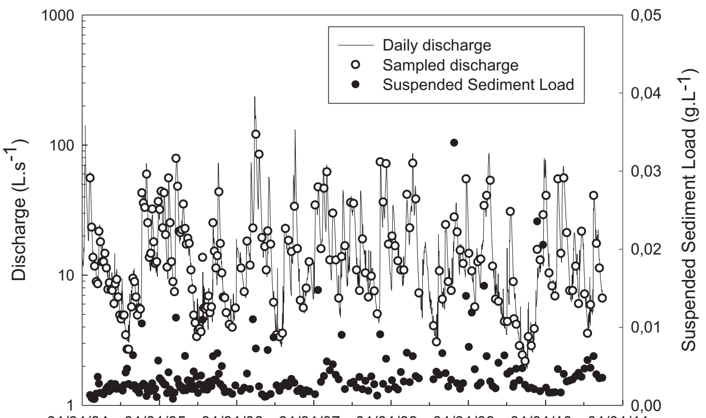

Figure 1: Suspended Sediment Load (SSL), daily and sampled discharge from January 2004 to September 2010

Abbildung 1: Schwebstofffracht (SSL), Tagesabflüsse und Beprobungsabfluss von Januar 2004 bis September 2010 pheric deposition similar to that of regions in Europe and northern America (Harriman et al., 2001; Stoddard et al., 1999); for almost all of these regions, a basic cation decrease has been observed.

4 Discussion

4.1 Robustness of the estimated mean fluxes

The estimation of chemical weathering and physical erosion implicitly depend on the classical assumption that these fluxes are representative for the values actually exported out of the catchment. In the Strengbach catchment, the discrete data set (213 values) corresponding to the discharge measurements at the time of the water and sediment collection yields a mean discharge value of 18.0 $L \cdot s^{-1}$; it is similar to the mean discharge calculated by using the continuous discharge record for the period 2004–2010 (17.9 $L \cdot s^{-1}$), suggesting that the variances are homogeneous.

The influence of the sampling time step on the SSL flux estimation has been studied at a daily time step basis for large watersheds (Coynel et al., 2004; Moatar et al., 2006). The results show that the reliability of the flux determinations strongly decreases when the time lag increases; but a weekly or even a fortnightly sampling is sufficient to allow the determination of fluxes at a ±20 % level, in comparison with a daily sampling and for a great number of rivers, as shown by Moatar et al. (2006). We therefore suggest that the estimated suspended sediment flux in the Strengbach catchment, which is based on a fortnightly sampling, yields a first and realistic value with an accuracy of ±20 %. On the other hand, the reliability of the bedload determination could be questioned further. However, at this stage, it is the first bedload flux given for the Strengbach catchment, representing approximately 50 % of the suspended flux; it is therefore not negligible.

The dissolved load fluxes of the Strengbach waters do not significantly differ (e.g., < 1 % for Ca and Na) due to the weak variation of the concentrations (Coefficient of Variation < 10 % for almost all of the elements). Therefore, the accuracy of the determination of the dissolved load can be considered very reliable.

4.2 Determination of the CW flux

As presented in §3.2, the flux of basic cations out of the Strengbach catchment is of 4.76 $t \cdot km^{-2} \cdot yr^{-1}$. This value cannot be directly associated with the weathering flux of the watershed because part of this flux includes atmosphere-derived material. As the watershed is largely covered by forest, the canopy collects a significant part of this "occult" material (particles, gas, dust). These deposits are leached by rain from the canopy and thereby brought by throughfall to the global chemical flux exported from the watershed.

The estimation of the atmospheric contribution to the chemical budget of the Strengbach waters is not so straightforward. Here, we decided to use the approach proposed in previous studies of the same site (Probst et al., 1992): the wet deposits are estimated from open field rainwater collected on one site of the watershed and the "occult" deposits are calculated from the analyses of throughfall corrected for biological cycling according the procedure

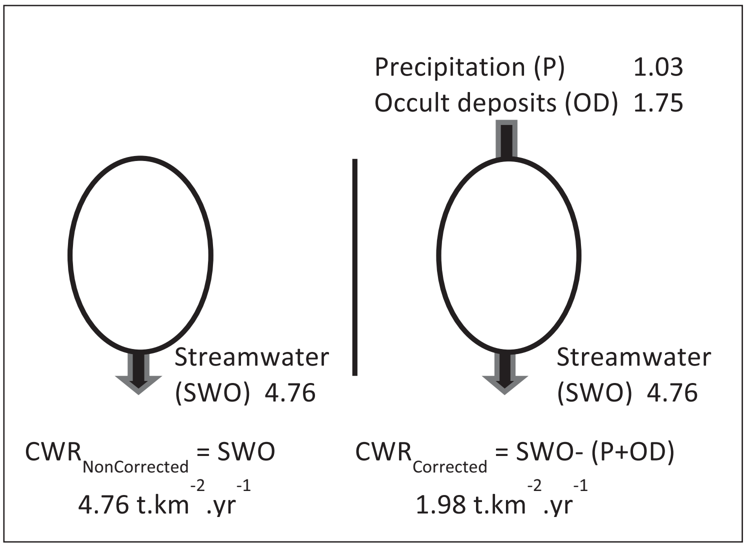

Figure 2: Chemical weathering rate without (left) and with atmospheric correction (right)

Abbildung 2: Chemische Verwitterungsrate ohne (links) und mit atmosphärischer Korrektur (rechts) of LINDBERG et al. (1986). The atmosphere corrected CW flux is 1.98 t·km^{-2}·yr^{-1} for the period 2004–2010 and is thus much lower than the streamwater output of 4.76 t·km^{-2}·yr^{-1} (Fig. 2).

This corresponds to a global atmospheric contribution of approximately 50 %. Indeed, the mean atmospheric contribution is approximately 2.78 t·km^{-2}·yr^{-1} for the 2004–2010 period. This value is similar to that determined for the period 1986–1990 but is higher than the values obtained in the 1990s. It seems that, more recently, the throughfall has increased significantly for some elements (K, Na). The reasons for these changes remain unclear and further investigation is needed to clarify this matter.

Nonetheless, whatever the value and parameters used for calculation of the CW flux, an important result is that this flux increases with increasing runoff. Such a relationship probably indicates that, even for a watershed disturbed by recent acidic atmospheric inputs, the main parameter controlling the weathering intensity remains the water flux circulating through the watershed. This does not mean that the anthropogenic impact has no influence on the weathering processes in the watershed, but that this impact is of a second order of importance (VIVILLE et al, 2012).

The chemical fluxes calculated for the Strengbach catchment fit the general trend defined by the other granitoid watersheds as shown in the diagram of CW rate vs. runoff (Fig. 3). The data set results from the compilation of MILLOT et al. (2002) and of data from other watersheds in which dissolved fluxes were available (VIVILLE et al., 2012). The consistency between these data confirms the above interpretation that the main parameter triggering the intensity of weathering flux is the runoff of the watershed.

4.3 Comparison of chemical weathering rate and physical erosion rate

A total erosion value of 5 (3.23 + 1.75) t·km^{-2}·yr^{-1} can be calculated from the SSL and bedload values for the Strengbach catchment for the year 2009–2010. This value is low compared to other granitic catchments, but it falls within the range of their sedimentary flux (and hence the erosion rate). This shows that the export of sediments in the Strengbach catchment is important; it is of at least the same order of magnitude as the export of dissolved load and is likely to be of greater importance if the atmospheric impacts are considered.

At a global scale, it has been found that a positive relationship exists between the CW and erosion rates; which corresponds to the widely accepted idea that physical erosion and chemical weathering are interrelated processes.

To illustrate this point, we have added to Millot's initial compilation five new granitoid catchments for which both the CW rate and the physical erosion rate have been estimated. All these catchments fit in the granitoid trend defined in the diagram, which plots the CW flux against runoff (Fig. 3). By contrast, when the data points are plotted in the diagram of the CW rates versus physical erosion rate, the correlation defined by the granitoid watersheds is clearly deteriorating compared to that defined without the newly added five watersheds (Fig. 4). The Strengbach catchment plots above the granitoid catchment trend, for example, but the bias is actually very dependent on the value obtained for the CW flux. This bias is important when the CW flux is the rough flux calculated without atmospheric correction, whereas it is much smaller when corrected for atmospheric

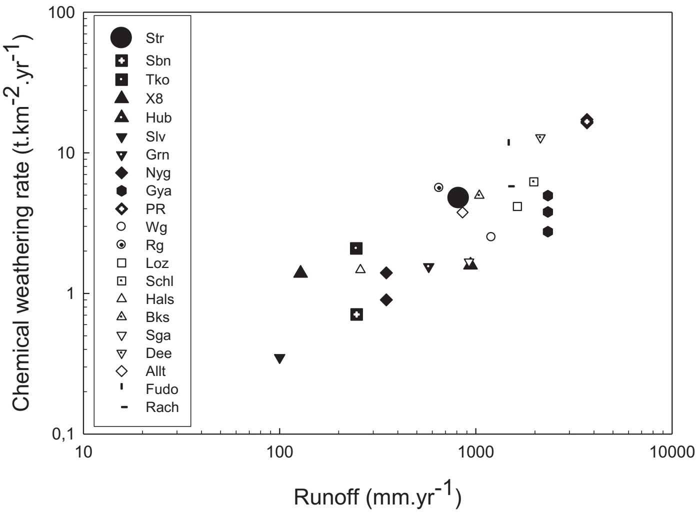

Figure 3: Relationship between the chemical weathering rate and runoff in granitoid catchments (Str – Strengbach)

Abbildung 3: Beziehung zwischen chemischer Verwitterung und Abfluss im granitischen Einzugsgebiet (Str – Strengbach) deposition. The fact that the atmospheric corrections have not (or have differently) been performed for all watersheds may explain the scattering of some of the data points in Figure 4. In some cases, corrections for atmospheric depositions have been performed by using a Cl-budget approach or a method using the Na/Cl ratio; in other cases, corrections have been performed by taking into account precipitation and throughfall (the Storbergsbäcken, Hubbard Brook and Strengbach catchments) whereas no corrections have been performed for the two remaining watersheds (the Tinkisso and X8 catchments). Furthermore, the biomass uptake is taken into consideration only in a restricted number of catchments (Hubbard Brook and Storbergsbäcken). In addition, the sampling strategy retained for estimating the fluxes differs from one watershed to another; these strategies are derived from annual averaged budgets or from spot samples, a fact that influences the reliability of the mass balance calculations. Therefore, some doubts remain about the reliability of the theoretical laws established up to now to describe the relationship between weathering and erosion rates. To confirm or refine these laws, it is now essential to have a set of watersheds for which all the components necessary for drawing up the weathering and erosion budgets are available and known with a sufficiently good accuracy. This would permit to correctly take into account the erosion flux transported as bedload, which, as for the Strengbach catchment, is not negligible. In future studies one should also determine more precisely the budgets by taking into account the atmospheric input, the biomass uptake and the biomass output when forested harvesting occurs.

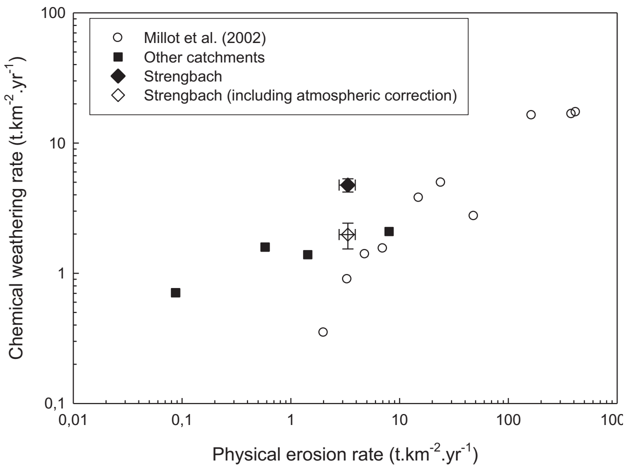

Figure 4: Relationship between the rates of chemical weathering and physical erosion (SSL) in granitoid catchments (other catchments; Storbergsbäcken: Northern Sweden (LAND & ÖHLANDER, 2000); Tinkisso: West Africa (ORANGE, 1992); W6-Hubbard Brook; New England (KIRCHNER, 1992; MARTIN et al., 2000); X8 Salacova Lhota at Trnavka: Czech Republic (JICINSKY & PACES, 1980))

Abbildung 4: Beziehung zwischen chemischer Verwitterungsrate und physikalischer Erosion (SSL) im granitischen Einzugsgebiet (andere Einzugsgebiete: Storbergsbäcken: Nordschweden (LAND & ÖHLANDER, 2000); Tinkisso: Westafrika (ORANGE, 1992); W6-Hubbard Brook; New England (KIRCHNER, 1992; MARTIN et al., 2000); X8 Salacova Lhota at Trnavka: Tschechische Republik (JICINSKY & PACES, 1980))

5 Conclusions

The continuous determination of dissolved, suspended matter and bedload fluxes has allowed the first estimation of the whole budget of the weathering and erosion balance for the Strengbach catchment. These results show that the erosion rate is at least equivalent to the chemical weathering rate of basic cations (CW) and could be twice this rate, depending on the corrections applied in estimating this CW rate. The erosion rate based only on suspended matter calculation, without considering bedload, induces an underestimation of approximately 30 %.

The results emphasise the importance of the determination of the whole solid fluxes exported from the catchments for the precise assessment of erosion rates. They also indicate that, to evaluate the net impact of a forested cover on the biogeochemical cycles, the weathering budgets need to be improved regarding the fluxes influenced by the vegetation. This is necessary for the correct estimation of the relationship between physical erosion and CW.

For the Strengbach catchment, the data show that the runoff is the main factor controlling the weathering flux interannual variations. Meanwhile, a slight decrease of the mean CW flux has been observed for the past twenty years and might be related to environmental modifications. Finally, this study indicates that the relationship between CW and erosion rates determined for the Strengbach catchment does not significantly differ from those established for other previously studied granitoid catchments.

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References

COYNEL, A., J. SCHÄFER, J.E. HURTREZ, J. DUMAS, H. ETCHEBER and G. BLANC (2004): Sampling frequency and accuracy of SPM flux estimates in two contrasted drainage basins. Science of the Total Environment 330, 233–247.

GABET, E.J. (2007): A theoretical model coupling chemical weathering and physical erosion in landslide-dominated landscapes. Earth and Planetary Science Letters 264, 259–265.

HARRIMAN, R., A.W. WATT, A.E.G. CHRISTIE, P. COLLEN, D.W. MOORE, A.G. MC CARTNEY, E.M. TAYLOR and J. WATSON (2001): Interpretation of trends in acidic deposition and surface water chemistry in Scotland during the past three decades. Hydrology and Earth System Sciences 5(3), 407–420.

JICINSKY, K. & T. PACES (1980): The flux of elements in suspended matter from experimental drainage basins in central Bohemia. In: The influence of man on the hydrological regime with special reference to representative and experimental basins (Proceedings of the Helsinki Symposium, June 1980) IAHS Publ. 130, 271–276.

KIRCHNER, J.W. (1992): Heterogeneous geochemistry of catchment acidification. Geochimica et Cosmochimica Acta 56, 2311–2327.

LAND, M. & B. ÖHLANDER (2000): Chemical weathering rates, erosion rates and mobility of major and trace elements in a boreal granitic till. Aquatic Geochemistry 6, 435–460.

LINDBERG, S.E., G.M. LOVETT, D.D. RICHTER and D.W. JOHNSON (1986): Atmospheric deposition and canopy interactions of major ions in a forest. Science 231 (4734), 141–145.

MARTIN, C.W., J.W. HORNBECK, G.E. LIKENS and D.C. BUSO (2000): Impacts of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Can. J. Fish. Aquat. Sci. 57 (Suppl. 2) 19–29.

MILLOT, R., J. GAILLARDET, B. DUPRÉ and C.J. ALLÈGRE (2002): The global control of silicate weathering rates and the coupling with physical erosion: new insights from rivers of the Canadian Shield. Earth and Planetary Science Letters 6095, 1–16.

MOATAR, F., G. PERSON, M. MEYBECK, A. COYNEL, H. ETCHEBER and P. CROUZET (2006): The influence of contrasting suspended particulate matter transport regimes on the bias and precision of flux estimates. Science of the Total Environment 370, 515–531.

ORANGE, D. (1992): Hydroclimatologie du Fouta Djalon et dynamique actuelle d'un vieux paysage latéritique (Afrique de l'Ouest). Sciences Géologiques Mémoire 93.

PROBST, A. & D. VIVILLE (2001): Bilan hydrogéochimique du petit bassin versant forestier du Strengbach à Aubure (Haut-Rhin). Rapport d'activité scientifique 1997–2000. Synthèse, IFARE, Karlsruhe-Strasbourg, 97–110.

PROBST, A., E. DAMBRINE, D. VIVILLE and B. FRITZ (1990): Influence of acid atmospheric inputs on surface water chemistry and mineral fluxes in a declining spruce stand within a small catchment (Vosges massif, France). Journal of Hydrology 116, 101–124.

PROBST, A., D. VIVILLE, B. FRITZ, B. AMBROISE and E. DAMBRINE (1992): Hydrochemical budgets of a small forested granitic catchment exposed to acid deposition: the Strengbach catchment case study (Vosges massif, France). Water, Air and Soil Pollution 62, 337–347.

STODDARD, J.L., D.S. JEFFRIES, A. LÜKEWILLE, T.A. CLAIR, P.J. DILLON, C.T. DRISCOLL, M. FORSIUS, M. JOHANNESSEN, J.S. KAHL, J.H. KELLOGG, A. KEMP, J. MANNIO, D.T. MONTEITH, P.S. MURDOCH, S. PATRICK, A. REBSDORF, B.L. SKJELVALE, M.P. STAINTON, T. TRAAEN, H. VAN DAM, K.E. WEBSTER, J. WIETING and A. WILANDER (1999): Regional trends in aquatic recovery acidification in North America and Europe. Nature 401, 575–578.

VIVILLE, D., F. CHABAUX, P. STILLE, M.C. PIERRET and S. GANGLOFF (2012): Erosion and weathering fluxes in granitic basins: The example of the Strengbach catchment (Vosges massif, eastern France). Catena, 92, 122–129.

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