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Active channel width as a proxy of sediment supply from mining sites in New Caledonia

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Abstract

Although channel morphology of upland fluvial systems is known to be strongly controlled by sediment supply from hillslopes, it is still difficult to isolate this effect from the other controlling factors of channel forms, such as the sediment transport capacity (depending notably on the size of the catchment) and local conditions (e.g., confinement, riparian vegetation, valley-floor slope). The rivers in New Caledonia offer an interesting field laboratory to isolate the morphological effect of contrasted sediment supply conditions. Some of these rivers are known to be highly impacted by the coarse sediment waves induced by the mining of nickel deposits that started in the early 1870s, which was particularly intensive between the 1940s and 1970s. The propagation of the sediment pulses from the mining sites can be traced by the presence of wide and aggraded active channels along the stream network of nickel-rich peridotite massifs. A first set of 63 undisturbed catchments in peridotite massifs distributed across the Grande Terre was used to fit a classic scaling law between active channel width and drainage area. A second set of 86 impacted sites, where the presence of sediment waves was clearly attested by recent aerial imagery, showed systematically wider active channels, with a width ratio around 5

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(established from the intercept ratio of width-area power laws). More importantly, this second set of disturbed sites confirmed that the residual of active channel widths, computed from the scaling law of undisturbed sites, is statistically positively related to the catchment-scale relative area of major mining sediment sources. It is therefore confirmed that the characterization of sediment supply conditions is crucial for the understanding of spatial patterns of active channel width, and this should be more thoroughly considered in morphological studies of rivers draining environments with contrasted geomorphic activities on hillslopes.

Introduction

Mining activities may significantly alter catchment-scale sediment dynamics by rapidly delivering considerable volumes of sediment to the stream network. The downstream transfer of coarse mining wastes and associated effects on channel morphology were first described as sediment waves (Gilbert, 1917). Since then this concept has been reexamined and redefined to better differentiate mining effects on channel morphology from those impacting sediment fluxes. The concept of bed wave was then introduced to refer to bed elevation changes of impacted stream reaches. The term “sediment wave” was then restricted to describe the impacted sediment fluxes (Hoey, 1992; James, 2006). Regardless of these terminology clarifications, the consequences are that mining activities contribute to building massive alluvial stores in valley floors that may impact sediment transport and channel conditions long after mines have been closed. This is known as the sediment legacy problem (James, 2010). Some well-known examples of mining impacts on fluvial systems are described in the literature, such as gold mining in the Sacramento River basin (Sierra Nevada, California), which produced 2.1 Gt of mining wastes over 31 years (James, 2006). Another well-documented case study is the Ringarooma River in Tasmania where alluvial tin mining introduced 40 million m^3 of mining wastes into the stream network (Knighton, 1989). Such dramatic sediment transport alterations raise management issues that are extremely difficult to solve, despite attempts to control or remove mine tailings (Kondolf et al., 2002).

Channel responses to increased sediment supply have been well documented from a large set of case studies including examples of mining impacts, but also dam failure (Pitlick, 1993), extreme floods (Nelson and Dubé, 2016), large landslides

(Germanoski and Schumm, 1993; Shimazu and Oguchi, 1996) and deforestation (Germanoski and Schumm, 1993; Madej and Ozaki, 1996; Gomez et al., 2001). The sediment feeding can greatly modify channel morphology by widening and aggrading active channels, resulting in the development of megaforms of sediment storage, sometimes referred to as sedimentation zones (Church and Jones, 1982; Hoey, 1992; Nicholas et al., 1995). The transformation of meandering patterns into braided patterns along large alpine rivers in France at the end of the Middle Ages has been interpreted for example as resulting from the Little Ice Age erosion crisis (Bravard, 1989). Once sediment supply starts to decline and progressively returns to pre-disturbance conditions, a degradation stage initiates upstream and propagates downstream (Liébault et al., 2005; James, 2006) while the aggradation stage is still observed downstream (Hoey, 1992; Germanoski and Harvey, 1993; Pitlick, 1993; Nicholas et al., 1995). This degradation stage leaves behind remnant terraces into which a new floodplain is progressively built. Vegetation establishes rapidly on these surfaces, leading to active channel narrowing (Liébault and Piégay, 2002). Thus, active channel width, defined as the area occupied by low-flow channels and unvegetated gravel bars (e.g., Liébault and Piégay, 2002; Haschenburger and Cowie, 2009), can be viewed as a sensitive metric informing about the spatiotemporal dynamics of bed waves, as exemplified by Jacobson and Gran (1999), who successfully used the longitudinal distribution of the gravel-bar area to document megaforms of sediment storage related to land-use changes. Gravel accumulation patterns were also used here to validate a simple model of sediment routing from disturbance sites along the stream network.

Since the early developments of hydraulic geometry in the 1950s (Leopold and

Maddock, 1953), we know that the active channel width of alluvial rivers increases nonlinearly with bankfull discharge, and therefore with drainage area. This kind of scaling law has been recently tested in braided rivers in southeastern France to develop a metric called *W**, which can be seen as the residual variance of the width once the catchment size effect has been removed (Piégay et al., 2009). This normalized width was successfully used to rank braided rivers according to their sediment supply conditions (Belletti et al., 2013). The analysis of historical long profiles also revealed that aggrading braided rivers during the last 100 years present higher normalized widths than degrading ones (Liébault et al., 2013). It therefore seems promising to use scaling power laws between active channel width and drainage area (in the form $W = \alpha {A_d}^{\beta}$, with W, the active channel width, and A_d, the drainage area) to infer sediment supply conditions, and therefore the magnitude of impact from mining activities along a stream network. For a given drainage area, one should expect a wider active channel for high sediment supply conditions, provided that other controlling factors independent of the catchment size do not play a critical role in explaining the variability of active channel width. These governing factors can be summarized in a conceptual scheme illustrating the complexity of interacting processes involved in the lateral development of channel geometry (Figure 1). The factors that may explain residuals from a drainage size scaling law not only concern sediment supply conditions, but also local conditions, such as lateral confinement or riparian vegetation conditions, as well as hydrological contingency, since it is well known that extreme floods may induce temporary active channel widening (Arnaud-Fassetta et al., 2005; Belletti et al., 2014; Rinaldi et al., 2016). Geological conditions governing the sensitivity to erosion (mainly lithology and tectonics) are considered here as second-order control, included in the sediment supply conditions.

In this study, we explored how the normalized active channel width variability at the scale of the New Caledonian peridotite massifs can be used to identify the reaches impacted by a large sediment supply from mining sites. The first step was to produce a scaling law between active channel width and drainage area for undisturbed river reaches in peridotite massifs, which can be seen as a reference condition of channel morphology from which residuals can be computed. The second step was to characterize residuals from reference conditions for a large set of channel reaches impacted by mining activities. The last step was to test for a correlation between these residuals and the magnitude of sediment supply from mining sites in the catchment, to confirm that the normalized active channel width can be used as a proxy of the mining impact on coarse sediment transport.

Study area

Physical setting

This paper investigated a large set of rivers draining peridotite massifs of the Grande Terre of New Caledonia, a NW-SE large and elongated Pacific island located about 1200 km east of Australia, between 163°30′ E and 168°15′ E, and 19°30′ S and 23°03′ S (Figure 2). The Grande Terre covers an area of 16,750 km², with elevations ranging from sea level to 1630 m a.s.l. It is mainly composed of a rugged and forested mountain range, partitioning the island into an eastern coast exposed to the dominant wind and diving steeply into the sea, and a western coast mainly composed of wide plains gently sloping from the foothills to the ocean. The climate is tropical oceanic, with two major seasons: (i) a hot and humid season between November and April during which hurricanes and tropical storms may occur and (ii) a colder and drier season between June and September. The temperatures are warm throughout the whole year, with mean annual temperatures ranging from 6° on the highest reliefs to 24° on the coast (Bird et al., 1984). Contrasting rainfall regimes are observed from each side of the mountain range, with mean annual rainfalls between 2000 and 3000 mm on the east side, and 1000 mm on the west side (Bird et al., 1984). Extreme mean annual rainfalls can reach more than 5 m on the reliefs.

On the Grande Terre, the main geologic formation (about one-third of the surface) is composed of peridotite massifs, which are residuals of an ophiolite sheet that covered the main island by obduction during Eocene (Guillon and Routhier, 1971; Cluzel et al., 2012). Under the tropical and humid climate, the ultrabasic rocks are highly altered in a thick layer, first as saprolite, then as laterite, allowing the nickel to percolate and concentrate as veins into the lower layer.

Mining activity

Nickel mining is the most important economic activity of New Caledonia, as the island contains 30–40% of the known nickel ore resources on Earth (Bird et al., 1984). The presence of nickel was discovered in 1864 and mining started in the early 1870s, but ore production stayed relatively moderate until World War II (Gay, 2014). From the late 1940s, the mechanization of ore exploration and production induced a dramatic increase in mining activity, with the exploitation of deeper and less rich deposits of laterites and saprolites (Danloux and Laganier, 1991). Since that time, the nickel production rate has fluctuated according to the nickel market value. The maximum production rate occurred during the nickel boom between 1967 and 1971 (Gay, 2014).

Nickel exploitation in New Caledonia proceeds by opencast mining, resulting in large deforested and excavated surfaces on mountain ridges (Figure 3a), from which active erosion processes were initiated. However, the main mechanism by which mining wastes enter the stream network is the direct dumping of debris into headwaters. This practice was active until its prohibition by a new mining regulation in the early 1970s. Therefore, most of the elementary headwater catchments below mining sites are characterized by massive accumulations of loose debris forming artificial cones or talus slopes from which active erosion processes such as gullying and landsliding initiate (Figure 3b). Exploration and exploitation roads opened on forested hillslopes have also dramatically modified the slope hydrology and are generally the sources of active erosion processes (Figure 3c). The sediment supply from mining activity conducted in some places to the downstream progradation of large sediment waves that has impacted the channel morphology of several rivers draining the peridotite massifs (Figure 3d).

Since the 1970s, mining wastes have to be stored in safe conditions on flat terrains at the mining sites and can no longer be dumped into ravines, but impacts on the sediment transfers are still visible on large portions of the rivers (Iltis, 1990). The sediment transfers from slopes to the stream network caused massive widening and aggradation of active channels. A few management actions, such as the dredging of the most aggraded river channels located close to villages, were conducted to reduce the flooding risk for rural populations.

Material and methods

The analyses presented here are based on a 10-m resolution digital elevation model

(DEM) and 2008 orthophotos at a spatial resolution of 50 cm.

Defining and predicting reference conditions of active channel width

We selected 63 channel reaches considered as undisturbed by mining activity (23 and 40 catchments on the west and east sides of the Grande Terre, respectively), spatially distributed across the peridotite massifs (homogeneous geological conditions) with a wide range of catchment sizes. This sample was constituted based on a visual inspection of the most recent orthophotos. The undisturbed character was defined according to the following rule-based approach: (1) no detected past and/or present mining activity in the catchment, or (2) if a mining activity is observed (presence of a mining site and/or exploitation or prospection roads), no sediment wave was detected in the downstream vicinity of the mining sites, or (3) the site is located downstream of the propagation front of the sediment waves induced by mining activity. This last rule was adopted for the integration of large catchments in the sample, because it is almost impossible to find large rivers without any mining site in their basin, due to the widespread diffusion of nickel exploitation across the peridotite massifs. Although the sites selected according to the third rule cannot be rigorously considered as undisturbed by mining, it seems reasonable to consider that their channel morphology has not been affected by a massive coarse sediment supply from mines.

An expert-based selection of sites was adopted instead of a random sampling of channel reaches. This allows avoiding a time-consuming preliminary step of manual extraction of the stream network suitable for assessing the relation between active channel width and drainage area, which is required for the masking of reaches where active channels are excessively constrained by local conditions (confinement, obstruction, human-induced artificialization). The total catchment area of selected sites (including impacted sites presented in the following section) represents around 40% of the peridotite massifs. This percentage is even higher if we do not consider the southern-most part of the peridotite massifs (the *Massif du Sud*), which is characterized by specific relief and geological conditions. The relief shows lower slopes, lower elevations, and subsequently a lower drainage density. Several hanging flat and large plains are observed here, such as the *Plaine des Lacs* or the Plaine de Yaté. The geology shows large outcrops of peridotite regolith and late Cenozoic fluvio-lacustrine deposits. We should therefore expect here a different morphological signature of active channels, certainly not incorporated into our observations, but not really representative of the peridotite massifs. This sub-region apart, our sample of catchments is homogeneously distributed across the mountainous peridotite units (Figure 2). It should also be noted that a large part of the stream network in the southern-most part of New Caledonia has been submerged or impacted by the construction of a large dam and its reservoir (Yaté Lake).

Several metrics were extracted using GIS procedures to characterize the reference conditions. The aim is to predict the undisturbed active channel width of rivers draining peridotite massifs using reach-scale and catchment-scale metrics (Figure 1). We digitized the active channel of each reach from a photo-interpretation of the orthophotos (acquisition at the 1/1000 scale), on a length ten times the width of the active channel. We adapted the procedures that were developed in the *FluvialCorridor* toolbox (Roux et al., 2015) in order to calculate the average width based on ten equally spaced active channel transects.

The average valley floor width was obtained by delineating the valley floor extent with the Multiresolution Index of Valley Bottom Flatness (MRVBF) algorithm available in SAGA software (Gallant and Dowling, 2003). The average width was obtained from ten regularly-spaced valley floor transects. Finally the channel slope was also extracted for each reach, calculated as the difference in elevation between both ends divided by the reach length.

The drainage area of each reach was obtained from a classic automatic delineation procedure using TAUDEM (Tarboton et al., 2009) and a 10-m resolution DEM. Each catchment polygon was manually checked and corrected if needed. The mean catchment slope, calculated as the averaged value of pixels within the catchment, was extracted. The proportion of the catchment area covered by forested area, based on a 2008 land-cover map (*Service de la Géomatique et de la Télédétection du gouvernement de la Nouvelle-Calédonie*), was also extracted.

Mapping of sediment sources

To characterize catchment-scale sediment supply conditions of undisturbed sites, an expert-based geomorphic mapping of sediment sources using an aerial photo-interpretation approach (Brardinoni et al., 2015) was done for each catchment by the same operator (Figure 4). The 2008 orthophotos with 10-m contour lines from the DEM were used as a basis for mapping. Sediment sources were defined as patches of active erosion on hillslopes where a connection to the stream network can be considered as effective. The effectiveness of the sediment connection was based on the proximity of the erosion patch to a thalweg recognized directly from images or indirectly from contour lines. Once a sediment source had been detected and delineated, a binary attribute was assigned to each patch according to the presence or absence of any mining activity (e.g., a mining site or an exploitation or exploration road) that can explain the initiation of erosion. Three variables were computed from this sediment source map: (1) the relative surface of total sediment sources, (2) the relative surface of sediment sources related to mining activities, and (3) the relative surface of sediment sources not related to mining activities.

Evaluating active channel width signature of impacted sites

To characterize and predict the active channel width under disturbed conditions by mining activities, 86 impacted sites were selected based on expert analysis of the 2008 orthophotos. The disturbed character was defined according to the following rule-based approach: presence of mining activity (mining site and/or exploration or exploitation roads) in the catchment, and detection of at least one sediment wave initiation and progradation from the mining sites.

We extracted for those sites the same reach-scale and catchment-scale metrics as for undisturbed sites: i.e., the active channel width, valley bottom width, channel slope, drainage area, mean catchment slope, proportion of the catchment area covered by forested area, and proportion of catchment area covered by sediment sources. For these 86 sites, we also differentiated the sediment sources related to mining activity that generated a sediment wave within the fluvial system and calculated their proportion within the catchments (Figure 4).

Results

Reference conditions of active channel width

The best scaling law between active channel width (W_a) and drainage area (A_d) for non-impacted sites was obtained with a linear regression model based on log-transformed data (Figure 5 and Equation 1) (p-value < 0.001 with an adjusted R^2 of 0.66 and an *AIC* criterion of 81.73). Intercept and slope 95% confidence intervals are 1.13–1.59 and 0.35–0.50, respectively. This confirms the classic size effect related to the dependency of water discharge and sediment load on drainage basin size, both key controlling factors of alluvial channel geometry. This empirical model can be considered as representative of the active channel regime of undisturbed rivers draining the peridotite massifs of New Caledonia.

Equation 1

$$\log(W_a) \ = 0.42\,.\log(A_d) + \ 1.36$$

Due to the contrasting rainfall regimes between the western and eastern sides of the Grande Terre, one could expect wider active channels for a given drainage size on the eastern humid side. This was confirmed by the data, revealing a slight east–west pattern of the morphological signatures (Figure 5, Table 1). For the same drainage area, active channel widths are on average 1.12 times wider on the east side of the island, as attested by differences of intercepts (Student t-test p-value = 0.06). No statistically significant difference was obtained for the slopes of the regressions (Student t-test p-value = 0.57), which means that the rate at which the width increases with drainage area is the same on both sides of the island.

A multiple linear regression model was tested to search for a better predicting model of undisturbed channel conditions, including the effect of other metrics that were significantly correlated with the active channel width: the average floodplain width (p-

value < 0.001 with R^2 of 0.19), the channel slope (p-value < 0.001 with R^2 of 0.34), or the proportion of the catchment area covered by forested area (p-value < 0.001 with R^2 of 0.16). All these variables were log transformed and the coordinates were calculated on the axis derived from a principal component analysis (PCA) to avoid collinearity. The results obtained from the multivariate analysis did not really improve the prediction using the simple linear regression model based on drainage area. Therefore, this simple bivariate model was used for the definition of reference conditions.

Active width signature of impacted sites

The morphological signature of impacted sites confirmed a dramatic effect of mining-induced sediment waves on active channel widths of rivers draining peridotite massifs, as can be seen on the W_a versus A_d scatterplot (Figure 6). All the impacted sites are situated above the reference condition line established from undisturbed sites, without any exception. The linear regression model based on the impacted sites' log-transformed data shows a high R^2 (0.62, p-value < 0.001) (Equation 2). Intercept and slope 95% confidence intervals are 2.80–3.07 and 0.25–0.36, respectively. The width ratio obtained from the ratio of intercepts of power laws for disturbed and undisturbed sites is 4.8. This means that for a unit drainage area, the active width of disturbed sites is on average five times larger than for undisturbed sites. Disturbed sites also display a lower increasing rate of active width with drainage area as compared to disturbed sites, as attested by the significantly lower slope of the regression. This can be seen as a sign of attenuated or more diluted mining impact for distal conditions.

Equation 2

$$\log(W_a) \ = 0.31\,.\log(A_d) + \ 2.94$$

The distance of impacted sites from the reference line shows great variability, which can be seen as the magnitude of the impact of mining on channel morphology. A residual width (noted W_a*), calculated as the difference between the observed and predicted (with Equation 1) log-transformed widths, was used to test for a correlation with sediment supply conditions in the catchment. One explanatory variable that is relevant for the prediction of W_a* is the proportion of catchment area covered by sediment sources feeding a sediment wave (SS_w). The data confirm a strong and significant positive correlation between these two variables, using a linear fit after log transformation ($R^2 = 0.44$, p-value < 0.001, *AIC* criterion = 102.02, *RMSE* = 0.43) (Figure 7).

As both variables share a common term (drainage area), several tests for spurious correlation were done (Kenney, 1982). The first test was based on the computation of the partial correlation coefficient (A_d being fixed) following Equation 3 (Fisher, 1924):

Equation 3

$$r_{\mathrm{Wa*SSw}.A_d} = \frac{r_{\mathrm{Wa*SSw}} - r_{\mathrm{Wa*}A_d} \cdot r_{\mathrm{SSw}A_d}}{\sqrt{1 - {r^2}_{\mathrm{Wa*}A_d}} \cdot \sqrt{1 - {r^2}_{\mathrm{SSw}A_d}}}$$

where:

$$r_{\mathrm{Wa*}RE} = \frac{Cov(\mathrm{Wa*},\ \mathrm{SSw})}{\sigma_{\mathrm{Wa*}} \cdot \sigma_{\mathrm{SSw}}}$$

$$r_{\mathrm{Wa*}A_d} = \frac{Cov(\mathrm{Wa*},\ A_d)}{\sigma_{\mathrm{Wa*}} \cdot \sigma_{A_d}}$$

$$r_{REA_d} = \frac{Cov(\mathrm{SSw}\,,\ A_d)}{\sigma_{\mathrm{SSw}} \cdot \sigma_{A_d}}$$

with *Cov* and σ the covariance and the standard deviation, respectively.

The correlation coefficient between W_a* and SS_w is 0.67, and the partial correlation is 0.55. This slight difference shows that the significance of SS_w in explaining W_a* is due, to a very small extent, to a size effect.

A second test was done by randomly producing 1000 series of W_a*, SS_w, and A_d (with the same number of impacted sites as in the original sample), following a similar procedure as the one presented by Jackson and Somers (1991). The random sampling was constrained to preserve the normal distributions of the original data sample. The R^2 between $\mathrm{W_a}$* and SS_w in these 1000 series are quite low. The 0.95 quantile of R^2 (0.42) is almost equal to the value of adjusted R^2 observed for the original sample (0.44). It confirms that the presence of A_d in both the terms $\mathrm{W_a}$* and SS_w does not generate a strong spurious correlation effect, and that the high R^2 in the original sample does not reflect a size effect.

Discussion

Reference conditions of active channel width

A robust regional scaling law between the active channel width and the drainage area for undisturbed alluvial systems of the New Caledonian peridotite ranges was calibrated with 63 channel reaches. The best fit was obtained with a classic power-law function, with a β exponent of 0.42 and an α coefficient of 3.9, for a three-order-of-magnitude range of drainage areas (0.5–500 km²). To the best of our knowledge, this width-area regional curve is the first ever reported for undisturbed New

Caledonian catchments, and one of the first for forested tropical mountain streams (e.g., Jiménez Jaramillo, 2015). The coefficient of determination ($R^2 = 0.65$) shows high goodness-of-fit if we consider commonly reported values for such scaling functions in upland environments (e.g., Modrick and Georgakakos, 2014). Although a recent investigation of width-area regional curves in the continental United States using a national data set of more than 1000 stream reaches found a scale-dependency of the scaling law, with major knots at 5 and 300 km² of drainage area (Wilkerson et al., 2014), our data set of undisturbed sites is not large enough to test the pertinence of a piecewise regression model for New Caledonian streams.

The contrasting rainfall regimes between the western and eastern sides of the Grande Terre are slightly expressed in active channel morphological signatures. For a given drainage area, one would expect wider active channels for catchments draining the eastern side of the Grande Terre, as well as a faster increase in channel width with drainage area, under the effect of stronger annual precipitations. This climatic effect on channel width has recently been confirmed by large national data sets from the continental United States, where humid ecoregions exhibit significantly higher α and β parameters (Faustini et al., 2009; Wilkerson et al., 2014). Bankfull widths of rivers draining humid ecoregions in the US are 1.5 times larger than for semi-arid ecoregions, according to data published by Faustini et al. (2009). In the case of New Caledonian streams, the ratio obtained by comparing α values for eastern and western drainage basins is only 1.12, and the sample size is too small to prove a statistically significant difference of regression intercepts. This means that the orographic effect on flow regimes in New Caledonia has a moderate effect on active channel width, likely much less than the influence of sediment supply conditions of undisturbed sites.

The results obtained from a multivariate statistical analysis including the average floodplain width, the channel slope, the mean catchment slope, and the proportion of the catchment covered by forests did not improve the active channel width prediction based simply on the drainage area. According to Faustini et al. (2009), the prediction of bankfull channel width for the continental United States has been largely improved by adding mean annual precipitation, elevation, and mean reach slope to the empirical model. This is consistent with the results obtained by Wilkerson et al. (2014): these authors found that using solely the drainage area does not yield a reliable relationship to predict bankfull width and that the mean annual precipitation should be included in the predictive model. Although this is certainly true when the variability of active channel width is investigated at a very large spatial scale, including several major climatic, orographic, and geological transitions, the use of a multivariate approach is not really justified when considering a relatively homogeneous physical setting, as is the case for the peridotite ranges of New Caledonia.

Active channel width as a proxy of mining impact

The data set of impacted sites clearly confirms a strong mining effect on active channel widths, which are on average five times larger compared to undisturbed conditions. This is clearly explained by the formation of massive alluvial stores along the impacted stream network, as already observed in fluvial systems affected by a sudden increase of the coarse sediment delivery (e.g., Madej and Ozaki, 1996; Gomez et al., 2001). The aggradation of stream channels in upland environments is generally associated with the formation of gravel bars and with the remobilization and/or burial of the floodplain (Korup, 2004). This was clearly the case along many of the New Caledonian streams situated downstream of the most active mining sites. Although all of the impacted sites present a positive residual of active width with respect to the undisturbed scaling law, it is clear that those residuals decrease with drainage area, suggesting that most of the sediment supply from mining sites is still stored in the proximal stream network and that only a small portion of the mining wastes have propagated far downstream. This observation based on morphological signatures at the regional scale nicely confirms detailed field-based investigations of mining sediment waves, which demonstrate that legacy sediments are generally stored for a long period of time close to their original location (James, 2006).

New Caledonian impacted streams also provide a good field laboratory to test for a relation between the active channel width and the catchment-scale sediment supply conditions. It was thus demonstrated that under a relatively homogeneous physical setting in terms of geology, relief and climate (e.g., the peridotite massifs of New Caledonia), the normalized active channel width, computed as the residual from a reference scaling law obtained from undisturbed catchments, is a function of the relative surface covered by major sediment sources in the catchment. Although such statistical relationships may be the result of a spurious correlation, both the partial correlation and results from a numerical experiment based on random sampling revealed that the statistical relation is only marginally affected by a size effect. It is then confirmed that the normalized active channel width can be considered as a very good proxy of sediment supply from mining sites, and that this proxy can be used to detect anthropogenic sedimentation (*sensu* James, 2017) along stream reaches. It can also be used as a metric for reconstructing channel recovery through time, as well as the dynamics of sediment wave propagation, using the historical imagery. This was already successfully tested in a lowland environment using the gravel bar area along the stream network (Jacobson and Gran, 1999). Our results demonstrate that the use of a normalized active width may provide a more sensitive metric of sediment wave deposition along stream networks, in the sense that this metric is not dependent on the catchment size.

Our results also confirm more generally that in upland environments, channel morphology is strongly controlled by the sediment delivery from hillslopes (inferred from the size of the most active sediment sources), as already shown by historical analysis of channel responses to changes in sediment supply conditions (e.g. Germanoski and Harvey, 1993; Liébault et al., 2005; Piégay et al., 2009). Although it should not be forgotten that active channel width is also influenced by local conditions (such as lateral confinement and valley-floor slope) and the recent hydrological disturbances (e.g., Rinaldi et al., 2016), our results demonstrate that such influences can be considered as secondary factors in the context of New Caledonian peridotite massifs. The successful use of normalized active channel width as a proxy of sediment supply from the catchment has been made possible in New Caledonia because the homogeneous geological, climatic, and relief conditions make the detection and mapping of major sediment sources much easier. This is not the case everywhere, such as in European alpine environments, where a great variety of sediment sources exists, due to the complexity of the geological settings, combined with imprints from the recent climatic fluctuations (e.g., end of the Little Ice Age) and the history of human disturbances (reforestation, torrent-control works).

Conclusion

The normalized active channel width variability at the scale of the New Caledonian peridotite massifs has been successfully used to identify the reaches impacted by a large sediment supply from nickel mining sites. A classic scaling law between active channel width and drainage area for undisturbed river reaches in peridotite massifs has been produced, and it has been used as a reference condition of channel morphology from which residuals can be computed. Residuals from reference conditions for a large set of channel reaches impacted by mining activities revealed a strong active width increase downstream of the most productive mines, as well as a more pronounced impact for proximal reaches. A correlation between these residuals and the magnitude of sediment supply from mining sites in the catchment is obtained, confirming that the normalized active channel width can be used as a proxy of the mining impact on coarse sediment transport along the New Caledonian stream network. More generally, this confirms that active channel width in upland environments is strongly controlled by the size of the most active sediment sources present in the catchment. Sediment supply conditions should therefore not be ignored in studies aiming to understand spatial patterns of active channel width along stream networks (in combination with the classic size effect related to drainage area), notably in environments characterized by contrasted geomorphic activities on hillslopes.

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Table 1. Width-drainage area linear fits obtained for east and west sides of the Grande Terre, with 95% confidence intervals and goodness-of-fit statistics.

	N	Value	95% Confidence interval	Adjusted R^2	*P*-value
Intercept for nonimpacted west coast sites	23	1.28	0.79–1.78	0.54	< 0.001
Intercept for nonimpacted east coast sites	40	1.40	1.14–1.65	0.72	< 0.001
Slope for nonimpacted west coast sites	23	0.42	0.25–0.58	0.54	< 0.001
Slope for nonimpacted east coast sites	40	0.43	0.34–0.52	0.72	< 0.001

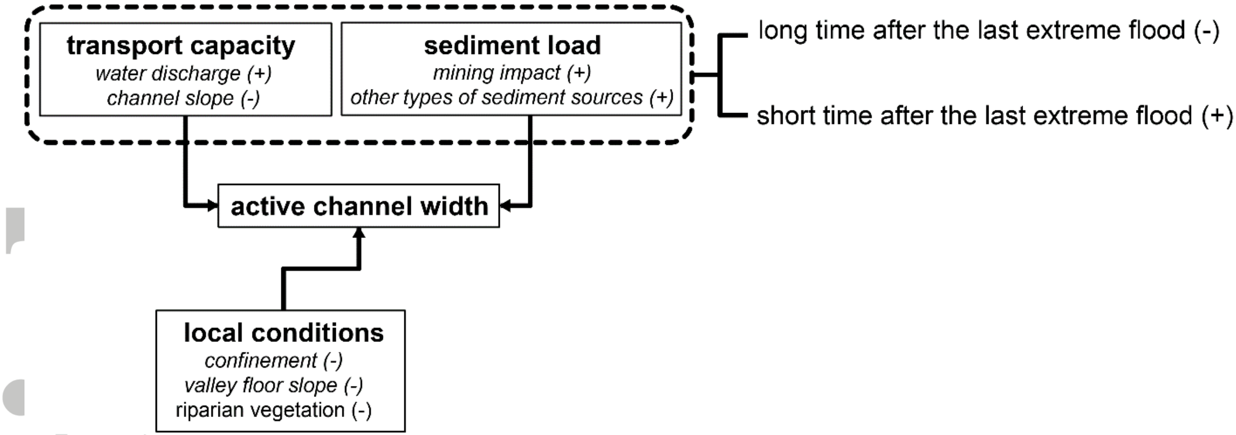


Figure 1 - Conceptual scheme of controlling factors of the active channel width within the New Caledonia context; + and − signs indicate positive and negative relationships with active channel width, respectively; controlling factors in italics are those that have been evaluated in this study

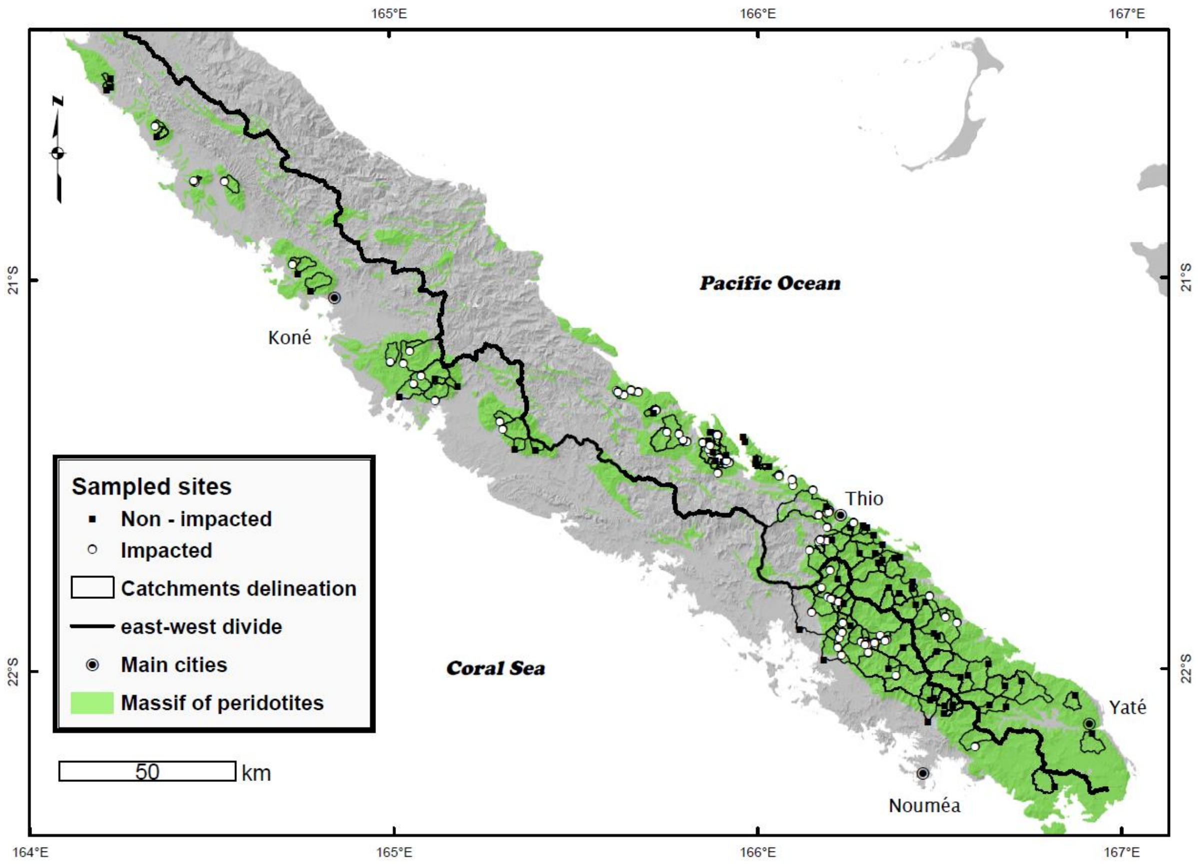


Figure 2 - Geographic context of New Caledonia and spatial distribution of the sites sampled

Figure 3 - a) Opencast mining in the Kouaoua catchment; b) massive accumulations of loose debris below mining sites: Wellington Cascade; c) active erosion induced by exploration and exploitation roads, Thio River basin; d) aggraded river channel downstream of mining sites, Neburu Creek in the Thio River basin

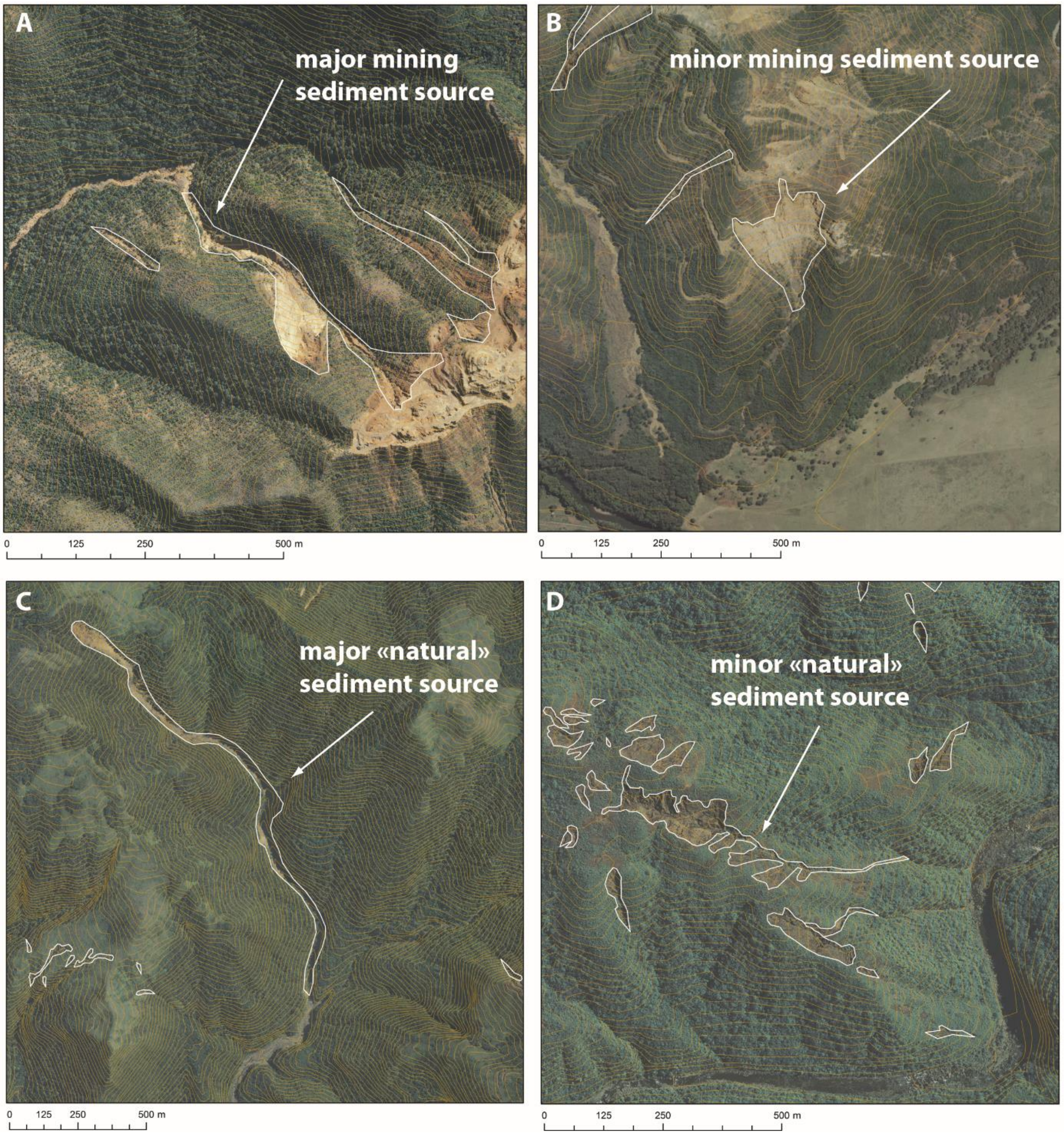


Figure 4 - Expert-based geomorphic mapping and classification of sediment sources; each sediment source has been classified according to its origin (mining source as in A and B, or "natural" source as in C and D) and to the magnitude of sediment delivery, visually assessed according to the presence or absence of loose debris immediately downstream from the source (major sources when loose debris are present, as in A and C, or minor sources when loose debris are lacking, as in B and D). Location information: (A) upper catchment of the Monéo River; (B) Dothio River catchment; (C) upper Bwarawa River catchment; (D) Pourina River catchment

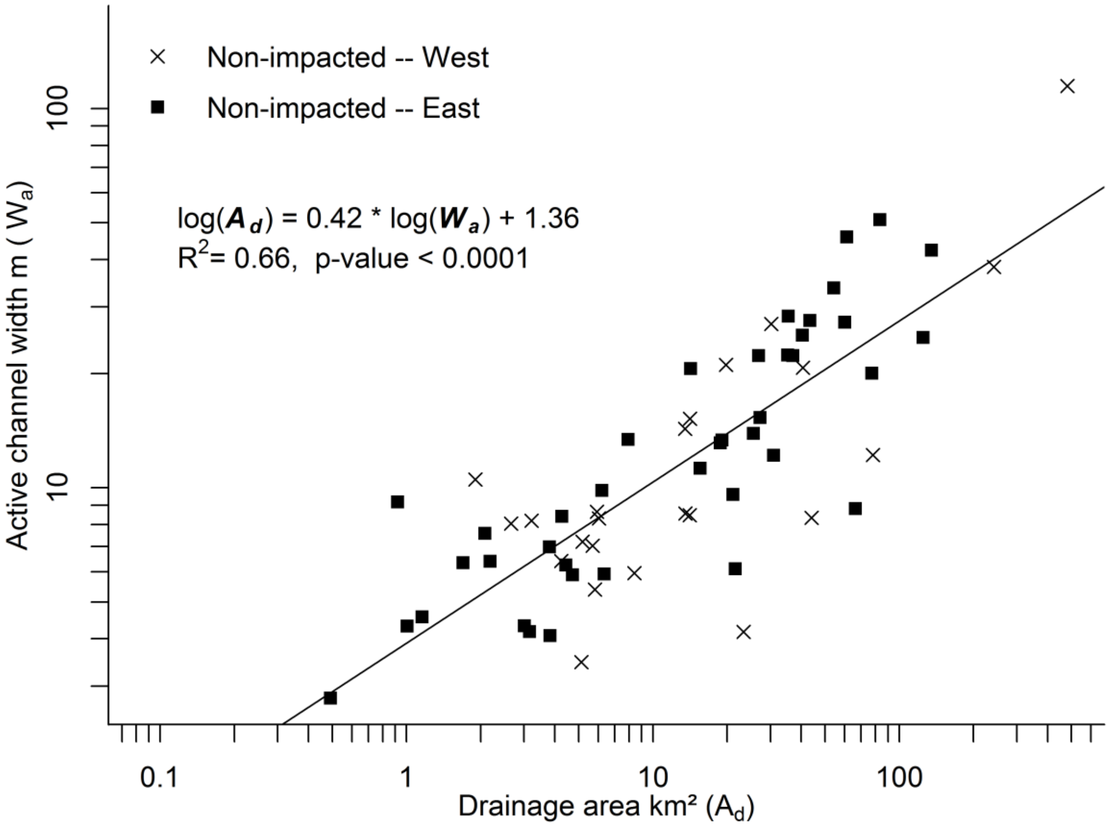


Figure 5 - Distribution of W_a and *Ad* for nonimpacted sites (east and west coast catchments were distinguished)

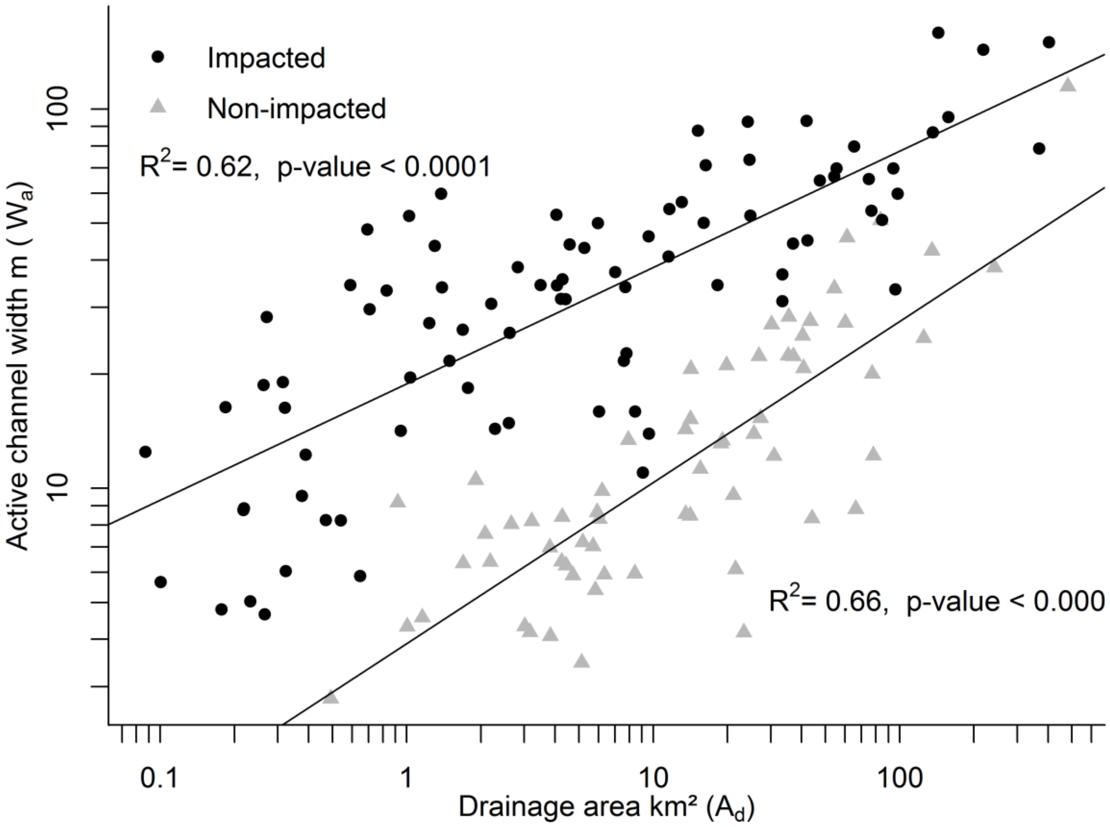


Figure 6 - Distribution of *Wa* and *Ad* for both impacted and nonimpacted sites

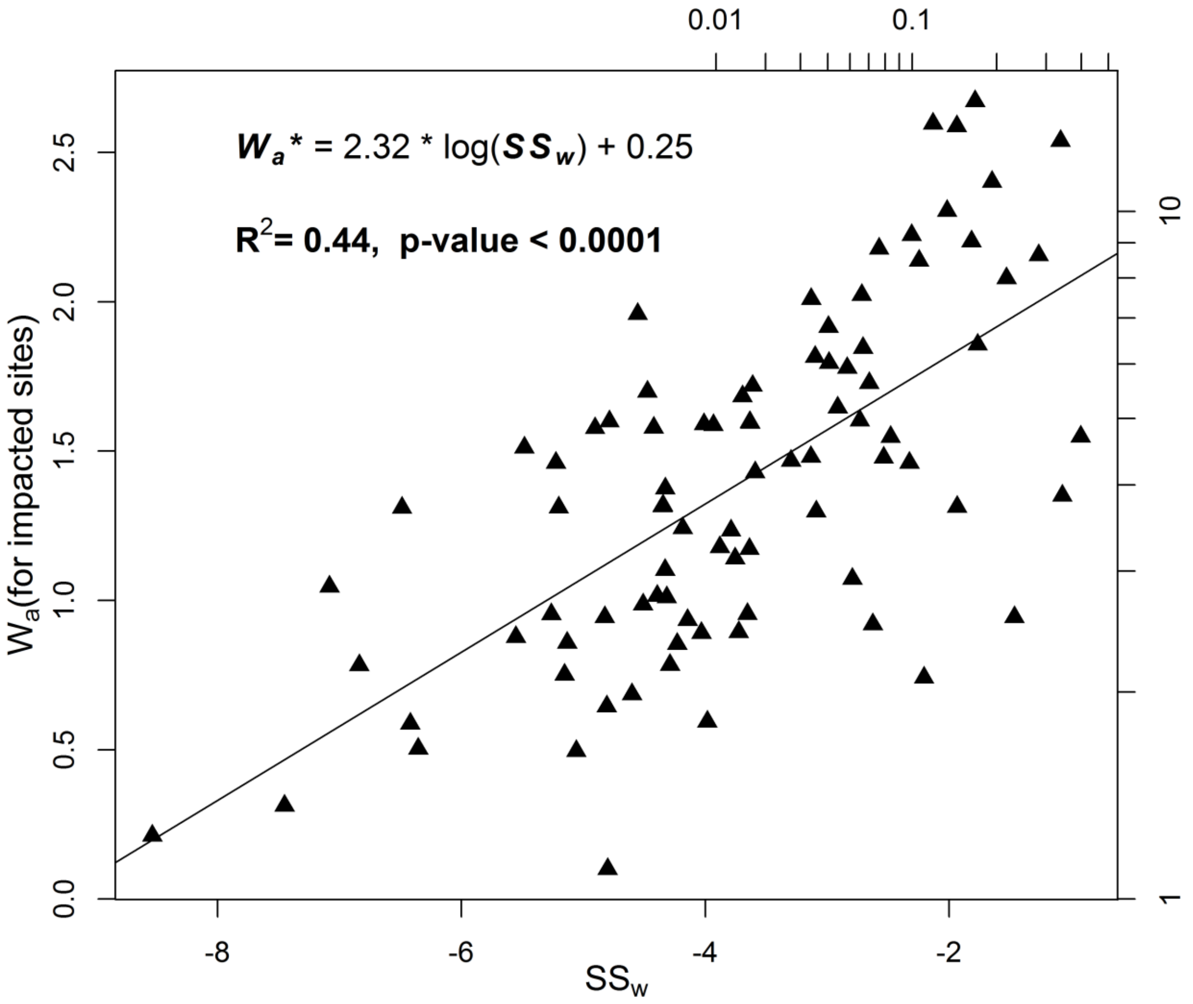
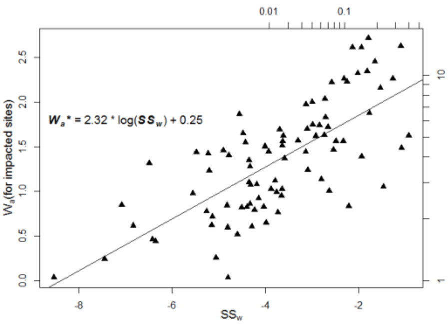


Figure 7 - Scatterplot of the residual active channel width of impacted sites (*Wa**) vs. the log proportion of the catchment covered by sediment sources feeding sediment waves (*SSw*)

The residual active channel width (scaling law based on non-impacted sites) is a very good proxy of catchment-scale sediment supply conditions, and it can be used to detect stream reaches highly impacted by sediment delivery from mines.		**Active channel width as a proxy of sediment supply from mining sites in New Caledonia** Mélanie Bertrand*, Frédéric Liébault