Towards a better integration of local populations in the design of projects to manage the massive aggradation of rivers stemming from mining activity in Thio, New Caledonia

Didier Richard, Catherine Sabinot, Lucie Gosset, Elisabeth Worliczek, A-Tena Pidjo, Mélanie Bertrand, Manuel Garcin

Towards a better integration of local populations in the design of projects to manage the massive aggradation of rivers stemming from mining activity in Thio, New Caledonia

Didier Richard*[a], Catherine Sabinot[b], Lucie Gosset[b], Elisabeth Worliczek[c], A-Tena Pidjo[b], Mélanie Bertrand[d], Manuel Garcin[e]

[a] Université Grenoble Alpes, INRAE, UR ETNA, 2 rue de la papeterie, F-38400 Saint-Martin-d'Hères, France – didier.richard@inrae.fr (corresponding author)

[b] IRD, UMR 228 ESPACE-DEV, Anse Vata - 101, promenade R. Laroque, 98848 Nouméa Cedex, New Caledonia – catherine.sabinot@ird.fr, lucie.gosset@live.fr

[c] Elisabeth Worliczek, BOKU Université des Ressources Naturelles et des Sciences, Vienne, Austria - elisabeth.worliczek@boku.ac.at

[d] Université de Lyon, UJM Saint-Etienne, CNRS, EVS UMR 5600, F-42023 Saint-Etienne, – bertrand.melanie@gmail.com

[e] BRGM, DRP/R3C, 3 avenue Claude Guillemin F-45060 Orléans cedex 2, France – m.garcin@brgm.fr

Corresponding author :

Didier RICHARD

INRAE
2 rue de la papeterie
BP76
F-38402 Saint-Martin-d'Hères Cedex

Tel. +33 4 76 76 27 73 – Fax +33 4 76 51 38 03

Aknowledgements

Thanks to all the inhabitants from Thio, especially to members of *Chavaa Xûâ* collective who shared their knowledge and their time for each step of the research project.

Funding: This work was supported and funded by the CNRT (French National Center for Technological Research) « Nickel and its environment », Noumea, New Caledonia (CSF no. 3PS2013).

Declarations of interest: none

Towards a better integration of local populations in the design of projects to manage the massive aggradation of rivers stemming from mining activity in Thio, New Caledonia

Abstract:

Nickel mining in New Caledonia has largely contributed to the supply of sediment to watercourses, so that some of the main watercourses of the island are considerably aggraded. One of the consequences of this massive aggradation is the elevation and widening of river beds and creeks, thus increasing the flood hazard and the associated risks for people and goods. In addition, it changes the aquatic ecosystems, deteriorates the quality of drinking water supplies, causes the deposit of mud on crops during floods, damages communication networks and affects customary practices and activities.

In this context, remediation measures are needed on a local level and they are required to consider technical aspects as well as social and cultural ones. Because of these requirements, the CNRT "Nickel and Environment" funds an applied and interdisciplinary research project with both physical and social sciences in order to (a) better understand local dynamics, and to (b) identify key factors for implementing remediation measures.

In addition to physical observation and the modelling of aggradation, observations and experiences concerning river and creek aggradation were collected from the inhabitants of six tribes (Kanak villages) in the Thio Valley. It was equally important to record their perception regarding possible remediation measures, some of which having already been put in practice. In these testimonies, people often referred to 'water holes' in the rivers. These are socially important for inhabitants, and their sedimentary dynamics are well known to local people and could represent interesting markers of morphodynamic evolution.

Linking lessons learned from both the physical and the social sciences approaches has led to the elaboration of a methodological guide dedicated to the management of sedimentary heritage from mining. This guide was presented to various actors in New Caledonia in 2018. Through the example of water holes as 'shared objects', this paper describes why and how the involvement of the inhabitants in the design and implementation of observations and monitoring is necessary and discusses the need to fully integrate people's perceptions into the project design.

Keywords: New Caledonia; Nickel; sediment transport; local perceptions; water holes; co-creation; interdisciplinarity

1. Introduction, context presentation

New Caledonia is an archipelago located in the Pacific Ocean 1500 km east of Australia and a few degrees north of the Tropic of Capricorn (figure 1). The main island, commonly called « Grande Terre », is surrounded by a coral reef forming one of the largest lagoons in the world, part of which is registered as a UNESCO World Heritage Site since 2008. New Caledonia is recognized as a biodiversity hotspot, both on land and in the water, due to its exceptionally high rate of endemic species (between 75% and 82%). However, New Caledonia's fragile ecosystem is threatened by increasing human impact, particularly through the mineral extraction of nickel.

Due to a specific tectonic event, a geological layer containing peridotite (a particular geological formation, Nickel ore bedrock) was brought to the surface (Gautier et al. 2016, Myagkiy et al. 2017, Cathelineau et al. 2017). The alteration of these peridotites in a tropical and humid climate allowed a slow enrichment of nickel by concentration, generating a new rock, the saprolites. These were in turn altered by surface erosion and transformed into laterites, which in turn degraded over time. These profiles ended up at the top of the mountain ranges, leading to the development of nickel mining in the upper catchment areas. The basement of the peridotites transformed into serpentines, a formation especially sensitive to erosion, which is located just downstream of areas highly impacted by the mining activity.

In 1863, engineer Jules Garnier discovered large quantities of nickel in New Caledonian soil. Mining began with a few pioneers eager to make a fortune, then the first mines opened at Mont-Dore in 1874 and at Thio in 1875 (figure 1). A first nickel-processing factory was built by the company SLN (Société Le Nickel) in 1880. For the next century, open pit mining evolved with the corresponding technology. Extraction increased considerably after the Second World War and especially since the 1950s due to the use of progressively high-performance machinery, which allowed to extract a lower-grade ore that was still profitable thanks to growing global demand. Tailings from the extraction sites were dumped on the slopes below the quarries, creating landfills and causing serious environmental problems. In particular, nickel mining in New Caledonia has largely contributed to the supply of sediment to watercourses, so that some of the main watercourses are considerably aggraded. One of the consequences of this massive aggradation is the elevation and widening of riverbeds and creeks, thus increasing the flood hazard and the associated risks for people and goods. This additional sediment supply changes the aquatic ecosystems, deteriorates the quality of drinking water supplies, causes the deposit of mud on crops during floods, damages communication networks and has an impact on customary practices and activities. Furthermore, the construction of tracks for accessing new concession sites and for prospecting caused soil erosion, which added to the ecological damage (Dupon, 1986).

Starting in 1975, new practices were adopted in order to reduce the damage:

- controlled storage of tailings in specific dedicated areas instead of discharging them on the slopes
- use of equipment with a lower environmental impact in the exploitation process (hydraulic excavator)
- implementation of water management and sedimentation control systems on the mining sites
- development of revegetation methods (from the 1990s onwards).

The growth of the mining sector during the XXth century in New Caledonia has caught growing interest from public and customary authorities. This period has led to a series of more or less rapid transformations that have multiple effects on knowledge and practices of people (Sabinot et al, 2015), demography and spatial planning, livelihoods (L'huillier et al, 2010), inter-clan and inter-tribal tensions, social cohesion (Kowasch, 2012), territorial conflicts, the relationship to territories and landscapes (Le Meur, 2009; Levacher 2018), and ecological (un)certainties (Levacher et al, 2016).

In this context, the local population demands remediation measures that consider technical as well as social and cultural aspects. These dynamics have led the CNRT (French National Center for Technological Research) « Nickel and its environment » to fund an applied research project involving natural and social sciences in order to better understand local dynamics and to identify key factors for implementing remediation projects (Garcin et al, 2017).

In addition to physical observation and the modelling of aggradation by physical scientists, observations and experiences were collected from the inhabitants of six tribes[1] in the Thio Valley. The aim was to understand their view regarding river and creek aggradation, to describe the transformation of these elements that they perceived, as well as their vision of possible remediation measures. Inhabitants very often referred to 'water holes' in the rivers. The sedimentary dynamics in these water holes is well known by the inhabitants and are interesting markers of morphodynamic evolution.

Linking lessons learned from both the physical and the social sciences approaches has led to the creation of a methodological guide dedicated to the management of mining sedimentary heritage, which was presented in New-Caledonia to various actors in 2018 (Richard et al, 2017).

Through the example of water holes as 'shared objects', this paper describes why and how the involvement of the inhabitants in the design and implementation of observations and monitoring is necessary and discusses the need to fully integrate people's perceptions into the project design.

2. Methods

The researchers in this project started with their respective usual disciplinary methods. In-depth discussions and exchanges between the project partners then led them to complement their approaches by integrating elements of knowledge from other disciplinary fields into their questioning and analyses. The following paragraphs summarize this converging interdisciplinary evolution.

2.1. Context – case study

The Thio mining centre is one of the most obvious examples of the environmental damage caused by mining activity in New Caledonia (Dupon, 1986). Thio Plateau and Thio Camp des Sapins (figure 2) are two mining sites that produce nearly 10 % of the total nickel ore in the territory. The Thio catchment area (figure 2) is one of the largest on the island with a total surface of about 386 km^2. It is located on the rainy east coast, exposing the Thio River to impressive floods.

Located in the southwest Pacific, New Caledonia is one of the regions that are most affected by cyclones (Danloux et Laganier, 1991). Its climate is dry from May to October, hot and rainy for the

---

[1](fr. "tribus") Kanak hamlets or villages resulting from the grouping of family units by colonization. Tribes are located on customary land. It is a special status that makes them inalienable, non-transferable, incommutable and elusive.

rest of the year. During the wet season, there can be significant cumulative rainfall during tropical cyclones and depressions; annual rainfall exceeds 2000 mm on the east coast of the territory. For example, cyclone Anne brought more than 500 mm to Thio in 1988 (and even more than 700 mm in other parts of the southern region) and cyclone David brought nearly 900 mm to the same area.

2.2. Physical study of sediment dynamics

The assessment of the sediment dynamics of a watercourse is a difficult exercise. This is due to the extreme complexity of the (often non-linear) processes involved and due to the lack of a full understanding of these processes. The available data are often limited and difficult to measure (due to the high stochasticity of events, high variability of physical parameters, almost no measurements and observations during extreme events and temporal and spatial scales that are not compatible with a short-term study). This complexity increases even more in tropical areas with extremely intense cyclones. At most, the morphological arrangement of the river bed can be observed in its normal state and not during flood events.

For nearly a century, science has been trying to develop calculation tools (hydraulic laws, solid transport equations) in order to compensate for this lack of observations and for the inability to measure sediment dynamics during floods. However, the results of these tools remain unreliable. The models themselves can be challenged when they are used in conditions that are very different from those used in the design process (often in a laboratory). Nevertheless, even assuming that a model should be reliant enough to reproduce the physics involved, the quality of the input data of such a model could never be guaranteed given the high natural variability in the field.
Hence, in order to obtain reliable knowledge about the sediment dynamics of a river, it is necessary to combine various approaches for a convergence of evidence. This is what has been done for this study, which combines a geomorphological analysis based on field observations, an analysis of data measured on site, and a series of calculations to validate or invalidate the preliminary conclusions deduced from the observation.

2.2.1. Expert approach in the field: observation and interpretation of sedimentary forms

This study took place in the Thio River and its tributaries. The researchers walked along each stream (from downstream to upstream or vice versa, depending on the accessibility) making as many observations as possible (basic measurements, photos, etc.). These visits aimed at acquiring a global vision of the catchment areas in order to deduce a dynamic and the corresponding functional units. Detailed measurements (topography, grain size distribution, etc.) could only be carried out to a relevant extent in a second step based on a sampling strategy from the first visit. Both current and past sedimentary dynamics have been analysed thanks to the observation of the different morphological units.

2.2.2. Evolution of the active channel width

The erosion of mining sites (of both closed and active mines) contributes to a significant production of sediment that feeds the solid discharge in downstream rivers.

These overabundant sediment inputs are periodically swept into the river system through "sediment waves". The river bed adjusts to these changes in sediment inputs by widening the active channel, defined as the area covered by low-flow channels and unvegetated gravel terraces, as well as through increased alluvial deposit on gravel terraces. The width of this river active channel was used as a proxy for aggradation related to mining activity (Bertrand and Liébault, 2018). Thus, for the same catchment area and with identical hydroclimatic forcing, the active channel should be wider if the sedimentary inputs from the mines are significant.

The active channel was measured for 149 study sites (63 sites considered as free of mining impacts and 86 impacted sites) across the Grande Terre (in zones that contain peridotite and that have varying catchment sizes). The average active channel width was then calculated in stretches of ten times the width of the active channel. For each point, the drainage area was also delineated by a hydrological analysis procedure of a 10 m resolution DEM (Digital Elevation Model).

A model of active width versus drainage area was then constructed from all 63 non-impacted sites. The relationship is significant enough to serve as a reference law. The widths predicted by this reference law for the 86 impacted sites are all lower than the observed values, which clearly confirms the relevance of using the deviation from the reference model as a proxy for mining-induced aggradation. The significant statistical relationship between residuals for impacted sites and the proportion of major active sediment sources in the watershed confirm that the deviation from the natural reference model is well controlled by sediment supply from the mines.

The work was then repeated using as many orthorectified sets of available aerial photographs as possible. For each corresponding period, between two successive sets of photos, the active channels were digitized and their widths extracted with a 50 m interval, which made it possible to analyse the evolution of river aggradation based on the changing width of their active channel induced by the downstream migration of sediments.

2.2.3. Modelling based on topography and grain size distribution surveys

The quantification of sediment fluxes typically consists of three steps: i) data collection, ii) the use of models and iii) analysis of the results. Ten study sections were chosen along the Thio River, from the upstream confluence with the Creeks Neburu and Nakale to the river estuary, and two sections on the creeks upstream of the artificially terraced zones: one on the Nakalé, one on the Neburu. The goal was to test the hypothesis based on the geomorphological analysis, in order to see if there are still significant inputs from the Creeks while there is a disconnection and low sediment transport in the Thio River.

The collected data contains:

- The grain size distribution of the bed, assessed based on the Wolman counting method (Wolman, 1954).
- The topography of cross-sections of the bed, measured with a tacheometer. The measurement points were chosen in relation to the slope changes of the cross section. The topography of the main bed has been deduced from the topographical map (the accuracy is approximate, but this has no consequences for the calculations because the associated hydraulics concerns the extreme flows which are themselves subject to high uncertainties).

- The length profile (for slopes). The local slopes were measured with the tacheometer over a distance of at least ten times the width of the bed; they were complemented by slopes calculated from the DEM established through a lidar survey.
- The hydrological data were obtained from a department of the Government of New Caledonia, the Directorate for Veterinary, Food and Rural Affairs (DAVAR). A timeline of average daily discharges measured at the Pont Saint-Michel station (figure 2) over a 34-year period (26/12/1981 to 08/11/2015) and a timeline of discharges at a 5 mn time-step for the February 2015 flood were the available data. Since no other data were available, these discharges were assigned to each sub-catchment area in proportion to the concerned surface by mean of the Myer's transformation formula (Jarvis, 1926).
- various types of information useful for modelling such as the state of vegetation, etc.

Sediment flow transported by bedload have been calculated, i.e. the coarse particles (from sand to blocks) moving near the bottom and responsible for changes in streambed morphology. The applied method is classic and relates the hydraulic force of the flow to a flux of moving material, which is done via two laws:

- a friction law: it transforms the liquid discharge (Q) flowing on the rough surface of the bed (sediment grain size distribution) into force F, more commonly translated as stress, which is the force divided by the bed surface (the force applied per m²).
- a transport law that gives an estimate of the sediment discharge that this flow force is able to mobilize.

All calculations were carried out with the BedloadWeb program that is available online (http://www.bedloadweb.com/) and that is especially designed to be used by non-specialists; in-depth guides are also available (Malavoi et al., 2011; Recking et al., 2013). The program offers the possibility to test several sediment transport formulas.

2.3. Anthropological study of lived realities, fears, and expectations

The aggradation of watercourses not only has impacts on the environment and causes landscape changes, but it also has an impact on society, and particularly on residents. Actions to rectify - or at least mitigate – massive aggradation must be appropriate, but they also need to be understood and agreed on by the concerned populations in order to be effective. For achieving this aim, it is necessary to understand the current perceptions regarding the situation of local residents of all ages, whether men or women, whether they have customary responsibilities or are elected to the town hall, whether they have activities related to the mining industry or not.

Hence, the team of anthropologists chose a classic ethnographic approach, based on recorded formal semi-directive interviews, observation, and participant observation.

Six months of field investigation (twice three months of immersion as well as regular fieldwork stays of three days) in 2016 made it possible to carry out participant observation and conduct 40 semi-directive interviews with the inhabitants of the "mountain tribes" of Saint-Pierre, Saint-Michel and Saint-Paul, in the upstream part of the catchment area; 26 interviews with the inhabitants of the tribes below the catchment area: Saint-Philippo 1, Saint-Philippo 2 and Urué (figure 2). In 2016, the anthropologists participated in meetings on aggradation management work involving residents, the SLN mining company and public authorities, as well as in the yam ritual (which marks the beginning of the Kanak year) and in a seminar on the promotion of agriculture presented by the services of the Southern Province in Thio.

Individual interviews and focus groups were carried out in 2017 and 2018. Moreover, the anthropologists made observations at fishing sites, during horticultural activities and during collective occasions (customary ceremonies, communal events, meetings, and technical committees attended by elected officials, scientists, representatives of the nickel mines and the population, etc.). Between 2016 and 2019, 37 women (23 in the upstream tribes and 14 in the downstream tribes) and 33 men (14 in the upstream tribes and 19 in the downstream tribes) aged 30 to 80 years were interviewed; ten of them had communal or customary responsibilities. Considering that some people were interviewed several times, the team carried out a total of 90 formal semi-directive interviews (48 upstream and 42 in downstream tribes), as well as about 100 unrecorded informal discussions.

Furthermore, during annual presentations of the results to the inhabitants, one or several anthropologists were present in order to observe how the results were received by the population. This made it possible to adjust future interviews with inhabitants and physical analysis accordingly and to guide interactions between researchers. These interactions aimed at improving reports and to consolidate the methodological guide.

2.4. Dialogue between the respective approaches

For our two disciplinary working groups (sediment transport geophysicists / antropologists), the discussions that took place during the project considerably offered perspectives to deepen and complement the respective ongoing investigations.

The anthropological approach is more qualitative and empirical while the hydro-morphodynamical one is more quantitative and technical. Whatever, it is not the difference between the two methods that is important to consider, but the connection and complementarity of theses disciplines.

Probably more interesting is the technical/empirical dialogue that these two co-driven approaches have been able to foster with the inhabitants and between them and the more technical actors.

The quantitative information resulting from the hydro-morphological approach was useful in the second order, as an "objective" reference for assessing possible discrepancies between the physical reality and the perception of the inhabitants.

For example, a better understanding of the perceptions of these physical phenomena by local populations, who are very regularly and directly confronted with the consequences of these phenomena, has enabled solid transport specialists to:

- know what terms are used by the local populations to describe the entities related to solid transport (rivers, sediments, flows, etc.) and to measure gaps with the technical-scientific terminology they are used to (and therefore avoid possible misunderstandings);
- discover the level of knowledge and understanding by the population of these mechanisms, their consequences and the positive and negative effects of possible remediation measures;

- integrate the knowledge of the inhabitants. Their in-depth knowledge of the field allows them to know things that scientists and experts do not know or have not necessarily analysed: local knowledge also sheds light on scientific knowledge on certain points;
- check whether the conclusions of our technical investigations relating to the sedimentary morpho-dynamics of the rivers match the knowledge and vision of the inhabitants (for instance, does the population acknowledge that based on our analysis, we conclude that the river is in a destocking phase?);
- identify the issues, tangible or intangible, that can be affected by these phenomena and to which local populations attach value and importance (including the filing of water holes, the decrease in fish, damage to homes and cultivated plots caused by flooding);
- accordingly extend the scope of their observations to additional observations that at first seemed less necessary for the physical analyses themselves, but more relevant for exchanges with populations (cf. the example of water holes further developed below);

and has allowed the anthropologits to return to the inhabitants and conduct new interviews with them to support and improve the analysis of the results produced by other scientifists (confirm or disprove hypotheses, …)

These continuous reciprocal exchanges between our respective disciplinary fields have made it possible to describe how the concrete implementation of disciplinary methodologies has been modified, adapted, and among other things, to discuss the inhabitant's perception of the river dynamics, in light of the results of the physical approach of morphodynamics.

3. Results

3.1. Convergence of physical approaches on sediment dynamics

Two approaches were chosen in order to understand the sediment dynamics of the Thio River and its creeks: a geomorphological approach and a computational approach. The geomorphological analysis of the catchment area made it possible to track the evolution of the Thio River and its creeks since the beginning of the mining activities, and to diagnose their current functioning. The first observation is that the Thio River, contrary to what might have been expected, does not have the characteristics of a river with high sedimentary activity. The shape is defined by a single sinuous channel, very clearly cut into a set of fixed, highly vegetated gravel terraces, which probably stem from a peak aggradation phase related to mining supplies.

These terraces, which are very disctinctive upstream, are less visible downstream, depending on the water depth influenced by the tides. Likewise, it does not seem that the estuary has large deposits that could disturb the flow.

However, the situation is different in the creeks. Three creeks have been identified as major sediment providers: Neburu, Nakaré, Tomuru (figure 2). In all three creeks, there are clear signs of sediment deposit remobilization, with a visible and significant reduction in large coarse sediment deposits. The supply of sediment from above the catchment areas continues to be very high, but the peak of massive aggradation of the creeks is over (as can be seen through the depth of the cuts in the terraces).

A shared history of the Thio River and its tributaries has been revealed, in that they were all exposed to a particularly strong period of accumulation and thus the building of high terraces, followed by a period of depletion with the low-flow channel incising into these terraces. These interpretations are confirmed by the analysis of active channel widths (cf. § 2.2.2), which shows a tendency for active channels to retract since the 1970s, whereas currently active channels are incised to a level that appears to correspond to the peak of aggradation, thus confirming the conclusions drawn from the geomorphological field analysis. However, nowadays the Thio River and its creeks function quite differently. The Thio River is not very dynamic, with a rather armoured bed, while the creeks still transport abundant coarse sediments.

These conclusions were supported by the results of the calculations. Indeed, the calculations clearly confirm the conclusions of the geomorphological approach, namely a significant transport in the creeks (several thousand m^3/year), and an almost zero to low transport in the Thio River (a few hundred m^3/year) – no matter what sediment transport formula was used. This conclusion is based on the existence of sedimentary disconnections that could be partly due to road dikes. The dynamics of the Thio river regarding fine suspended particles could therefore have its roots in the possibility that the fine suspended particles could be brought from the creeks to a significant extent and then be deposited on the terraces (a deposit increased by the « rakeing » effect of vegetation), as well as in the estuary. In this scenario, the coarse sediments of the Thio River would only be mobilized during extreme floods (cyclones). Given the current dynamics and the deposits still present on the slopes, it can be expected that the reduction of sediment deposits of the creeks could still occur over many years, which limits the possibilities of remediation for populations living downstream of the creeks. However, in the Thio River, it is unlikely that the deposits of the terraces (which rise very high compared to the current active bed) can be reactivated by even extreme floods, which means that the landscape is probably affected for very long periods.

3.2. Understanding the deep ecological knowledge of the inhabitants

In addition to an understanding of the inhabitants' experiences of the impacts that the river transformations are having on their living environment (housing, plantations, reefs), the study found that regular observations made during people’s daily interactions with their environment have built a solid knowledge of hydrosedimentary mechanisms that is shared among the Thio population.

This shared knowledge leads the population to react on the old remediation measures and on those envisaged to face the challenges caused by aggradation by debating the positive points and constraints of each one. One of the remarkable facts is that, although the observation methods diverge between the inhabitants and the experts, their analyses converge on several points, as shown in Table 1. This table compares what has been expressed by the inhabitants, with the lessons learned from more than a century of experience around the world, in managing sediment transport in steep slopes streams (Piton et al, 2016, 2017). For example, it has been widely observed by the inhabitants that the infrastructure called the "fins" are effective in retaining coarse sediments but allow suspended matter to pass through, which is also one of the constraints that has been highlighted by the scientists of the physical studies.

There is often a convergence between the points of view of the inhabitants and the scientists specialized in hydro-sedimentary dynamics. Nevertheless, different positions could be observed concerning the perception of the benefits of bed excavating.

Although the population has been informed by physical scientists that this intervention is not a sustainable alternative to remedy the problem of aggradation, they still request that bed excavating be carried out from the mouth of the Thio River to the sources of sedimentary inputs upstream.

However, past experiences of implementing this type of intervention on two tributaries of the Thio River and the scientists' speeches have given residents the opportunity to better identify the potentially undesirable effects of the operations on the watercourses and to have better arguments in their claims for remediation measures (necessary maintenance of operations and infrastructures, remove stones from the riverbed of watercourses during excavating, etc.).

Moreover, the regular visits of different type of experts (scientists, consulting firms, site maintenance companies, etc.) during the last years in Thio, working in different ways on the issue of watercourse aggradation (works, evaluation of the relevance of infrastructures, etc.) has also made it possible to establish complementary “connections” between the perceptions of the inhabitants and the experts' analyses. One of the remarkable elements is the diffusion of a rather technical language among the population in Thio.

Knowing that the population and the scientific experts have a similar physical understanding regarding hydrosedimentary mechanisms, remediation measures and to some extent a common language are clearly crucial prerequisites to hopefully be able to co-construct appropriate strategies and devices in the future.

3.3. Water holes: a possible candidate for functioning as a 'shared object' in the design process of remediation projects?

Traditional attachment to some water holes in rivers was very often mentioned in the testimonies collected during the surveys carried out by the anthropology researchers of the project. This reminded the hydro-morphodynamics researchers of comments they had heard earlier during another project, but in the meantime, they had forgotten.

3.3.1. Why choosing water holes?

During an expert assessment in 2007-2008 on other sites in the context of the failure of sedimentation dams, the disappearance of water holes was one of the issues highlighted by the miners as having triggered a strong dissatisfaction among the concerned populations. Four main problems had been highlighted by the inhabitants: red water flows, the massive aggradation of creeks and the associated risks of flooding, as well as the disappearance of water holes in which they used to fish for shrimp. However, the consideration of these issues had not been taken into account in related studies. During the 2016-2017 surveys of this project, the water holes were directly mentioned by the inhabitants in their descriptions of the transformations of watercourses:

> « Personally, when I think of water holes, I think of how the river was in the old days when there was a lot of water. If there is enough water, you get water holes, where the water stops for some time and it is deep. It's good for the fish and for the people. » (women from Saint-Paul 2017, translation by authors)

Several factors led the project team to focus on all the dimensions associated with water holes: they turned out to be valuable sites that are strongly impacted by the river transformations, the inhabitants describe them in detail and give them a great importance (their role as a pantry, social and cultural dimension).

The inventory and location of water holes valuable to inhabitants was refined, with the aim of collecting information that is likely to qualify or even quantify the changes observed. At this point, whether many dimensions of the changes had been observed by people and provide a detailed knowledge of some changes (depth, width, substrate, sediments, color…), the information is still insufficient to obtain a complete view of the evolution of the river due to a number of reasons:

One reason is that these observations were not made on an ongoing basis. Depending of the location, the use, and the value of the waterholes, observations remain more or less sporadic, allowing sometimes only estimates of changes over fairly long-time intervals. A second reason is that the dimensions of the water holes are mainly measured using senses and size scales (height of a man, time required to touch the bottom, etc.) and not measured in standardized metric units. Above all, the estimation of the evolution of water holes by the people depends on their individual value and use and the frequency of using them. Thus, observations of reduction, narrowing, or decrease in depth, are insufficient to provide answers to a question such as: after major rainfall events, and in a context of a scouring trend, to what extent and at what speed can water holes recover? This raises the question of how participatory observational data could be obtained in the future. Consideration needs to be given to whether such observation would be suitable for monitoring changes in the physical characteristics of waterholes, following a minimum observation protocol.

3.3.2. What is the relevant unit of observation and analysis to be co-constructed with the inhabitants?

For the inhabitants, the definition of a unit related to their observation of change is directly linked to the kind of value that is given to a certain place (nourishing value, associated taboos, symbolic value), and depends in particular on the practices related to them (fishing, swimming, etc.). A loss of use or value resulting from the aggradation process leads to a certain vulnerability of the inhabitants, because they are important fishing sites for the inhabitants of the "mountain tribes" whose way of life is based on this practice (Gosset et al, 2019). In this context, the inhabitants have their own way of noting and measuring the experienced transformations:

> « *No, no, it's a little deep, you have to go down to hit the bottom, but you can already see the bottom from the banks of the river. Whereas in the old days, you couldn't see it,*

it was so deep, it was blue down there » (Woman from Saint-Paul, 2017, translation by authors)

« *Not everyone went fishing. It was so deep that before even reaching the bottom, you had to go up. Below, there were shoals of fish. But people didn't go all the way down, because was too deep* » (Man from Saint-Pierre, 2017, translation by authors)

Hence, there are different units that are used to "measure" a place to express its use and value (fishing, taboo place, swimming place, etc.):

- *depth.* Locally, a waterhole doted of a fishing value, the depth is assessed by the inhabitants through the time necessary to reach the bottom when diving down, the degree of ease to do so, or with through the depth of the blue colour. Geomorphodynamic engineers would measure it in metres in a time frame dependent on climatic events and seasons, in order to gain a better understanding of river dynamics. For water holes with a taboo value in which diving can be prohibited according to specific rules, other tools and units of measurement could be used.

The most relevant unit changes according to the importance given to a site. It would be interesting to determine how the different unit systems can match and which temporality of measurements would be adapted to needs.

- *width.* Inhabitants refer to the sense of sight to describe the narrowing of the water holes. They observe the transformations of the river bed (displacement, narrowing) and the emergence of sediment deposits on the banks (stones, gravel and sand). Sometimes they also mention the appearance of vegetation in some areas.

« *When the pollution is coming, well there is the gravel, the stones, the soil and there is also what comes from the bottom [of the riverbed] which is... it is the nickel, the pollution from the nickel. So that why this vegetation... to cover the river; and every year, well, it takes up more space, and it covers the riverbed* » (woman from Saint-Paul, 2017, translation by authors)

« *When I hear about water holes, it reminds me of my childhood, when the river was a beautiful river, there were already the water holes, there was water, there was nothing between the river and the places where there were houses. Today this empty space no longer exists. There is so much grass, bamboos, trees that grow there along the river, washed up by the floods* » women from Saint-Paul, 2017, translation by authors).

According to the descriptions given by the inhabitants, although the transformations of the water holes are specific to each individual hole (rate and extent of change), they are always described in terms of decreasing width and depth. However, these two characteristics evolve differently: the inhabitants notice a dynamics of significant change in depth (low intensity meteorological events would fill the water holes while heavy rains would help to remove the sediment load stocked inside the water holes, allowing the original "stones" to appear on the bottom), whereas the width of the deep water holes seems to have stabilized.

Either way, this raises the question of how to produce indicators that are adapted to each type of water hole; these indicators would then be crossed and would define the points to be followed up from a scientific expert point of view.

3.4. The need to integrate physical and social analyses

This study shows that the integration of physical and social analyses is an absolute requirement in order to elaborate really efficient remediation strategies. A first prerequisite is to ensure that the definitions of the terms that are used respectively by the scientific experts and the inhabitants are mutually understood and shared.

3.4.1. Terminologies (technical, in French, and in xârâcùù)

The definitions of aggradation used by hydromorphology specialists and the terms they use to talk about it are not the same as those used by the inhabitants (both in French and in the local language, called *xârâcùù*). The latter define them very logically first through the inconveniences they associate with these phenomena. However, even if the words are different, there are some obvious matches in perception both at the level of the phenomenon itself and at the level of the sedimentary materials involved.

Two terms are mainly used by the population of Thio to define aggradation. A distinction is made between « *boue* » (mud) and « *caillasse »* (gravel), both of which are associated with discharges from mechanized mining activity.

- *Caillasse* - The term « *caillasse* » roughly corresponds to the scientific definition of what constitutes aggradation. It refers to the accumulation of gravel, and small broken pebbles. The *caillasse* may deposit near the river, near homes and in the creeks.
- *Boue* – « *Boue* » is made up of fine particles, « finer than *caillasse* »: for the inhabitants, it is « the earth brought with the water » that is deposited in fields and in houses and is transported in the river. The term « *boue* » (mud) is used both to refer to the mixture of water and fine sediment and to the dry layer of fine particles that stays as the water withdraws. Mud is sticky when it settles in fields and houses and it is difficult to remove in order to access the soil layer beneath that is deemed to be of good quality.

  The colour of the mud varies according to the elements it contains. The inhabitants distinguish between « nickel red mud » and « brown mud ». According to our informants, the nickel or rust red colour indicates that it comes from mining activities, mining grounds and is particularly associated with "pollution" (Gosset 2016).

Even if these are mainly the two terms that are cited by the inhabitants to talk about aggradation, they also use the term « *caillou* » (stone), which is important to define:

- *Cailloux (sêgè)* – The « cailloux » (stones) are rather large cut stones (about 20 centimetres in diameter). The inhabitants distinguish the stones of the mine from those of the river by their colour and texture. Those from mining are caramel brown and those from the river are black and smooth (Gosset 2016).

According to the inhabitants of Thio, aggradation is therefore an unusual and consequent accumulation of stones and gravel (« *cailloux* » and « *caillasse* ») and/or mud (« *boue* »).

For fluvial hydromorphology specialists, an aggraded river can be defined as a river that experiences or has experienced coarse sediment inputs exceeding its transport capacity, resulting in visible morphological changes over a significant length of the bed, i.e. elevation and widening (Garcin M. and Lesimple S., 2013).

In that context, the grain size distribution of the aggradation deposits generally varies from those of stones or even blocks for the biggest ones (corresponding more or less to the « cailloux ») to the gravel and sand for the finer ones (corresponding more or less to the « *caillasse* »), depending on the distance to the source area of the materials.

In hydraulics, in general there are three main types of watercourses in mountain regions, depending on their longitudinal slope ranges. Even if this classification by Surell (as early as 1841) is necessarily reductive, it has the double merit of defining orders of magnitude and highlighting the importance of the slope factor in the hydro-sedimentary behaviour of these rivers.

This distinction is important because depending on the slope ranges, the sediment transport modes are not necessarily the same; the consequences on the evolution of the morphology of rivers or the exposed issues at stake can vary.

A torrent is generally considered to have a slope of 6 % or more, with the largest torrents having slopes of up to 2 % in the lower parts of their alluvail fans (Surell 1841). This threshold of 2-6 % corresponds essentially to the minimum slope where debris flows or hyperconcentrated bedload phenomena take place.

Torrential rivers are the natural outlets for torrents. They receive sediment inputs provided by their tributary streams, with more or less regularity. Surell (1841) defines the limit between torrential rivers and rivers around a 1 % slope but agreed that this threshold was more difficult to identify than that between torrent and torrential river. Recent floods have shown that some rivers with a slope of slightly less than 1 % can cause very strong erosion and can have an impressive morphogenic activity.

The terms used by the inhabitants of the Thio river basin to refer to the types of watercourses in the valley are only those of river and creek.

- *Creek (xwârè)* - Creek is defined by the inhabitants as a rather narrow stream that can dry up permanently or episodically. There are, for example, many creeks in the municipality of Thio, that cross through almost each tribe. This term reflects the Anglo-Saxon cultural influence, since in North America, for example, it is used to designate small streams.
- *River (xwârè)* - The river is described primarily by its width (several meters), the permanent presence of water and its greater depth. For example, the rivers mentioned by the inhabitants of Thio are those of the Thio River itself - commonly referred to as "the great river" - the Nembrou (Xwâ Nèbürü) and the Nakalé (Xwâ Nakaré).

Unlike for sediments, the criteria for classifying watercourses do not use the same reference frame and it is therefore not possible to establish a correspondence between these terms two by two.

The approach of co-creating a collection of terms commonly used by the local population as well as cross-analysing observations of the population with scientific measurements was crucial for the implementation of the project, which aimed at reflecting life realities within their social and natural environment. The representation of a given natural environment sometimes differs from the results in scientific analysis, but more often, these two aspects are complementary and reinforce certain perceptions. In our case, the exchange with the local population was of high value as it allowed to verify if our results correspond to the experienced life realities. Moreover, the deep ecological knowledge of the inhabitants related to their environment and their good knowledge of the area highlight with precision the effects of aggradation and flooding for each area, which contributes to the clarification of certain analyses of physical scientists. In the given context, this is even more important, since the results feed into a Methodological Guide, which should support future exchanges between mining companies, the public administration, and the population. Hence, this process of co-creation was very crucial from the outset, starting with the project design throughout the implementation with numerous feedback loops. The scientific debate advocates for effective co-creation of knowledge (e.g. Regeer and Bunders, 2009, Voorberg et al., 2015, Yndigegn, 2016), and in our case, this was at the core of our ambitions right from the beginning.

3.4.2. Suggestion for a step-by-step plan to describe the socio-environmental context

In order to facilitate mutual understanding between the actors involved in the future planning on similar measures/arrangements, the team suggests the use of a protocol (figure 3) to report on the various social issues and constraints. Following these six steps helps to inform geophysical analyses and to take into account the values that residents attach to the site, their experiences, expectations and fears.

4. Conclusions

Upon confrontation to industrial projects in their vicinity, local populations generally face the challenges of becoming fully involved, recognized and respected by industrials as well as public institutions. The case of Thio is uncommonly specific because of the long history of mining activities that began when no environmental rules existed. Inhabitants say: “we are the garbage and the laboratory of New Caledonia”. The methodological development done in Thio is of interest for all the country, where concerns about the future of rivers and the consequences on living places have raised and are supposed to raise because of cyclones and other increasing pressures.
The understanding of the inhabitants' different experiences, perceptions and expectations helps to throw light on possible correlations as well as the lack there of between the reality of geophysical processes and their perception. Because of the comprehensive knowledge acquired from the inhabitants, the interdisciplinary team was able to present and explain the possible solutions most appropriate to each issue, in a way that is adapted to the perception of each category of inhabitants; this proved to be useful during a presentation of the results to the population of Thio.

The *Chavaa Xûâ* collective, which both defends the claims of the inhabitants related to the aggradation and the floods and is involved in the monitoring and the rehabilitation of watercourses, was grateful for the team to have shared the results. These results help to translate the cultural and social implications experienced locally and increase their visibility when exchanging with the institutions. In addition, both the anthropological and physical study results provide a solid basis that will give strength to the collective members’ claims. After sharing the results, the researchers often heard: « Thank you for your feedback, it reflects well what we have experienced and what we are experiencing. » Nevertheless, members from the *Chavaa Xûâ* collective regularly asked for more data during the project in order to explain river dynamics and sediment transport processes to the residents.

The methodological guide was most appreciated, which underlines the importance of the integration of physical data with social data; it delivers protocols enabling approaches that recognize and take into account both dimensions in any development, intervention project or technical measure. Accordingly, the water holes, which the population largely refers to when describing the transformations of the river due to aggradation, have proved to be key objects that should be taken into consideration for future designs of technical measure, which, until now, were largely ignored. Indeed, as places that unite a certain number of issues and concerns (ecological as well as social and cultural), it seems necessary to evaluate the potential impact of the measures implemented on existing water holes.

The methodological guide is thus more solid in terms of operability because it provides a better shared understanding (e.g. water holes that were not identified as crucial in the physical expert assessments in 2007-2008), better technical proposals adapted to the diversity of issues, and a better acceptability by residents who feel they are recognized and more in control of the knowledge of phenomena and the choice of measures.

Two conclusions are worth pointing out. First, the knowledge produced by the different disciplinary approaches is prominently communicated in the methodological guide. Secondly, the evolution of the collective's position towards shared results on the functioning and disadvantages of structures and measures is remarkable. The needs expressed by the *Chavaa Xûâ* collective have evolved towards the formulation of a need for support to help them explain to the rest of the population the results that they themselves have now understood.

Aknowledgements

Thanks to all the inhabitants from Thio, especially to members of *Chavaa Xûâ* collective who shared their knowledge and their time at each step of the research project.

Funding: This work was supported and funded by the CNRT (French National Center for Technological Research) « Nickel and its environment », Nouméa, New Caledonia (CSF no. 3PS2013).

References

BERTRAND, M., LIEBAULT, F. (2018). “Active channel width as a proxy of sediment supply from mining sites in New Caledonia”. Earth Surf. Process. Landforms, published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/esp.4478

CATHELINEAU, M., MYAGKIY, A., QUESNEL, B. et al. (2017). ”Multistage crack seal vein and hydrothermal Ni enrichment in serpentinized ultramafic rocks (Koniambo massif, New Caledonia)”. Miner Deposita 52, 945–960 (2017). https://doi.org/10.1007/s00126-016-0695-3

DANLOUX, J., LAGANIER, R. (1991). ”Classification et quantification des phénomènes d’érosion, de transport et de sédimentation sur les bassins touchés par l’exploitation minière en Nouvelle-Calédonie”. Hydrologie continentale 6, 1 (1991) pp. 15-28.

DUPON, J.F (1986). ”Les effets de l’exploitation minière sur l’environnement de îles hautes : le cas de l’exploitation du minerai de nickel en Nouvelle-Calédonie”. Environnement : études de cas, Pacifique Sud étude 1.

GARCIN, M., LESIMPLE, S. (2013). ”Identification des rivières surengravées de la Grande-Terre (Nouvelle-Calédonie) - Aptitude à l’exploitation pour granulats”. Rapport BRGM/ RP- 62297-FR

GARCIN, M., RICHARD, D., LIEBAULT, F., RECKING, A., PITON, G., SABINOT, C., WORLICZEK, E., LESIMPLE, S., BERTRAND, M., GASTALDI, Y., BURLAT, T., GOSSET, L., PIDJO, A. (2017). ”Gestion du passif minier” - Rapport scientifique. CNRT « Nickel & son environnement ». http://www.cnrt.nc/wp-content/uploads/2018/12/CNRT-Tome-ENV-2018-GESTION-DU-PASSIF-DE-LACTIVITE-MINIERE-edition-2018.pdf

GAUTIER, P., QUESNEL, B., BOULVAIS, P., and CATHELINEAU, M. (2016). ”The emplacement of the Peridotite Nappe of New Caledonia and its bearing on the tectonics of obduction”, Tectonics, 35, 3070– 3094, doi:10.1002/2016TC004318.

GOSSET, L. (2016). ”Rivières engravées à Thio, Nouvelle-Calédonie : vécus et attentes de la population”, Mémoire de master 2, sous la dir. de GUÏOUX Axel, Université Lumière Lyon II, 150 p.

GOSSET, L., SABINOT, C., WORLICZEK, E. (2019). ”Quand cyclones, pluies et pollution interrogent les liens des Kanak à leurs rivières et participent au renouvellement des savoirs écologiques (Thio, Nouvelle-Calédonie)”, Ethnographiques.org, Numéro spécial “Approche anthropologique des changements climatiques et météorologiques".

JARVIS, C. S. (1926). ”Flood flow characteristics”, Trans. Am. Soc. Civil Engrs. 89, 985-1104, 1926.

KOWASCH, M. (2012). ”Le développement de l’industrie du nickel et la transformation de la valeur environnementale en Nouvelle-Calédonie”. Journal of political ecology, vol 19.

LE MEUR, P-Y. (2009). ”Opérateurs miniers, gouvernementalité et politique des ressources à Thio, Nouvelle-Calédonie”.

MALAVOI, J.-R., GARNIER, C., LANDON, N., RECKING, A., BARAN, P. (2011). ”Éléments de connaissance pour la gestion du transport solide en rivière”, 216 pp., ONEMA, ISBN: 978-2-9516393-5-5.

MYAGKIY, A., TRUCHE, L., CATHELINEAU, M., GOLIER, F., (2017). "Revealing the conditions of Ni mineralization in the laterite profilesof New Caledonia: insights from reactive geochemical transport modelling", ChemicalGeology (2017), doi:10.1016/j.chemgeo.2017.06.018

PITON G., RECKING A. (2016). "Design of sediment traps with open check dams. I : hydraulic and deposition processes", Journal of Hydraulic Engineering, Vol. 142, No.2, 1–23.

PITON G., RECKING A. (2016). "Design of sediment traps with open check dams. II : woody debris", Journal of Hydraulic Engineering, Vol. 142, No.2, 1–17.

PITON G., RECKING A. (2016). "Effects of check dams on bed-load transport and steep slope stream morphodynamics", Geomorphology, Vol. 291, No. Sediment dynamics in alpine basins, 94–105.

PITON G., CARLADOUS S., RECKING A., LIEBAULT F., TACNET J., KUSS D., QUEFFELEAN Y., MARCO O. (2017). "Why do we build check dams in Alpine streams? An historical perspective from the French experience", Earth Surface Processes and Landforms, Vol. 42, No.1, 91–108.

RECKING, A., RICHARD, D., DEGOUTTE, G. (2013). ”Dynamique et aménagement des torrents et rivières de montagne”, QUAE.

RICHARD D., GARCIN M., LIEBAULT F., RECKING A., PITN G., SABINOT C., WORLICZEK E., LESIMPLE S., BERTRAND M., GASTALDI Y., BURLAT T., GOSSET L., PIDJO A., GOSSELIN N. (2017). ”Gestion du passif minier – Guide méthodologique”. CNRT « Nickel & son environnement ». 79 pages, 20 fig., 15 Tab. http://www.cnrt.nc/wp-content/uploads/2018/11/CNRT-Tome-ENV-2018-GUIDE-METHODO-GESTION-du-PASSIF-%C3%A9dition-1.pdf .

SABINOT, C., LACOMBE, S. (2015). ”La pêche en tribu face à l’industrie minière dans le sud-est de la Nouvelle-Calédonie”. Revue internationale d’ethnologie, 120-137.

SURELL, A. (1841). ”Étude sur les Torrents des Hautes-Alpes”. Dunod, Paris, 280 pp.

WOLMAN, M. G. (1954). ”The natural channel Branywine Creek Pennsylvania”, Report, 56 pp, USGS report n°271.

	Benefits perceived by the population (a)	Hydro-sedimentary functions / interests (b)	Disadvantages / concerns (c)	Weaknesses / vigilance points (d)	Expectations (e)
Dikes	• channelize the water from the river • allow a better flowing	• contain the flood flow • prevent overflow • favours the flows transit	• stored sediment in the bay • are broken	• efficient up to a given flood height • and as long as they resist • stability to be assessed	Repair the dikes
Hydraulic spurs	• protect issues locally	• prevent the erosion of banks (natural or embankments) • therefore limit sediment remobilisation • if well designed, they can follow the bed sinking and remain effective	• have stored sediment on their banks • have disappeared	• possible impact on the opposite bank • become inefficient if buried	To be rebuilt
Fins	• retain coarse sediments	• stop and store the coarsest sediments, depending on the spacing of the "piles" of the fin	• allow fine sediments to pass through	• very limited effectiveness on suspended materials	Maintain the structure
Creeks maintenance	• reduces the extent of flooding		/		To be repeated
Bed excavating	• removes a large amount of sediment • secures homes	• increase the flow cross-section • restore storage capacity • regulate solid transport	• is not deep enough • is not associated with bank protection • can lead to a rectilinear bed • disappearance of water holes	• requires regular interventions to maintain its effectiveness • volume per unit length proportional to width (narrow bed → little storage volume → increased risk of overflow) • destruction of aquatic habitats	Excavate the embouchure , near the tribes; deeper Secure the banks

Table 1: Structures and remedial measures. Comparison between the advantages / disadvantages perceived, and expectations expressed by the inhabitants (columns a, c, and e) and the functions / interests / weaknesses seen by the sediment transport specialists (columns b and d)

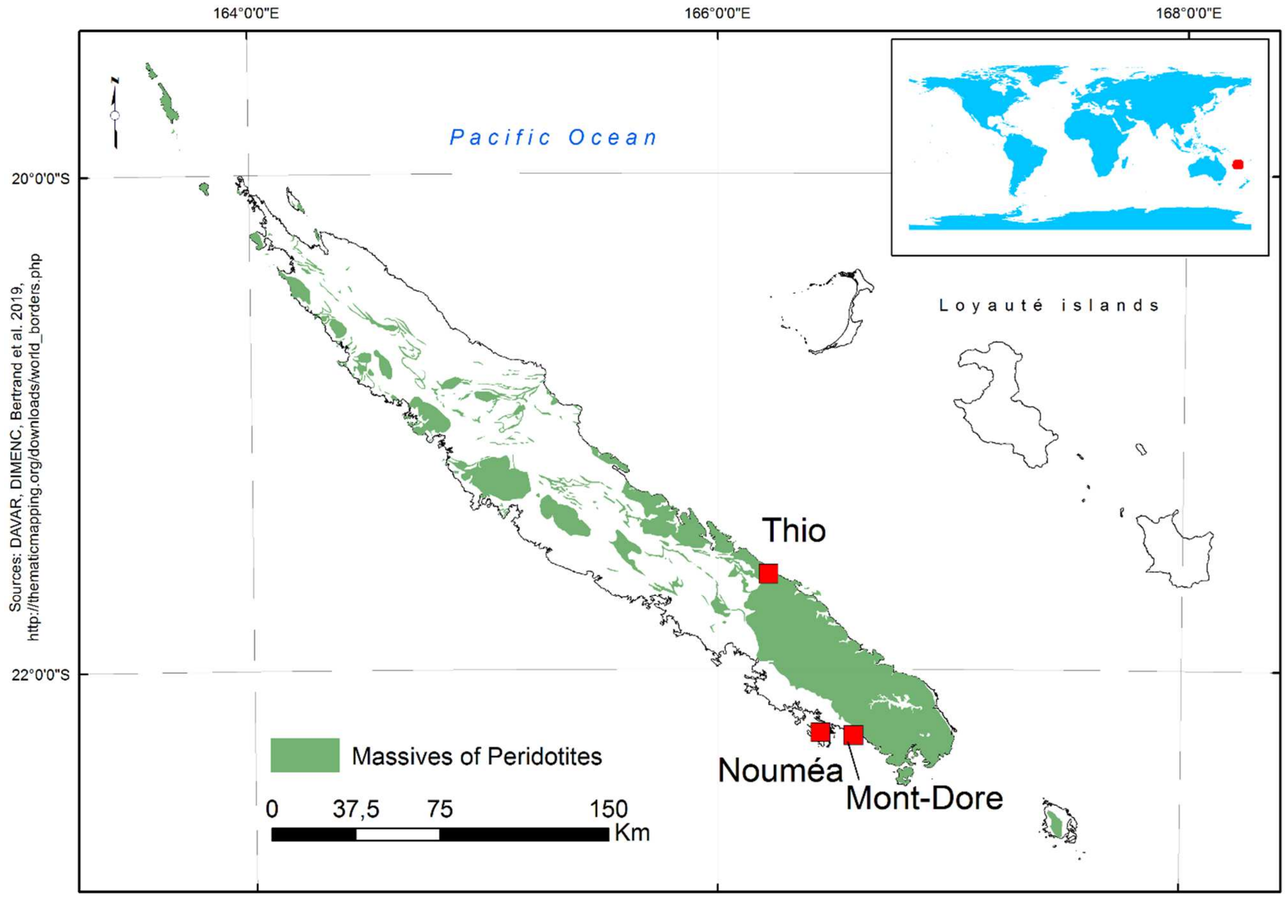

Figure 1: Location of New Caledonia, its capital Nouméa and the first two mining sites opened

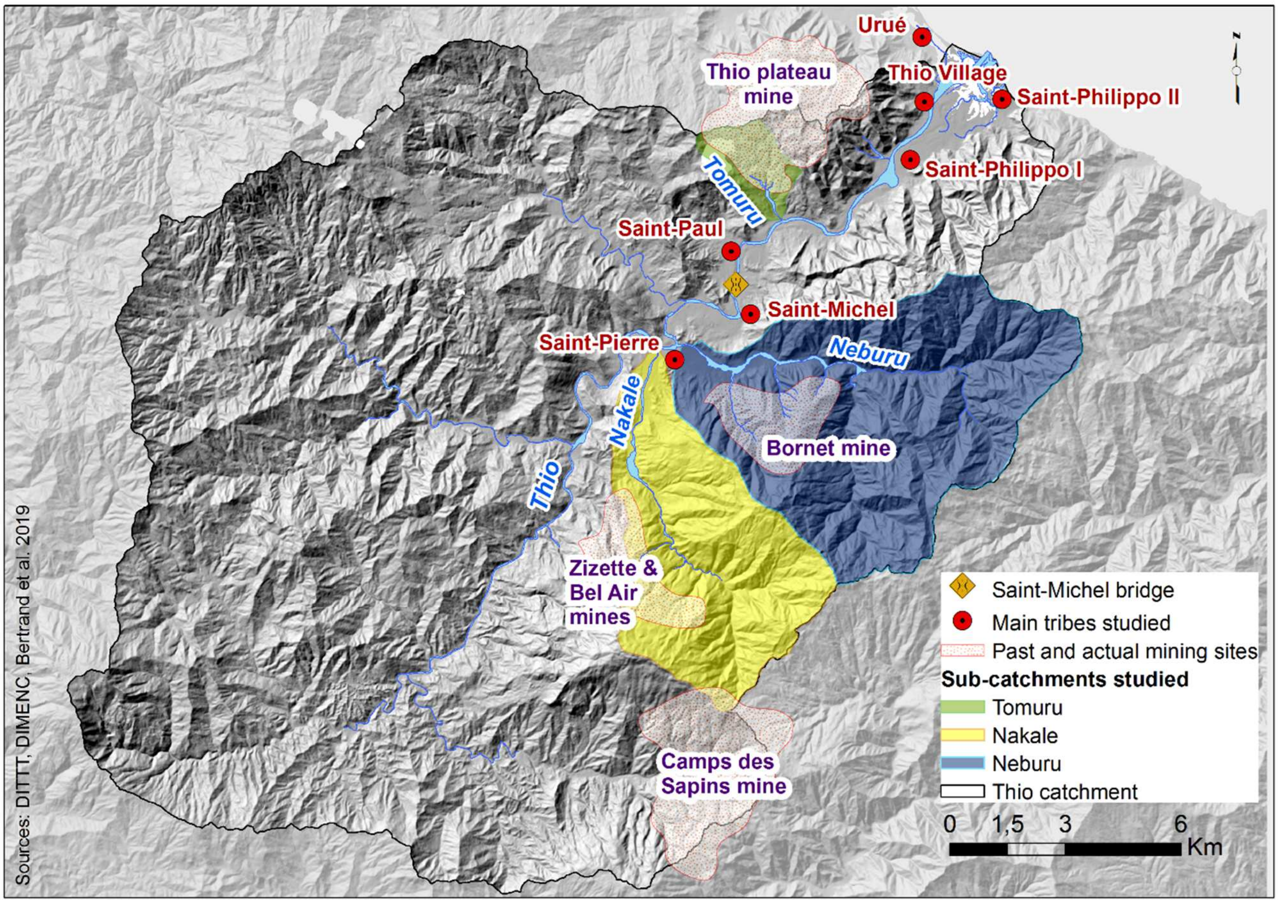

Figure 2: The Thio River catchment. Location of the studied sub-catchments and tribes

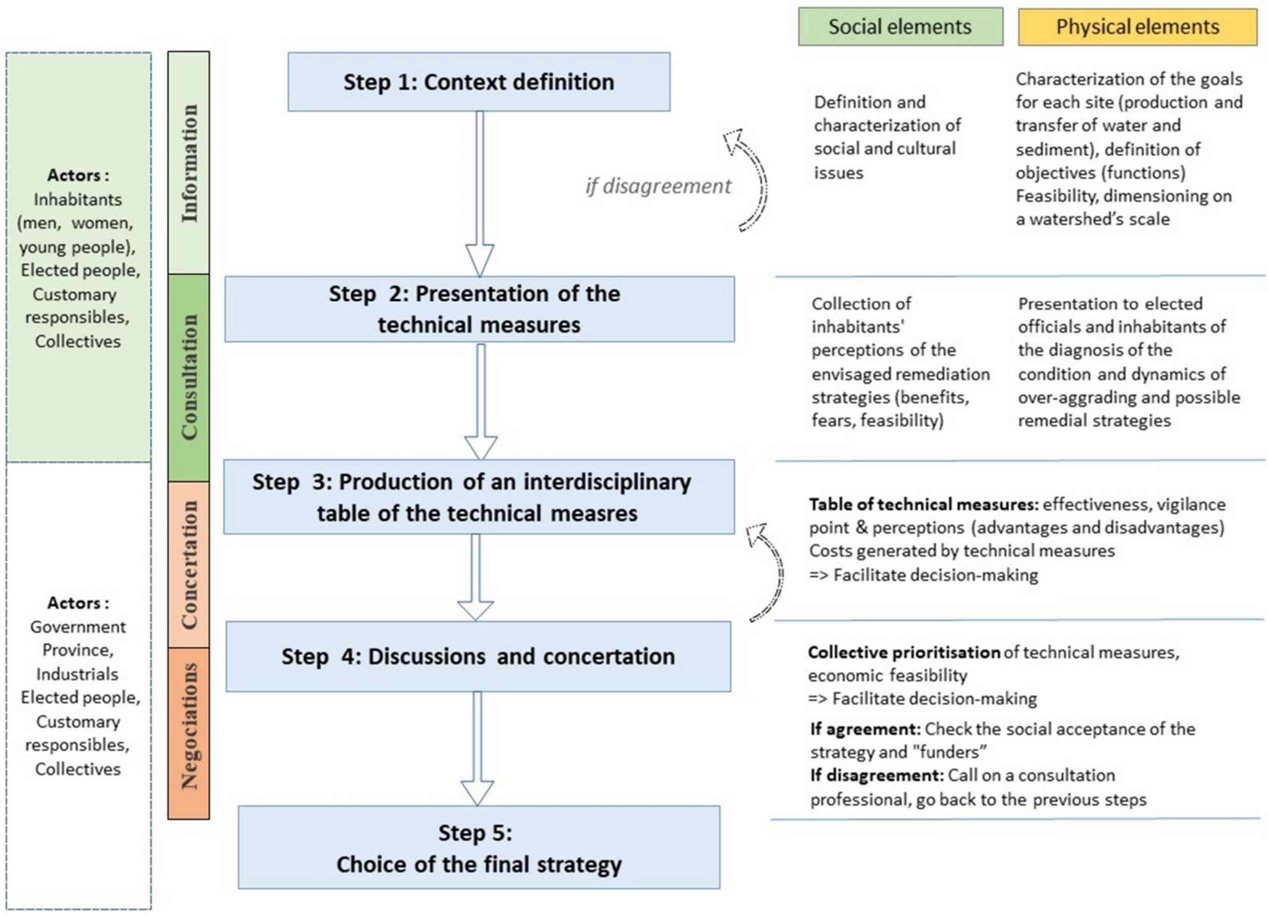

Figure 3: Overall approach to developing a strategy for aggradation remediation, taking into account socio-anthropological and physical contexts and constraints