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Mining risk assessment at the territory scale: development of a tool tested on the example of gold mining in French Guiana

L'analyse des risques des projets miniers à l'échelle territoriale : développement d'un outil d'aide à la décision testé sur le cas de l'exploitation aurifère en Guyane française

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Et voilà, trois ans écoulés à la fois rapides comme des éclairs et lents comme une tortue fatiguée. Le temps d'une thèse ! Le temps, quand même, de vraiment beaucoup de choses, beaucoup d'émotions, beaucoup d'amis et de connaissances, vieilles et nouvelles, beaucoup d'expériences, en solo ou en compagnie, beaucoup de « dernières lignes droites », beaucoup de tout ! Et c'est vrai que, comme tout, la thèse est une expérience de vie qui aide un peu à la connaissance de soi...On devient tellement habitués à remettre tout en question et tout analyser pendant trois ans, jour par jour, qu'on risque de faire pareil avec nous-mêmes, et plonger dans des abysses débordants de réflexions et pensées.

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List of publications

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Sauer Lorenzo, Robert Louis-Guilhem, **Scammacca** Ottone, Mehdizadeh Rasool, Gunzburger Yann, Development of a method to assess the susceptibility of tailints dams' failure due to overtopping, Proceedings of the 29th European Safety and Reliability Conference, Hannover, 2019

Scammacca Ottone, Mehdizadeh Rasool, Gnzburger Yann, An integrated methodology for risk assessment of mining projects at different spatial scales, Proceedings of the 29th European Safety and Reliability Conference, Hannover, 2019

Others

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Glossary

Term	Definition	References
Accident	Failure of a system, due to unexpected conditions.	
Accidental (or abnormal) conditions	Unexpected and extraordinary operating conditions of a system deviating from normal conditions and resulting in a potential failure, a malfunction	49 CFR 192.503
Consequence	Outcome of an event positively or negatively affecting the objectives. Initial consequences can also escalate through cascading and cumulative effects. Consequences can be direct when they occur on the short term immediately after the risk event, or indirect when they are generated by direct consequences	ISO 31000, (2008); Andreoni and Miola, 2014
Ecosystem service	Conditions and processes through which natural ecosystems - and the species that make them up - sustain and fulfill human life through the production of ecosystem goods the harvest and trade of which represent an important and familiar part of the human economy.	Costanza <i>et al.</i> , (1997); Daily, (1997)
Failure	Event that negatively alter the achievement of the functions of a system.	
Impacted Area	Geographical space that is influenced by the occurrence of a risk event.	
Indicator	Variable that represent a specific quantity, a state, or interactions that are not directly accessible or may be difficult to estimate.	Kandziora <i>et al.</i> , (2012)
Mining project (or “mine”)	Temporary set of coordinated and controlled activities – with start and finish dates, conforming to specific requirements, including the constraints of time, cost and resources – that undertakes a process to exploit a geological deposit.	(ISO 10006, 2017); (PMI, 2004)
Ordinary (or normal) conditions	Operating conditions of a system that represents as closely as possible the range of performance, use, activity that can reasonably be expected.	IEC 62368-1, (2010)
Performance	Capability of a structure, a component or a system to perform the functions for which it was designed.	Talon and Curt (2016)
Probability	Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty.	ISO 31000, (2008)
Risk	Effect of uncertainty on objectives. Risk equals the product of probability and consequences. It can be positive , when it enhances the expected objectives and negative , when it worsens them.	ISO 31000, (2008)
Risk aggregation	Process to combine individual risks to obtain a more complete understanding of risk.	ISO 31000, (2008)
Risk assessment	Overall process of risk identification, risk analysis and risk evaluation.	ISO 31000, (2008)

Risk event	Occurrence or change of a particular set of circumstance.	ISO 31000, (2008)
Risk management process	Systematic procedure consisting in communicating, consulting, establishing the context, identifying, analyzing, evaluating, treating, monitoring and reviewing risk.	ISO 31000, (2008)
Risk perception	Stakeholder's view on a risk.	ISO 31000, (2008)
Risk scenario	Result of a simulation that foresights some possible alternatives and future realities involving the occurrence of a series of risk events during normal (RSo) or accidental (RSa) operating conditions.	
Socio-Ecological System	A system composed of biogeophysical components and human actors (individual and collective) in mutual interaction. They provide ecosystem services that satisfy societal needs and support human well-being.	Gotts <i>et al.</i> , (2018)
Stakeholders	Any person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity.	ISO 31000, (2008)
System	Any set of connected, interacting, interdependent processes and group of units forming an integrated whole which drives itself or is driven to achieve one or several specific goals, in a dynamic and active environment, through the performance of specific functions.	Le Moigne, (1990) ; Erodney (2016)
System component	Characteristic element part of a specific system which assures the achievement of the performances and the functions of the whole system.	
System function	Characteristic purpose of a system as well as the values provided by it.	Merriam-Webster, (2016)
Territorial Mining Scenario (TMS)	Result of a simulation that foresights some possible alternatives and future realities involving different land-planning strategies for the development of mining activities at the territory level.	
Territory	Integrative space of physical phenomena and human and societal relationships, a conformation of morphological characteristics and heterogeneous distribution of its resources. The territory is a Socio-Ecological System.	Simone <i>et al.</i> , (2018)
Vulnerability	Intrinsic properties of something that create susceptibility to a source of risk that can lead to a consequence. See Table.	ISO 31000, (2008)

Acronyms

ASM	Artisanal and Small Scale Mining
BT	Bow-Tie diagram
DEM	Digital Elevation Model
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ES	Ecosystem Services
ESIA	Environmental and Social Impact Assessment
FG	French Guiana
GIS	Geographic Information Systems
GRI	Global Report Initiative
i-ASM	Illegal Artisanal and Small Scale Mining
LCA	Life Cycle Analysis
LSM	Large-scale Mining
MSMc	Medium-scale Mining with cyanidation
MSMg	Medium-scale Mining with gravimetry
PSM	Proactive Safety Measures
RB	River Basin
RSa	Accidental Risk Scenario
RSM	Reactive Safety Measures
RSo	Ordinary Risk Scenario
SD	Sustainable Development
SDGs	Sustainable Development Goals
SES	Socio-Ecological System
SIA	Social Impact Assessment
TLCA	Territorial Life Cycle Assessment
TMS	Territorial Mining Scenario
TSF	Tailings Storage Facility

General introduction

In the current context of worldwide natural (e.g. climate change) and human (e.g. population growth) changes, mining industries must respond to a growing demand for minerals and metals while facing critical social and environmental challenges (Aznar-Sanchez *et al.*, 2019). Since socio-economic development should not compromise socio-environmental integrity, the concept of sustainability has been introduced into mining through “the adoption of practices (...) that result in environmental and social improvements over traditional resource development methods, as well as negative impacts, while maintaining the health and safety of mine workers and the interests of stakeholders and affected communities” (Gorman and Dzombak, 2018).

Indeed, mining projects are the source of both positive (i.e. opportunities) and negative (i.e. losses) risks of different natures: social, environmental, economic. Such risks overcome the mere sphere of the mine sites themselves and affect the territories in which these activities are located. Furthermore, when opportunities are outweighed, negative outcomes of mining rebound on mining operators through sanctions or oppositions, leading to considerable entrepreneurial risks and financial losses (Bergeron *et al.*, 2015).

Hence, mining activities should be evaluated according to the level of their positive and/or negative contributions to the socio-ecological system in which they are located. Moreover, the assessment of these contributions should focus on all the coexistent and variegated mine-types located within a given territory. For such reasons, we claim that **mining projects are a matter of land-planning rather than simple standalone industrial objects**. Fig. 1 presents the conceptual reciprocal interactions between a mine and the territory, as a socio-ecological system. Mining provides services to the human sphere but at the same time affects ecosystem services delivery and, thus, the satisfaction of the corresponding human needs.

The engagement of mining into land management relies on multiple factors of different orders. One of them concerns land-use, which means questioning on which purposes a territory is intended to be managed for and what are the potential positive or negative risks associated to such uses. For instance, what is the level of ecosystem services supply that a given land-use can guarantee for the viability of human society? As a matter of land-planning, mining is also a (geo)political key-issue, considerably tied to governance factors and global market trends. This implies the questioning of which development model(s) and future scenario(s) decision-makers, public authorities and civil society might choose for a given area (e.g. municipality, region, country) and what implications might be derived.

A wide range of tools are currently used for industrial risk assessment (Tixier *et al.*, 2002): such tools are designed to be performed at the mine-scale, often on one project at the time. Also, from a regulatory point of view, socio-environmental impact statements are

required by many legislations worldwide. However, by our knowledge, no tools are specifically designed to account for the technical specificities and the variability of mining activities or for their integration into land-planning strategies at the territory level.

This PhD thesis researches how **mining activities and their specificities can be included into land-planning strategies based on their level of risks**. Whether one or more mining projects should be developed on a territory implies political answers and political objectives. This thesis has the purpose to suggest a new way to look at this question and to propose **a pluridisciplinary approach to support decision-making and land-planning through the development and comparison of potential alternative scenarios of mining development, according to their risks**. These scenarios do not involve one single mine localized in a specific site but multiple and variegate mine types distributed in a given territory.

In order to operationalize this approach, a methodological framework has been developed based on existing methods and adapted to our purposes. The methodology has been tested on gold mining in French Guiana for a first application.

It is important to underline that this study does not propose a method to detail the level of risk (for which specific methods already exist) but to compare territorial scenarios based on their global level of risk and discuss them. The approach proposed in this study is an analytical approach to simulate and compare potential scenarios – rather than predict them – for decision-making purposes in a sector highly affected by uncertainty.

The thesis is divided in eleven chapters, grouped in four parts. **Part I** is destined to present the general context of the study. Three general concepts are behind the approach we wish to present: “mining”, “territory” and “risk” as well as their interactions (**Chapter 1**). The first part addresses as well the philosophy and the objectives of this thesis, the methodological framework developed to apply our approach and finally the case-study on which a demonstrative application will be performed (i.e. gold mining in French Guiana) (**Chapter 2**).

Parts II and III reflect the structure of the methodological framework followed to apply our approach to the selected case-study. **Part II** shows the first part of this demonstrative application. The territory and mining systems are detailed (respectively in **Chapters 3 and 4**) and combined to obtain multiple territorial mining scenarios (TMS) (**Chapters 5**). The risks related the TMS are then identified and used to develop two different risk scenarios related to the normal and accidental functioning of the mining projects (**Chapter 6**).

Parti III presents the final steps of the application, which consist in the assessment of the different risk scenarios independently (**Chapter 7 and 8**). Finally, the results of each risk scenario are combined in order to assign a global score to each territorial mining scenario (**Chapter 9**).

Part IV is destined to the discussion of the proposed approach and its demonstrative application (**Chapters 10-11**). Advantages and gaps are addressed along with the future perspectives and challenges that future studies should consider in order to improve our approach.

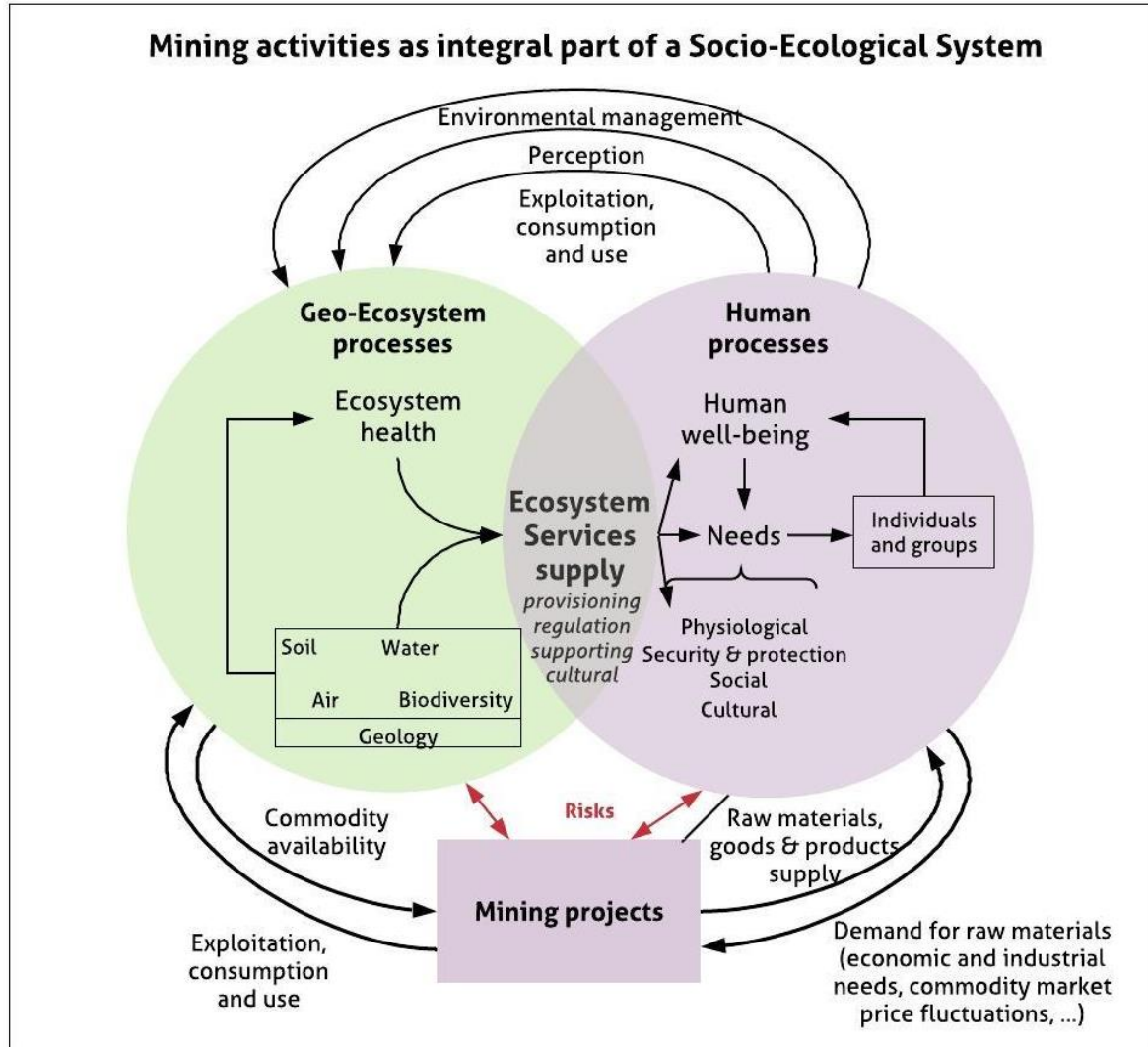


Figure 1 Integration of mining projects in Socio-Ecological Systems taking into consideration the reciprocal interactions between biophysical and human processes. Original, based on Bennet et al., (2009) and Berrouet et al., (2018) conceptual representations.

Part I – General context and objectives of the thesis

Chapter 1. Mining, territory and risks

This first chapter aims to introduce the three key-concepts of the current thesis: mining, territory and risk assessment. The chapter reviews the unique features of a mining system and its integration in wider territorial units (i.e. a socio-ecological system). As it will be detailed, the interactions between a mining system and the territory where this activity is performed can result in different outcomes (i.e. risks) that affect both the territory and mining projects themselves. These risks and the emerging difficulties for their assessment are here described in order to underline the current need for holistic and integrative approaches of risk management applied to the mining sector at wider spatial scales for land-planning purposes.

1. The mining system

For the methodological purposes of the current thesis, a mining project is here considered as a technical **system** whose main **function** is the exploitation of a mineral deposit in order to supply marketable products, with the objective of answering a world-wide demand for raw materials. In this section, the technical and operational dimensions of mining activities are described before a synthetic description of their reach at a world-wide scale.

1.1. What is a mining project?

As other human activities, mining is a socio-technical system characterized by complex interactions between humans and various technical processes at different spatio-temporal scales (Badri *et al.*, 2012; Pactwa *et al.*, 2018). A **mining system** could be considered as an organized set of connected mining processes (i.e. mining phasing), a scheme of facilities, tangible and intangible assets (e.g. exploitation engines, processing plants, mining licenses) and human resources needed to achieve one main goal: the extraction of minerals and/or metals from orebodies. It requires a special investment or allocation of resources such as capital, and completion within a specified time period (Allen, 2006).

From a traditional business perspective, a mining project is an investment business project which seeks an economically viable geologic deposit to explore and, in case, to extract in order to originate one or several marketable products (Lechner *et al.*, 2017). The mining techniques involved for the exploitation of the deposit, the size of the project it-self and the entrepreneurial structure of a mining project can take a wide range of forms, according to the targeted commodity, the technical and financial capability of the mining operator and external factors related to the territory where mining is performed (e.g. regulatory frameworks, climatic conditions, accessibility of the mine site).

1.2. Mining phasing

Technically speaking, the exploitation of a mining deposit follows **four main phases** (Fig. 2). The first phase of prospecting and exploration has the purpose of defining and delimiting the geologic deposit. The spatial scale of the prospecting is considerably broad, during strategic exploration, in order to detect geochemical anomalies and tightened increasingly as the target deposit is identified, delimited and the reserves are estimated (Charles *et al.*, 2017).

Once the results of mineral prospection are promising, the second phase involves scoping, prefeasibility and feasibility studies of the mining project, its planification, financing and finally, its construction (Kister *et al.*, 2017). This phase has the purpose to evaluate the construction and operational costs in order to assure the financial and technical viability of the project before its operation. Every technical aspect of the mining operation is defined during this second step (*e.g.* ore exploitation techniques, mineral processing method, waste and water management procedures, site rehabilitation and mine closure) along with a general state of the art of the mine site, the identification of the related impacts likely to occur, the measures and safety procedures to reduce and stop the dysfunctions, the dismantling and reorganization of the mine site and its infrastructures, the monitoring and the anticipation of the residual risks (Poulard *et al.*, 2017).

The third phase consists in the exploitation of the deposit, the processing of the extracted materials and their transformation into marketable products. This phase involves as well the management of wastes, water and processing residues as well as the progressive rehabilitation of the mine site.

During the final phase, the mining operator must implement the rehabilitation measures that have been detailed during the prefeasibility and feasibility studies (potentially modified and adapted all along the operation of the mine). This phase aims to return the mine to its initial state and it is accompanied with land reclamation measures, the application of procedures to stop, reduce or compensate socio-environmental dysfunction that the mining project might generate (*e.g.* reduction of acid drainage from old uncovered mine wastes, revegetalization of the mine site) (Poulard *et al.*, 2017).

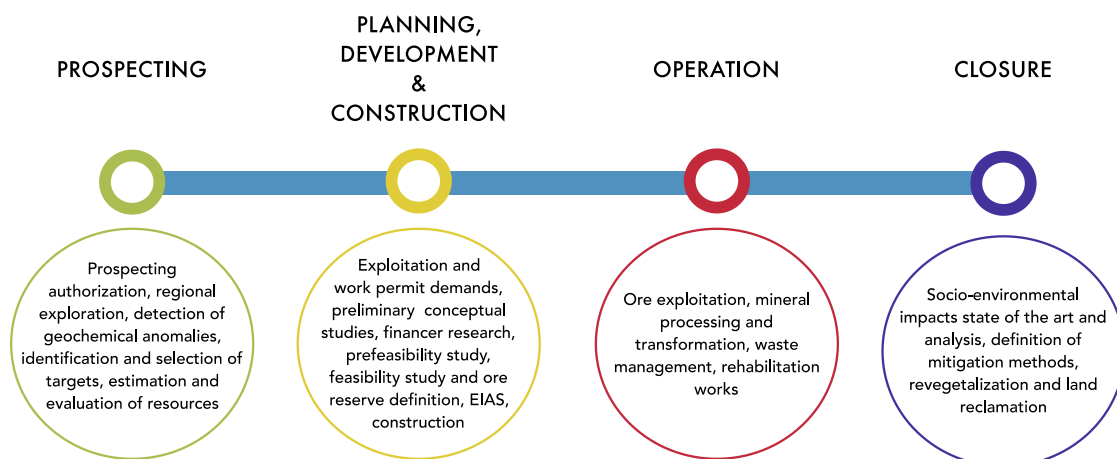


Figure 2 Mining phasing and the main tasks performed by mining operators for each phase

2. Mining performances at the territory level: a call for sustainability in the mining sector

The main objective of a mining system is the exploitation of a geological deposit for the production of marketable raw materials. This goal is achieved through the satisfaction of specific technical and operational performances. A **performance** is defined as the aptitude or the capability of a mining system or its components to perform the functions (i.e. objectives) for which it was designed (i.e. exploit the mineral deposit) (Talon and Curt, 2017).

However, in order to achieve such objective, mining activities might generate a wide range of outcomes that could exceed the mine site it-self, and positively or negatively affect the territory in which mining is performed. The *territoriality* of mining has been highlighted by scientific literature and public authorities during the years, in order to underline the need of the implementation of more pertinent land planning strategies for mining regions. During the last decades, the issue of sustainability has been increasingly addressed in the mining sector through the integration of socio-environmental performances intended to switch mining projects from mere business activities to development-aiming projects. The territorial footprint of a mining project is thus represented by the nature of its performances and how mining contributes to the socio-ecological functions (i.e. ecosystem services delivery, well-being enhancement) of the territory in which mining is performed.

2.1. “Traditional” vision of mining activities as business projects

The consideration of a mining project as a system aiming at the only extraction of a given commodity from a business-based perspective represents the *traditional* vision of mining activities. This vision is nevertheless significant since in some regions it is more complex to efficiently integrate development and mining sustainable performances for political, regulatory, technical, cultural and socio-environmental factors.

During all the mining life cycle, a wide range of **technical, operational and financial performances** must fulfill such primary business functions. These performances are related to all the internal aspects of a mining project (Badri *et al.*, 2012), including internal processes (e.g. methods and work procedures), systems (e.g. technical, management and organizational) and persons (within the organization or externally in interaction with the organization). They concern mining techniques (engineering, energetic performances, etc.), labor force (occupational safety and health performances, working conditions, training of workers, etc.), the geological deposit (existence and size of the deposit), production (financial viability, productivity and profitability performances, access to capital, subcontracting, etc.), logistics (accessibility to the site, communication, etc.) (Mancini and Sala, 2012; Pactwa *et al.*, 2018). Technical, operational and financial performances depend also on legal and political requirements such as the possession of a mining license and the fulfillment of all the regulatory obligations, including the respect of

national and international public policies and potential political support from local Governments where mining is performed.

The level at which mining performances are or are not guaranteed depends intrinsically on the structural and functional organization of the different **components** of the mining system (e.g. human, material and immaterial assets) like any business activity. Mining components vary considerably according to the targeted commodity, the type of geological deposits and mining techniques employed but also to the structure of the mining company and external socio-economic factors. Durucan *et al.*, (2006) perform a Life-Cycle Assessment on mining projects describing the links between each structural component of a mining project (Fig. 3).

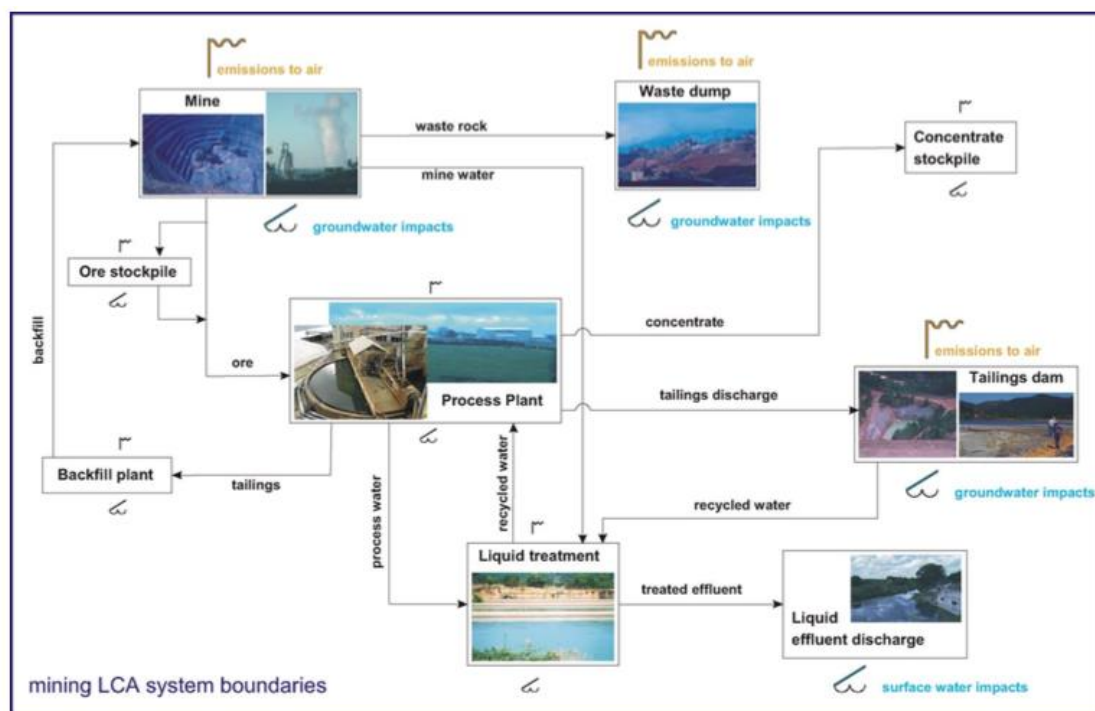


Figure 3 Boundaries of a mining system described by Durucan *et al.*, (2006) for a Life-Cycle assessment

2.2. Mining and Territory: a Socio-Ecological approach

As mentioned, as other human activities, mining might be an essential source of income and a potential driver for economic development (e.g. creation of wealth, job opportunities, technological development, raw materials supply, local business development, social infrastructures expansion) (Amirshenava and Osanloo, 2019), especially in regions where the opportunities for other economic activities might be limited. Mining is also the potential source of negative outcomes of different natures affecting ecosystem services supply (e.g. soil, water and air degradation, fragmentation of natural habitats), the derived socio-ecosystem services and, hence, human well-being (e.g. poor health condition, social conflicts, insecurity) (Badri *et al.*, 2012; Schimann *et al.*, 2012; Falck and Spangenberg, 2014; Nguyen *et al.*, 2017; Bansah *et al.*, 2018). Such impacts often exceed the perimeter of the mine-site and affect the territory

where the mining project is located. However, unlike some other human activities, mining presents a peculiar feature, since it does not question project location (Castilla- Gomez and Herrera-Herbert, 2015).

Despite the many definitions given by scientific literature (Simone *et al.*, 2018), in this thesis, a **territory** is defined as every Socio-Ecological System (SES), composed of biogeophysical components and human actors (individual and collective) in mutual interaction (Blair and Buytaert, 2016; Gotts *et al.*, 2018): socio-ecosystems are affected by human activities and in turn, they provide ecosystem services – or disservices – that might satisfy societal needs and support human well-being (Schulze *et al.*, 2017; Berrouet *et al.*, 2018; Gotts *et al.*, 2018) (Fig. 1). This definition is independent from any administrative, geographical or biophysical boundaries that might be inferred (e.g. municipality, water catchment, region, nation). A territory system has, thus, two main functions to which a mining project must contribute as well. On one side, the delivery of ecosystem services, as the “benefits supplied to societies by natural ecosystems” (Daily, 1997; Costanza *et al.*, 1997) and on the other one, the support of well-being as a global assessment of a person’s *quality of life* (WHO, 1997; Dodge *et al.*, 2012).

2.3. Mining and sustainable development

Because of its negative impacts, during the last decades mining has increasingly come under the spotlight of international media and civil society criticism, and experienced increased conflicts and opposition from local communities (Hilson, 2002a; Falck and Spangenberg, 2014, Conde and Le Billon, 2017). This has pointed out the urgency for mining operators to consider in our modern society the concept of sustainable development and to include standards for the improvement of environmental and social mining performances (UNDP, 2018). Mining projects started being considered through a holistic approach as a part of a larger system – rather than as an industrial object left alone – integrating both a human and natural component on a broader spatial scale (Fig. 1). The consideration of mining projects as contributing parts of a larger socio-ecological system allowed a major shift from the traditional vision of mining as mere business activity towards a modern vision of potential development projects (Falck and Spangenberg, 2014; Singh and Singh, 2016).

The rise of sustainability and development concerns, as well as the associated new regulatory frameworks, encouraged industrials to take into consideration the socio-environmental and governance dimensions of mining (Christmann *et al.*, 2016; Husted and Sousa-Filho, 2017). Despite this switch has not been made clear yet, this new dimension allows the incorporation of new socio-environmental and “**sustainable-development (SD) performances**” that may be sought by mining operators (Azapagic, 2004; McLellan *et al.*, 2009; Hodge, 2014; Nguyen *et al.*, 2017; Betancur-Corredor *et al.*, 2018; Pactwa *et al.*, 2018; Zvarivadza, 2018; Amirshenava and Osanloo, 2019; Aznar-Sanchez *et al.*, 2019). Among them, several international initiatives propose the integration of the frameworks proposed by the

International Finance Corporation (IFC) or the Equator Principles (UNDP, 2018; Equator Principles, 2020) in the mining sector.

At the international level, SD performance indicators for mining have been proposed withing the **Global Reporting Initiative (GRI)** (Azapagic, 2004; GRI, 2013; Mancini and Sala, 2018). Mancini and Sala (2018) reviewed and compared all these different frameworks for socio-environmental indicators to be integrated within the mining sector, including the GRI indicators and the **Sustainable Development Goals (SDGs)**. At the national level, countries such Australia, have developed their own handbooks and guiding manuals to implement SD performances into mining activities (Australian Government, 2011).

The SDGs have been set by the U.N. General Assembly set in 2015 – as part of UN Resolution 70/1 and the 2030 Agenda – to be achieved by the year 2030: these 17 goals include the three different dimensions of sustainability (*e.g.* zero hunger, good health and well-being, land and water quality, education quality). The relevance of SDGs in the mining sector has been pointed out by multiple authors (Mancini and Sala, 2018; Monteiro *et al.*, 2019; Kumi *et al.*, 2020) and a White Paper published by the U.N. presents the discussion of what should be considered to implement SDGs specifically in the mining industry (UNDP *et al.*, 2016) (Fig. 4).

For instance, the Responsible Mining Index evaluates the performances of single mining companies and their achievement of the SDGs (RMF, 2020).

The International Council of Mining and Metals (ICMM) proposes also an index to assess the worldwide contribution of mining to the socio-economic development of each country based on multiple existing performance indicators (ICMM, 2012; ICMM, 2016).

Other initiatives concern the framework defined within the Earth Observation Miners (EO Miners) project, supported by the European Commission (<http://www.eo-miners.eu>), that aims to facilitate and improve the interaction between the mineral extractive industry and society in view of its sustainable development while improving its societal acceptability (Falck and Spangenberg, 2014).

General **SD indexes** have been proposed over the years in order to measure SD performances. For instance, Amirshenava and Osanloo (2019) review and combine different methods in order to propose a quantitative assessment methodology for SD-related impacts in the mining sector. Or else, Dialga, (2018) try to estimate SD indexes per each mining country. A quantitative model has been proposed by Husted and Sousa-Filho., (2017) in order to assess the impact of sustainable governance practices on **environmental, societal and governance (ESG)** performances including country-level variables such as country stakeholder orientation and country financial stability risk. Other authors discussed specific aspects of the mining industry, such as the implementation of SD performances within the mining design phase (McLellan *et al.*, 2009), or in other cases the integration of SD through new innovations and

technologies for mining activities (Aznar-Sanchez *et al.*, 2019). Few papers are discussed on a commodity-basis: Betancur-Corredor *et al.*, (2018) point out the challenges and constraints to meet more sustainable conditions in gold mining sector while Hoadley and Limpitlaw, (2004) focus on artisanal and small-scale gold mining.



Figure 4 Major issues areas for mining and the implementation of SDGs (UNDP *et al.*, 2016)

2.4. Mining activities as development projects: the integration of new performances

Therefore, to the traditional operational performances of a mining project, which are related to its technical and economic viability as a business project, a new range of social, economic and environmental performances have been integrated. Such performances involve the capability of a mining project to support and contribute to the well-being and growth of the territory where it is located while avoiding environmental degradation (Fig. 5). For instance, **economic performances** might concern the economic profitability of the mining activity outside of the project-itself, i.e. to the surrounding human and physical environments. They include contributions to local and national incomes, the generation of foreign exchanges, raw materials supply, business and employment opportunity development. **Social performances** include the support to local livelihood (local direct and indirect employment, promotion of local commerce, education improvement, infrastructure improvement, societal acceptance, etc.), to the

preservation of human health (related to potential impacts on air, soil, water and other natural resources that may affect health of local community and their safety), human rights (child labor interdiction, respect of indigenous rights, control on the development of illicit mining communities, gender equality, etc.), land-use and planning contributions (residential, agricultural and urban areas maintain and support, adequate distance from sensitive areas, etc.), product responsibility (customer health and safety, materials stewardship), communication and stakeholders involvement (Voinov *et al.*, 2016). **Environmental performances** are represented by the capability of mining operators to preserve the bio-geo-pedological resources and ecosystems of a territory, avoiding their bio-physical and chemical degradation but also implementing measures for the restoration of the site, revegetalization and land rehabilitation.

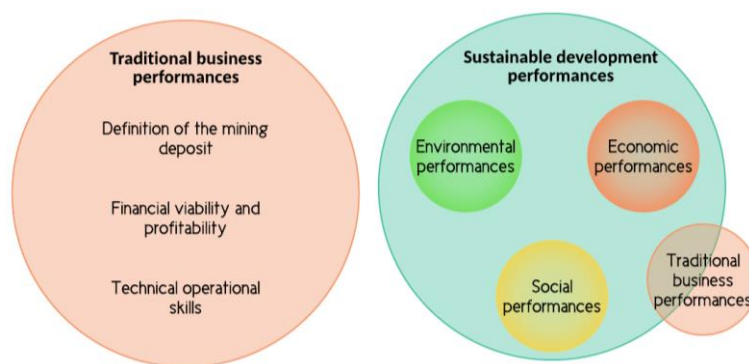


Figure 5 The transition from the traditional connotation of mining activities as merely business projects to projects integrating SD performances

2.5. Socio-ecological vulnerability of mining territories

Based on what has been presented until now, a mining project is much more than a simple and local industrial object. Its functioning and its outcomes – positive or negative they might be – exceed the mine perimeter and may affect the functioning of a larger territorial system. Therefore, the management of a mining project and the assessment of its risks – depending on the implementation or not of the mentioned performances – cannot overlook the specific features and the **vulnerability** of the SES where mining is performed. At the same time, decision-makers and land-planners should account for the peculiar interaction between the territory, its vulnerability and the different mining activities there located: both project-management and land-planning decisions should be performed on different spatial scales.

The definitions of vulnerability are very variegated (Table 1). They are not unanimous, and some terminological gaps should be addressed. For instance, the definition of Muller *et al.*, (2011) focuses on the susceptibility to experience damage, limiting vulnerability only to “negative” events affecting the functioning of a system. Based on the general definitions presented in Table 1 and the consideration of a territory through a SES approach, territorial vulnerability to mining might be considered as the socio-ecological vulnerability, i.e. the socio-

ecological conditions and processes of a territory that determine its level of exposure and susceptibility to – positive or negative – stresses, changes and regime shifts due to mining activities. Therefore, vulnerability is an important component of risk that influence both the likelihood of occurrence of a risk event and the intensity of its consequences (Lauerbourg *et al.*, 2020).

Table 1 Examples of definition of "vulnerability" in scientific literature

Vulnerability definition	References
The susceptibility of a system to experience damage	Muller <i>et al.</i> , 2011
The conditions and processes that determine the exposure and susceptibility of an individual, a community, a system, or a unit to disaster as well as their capacities to respond effectively to them	Maikhuri <i>et al.</i> , 2017
The affinity of a system to changes, determined by both, the exposure to external stresses and shocks and the intrinsic factors that determine the systems' resilience	Lauerbourg <i>et al.</i> , 2020
The function of system exposure to changes, its susceptibility to be affected by a change and its resilience to restore its functioning after the change occurred	Nasiri <i>et al.</i> , 2015; Sowman and Raemaekers, 2018
Intrinsic properties of something that create susceptibility to a source of risk that can lead to a consequence	ISO, 2008

The application of vulnerability assessment of SES has been discussed by several recent papers (Berrouet *et al.*, 2018; Sowman and Raemaekers, 2018; Mekonnen *et al.*, 2019). The interest of a socio-ecological vulnerability assessment is the identification of **vulnerable areas** (Lauerbourg *et al.*, 2020), which would be an important parameter that must be accounted for in risk assessment and as support for decision-making for land-planning. Since this approach is relatively recent, no applications to the mining sector have been found except for sectorial studies which aimed to assess the ecological vulnerability of given mining systems at a territory level (Pandey and Bardsley, 2015; Peng *et al.*, 2015; von der Forst, 2018). For instance, Peng *et al.*, (2015) explores ecological and vulnerability assessment of mining cities at the landscape scale.

SES vulnerability assessment has been often coupled with the ecosystem services framework (de Chazal *et al.*, 2008; Berrouet *et al.*, 2018). Berrouet *et al.*, (2018) propose a conceptual framework for the vulnerability assessment of SES with a particular regard on soil-related ecosystem services. As suggested by the same authors, socio-ecological vulnerability depends on the level of provided/lost benefits and assets that a system might supply and, most of all, “on the type of need that such benefits satisfy”.

Among the different methodologies to assess vulnerability, one of the most common method is the use of **vulnerability indicators** (Nasiri *et al.*, 2016). In the cases of such large spatial areas, some methods use available data for providing a logical image of vulnerable spots through GIS-based tools, which help support decision-making and land-planning. According to Nasiri *et al.*, (2016), indicator-based assessment approaches can be “the greatest policy-making tool for

raising public awareness, support governments in priority of budget allocation and land-planning purposes”. However, according to these authors, such methods face considerable complexity related with standardization, weighting, uncertainty, interdependencies between the selected indicators and aggregation methods.

2.4. Why and how to evaluate the « performance » of a mining system?

The notion of mining performance plays a key-role for the development of a risk assessment methodology of mining projects at the territory level because it can support the evaluation of the contribution of mining to the mentioned territorial performances. As it has been said, the contribution of the mining system to the territory in which it is located is realized through the shift of mining to development activities rather than mere business projects, and through the integration of new socio-environmental performances.

Thus, the quantification or the quantification of the footprint of mining in a given territorial system, through the assessment of their performances, could represent an important tool to help land-planning strategies in order to maximize benefits and opportunities (i.e. positive risks) and reducing losses (i.e. negative risks) of different natures (e.g. environmental, social, economic). Moreover, the satisfaction of socio-environmental performances improves the social footprint of a mining project allowing positive feedbacks for mining operators.

The implementation of such performances has been encouraged through the years the development of tools such as the **Corporate Social Responsibility (CSR)** (Littlewood, 2015; Nxele, 2015; Pimpa *et al.*, 2015), considered as a “business's commitment to contribute to sustainable economic development, and also as the commitment to collaborators and their families, local communities and society in general, to provide a better quality of life” (Rodrigues and Mendes, 2018). During the last decades, another tool that has been developing is the **Social License to Operate (SLO)** which has been discussed by a very wide literature (Dare *et al.*, 2014; Harvey and Bice, 2014; Parsons *et al.*, 2014; Zhang *et al.*, 2015; Mercer-Mapston *et al.*, 2017; IGF *et al.*, 2018). Today SLO is viewed by some authors as a ‘key condition for successfully establishing and running a mining project’ (Falck and Spangenberg, 2014; Hall *et al.*, 2015). These tools have been combined, at least from a theoretical point of view, also with the realization of the SDGs (IGF *et al.*, 2018). Nevertheless, some authors criticized such concepts as they would seem a poorly conceptualized idea “invented by business, for business” or as a tool of limited applicability and currently used to merely serve as a “window-dressing strategy for controversial business practices” (Brueckner and Eabrasu, 2018).

From a juridical point of view, the evaluation and monitoring of the socio-ecological performances of mining projects was performed through the implementation of common formal tools such as regulatory frameworks and public policies specific to mining. The respect of these new performances considerably influences the feasibility of mining projects (Pactwa *et al.*, 2018): for instance, the delivery of a mining permit or external financial investments and

loans to the mining company depend on how the operators would meet specific socio-environmental requirements.

Nevertheless, these performances should be considered by mining operators as an “ideal state” to be aimed and not as an administrative requirement (Voinov *et al.*, 2016; Betancur-Corredor *et al.*, 2018). Indeed, the negative outcomes of mining have a rebound effect on mining operators which are under pressure from governments, and/or financial institutions, civil society and local communities (Kemp *et al.*, 2016). When their socio-ecological performances are unsatisfactory, mining projects might be at the origin of social conflicts (Clifford, 2017) and the target of considerable entrepreneurial risks (Pokorny *et al.*, 2019) leading to delays, investment losses or even the cessation of the mining activity (Bergeron *et al.*, 2015). Thus, the actualization of such performances represents an important criterion to sustain public tolerance of mining activities and secure legitimacy from local communities (Wessman *et al.*, 2014; Poudyal *et al.*, 2019). Therefore, the success of a mining project as a business project depends also on its contribution to the socio-ecological performances (e.g. human well-being, ecosystem health) of the territory in which mining is performed. Jeopardizing of one of these objectives might cause severe socio-environmental disruptions and compromise the project itself (e.g. public contestations, juridical sanctions, administrative halt measures).

3. Risks associated with mining projects

Until this point, it has been often mentioned the importance of the positive and negative “outcomes” generated by mining describing them as the factual effects of such activity. The assessment of such outcomes can help to identify, qualify or quantify the overall performance of a mining project. Such outcomes have been described here as “effects”, “benefits”, “opportunities”, “losses”, “threats”. However, the purpose of this thesis is the development of a methodology for risk assessment of mining projects at the territory level. Therefore, a formally precise and specific terminology urges to be defined. To serve this purpose, a Glossary is available at the beginning of this manuscript.

This section aims to fix several definitions related to the general risk assessment and management practices as described by ISO, (2008) or the PMBOK (2013). A general review of the main risks related to mining projects is given as the result of a thorough bibliographic review. Finally, different methods for risk and impact assessment applied to the mining sectors are reviewed and discussed in order to highlight their advantages and limitations.

3.1. Risk definition

A “**risk**” is defined as the positive or negative “effect of uncertainty on the objectives” of a system (ISO, 2008) or as “an event or an uncertain condition”, the occurrence of which might have an unexpected positive or negative effect on one or several objectives of a project

(PMBOK, 2013). Risk is composed of two main elements ISO, (2008). The first one is **probability**, as “the measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty”. The second one is represented by its **consequences**, i.e. the outcomes of a risk event which can positively or negatively affect the objectives of a system, according to its exposure or vulnerability (ISO, 2008). However, the definition of “risk,” is inherently controversial (Fischhoff *et al.*, 1984). Often it is confused with a variegated terminology that includes “hazard”, “danger” or “impact”, when the probabilistic dimension is not taken into account.

In this thesis, a **mining risk** is considered as the “effects of uncertainties on the objectives” (i.e. functions) of a mining project. Hence, a **risk** is a ‘change-state **event**’, a “regime shift’ (Filatova *et al.*, 2016), a “deviation from the expected” (ISO, 2008) driven by exogenous and/or endogenous events which alter the state and functioning of a system to another one in which the performances are different: thus, each probable event modifying the performances of a mining project – and consequently the achievement of its functions – can be considered as a risk. A risk will be considered as positive or negative depending on whether it increases or decreases the associated performance(s).

Since the concept of risk and performances are tightly linked, the nature and types of risks depend on how and whether the performances of the mining project and/or the performances of the territory in which a mining project is located are altered. Therefore, mining risks vary depending on which performances are considered for the mining projects (e.g. traditional or socio-ecological). The traditional vision of mining projects might lead the risk assessment process to focus rather on entrepreneurial and technical-operational risks. In this thesis, the integration of SD-performances to mining projects, consequently, include a wide range of risks affecting the socio-ecological components of the territory where the project is located. Furthermore, depending on the project-management or land-planning purposes of the risk assessment process, the integration of these new performances should lead to assessments at the scale of territory level – rather than at the project-scale – that focus on multiple mining projects at the same time to support future strategies for mining territories.

3.2. “Categories” of risks

During a mine lifetime, each mining phase present its level, natures and types of risks according to the different techniques used. Since the prospecting phase involves mainly non-invasive techniques, the risks associated are relatively low. On the other hand, the operational phase is considered as the most susceptible source of risks of different natures. Castilla-Gomez and Herrera-Herbert, (2015) distinguish between temporary and structural impacts of mining depending if they stem directly from the mining projects and respectively disappear when mining stops or actively continue even after mine closure. The authors show a considerable increasing of impacts as the construction of the mine begins and with the highest peaks during the operational phase (Fig. 6).

Mining risks also vary considerably depending on the intrinsic features of the mining project – such as the targeted commodity and the characteristics of the deposit – and the techniques used for mineral exploration, ore exploitation and mineral processing, as well as for site remediation. Sometimes, a great heterogeneity of techniques might be employed for the exploitation of a given commodity (e.g. gold, diamonds, copper), which are exploited both by artisanal miners and large companies. At the same time, based respectively on its human and natural features and its vulnerability, the SES where mining is performed might be the source of or the target of specific risks.

Concerning the “nature” of the risk, both **positive** (i.e. opportunities) and **negative** (i.e. losses) **risks** might be distinguished. Indeed, usually the controversial nature and the restrictive use of the term “risk” might suggest a focus exclusively on its negative connotation. For instance, the main typical positive risks related to mining projects concern the creation of jobs and the economic outcomes that mining activities might produce at a territory-level. However, the positive/negative dichotomy implies the integration of a subjective and multi-perspective dimension which varies according to each given stakeholder, for whom negative risks should not outweigh positive ones.

The “**target**” of the risk varies accordingly to the predefined performances and functions (i.e. objectives) of a given system. Mining performances are strictly tied to territorial performances and vice-versa. Therefore, a mining project might generate but also suffer risks of different natures. As mentioned, when its socio-ecological performances are unsatisfactory, a mining project is the source of negative risks which might be at the origin of social conflicts (Clifford, 2017). Such conflicts, derived from the social and environmental risks of mining activities, are translated into business costs and considerable entrepreneurial risks are suffered by mining operators themselves and affecting the success of a project (Franks *et al.*, 2014; Bergeron *et al.*, 2015; Pokorny *et al.*, 2019). For instance, some authors borrow the concept of “**rebound dynamics**” to refer to business, financial, legal, enterprise, reputational, and project risks in mining (Kemp *et al.*, 2016).

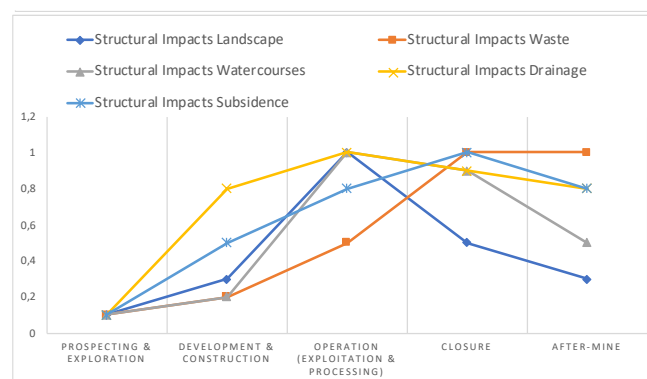


Figure 6 Structural impacts of mining projects for each mining phase (adapted from Castilla-Gomez and Herrera-Herbert, (2015))

The most typical distinction of the different types of risks related to mining projects concerns the nature of the impacted “**object**”, thus of the objectives or performances which are affected by the risk (Fig. 7). A great number of risks related to mining is widely discussed by scientific literature (Badri *et al.*, 2012; Haldar, 2013; Gorniak-Zimroz and Pactwa, 2016; Singh and Singh 2016; Lechner *et al.*, 2017; Nguyen *et al.*, 2017; Bansah *et al.*, 2018). For instance, Badri *et al.*, (2012), distinguish between five main categories of risks with a particular attention on the technical and operational sphere of a mining project: operational, financial and economic, legal and political, environmental and health and safety risks (Donoghue, 2004). Betancur-Corredor *et al.*, (2018) focus mainly on the potential societal (e.g. poverty, illegality, and violence) and environmental (e.g. waste generation, mercury and greenhouse gas emissions) negative risks of gold mining in Colombia, based on the types of mining processes involved for each mining phase. Mancini and Sala, (2018) discuss the integration of the GRI and SDGs within social performances of mining projects, categorizing both positive and negative risks based on performance categories (e.g. economy, income and security, employment and education, land use and territorial aspects, demography, environment, health and safety, human rights). In this thesis, mining risks are regrouped in 4 categories: economic, social, technical operational, and environmental (Figure 7, Table 2). In the table, some examples of these risk categories are detailed for gold mines (Table 2) (Scammacca *et al.*, 2020a).



Figure 7 Link between the socio-ecological and technical operational performances and risks of mining projects

Environmental, economic and social risks are related to the mentioned contribution of mining to economic recovery and well-being and its potential deterioration of the ecological and social systems in which mining is performed (Franks *et al.*, 2011; Badri *et al.*, 2013; Nguyen *et al.*, 2017; Nguyen *et al.*, 2018) (Fig. 7). Environmental risks might concern the effects of mining activities on biodiversity (Donato *et al.*, 2017; Owusu *et al.*, 2018; Sonter *et al.*, 2018; Bax *et al.*, 2019), deforestation (Dezecache *et al.*, 2017; Ranjan, 2019), water and soil quality (Pirrie *et al.*, 1996; Benito *et al.* 2001; Bissacot and Oliveira, 2017), soil erosion (Lei *et al.*, 2012; Sinha *et al.*, 2017;

Karan *et al.*, 2019), land-use related impacts (Sonter *et al.*, 2014; Zhang *et al.*, 2017; Venancio Aires *et al.*, 2018; Vasuki *et al.*, 2018). Social and economic risks concern health-related risks (Castellanos *et al.*, 2016; Obiri *et al.*, 2016; Sanchez *et al.*, 2016; Gabari and Fernandez-Caliani, 2017) but also the positive and negative risks affecting the whole human dimension of a SES (e.g. human rights-related issues, creation of job opportunities, development of local infrastructures, investment in research and academic programs). This dimension has been poorly addressed over the years and new developments are currently being made (Aznar-Sanchez *et al.*, 2019). Finally, technical and operational risks concern all risks affecting directly the internal sphere of a mining project.

Table 2 Bibliographic review of the typical risks of gold mines and the natures of the risks (Scammacca *et al.*, 2020a)

Risk Category	Risk	Nature	Reference(s)
Economic	Crimes and insecurity for local communities (e.g. corruption, drug and arm dealing, prostitution, child labour)	Negative	Hentschel <i>et al.</i> , 2002 WWF, 2018
	Development of local business as services providers	Positive	Amirshenava and Osanloo, 2019
	Development of research programs	Positive	MDO, 2018
	Direct economic outcomes (e.g. taxes, royalties)	Positive	Amirshenava and Osanloo, 2019
	Direct jobs opportunities	Positive	Pokorny <i>et al.</i> , 2019
	Enhancement of local education and competence development	Positive	MDO, 2018
Social	Enhancement of technological development	Positive	MDO, 2018
	Enhancement of women status	Positive	Keovilignavong, 2019
	Health problems and epidemiological diseases (e.g. malaria, HIV, food chain contamination)	Negative	Douine <i>et al.</i> , 2018
	Expansion of social infrastructures (e.g. roads, energy, services)	Positive/ Negative	Amirshenava and Osanloo, 2019
	Fight against illegal mining	Positive	MDO, 2018
	Migration of legal and illegal miners from bordering countries (“gold rushes”)	Negative	Moulet <i>et al.</i> , 2006; Hook, 2019
	Price increase of local primary goods	Positive/ Negative	Pokorny <i>et al.</i> , 2019
	Raw material supply	Positive	Amirshenava and Osanloo, 2019
	Resource dispossession (e.g. land, water, crops) and reallocation of communities	Negative	Keovikignavong, 2019
	Social disruption (e.g. opposition, conflicts, increase of inequalities)	Negative	Moisan and Blanchard, 2012
Technical and Operational	Support to ethnic minorities	Positive	MDO, 2018
	Acid mine drainage (AMD)	Negative	Miramond <i>et al.</i> , 2006
	Cyanide spills	Negative	Urien, 2018
	Delays and cessation of the activity	Negative	Bergeron <i>et al.</i> , 2015
	Financial loss for the operator	Negative	Bergeron <i>et al.</i> , 2015

	Landslides	Negative	Laperche <i>et al.</i> , 2008
	Mine subsidence	Negative	Bourbon, 2015
	Pit instability	Negative	Bourbon, 2015
	Technical infrastructures development	Positive	MDO, 2018
	Enhancement of local skills and training programmes	Positive	MDO, 2018
	Work injuries	Negative	Hentschel <i>et al.</i> , 2002
Environmental	Atmospheric pollution	Negative	Melières <i>et al.</i> , 2003
	Dam failure related flood, contamination and turbidity	Negative	Bourbon and Mathon, 2012
	Deforestation	Negative	Rahm, 2017
	Destruction of ecological habitats and biodiversity	Negative	Galochet and Morel, 2015
	Direct mercury pollution (e.g. gold recovery techniques)	Negative	Clifford, 2017
	Food chain contamination with mercury	Negative	Fréry <i>et al.</i> , 2001
	Heavy metals contamination in water and soils	Negative	Marchand <i>et al.</i> , 2006
	Landscape degradation	Negative	Laperche <i>et al.</i> , 2008
	Physical alteration of riverbeds (hydromorphological impacts)	Negative	Laperche <i>et al.</i> , 2008
	Remobilization of ancient mercury and sources of methylmercury	Negative	Guedron <i>et al.</i> , 2011a
	Soil erosion	Negative	Labriere <i>et al.</i> , 2015
	Surface water turbidity	Negative	Gallay <i>et al.</i> , 2018

3.3. Risks and conflicts / controversies about mining projects

As mentioned, since mining risks exceed the mine-site itself, they are often the source of debates, strong oppositions and potential conflicts which are translated into an entrepreneurial and business cost suffered by mining operators (Franks *et al.*, 2014). Indeed, negative mining risks are often perceived as lack or loss of ecological and socio-economic benefits for local communities (Verbrugge and Greenen, 2019). For instance, Nevada's largest mining company has suspended its proposed expansion of what would become one of the biggest gold mines in the world Facing fierce opposition from conservationists and tribal leaders (The Associated Press, 2020). Or else, in French Guiana, the large-scale gold mine of *Montagne d'Or* has been strongly criticized by both local and French metropolitan communities because of the potential environmental impacts were not considered as outweighing the economic outcomes derived from the project. These conflictual dynamics exceed the mining project scale and involve broader issues related to the re-thinking of potential strategies for the development of mining territories.

The conflictual nature of mining projects has been widely discussed by scientific literature (Hilson, 2002a; Adoteng-Kissi *et al.* 2015; Clifford, 2017; Conde and Le Billon, 2017;

Aguilar-Gonzalez *et al.*, 2018; Davis and Manzano, 2018). As shown in the following maps, comparing the distribution of currently active mine sites and the conflicts related to mining activities (Appendices 1-2), social disruptions are spread worldwide. Yet, their distribution could be related to specific sensitive areas, as showed by the “Environmental Justice Atlas” (<https://ejatlas.org/>), a research project funded by the European Commission, which proposes an on-line platform for digital maps of conflicts related to natural resources exploitation (Appendix 2). However, data availability is a major concern and the information concerning the distribution of such conflicts may be strongly biased in countries where reporting is severely constrained. Another example is the Australian project “Complex Orebodies” (<https://smi.uq.edu.au/complex-ore-bodies>) which is a transdisciplinary program that aims to enhance the “social understanding, environmental innovation, and mining and processing efficiency” in the mining industry (Lèbre *et al.*, 2019; Valenta *et al.*, 2019)

Economic development and socio-environmental integrity should not compromise each other (Castilla-Gomez and Herrera-Herbert, 2015) and nowadays, the real challenge of mining is if where and how the development might proceed without significantly disturbing the ecosystems, communities and economies overlying and surrounding mineral deposits/ processing sites (Franks *et al.*, 2011; Nguyen *et al.*, 2017). Most of the time, the failure of technical and operational performances at the mine sites, triggers the occurrence of negative risks of various natures affecting the whole territory and rebounding inexorably on mining operators themselves. Hence, the success of a mining project, as a business project, relies on its positive contribution to socio-ecological performances of the territory where mining is performed, as a development project. Such spatial variability also contributes to point out the territorial reach of mining, the progressive integration of socio-ecological performances at the project level and encourages **integrated and structured risk management strategies that are transversal, multi-scale** and that holistically consider mining as a real matter of land-planning and management.

4. Existing methods for risk assessment in the mining sector and their gaps

Mining activities are under a continuous regulatory and public scrutiny. The achievement of mining performances and the respect of current regulatory frameworks impose a strict control from public authorities but also from non-governmental organizations. Such controls result in the implementation, both by authorities and mining operators themselves, of tools – not peculiar to mining projects – designed for the identification, the analysis, the assessment and the management of mining risks. Whether a mining project is acceptable or not for society and all the stakeholders involved depends also on the assessment of their specific risks (Christmann *et al.*, 2016). However, the management of a mining project is a multidisciplinary and complex task and literature “is not unanimous on the subject of risk management processes that mining enterprises should put in place” (Chinbat, 2011; Badri *et al.*, 2012).

The present section aims to present some of the existing risk assessment methods that are currently applied also to the mining sector. These methods will be furtherly discussed in order to understand their advantages and limits but also their suitability to be integrated as methods to support the development and comparison of potential land-planning strategies for mining territories. In this study, two main groups of **risk assessment methodologies** are distinguished.

A first group (A) which includes all the methodologies and tools used to perform **industrial risk management** (Badri *et al.*, 2012) at a very technical and operational scale. The risk management process is defined by ISO 31000 and it involves the systematic application of management policies, procedures and practices to the tasks of communicating, consulting, establishing the context, identifying, analyzing, evaluating, treating, monitoring and reviewing risk (ISO, 2008). Usually these methodologies are performed at the scale of the project itself and they involve the utilization of considerable amount of qualitative and quantitative data.

The second group (B) represents the current methods used for the assessment of impacts generated by a project. In this category two main tools are considered: **Environmental and/or Social Impact Assessment** (EIA and ESIA) and **Life-Cycle Assessment** (LCA) studies. These methods concern mainly the identification and assessment only of the consequences generated by a project, usually without any consideration of probability (in some cases such methods might include probabilistic assessments and vulnerability analysis). Further typologies could include also the methods conceived solely for probability or vulnerability assessment, but such methods can be considered as complementary to the first two categories here described. The vulnerability assessment at the territory level is detailed in Chapter 2.

A specific tool usually applied also to mining projects is the **SWOT analysis**. This method does not involve a proper risk-assessment, but it represents rather the holistic description and representation of the Strengths, Weaknesses, Opportunities and Threats that might affect a specific project, an industrial sector or even a whole territorial system. This tool is widely used in the industrial sector for project management, including the mining sector (Cluett, 2012; Neagu *et al.*, 2015) Since it allows the analysis and comparison of scenarios for decision-making support, this tool will be furtherly discussed in Chapter 10 and 11.

4.1 Risk-based methodologies of risk assessment (A)

Verma and Chaudhari, (2016) propose a detailed comparative review of the main risk assessment methodologies adopted in the mining sector. The authors show that often assessment is performed through a combination of different complementary tools and methods. Among the most common methodologies applied to the mining sector belonging to the first group, we might list the **Hazard and Operability Study** (HAZOP) and the **Failure Mode and Effect Analysis** (FMEA). HAZOP is a “highly disciplined procedure meant to identify how a process may deviate from its design intent” (Dunjó *et al.*, 2009) and which potential undesirable

events may create hazards or operability problems. (Robu *et al.*, 2007 ; Paithankar, 2011; Krzemien *et al.*, 2016). FMEA is a systematic, inductive and qualitative technique used to identify and eliminate faults or deviations in a system before they cause problems. Each function in a system is analyzed and it can easily be very extensive (Onofrio *et al.*, 2015). The results may include causes of failure, effect, frequency, severity, probability and recommended actions. FMEA objectives include the identification of failure causes, modes and effects (Bouti and Kadi, 1994; Onofrio *et al.*, 2015; Kritzinger, 2017; Spreafico *et al.*, 2017). FMEA improvements involve the integration of a criticality analysis procedure (FMECA) which provides ways to perform probabilistic analysis to determine the criticality of failure modes. (Alverbro *et al.*, 2010; Paithankar, 2011; Kabir, 2017; Hatayama and Tahara, 2018).

Besides these two methods, the **Preliminary Hazard Analysis** (PHA) is a technique for the brief identification and estimation of risk sources and potential negative events (Alverbro *et al.*, 2010). The results are usually displayed in a table and may include descriptions of causes and consequences of an event, estimations of probabilities and severity of the consequences, current protection and recommended actions (Robu *et al.*, 2007; Alverbro *et al.*, 2010).

In some cases, specific methodologies aim to perform in a detailed way only one of the steps of the risk management process. For instance, the **“What-if” method** is a technique mainly used for the *identification* of risk sources by analyzing the potential consequences of deviations in a system. It is very similar to PHA, but more detailed (Robu *et al.*, 2007; Alverbro *et al.*, 2010).

In other cases, the analysis result in the development of “risk trees” which aim to the reconstruction of the potential causes and consequences of a deviation in a system. It’s the case of the **Fault Tree Analysis (FTA)** and the **Event Tree Analysis (ETA)** (Perret and Adrian, 2001). Both FTA and ETA are deductive techniques widely used to determine system dependability by showing the logical connections between faults, their causes and consequences. Their main objectives are to: identify respectively the root causes and the accidental consequences of a system failure; support the development of proactive and reactive safety measures to improve system performance; comprehensively assess the risks and their importance (Robu *et al.*, 2007; Alverbro *et al.*, 2010; Paithankar, 2011; Kabir, 2017). The FTA and ETA are often integrated in a wider approach called the **Bow-Tie (BT) method**, a highly-structured tool which offers the possibility to construct major risk scenarios around a main initial event (Delvosalle *et al.*, 2017). This method allows one of the best graphical approaches to represent complete risk scenarios around a single risk event (Khakzad *et al.*, 2013) and involves the use of a diagram in which the central part is represented by a main initial event. For this reason, the BT is widely used in high hazard industries like oil and gas, aviation and mining (de Ruijter and Guldenmund, 2016). The main components of the BT are, on the left, the Fault Tree, on the right, the Event Tree, representing respectively the causes and the consequences of the initial event (Aqlan and Ali, 2014; de Ruijter and Guldenmund, 2016). These trees can be divided into sub-trees that represent intermediate events of causes or consequences (Delvosalle *et al.*, 2017). A third

essential element in application of BT diagrams is the use of safety measures, defined as “barriers”, which can be proactive (PSM) or reactive (RSM), if their purpose is respectively to prevent the ICE to occur or to reduce its consequences once occurred (Ehlers *et al.*, 2017). However, other methods can serve, in different ways, the same purpose of the BT (for instance the Ishikawa diagram).

Finally, another method which can be used is the **Hazard Analysis and Critical Control Points (HACCP)** study, a bottom-up approach that considers how to prevent hazards from occurring and/or propagating (Frank *et al.*, 2008; Ovocom, 2016).

Further methodologies for industrial risk assessment could be found in Tixier *et al.*, (2002) which compared sixty-two risk assessment methodologies in the industrial sector, without any special mention to mining activities. The authors distinguish between deterministic and probabilistic methods (or a combination of the two), the type of data used etc.

4.2. *Impact-based methodologies of risk assessment (B)*

The second group of methodologies includes two procedures widely used by mining operators, consulting services, governments and researchers to assess the impacts of a specific project system. In this study, **Environmental and Social Impact Assessment (ESIA)** and **Life-Cycle Analysis** methodologies are considered.

4.2.1. *Environmental Impact Assessment (EIA) and Social Impact Assessment (SIA)*

The **EIA** has been increasingly positioned within a broader context of sustainability and it became in the second half of 20th century the most widely recognized and practiced of assessment methods with legal and institutional force in many parts of the world (Jay *et al.*, 2007). Originated from the U.S. National Environmental Policy Act (NEPA) of 1969, the EIA has the objective to supply decision-makers with an indication of the likely environmental consequences of specific projects and it is now an integral process of environmental management (Clark *et al.*, 2019). The EIA is an important tool for decision makers and its definition is widely discussed in the scientific literature (Crawley and Aho, 1999; Cashmore *et al.*, 2004; Jay *et al.*, 2007; Enríquez-de-Salamanca *et al.*, 2018; Clark *et al.*, 2019). It can be considered as a technical and rational evaluation to identify and evaluate the probable environmental consequences of certain proposed development actions to facilitate and provide a basis for objective decision-making processes. Therefore, the main result of the EIA is to produce a report – i.e. the Environmental Impact Statement (EIS) – which identifies, describes, and evaluates the environmental impacts stemming from the interaction of the project with environmental factors (Toro *et al.*, 2003). The EIS contains a rigorous project-by-project evaluation (e.g. screening, baseline data, identification and impact assessment, management and monitoring measures) of the significant impacts on the environment; allows

the anticipation of such impacts and their effects in order to eliminate, reduce, compensate them before any prior commitment; provides the necessary elements for pertinent decision-making process to make the project acceptable.

Nowadays, the carrying out of a EIA is a general obligation under customary international law (Clark *et al.*, 2019). It is up to the national regulatory framework of each country adopting the EIA to specify the types of projects concerned by the EIA process. In the European Union, the Directive 2014/52/EU of 14th April 2014 states mandatory and discretionary procedures to assess the effects of certain private and public projects on the environment. EIA is widely applied to the mining sector, both for research and public policies perspectives (Cashmore *et al.*, 2004; Suopajärvi, 2013 ; Toro *et al.*, 2013 ; Galas and Galas, 2016; Esteves, *et al.*, 2017 ; Gimpel *et al.*, 2018; Hresc *et al.*, 2018). For instance, in France the article R.122 of the Environmental Code lists all the types of activities for which an EIS is mandatory, such as mineral and geothermal exploitation. In Italy, the EIA (or *Valutazione di Impatto Ambientale*, VIA) applied to quarrying and mining have two different regulatory frameworks (Cormio, 2005).

The structure and the methodology for the EIA vary considerably on a country-basis, especially where legislations are highly different (Castilla-Gomez and Herrera-Herbert, 2015; Yao, 2018). For instance, interaction or prediction matrices are widely used in EIA (Toro *et al.*, 2003). Based on the dispositions of the EU Directive, the most frequent method is a qualitative tool called Leopold matrix. The matrix combines socio-environmental key aspects with each phase of the considered project in order to give importance scores (from 1 to 100) for each of the identified environmental impacts, which may, at the end of the process, produce a total score of environmental impacts generated by the activity or project.

Recently derived from the EIA, the **Social Impact Assessment (SIA)** the process of identifying and managing the social issues of project development and includes the effective engagement of affected communities in participatory processes of identification, assessment and management of social impacts (Ocampo-Melgar *et al.*, 2019; International Association for Impact Assessment, 2015). Although it is still under development, the SIA has been adopted by several countries (e.g. Canada, Australia) but at the moment there is not a world-wide recognition of this tool on a regulatory and juridical level as for the EIA.

In this category of assessment methodologies, we include as well all sort of impact-based studies that have been developed during the last few decades based on the same general methodological structure and objectives of EIA. These methodologies can be performed at different geographic levels. Examples of such methodologies are, for instance, the Health Impact Assessment (HIA), Strategic Environmental Assessment (SEA), Strategic Environmental Impact Assessment (SES), the Social Cumulative Impact Assessment (SCIA), Human Rights Impact Assessment, (HRIA), Gendre Impact Assessment (GIA) and so on (Fig. 8) (UNDP, 2018).

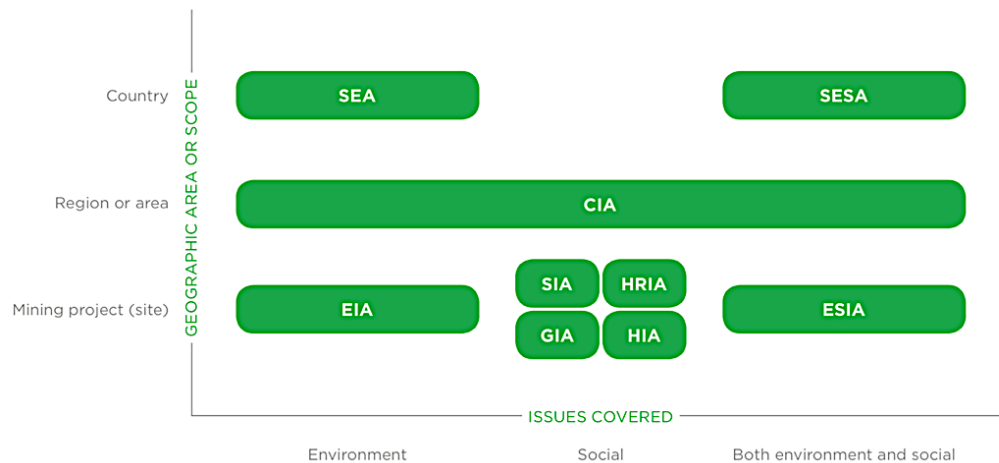


Figure 8 Families of Environmental and Social impact assessment methods, the geographic areas considered, and the issues covered (UNDP, 2018)

4.2.2. Life Cycle Assessment (LCA)

The second group of methods concerns the recent and still under development **Life Cycle Assessment (LCA)** analysis. LCA is applied in the mineral and metal sector and can help meet SDGs (Yellishetty *et al.*, 2009; Awuah-Offei and Adekpedjou, 2011; Gemechu *et al.*, 2016; Yao, 2018; Farjana *et al.*, 2019; Beylot *et al.*, 2020). A short review of some examples of case-studies of LCA in the mining sector is available in Table 3, according to the targeted commodity and the spatial scale of the assessment.

LCA consists in the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product, process or activity throughout its life cycle (“cradle-to-grave” approach) or a specific defined moment (“cradle-to-gate”) (Durucan *et al.*, 2006; Yellishetty *et al.*, 2009; Awuah-Offei and Adekpedjou, 2011; Bjorn *et al.*, 2018). It is an excellent tool to evaluate the environmental performance of current and future policies and support decision-making in the mining industry through a systemic approach (Durucan *et al.*, 2006). In some cases, LCA might be included in EIA studies as well (Yao, 2018).

One of its fundamental features is that, unlike EIA and SIA procedures, LCA is today a standardized process, which means that its principles and framework are defined by a common and internationally recognized norm of the International Organization for Standardization (ISO 14040 and ISO 14044).

The main objectives of an LCA are to: identify the opportunities to improve the environmental performance of products at various points in their life cycle; inform decision-makers in industry, government or non-government organizations; select relevant indicators of environmental performance, including measurement techniques; and finally include marketing purposes (e.g. eco-labelling schemes) (Olsen, *et al.*, 2001).

Table 3 Brief review of some examples of LCA applications within the mining sector based on the targeted commodity and the country where the mining project is located

Reference	Objective of the study	Commodity	Country
Chen <i>et al.</i> , (2018)	LCA assessment to Chinese gold production sector	Gold	China
Blanco <i>et al.</i> , (2018)	Development of a framework for impact assessment and economic valuation of water-related ecosystem services in LCA in order to compare two mining water supply systems	Copper	Chile
Islam <i>et al.</i> , (2020)	Integration of remote-sensing based imagery data within the LCA process to quantify the environmental impacts of a copper-silver-gold mine in Laos	Copper Silver Gold	Laos
Alves and Coutinho, (2019)	LCA applied to niobium mining sector in Brazil	Niobium	Brazil
Agwa-Ejon and Pradhan, (2018)	Quantification of the environmental and health impacts related to sandstone artisanal and small-scale mining in South Africa.	Sandstone	South Africa
Ingwesen, (2011)	Quantification of the total environmental contribution underlying production of gold-silver bullion at the Yanacocha mine in Peru	Gold, Silver	Peru
Hengen <i>et al.</i> , (2014)	Comparison of the environmental impacts over the life cycles of several implemented and optional AMD treatment methods, incorporating both passive and active approaches employed	Coal	New Zealand
Awuah-Offei <i>et al.</i> , (2009)	Development of a method of evaluating the environmental impacts of belt conveyors and truck haulage systems by conducting a LCA of the two systems for a hypothetical hard rock gold mine located in Alberta, Canada	Gold	Canada
Zhang <i>et al.</i> , (2018)	Environmental impact analysis including land reclamation stage using life cycle assessment (LCA) method.	Coal	China
Roychoudhury and Khanda <i>et al.</i> , (2016)	Review of the current application of LCA in the coal mining industry.	Coal	Worldwide
Northey, (2018)	Assessment of water-use related risks in mining	Copper Lead-Zinc Nickel	Worldwide

Four main steps are generally considered: goal and scope definition, the inventory analysis (LCI), impact assessment and finally the interpretation of the results. The LCI phase is extremely important since it concerns the acquisition of data for each considered process in the LCA and their assessment. Several LCI databases are currently available and used such as *Ecoinvent*, or those proposed by the National Exposure Research Laboratory (NERL) or the Environmental Protection Agency (EPA) (Chen *et al.*, 2018). The assessment implies the transformation of « environmental flows » listed during the LCI to potential impact indicators according to different empirical and mathematical methods. LCI might be based on mid-point (it considers the environmental flow between the project and the target, quantifying only a

fraction of the impacting mechanism) and end-point approaches (assessment of the whole mechanism, until the quantification of the environmental impact) (Yao, 2018).

Besides the systemic approach, what is interesting in LCA is also the fragmentation of the studied system(s) in functional or multi-functional units, based on the services and the functions that each system component can deliver and the comparison with the corresponding impacts generated. Energy is commonly used in LCA as a main parameter to help quantifying the total energy supplied to drive processes in all the industrial life-cycle (Ingwersen, 2011).

Finally, few researches have recently emphasized the interest of performing LCA studies at wider scales, developing **“Territorial LCA” (TLCA)** which attempts to provide more appropriate indicators to stakeholders in charge of managing and developing their territories (Loiseau *et al.*, 2018; Roibas *et al.*, 2018; Jouini *et al.*, 2019). In this case, the broader contextualization of the LCA extends the assessment to the intimately related territorial features to production-consumption patterns where a mining project is located. Loiseau *et al.*, (2018) suggests two types of TLCA:

- a first type when it assesses the environmental impacts of a specific activity or supply chain performing in a given territory;
- a second type which considers all the production and consumption activities to quantify its “eco-efficiency”, or the ratio between the services provided by the territory and the corresponding impacts on the environment.

4.3. Discussion: gaps and limits of the current assessment methods

A great range of approaches for risk and impact assessment of mining projects has been presented in Section 3. However, as mentioned, the management of a mining projects and their risks is a multidisciplinary and complex task, mainly because of the presence of dynamic environments and a great number of constraints of various character (Badri *et al.*, 2012). Moreover, mining activities present a considerable amount of intrinsic unique specificities – related to the type of commodity and their geological features, the mining phasing and mining techniques employed – that need to be apprehended during risk assessment.

As it is highlighted in this first Chapter, mining is a matter of land planning and, thus, of public policies and politics, since mining involves the appropriation of a space and the exclusive change of land-use. Therefore, risk assessment practices can play an important complementary tool to support the development and comparison of strategies for the management of mining territories that overcome the sphere of the mining project alone, for instance through scenario-based approaches. In order to do so, risk assessment methodologies need to account both for the plurisciplinary of the territorial dimension of mining and for the technical and operational specificities of mining activities themselves. However, decision-making support purposes require an easy operationalization that should be guaranteed by the adaptability of the

methodology to the available data, its spatialization and the homogeneity of its results that allows an easy understanding and communication.

Despite the peculiar advantages of each risk and impact assessment methods here presented, there are important gaps that urge to be addressed. From a general point of view, current mandatory assessment methods do not properly take into consideration the holistic understanding of the larger system in which a mining project is located. They neglect the occurrence of multiple mining projects in a same given area and the cumulative risks generated (Franks *et al.*, 2013). The methods currently adopted in the mining sector are not generalized and resistant to uncertainties in the availability of the data (Verma and Chaudhari, 2016). Furthermore, such methods are often project-centered, performed on large capital stock investment projects and they do not take into consideration the great variety of existing mining project types at the same time (Castilla-Gomez and Herrera-Herbert, 2015). For instance, Agwa-Ejona and Pradhan, (2018) put the attention on the fact that the impacts related to informal or legal artisanal and small-scale mining of specific commodities (e.g. gold, gems, diamonds, sandstone and limestone) are extremely complex to quantify and that very few or no studies address their structured assessment. Moreover, current assessment methods do not account for the transversal nature of risks (e.g. social, environmental, geotechnical) (Gotts *et al.*, 2018), they might be extremely time-consuming, expensive and rely on the skills and training of the experts employed for the assessment (Paithankar, 2011).

Table 4 is the result of a bibliographic review concerning the main risk-based (group A) and impact-based (group B) methodologies here presented. On the left column, the main specificities considered for each method are divided in five main categories depending if they are related to the methodology, to the types of risk or impacts considered, the scale of the impacts and the final output. The purpose of Table 4 is to highlight the main characteristics of the mentioned methodologies in order to facilitate their qualitative comparison. From a general point of view, the main distinguishing criterion between the two groups of methodologies is the object of the assessment.

4.3.1. Risk-based methods (A)

Risk-based tools have the advantage to integrate the probabilistic dimension of the occurrence of a failure event and to assess the risk based on considerable technical and operational data internal to the project it-self (Olsen *et al.*, 2001). These methods can be deterministic, probabilistic or a combination of the two (Tixier *et al.*, 2002). The advantages in terms of technical knowledge of the project imply at the same time a lack of spatial extension since risk-based methods. Indeed, although risk assessment methodologies do consider the interactions between the project and its external environment (Esra Tepeli, 2016), in most of the cases, only the achievement of the project objectives is considered in risk analysis, i.e. only the events that might affect project objectives and performances are considered as risks.

Therefore, it might be complex to integrate such methods for assessment purposes at broader spatial scales for land-planning perspectives. Moreover, such methods usually consider only accidental conditions (i.e. outside the ordinary functioning of a project), without being applied to assess the impacts generated by the normal functioning of a project, i.e. ordinary operational conditions (Paithankar, 2011).

The rendering of the results of risk assessment methods are often expressed in a graphical form or diagrams that might be difficult to share and communicate for the understanding of the general public and public authorities. This may lead to acceptability concerns regarding the transparency of the procedure and the functioning of the project itself but also to operational constraints for decision-makers, especially at larger spatial scales. For instance, this is the case for HAZOP methods. Because of their considerable level of detail, such tools might be very time-consuming. Nevertheless, they are site-specific, not graphical, concern usually accidental conditions. Some of these gaps also apply to FMEA and FMECA. However, these two methods can be even more expensive and time-consuming than HAZOP since the level of detail is considerably higher. For the same reason, FMEA and FMECA are not easily adaptable when data are unavailable. Moreover, these methods are subjective and not fully pertinent to be applied to complex systems. They are very extensive studies but, in some cases, they might lack of criteria for assessment, integrative methods, guidelines or a structured terminology. FMEA and FMECA are realized by a multi-disciplinary team which covers the transversal dimension of the risk assessment. PHA are based on available data and propose good risk ranking tools. However they are not graphical nor spatialized and site-specific. “What-if” methods on the other hand, are moderately detailed and only qualitative (Table 4).

Concerning FTA, Table 4 shows a very poor suitability for the consequences of a risk event considered, since FTA concerns only the causes to an initial central event. Also, FTA and ETA are usually rendered through a tree structure which make them suitable to visual outputs.

4.2.3. Multi-projects risk-based methods

It is important to underline the existence of specific methods developed for the risk assessment of multiple projects at the same time (Pillai *et al.*, 2002) and for project portfolio risk management (De Maio *et al.*, 1994; Olsson, 2007). Nevertheless, these methods are project-centered in the sense that they focus on the industrial dimension of the project itself, rather than the territory where such activities are performed. Actors such as “stakeholders” are replaced by “customers” (Pillai *et al.*, 2002) that might profit of the economic and industrial activity of such projects. Moreover, by our knowledge, no application of such methods to the mining sector has been highlighted.

4.3.3. Impact-based methods (B)

This sub-section highlights the main limitations (Table 4) of the impact assessment methods presented in sub-section 4.2 of the present chapter.

4.3.3.1 Limits of Environmental Impact Assessment and Social Impact Assessment

Despite its extensive utilization, its legal formalization and its vital role for the analysis the impacts related to a mining project for general land planning purposes, EIA is considerably criticized by professionals and scientific literature (Crawley and Aho, 1999; Jay *et al.*, 2007; Enríquez-de-Salamanca *et al.*, 2018). If some issues concern the theoretical grounding, quality and effectiveness of the EIA and their linkage with sustainable development (Cashmore *et al.*, 2004; Clarks *et al.*, 2019), critics might be considered of two main orders: methodological and substantial.

Concerning the first order of gaps, no common and predefined methods for impact assessment are available for EIA. Indeed, EIA is not a normalized procedure – unlike LCA for instance – and no common standard dispositions are assessed for the elaboration of this analysis. The methodologies to qualitatively or quantitatively assess the impacts of a given project vary on a case-to-case basis. They highly depend on the experts performing the assessment and methodological choices are often poorly discussed (Suopajärvi, 2013). Thus, EIA come in different shapes and sizes as different contractors and consultants have their own assessment methods, which increase the complexity of reviewing regulatory frameworks (Clark *et al.*, 2019).

Moreover, some authors criticize the insufficient integration and linkage as well between EIA and other methodologies for risk assessment and project management (Clark *et al.*, 2019). The same authors point out the need to develop systemic and eco-systemic approaches within the EIA process, in order to take into consideration the structural and functional dimensions of natural ecosystems during impact assessment. Castilla-Gomez and Herrera-Herbert, (2015) criticize the temporal dimension of EIA since they are developed during the feasibility phase of a mining project and, thus, they are based only on hypothetical data.

Substantial gaps of EIA are the most criticized since they have considerable repercussions on its effectiveness on decision-making support. Authors point out the poor the implementation of EIA within decisional processes where such tools are “not fully integrated into determinative institutional patterns of decision-making” (Jay *et al.*, 2007). Indeed, it is important to underline that EIA are not legally binding since the assessment is carried by institutions or professionals hired directly by the promoters of the project. The content of the EIA gains legal importance when they are integrated within the administrative acts (e.g. mining permits or authorizations) which embody the final decision of public authorities. Hence, the effective application of EIA is affected by the regulatory and political strengths/weaknesses of a country (Jay *et al.*, 2007): EIA might be circumvented by decision-makers, marginalized in favor of other non-environmental or political factors (Wood and Jones, 1997; Jay *et al.*, 2007).

These limitations derive from the fact that, as pointed out by Cashmore *et al.*, (2004), EIA originated from a political imperative rather than a scientific theory. Therefore, in the practice, EIA might contribute to environmental governance with very moderate effectiveness (Cashmore *et al.*, 2004; Clark *et al.*, 2019).

Besides these important gaps, EIA is conceived as a project-centered assessment tool (Castilla-Gomez and Herrera-Herbert, 2015) where cumulative and indirect impacts and societal impacts might be neglected (Frank *et al.*, 2012; Yao, 2018; Clark *et al.*, 2019). The integration of stakeholders represents another flaw pointed out by some authors (Enríquez-de-Salamanca *et al.*, 2018; Oscampo-Melgar *et al.*, 2019) even within the SIA process (Suopajärvi, 2013). Issues of transparency might be addressed, especially when the EIS is not accessible to the public (Castilla-Gomez and Herrera-Herbert, 2015; Yao, 2018).

Several other specific concerns must be considered for the application of EIA to the mining sector. Although technical information is vital for pertinent risk and impact assessments, EIA seems to insufficiently detail the mining operational dimension (Clark *et al.*, 2019). Also, Castilla-Gomez and Herrera-Herbert, (2015) emphasize the difficulty to develop pertinent assessment tools due to the great variety of methods and techniques used in mining projects, which vary according to the targeted commodity and the related geological deposit.

4.3.3.2 Limits of Life Cycle Assessment

Before its standardization, as the EIA, LCA was conducted by different approaches leading to a wide variation of results (Yellishetty *et al.*, 2009). However, this method is mostly used by scientific authors and Awuah-Offei and Adekpedjou, (2011) suggest that there is “limited life-cycle thinking among mining professionals”.

Despite the imperative acknowledgment of the internal technical and operational features of a project, according to some authors, in the mining sector, mining projects are often represented as a “black box”, and that LCA software and tools neglect the specific features and processes of mining, relying on data often considered inadequate (Awuah-Offei and Adekpedjou, 2011). Indeed, one of the most important issues in LCA is data availability, especially in industrial sectors such as mining, with limited datasets and life-cycle inventories (Durucan *et al.*, 2006; Farjana *et al.*, 2019) where data are often in the form of corporate reports (Awuah-Offei and Adekpedjou, 2011).

Regarding the object of the assessment, LCA focus on the ordinary functioning of an activity and, thus, it is not capable to pertinently integrate accidental scenarios (Crawley and Aho, 1999). Yellishetty *et al.*, (2009) discuss the importance of the integration of the spatio-temporal differentiation of the impacts related to a mining but also the issue of abiotic resources depletion which is peculiar to mining (Beylot *et al.*, 2020) or the better inclusion of socio-economic impacts (Crawley and Aho, 1999). Also, land use impacts are very important to community, professionals and companies and they can be an important indicator to estimate

the environmental footprint of some mining projects. However, some authors discuss the insufficient integration of such aspects, specifying the difficulty in LCA to compare systems with different annual disturbed land area (underground vs surface mining) or to potentially underestimate the effect of land quality (Yellishetty *et al.*, 2009; Awuah-Offei and Adekpedjou, 2011). For instance, Islam *et al.*, (2002) address these gaps, using remote-sensing technology to better integrate mining-related land use changes in LCA.

Table 4 Synthetic review of the main risk-based and impact-based methodologies presented in this chapter and their main features. For each methodology, a qualitative score is given whether it shows: a poor, moderate, or good, suitability to the corresponding feature. The green areas represent the features that specifically feat in the considered methodology

Features		Methodologies								
		A						B		
		HAZO P	FMEA/ C	What- if	PH A	HACC P	FT A	ET A	ESI A	LC A
Method features	System approach	✓	✓	✓	n/a	n/a	✓	✓	●●	✓
	Standardized	●●	●●	●●	●●	●●	●●	●●	●	✓
	Risk-based	✓	✓	✓	✓	✓	●● ●	●● ●	●	●
	Top-down	n/a	n/a	n/a	n/a	n/a	✓	●	n/a	n/a
	Bottom-up	n/a	n/a	n/a	n/a	n/a	●	✓	n/a	n/a
	Qualitative	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Quantitative	✓	●●●	●	●	●	✓	✓	✓	✓
	Applied to all projects	n/a	n/a	n/a	n/a	n/a	n/a	n/a	●	n/a
	Scenario-based	●●●	●●	✓	✓	●●●	✓	✓	●	●●
	Decision-making support	✓	✓	✓	✓	✓	✓	✓	●●	✓
	Uniform terminology	●●●	●●	●●●	●● ●	●●●	●● ●	●● ●	●●	✓
	Dynamic	●●●	●●	●●	●●	●●	●●	●●	●	✓
	Multi-actor	n/a	n/a	n/a	n/a	n/a	n/a	n/a	●	n/a
	Adaptable to available data	n/a	n/a	n/a	n/a	n/a	n/a	n/a	●●	●●
Type of risk	Chronic	●	●	●	●	●	●	●	●●	●● ●
	Accidental	✓	●●●	●●●	●● ●	●●●	✓	✓	●●	●
Type of impacts considered	Positive impacts	n/a	n/a	n/a	n/a	n/a	●	n/a	✓	●● ●
	Negative impacts	●●●	✓	✓	✓	✓	●	✓	✓	✓
	Inbound impacts	✓	✓	✓	✓	✓	●	✓	●●	●
	Outbound impacts	●●	●●	●●	●●	●●	●	●●	✓	✓
	Indirect impacts	n/a	●	n/a	n/a	n/a	●	●●	●	●● ●
	Cumulative impacts	n/a	n/a	n/a	n/a	n/a	●	n/a	●	●● ●
	On-site impacts	✓	✓	✓	✓	✓	●	✓	✓	✓
Off-site impacts	n/a	n/a	n/a	n/a	n/a	●	n/a	●●	✓	
Rendering	Graphical	●	●	●	●	●	✓	✓	●●	●●
	GIS adaptable	n/a	n/a	n/a	n/a	n/a	●● ●	●● ●	●●●	●● ●
Legend : qualitative suitability to meet the corresponding feature										
n/a No information		●	Absent or very low suitability				●●●	Good suitability		
		●●	Moderate suitability				✓	Feature fitted		

Conclusion

Mining is an inherently interdisciplinary pursuit (Lechner *et al.*, 2017) that reflects a socio-technical system presenting complex interactions between humans and various technical processes at different spatio-temporal scales. This first chapter reviews and details the three main concepts that this thesis aims to address for the development of a risk assessment methodology of mining projects at the territory level. To do so, the main features of mining activities are here presented and defined, highlighting the contributions that mining can achieved within the territory, i.e. a socio-ecological system, where such activities are performed. Such potential contributions are defined as risks (ISO, 2008) that might be positive or negative, whether the mining project generate respectively opportunities or losses that might alter the socio-ecological spheres of the territory where it is located. Several risk and impact assessment methods are presented in order to underline the advantages and limitations of their application within the mining sector at broader spatial scales.

As mentioned, mining is a matter of land planning and public policies. Risk assessment methodologies can play an important complementary tool to support the development and comparison of strategies for the management of mining territories that overcome the sphere of the mining project alone. In order to do so, these methodologies need to account at the same time for the technical and operational specificities of mining projects and the plurisciplinary of the territorial footprint of mining. Nevertheless, decision-making support purposes require an easy operationalization that should be guaranteed by the adaptability of the methodology to the available data, its spatialization and the homogeneous structure of its results that allows an easy understanding and communication.

Chapter 2. Objectives of the thesis and development of a methodology via the application on a case-study

Given the general state of the art concerning risk management in the mining sector and the main shortcomings reviewed in Chapter 1, this study aims to propose an original approach to support the analysis of potential scenarios of mining development **at the territory level**. To do so, a specific methodological framework is developed and adapted to address existing shortcomings while simultaneously addressing operational needs to support decision-makers, mining operators, and civil society for land-planning purposes. Pertinent questions to be addressed are:

- What are the risks related to mining and what are their driving factors based on the diversity of techniques employed?
- If risk analysis is related to territory and project management, is it possible to integrate the variability of mining projects and their risks into decision-making processes at the territory level?
- Then, is it possible to perform and compare sector-based – rather than project-based – scenarios of mining projects at larger territorial scales, according to their level of risk?

In this chapter, the main philosophy behind our approach and the objectives of our study are presented. To meet such objectives, the theoretical framework of the methodology is developed in Section 2. This framework has been developed via a demonstrative application on a case-study (Fig. 9) that has been selected through multiple criteria that will be presented.

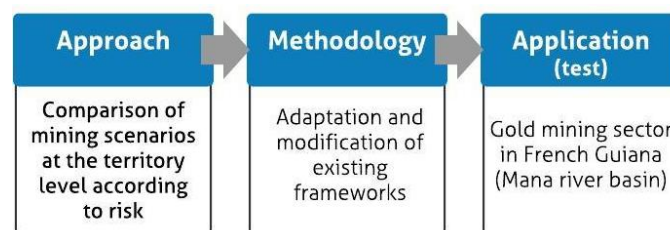


Figure 9 This study aims to present an original approach to integrate mining projects at the territory level to support land-planning. This implies the development of a methodology via a test application on a case-study

1. Our approach and objectives of the study

As mentioned in Chapter 1, mining projects should be considered matters of land-planning and territorial management rather than simple industrial objects. Whether mining should be performed requires political answers rather than scientific ones alone. Hence, this thesis suggests a different way to look at the question and **proposes an original approach to develop and compare – based on their level of risk – different mining scenarios to support land-planning strategies at the territory level**. The application of this approach depends on a

methodological framework that has been developed based on existing methods and adapted to the objectives of this thesis. The Section 3 of this chapter presents the structure of this methodology.

Several territorial mining scenarios (TMSs) can be developed based on general objectives predefined at the territory level by decision-makers, public authorities, etc. (e.g., a given rate of employment or economic incomes or commodity production related to the mining sector, reduced land surfaces available to mining). The comparison of TMSs is based on the development, assessment, and combination of specific risk scenarios. Finally, a global score is given to each TMS based on the assessment of these risk scenarios. This will allow to compare different mining scenarios at the territory level that equally meet the same objectives but potentially present different levels of risk.

It is important to note that the present methodology is not meant to be a substitute for existing methods and techniques that offer more accurate assessments especially for each specific risk related to isolated mining activities on a case-by-case basis.

From a general point of view, this study is intended to:

- i) Provide a structured, consistent, and transversal approach based on international standard guiding principles (ISO, 2008) at broader spatial scales;
- ii) Classify standardized mining project types to consider the potential coexistence of a great variety of projects – depending on the targeted mining commodity – with different functionalities, mining techniques, and risks at the territory level;
- iii) Integrate the socio-ecological vulnerability of territories in which mining activities are performed;
- iv) Integrate both the positive and negative risks related to mining projects with their different natures (e.g. technical, environmental, socio-economic, financial);
- v) Adapt to the amount and consistency of available qualitative and quantitative data required for the assessment;
- vi) Include the involvement of stakeholders' perceptions of risks;
- vii) Provide spatial, cartographic renderings for communication with stakeholders and decision-makers; and
- viii) Provide an operational tool that might be integrated into decision-making methodologies.

2. Theoretical development of the methodological framework

Fig. 10 presents the general structure and flow of the methodological framework developed in this study. Because the notion of risk, and, more generally, the field of risk assessment and management, are particularly affected by vague and fuzzy vocabulary (e.g. “hazard”, “danger”, “accident”, “risk”, “impact”, “consequence”; Serraino, 2014; Matteini *et al.*, 2018), the initial step (Step 0) of the methodology aims to develop and formalize a common terminology (see the Glossary) to facilitate the extensive application of the methodology. The methodology involves four main steps (Steps 1–4) that are adapted to the general risk assessment procedure suggested by ISO 31 000: system definition, risk identification, risk analysis, and risk evaluation. However, for each step, specific tasks are proposed in order to adapt the methodology to the objectives depending on, for example, the variability of mining project types and their risks, the territorial scale of the assessment, and stakeholder involvement. A final step is included to compare and discuss the assessed mining scenarios developed at the territory scale. In the following subsections, each step is described in detail.

2.1 Step 1: System(s) definition and boundary conditions

A system is defined as any set of connected processes and resource quantities (Rueter, 2013). Mining projects are complex systems because of the interactions of different socio-technical components at different spatial and temporal scales. Therefore, they cannot be adequately understood without a description of intermediate structural interactions (Gotts *et al.*, 2018). A structured understanding of the different types of mining projects and the adequate characterization of their spatial dimensions and specific features (e.g. annual production, soil footprint, chemicals used) is therefore critical to risk assessment (Lechner *et al.*, 2017).

As mentioned, mining risk assessments must include both spatial and temporal assessments through multidisciplinary and geographically representative” frameworks (Kelly *et al.*, 2013; Blair and Buytaert, 2016; Fernandes *et al.*, 2016). For this reason, the first step of our methodology involves the definition of the boundary conditions (e.g. Where? When? With who?) and the conceptual modelling of:

- a **mining system**, representing one or more mining project types located in a given territory; and
- a **territory system**, which is the wider socio-ecological context of the mining system (e.g. a municipality, a river basin, region, country).

The link between these two systems and their relative risks have three fundamental dimensions that concern their spatial occurrence and extent, their perception, and their temporal manifestation. In the following paragraphs, three sub-steps are presented: the specification of these three fundamental dimensions, the definition of the mining and territory systems, and the definition of the TMSs to be considered during the assessment.

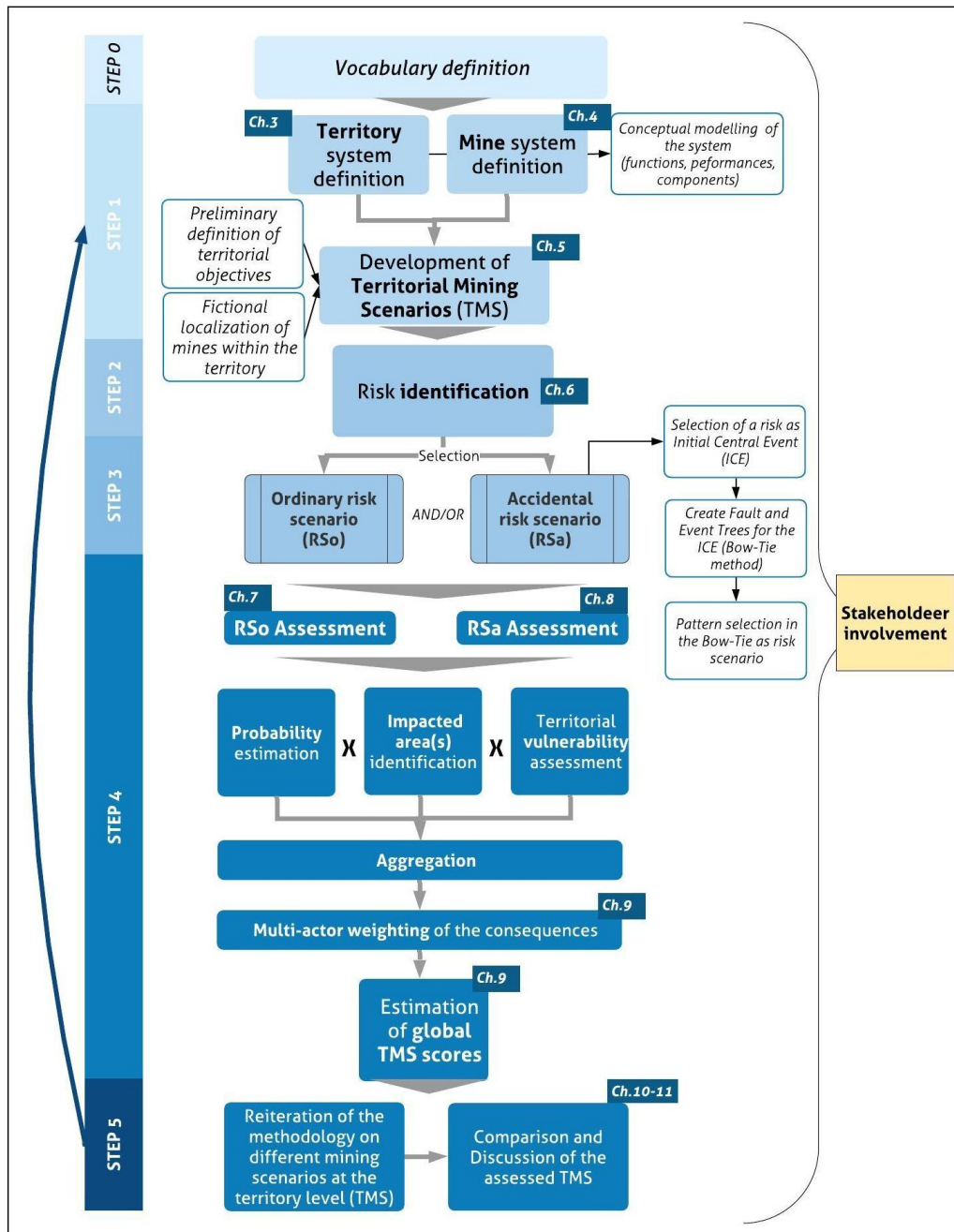


Figure 10 Flow chart of the methodology developed for the application of the approach proposed in this thesis. The boxes in dark blue indicate the corresponding chapters in this manuscript.

a) Multi-scale, multi-perspective, and temporal boundaries of the methodology

Concerning the **spatial dimension** of mining and territory systems, the definition of spatial boundaries and assessment scales is crucial because it influences which variables can be considered exogenous vs. endogenous (Filatova *et al.*, 2016). A scale can be defined as “the window through which the investigator chooses to view the world” (Marceau, 1999): in this case, it is the spatial dimension at which entities, patterns, and processes are observed and characterized. From the mining project to the territorial scale, risk assessments gain complexity

because multiple levels of processes, interactions, perceptions, and interests must be considered (Auyang, 1999, Zurlini *et al.*, 2006).

The spatial variability of risk is acknowledged in the methodology varying systems' functions, performances, and components at each scale. Five general geographical scales can be considered (from micro to global scales) (Meentemeyer, 1989), each representing a specific spatial unit (e.g. structure, project, municipality, river basin; Fig. 11). For instance, within a mining project, risks could be identified and assessed at the scale of individual structures (e.g. tailings dams, waste rock piles, excavation pits) or at the scale of the entire mine site. Similarly, the territory system could include a city, a water catchment, a region, etc.: at each scale, the results of risk assessments will change.

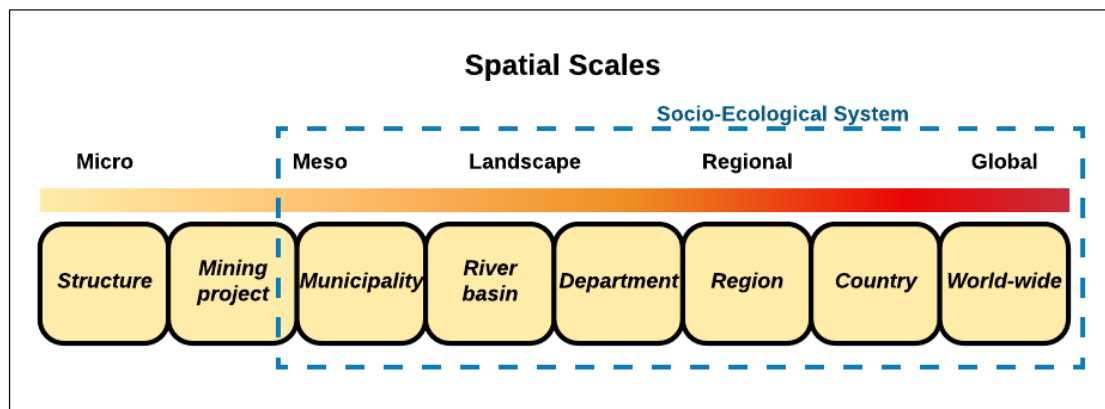


Figure 11 General spatial scales considered by the present methodology. The five main categories can include a great range of sub-categories. In the case of mining projects, the smallest unit is the geotechnical structure. Socio-ecological sub-categories refer to French administrative divisions.

Since the concept of risk itself has an implicit subjective connotation, the **multi-perspective dimension** of risk assessment is a key-element of our methodology. Indeed, human nature, both individual and collective, has a considerable influence on the results of mining project risk assessments through perceptions, beliefs, values, and biases (Voinov *et al.*, 2016; Gotts *et al.*, 2018). The variability of risk perception and the existence of various, often conflicting objectives requires consideration of the various actors involved in spatial management (Mehdizadeh, 2012), particularly in the mining sector; the contrary would be regrettable from scientific and governance points of view (Gotts *et al.*, 2018).

The multi-perspective nature of our methodology takes the form of so-called “participatory modeling” (McLellan *et al.*, 2009; Blair and Buytaert, 2016; Voinov *et al.*, 2016), i.e. the general and pluridisciplinary integration of stakeholders’s perspectives during each phase of the development and application of the methodology. Stakeholders’ perspectives can be integrated in different ways (e.g. model design, validation and refinement, interviews, data sharing, risk weighting surveys).

Finally, with regard to the **temporal dimension** of the methodology, interactions between system components are continuously changing due to feedbacks and internal and/or external factors (Schulze *et al.*, 2018). Hence, mining risk assessments must dynamically account for temporal variations of mining activities and of the territory in which they are

performed, and how these variations affect the nature, probability, and intensity of risks (Kelly *et al.*, 2013; Domingues *et al.*, 2017): i.e. risks evolve because the elements that trigger risk events evolve, as well as their consequences and the vulnerability of the territory.

Therefore, two temporal sub-dimensions are integrated in the methodology. The first, intrinsic to the mining system, refers to the different mining phases selected for the assessment (Fig. 2). The second, intrinsic to the territory system, involves consideration of larger territorial changes over time that might influence the results of the assessment (e.g. demographic growth, increase of population vulnerability, climate change).

b) Conceptual modeling of the mining and territory systems

The first phase of the methodology involves the definition of the **mining system** and the territorial spatial units chosen for the assessment. The purpose of this phase is to describe the main functions of each system, the performances needed to achieve those functions, and the system components that guarantee those performances. Fig. 12 shows the technical, operational, and socio-ecological performances of a mining system as considered both as a business and a development project. Concerning the mining system, this first step can be achieved through the development of standardized mining project types with specific features and characteristics (e.g. surface vs. underground mines, large- vs. small-scale mines) (Fig. 12). System components have specific properties (variable or constant) that may affect their performance. For instance, Durucan *et al.*, (2006) subdivide the mining system into three sub-systems for life-cycle assessments: extraction and production, mineral processing, and waste handling (Fig. 3).

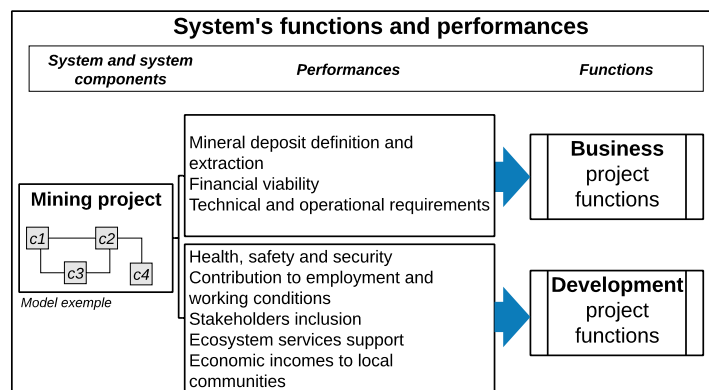


Figure 12 Conceptual representation of the causal modeling of the spatial systems considered in the approach

Regarding the **territory system**, as mentioned above, each spatial unit from the municipality to the global scale is considered as a socio-ecological system (SES) (Fig. 11). Therefore, regardless of the territorial spatial unit chosen (e.g. water catchment, region), the main functions of a SES are here defined as the support of human well-being and the delivery of ecosystem services. As discussed in Chapter 1, sustainable development goals (SDGs) are integrated within the methodology to represent the socio-economic (e.g. poverty and hunger reduction, education, sanitation) and environmental (e.g. climate actions, soil and water protection) performances expected from a territory system. As shown in Fig. 13, the mining

system is thus included within the territory system and can positively or negatively contribute to its performances. The definition of these two systems is a key-step in developing the territorial mining scenarios and the risk scenarios that will be assessed and compared at the end of the methodology.

c) Definition of territorial mining scenarios and fictional mining project siting

The main purpose of the methodology is to compare different scenarios for mining development at the territory level. Each **territorial mining scenario (TMS)** is developed based on stakeholders' (decision-makers, public authorities, civil society, etc.) objectives for a given territory (e.g. increased employment or mining royalties, increased mine production, reduced mining land-use), which must be preliminarily defined. As an example, let us assume that decision-makers in a given territory aim to develop a mining sector that would produce at least 1 million tons of copper per year. Based on the first step of the methodology, two types of copper mining projects are defined: type A, surface mining producing 400,000 t/year, and type B, underground mining producing 150,000 t/year. Once the territorial objectives are defined, it is possible to estimate how many mining projects of one of more types should be considered in the simulated risk assessment for each TMS. For instance, three TMS could be considered in the mentioned example:

- 1 type-A and two type-B projects;
- 2 type-A and four type-B projects, or;
- 7 type-B projects.

These three TMSs meet the predefined objective approximately at the same level. However, the associated global risks might vary based on the specific type of mining project(s).

For each scenario, the corresponding number and types of mining projects are located on fictional sites within the chosen territory system (e.g. a river basin, region, or country). This **fictional siting** can be based on different criteria (e.g. localization of geological deposits, authorized areas for mining, distance from urban areas or protected sites).

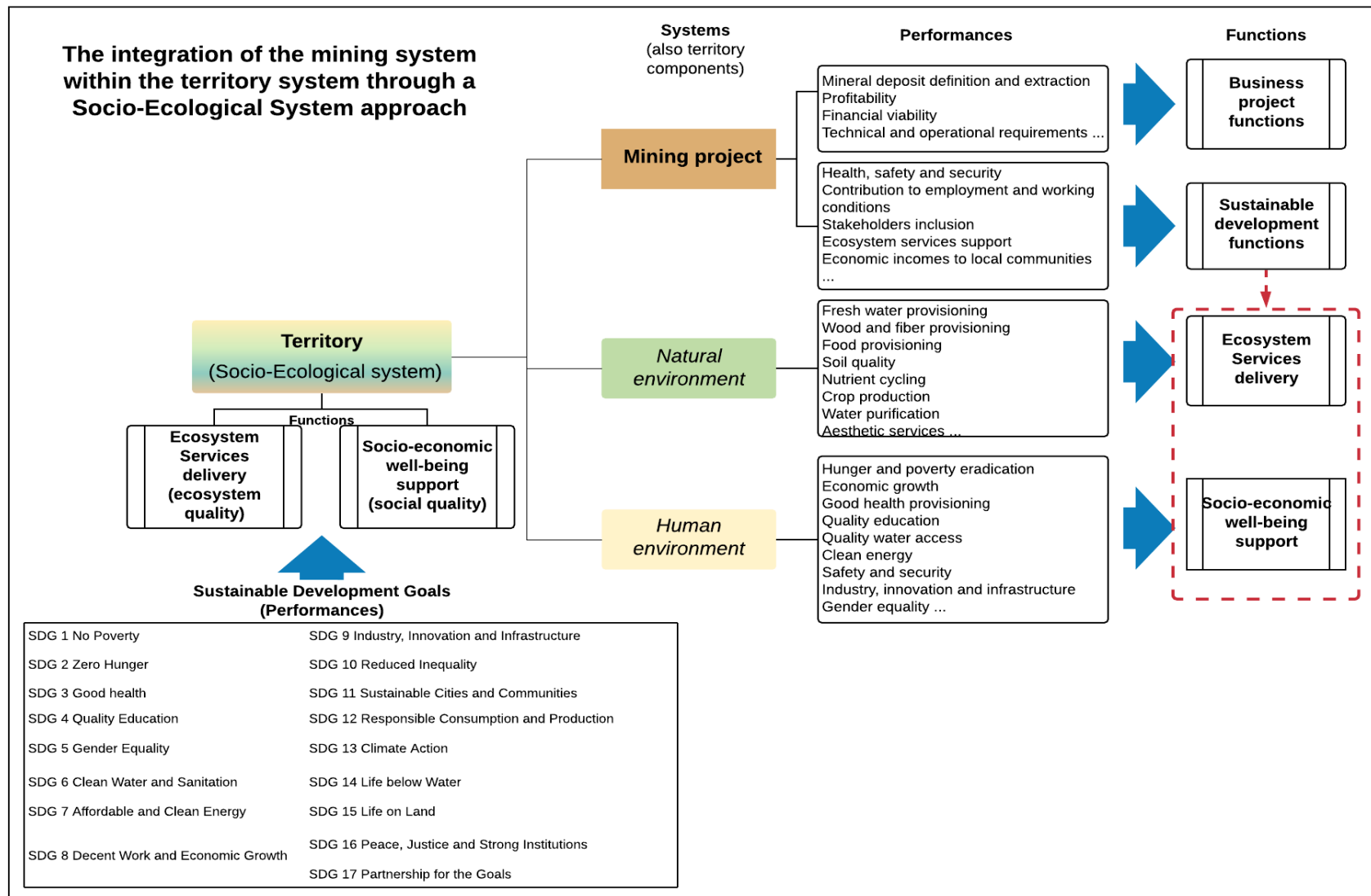


Figure 13 . Integration of a mining system within a larger SES. For each system, a set of functions and performances are indicated. The general performances of the SES represent the SDGs. Because the mining system is part of the conceptualized territorial system, each territorial sub-system contributes to the overall performance of the territory system

2.2 Step 2: Risk identification

Risk identification is the process of identifying, recognizing, and describing risks and their causes and consequences (ISO, 2008), and is a non-exhaustive process that is updated during the entire assessment. Risk identification may be performed using a range of tools and methods, such as interviews, Delphi's method, brainstorming, literature and historical data reviews, surveys, focus groups, questionnaires (Rozas-Vasquez *et al.*, 2017; Holzer *et al.*, 2018; Sahle *et al.*, 2019), meetings and workshops, participatory modeling, theoretical analysis, and stakeholder needs assessments (Chinbat, 2011; Ioppolo *et al.*, 2012; Moura *et al.*, 2017; Orymowska and Sobkowicz, 2017; Guo *et al.*, 2018). The results of such risk assessments consist of a database of identified risks that can be classified depending on their nature, causes and consequences, or multiple criteria defined by the modeler (Mehdizadeh *et al.*, 2013).

Once the risks have been reliably identified, it is important to understand the mechanisms triggering each risk event. More importantly, a first conceptual and descriptive analysis should associate each risk to the type of mining project considered. Assessments of multiple mining projects at the territory level therefore require clear distinctions between, for instance, surface mining projects, underground mining projects, and combinations thereof. Each type of activity should be associated with different identified risks.

2.3 Step 3: Risk analysis and risk scenario development

The TMS are compared based on their level of risk. Therefore, two distinguished **risk scenarios** are developed based on the identified risks and associated to each TMS. Therefore, the TMS will be comparable based on the assessment and combination of the final scores of these risk scenarios. Our approach considers risk scenarios of two different conditions: the ordinary (RSo) and accidental operating conditions (RSa) of a mining project (Fig. 14). The assessment of “**ordinary risks**” will cover a wide range of activities related to the standard operational conditions required to achieve mine performances and functions. These risks – that can be assimilable to the notion of “chronic” risk” or “nuisance” – typically have less important consequences, especially for the project itself, but a higher probability of occurrence because they are necessary and inherent to mining activities (e.g. a given surface will be deforested for site development). Nevertheless, according to the definitions given in Chapter 1 and in the Glossary, these events are not properly a risk, since their occurrence is certain. What is uncertain is the occurrence of their consequences. For instance, a mine site implies inexorably the deforestation of a given surface, which might have consequences on climate regulation, biodiversity or landscape quality. Despite the assessment should focus rather on these latter consequences, which are uncertain, in this study we choose to include certain events as well, in order to distinguish the normal and anormal operating conditions of a mining project. Indeed, in the second case, “**accidental risks**” are considered as unexpected risk events to the mining operator that switch ordinary operating conditions into “extraordinary”. Such events have a lower probability of occurrence – they might be even rare – but their consequences can

be considerably high, both for the mining project and the socio-ecological system in which it exists (e.g. explosions, dam failures, chemical spills).

Both RSo and RSa can be conceptually represented in different ways to comprehend both (1) how risks occur (causes) and affect systems' components (consequences) and (2) how systems may respond to risks through proactive (risk prevention) or reactive (mitigation) safety measures. A simple, well-constructed conceptual scheme can be sufficient to describe such interactions. A method often used to assess such accidental events is the Bow-Tie diagram where causes and consequences trees are developed around an initial central event (ICE) (see Chapter 1).

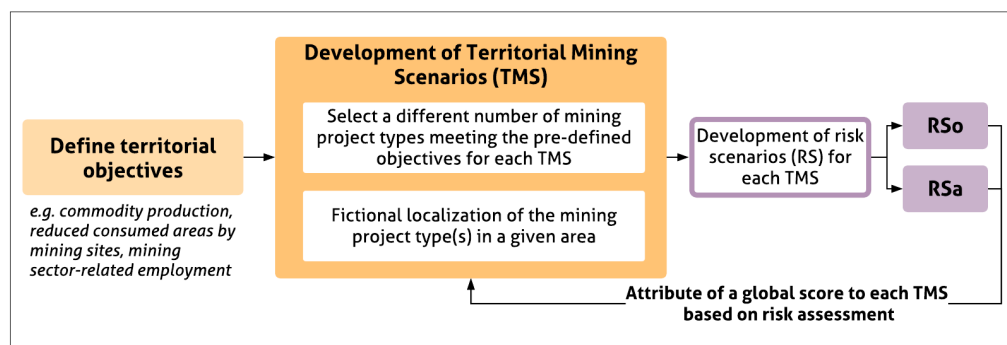


Figure 14 Conceptual flowchart illustrating the development of Territorial Mining Scenarios (TMSs), including the fictional siting of different mining project types. Two categories of risk scenarios (RSo and RSa) are then developed for each TMS, allowing further assessment in order to obtain a final global score for each TMS based on risk analysis.

2.4 Step 4: Spatialized risk assessment – probability, consequences, and vulnerability

Step 4 involves the qualitative or quantitative evaluation of each risk scenario (Fig. 15). As risk is defined as the product of the probability of an event's occurrence and its consequences, risk assessments must inexorably estimate both.

Consequence assessment involves different sub-steps. According to the proposed methodology, a “consequence” is defined by the conjunction of two intrinsic elements: the identification/estimation of impacted areas and the assessment of the socio-ecological vulnerability of the territory. Therefore, this steps implies:

- The identification of the **impacted areas**, defined as the areas where the consequences of a risk event are manifested, whether they are mappable or not. They are areas where positive or negative modifications to the the mining and territorial systems' performances occur. The methodology distinguishes between the zones directly impacted by the physical consequences of risk events (e.g. the area contaminated by a chemical spill) and those secondarily (indirectly) affected by such direct impacts (e.g. areas where drinkable water is diminished due to the spill).

- The **vulnerability assessment** proposed in our methodology involves the identification of the human (e.g. individuals, collectivities, technical infrastructures) and natural assets (e.g. natural reserves, soil and water resources, biodiversity) located within the territory and the assessment of their susceptibility to be positively or negatively affected by risk events. Because the proposed methodology must be operational and immediately applicable to counterbalance decision-making needs, vulnerability is estimated through “vulnerability indicators”. Indicators provide a reasonably simple tool that allows the analysis and communication of complex ideas. As mentioned in Chapter 1, vulnerability indicators might be assessed via a great range of methods and tools (e.g. direct biophysical measurements, laboratory analyses, numerical and empirical modelling, expert-based estimations, bibliographic reviews). A synthesis of the applications of vulnerability indicators is given in Appendix 3 showing the object, the assessment methods used and whether they concern the mining sector or address sustainability issues. According to Bell and Morse (2008), vulnerability indicators should be simple, relevant, easy to interpret, minimally redundant, and useful for communication with the non-scientific public. For each vulnerability indicator, an assessment methodology must be pre-defined, if not already available, and the resulting values must be compared to reference situations or threshold values (Morel *et al.*, 2015; Banos Gonzalez *et al.*, 2016). The definition of threshold values is essential, as it inexorably influences the outputs of the assessment. Available thresholds can be found in international standards, such as those proposed by the International Finance Corporation (IFC, 2007), the World Health Organization (WHO, 2011), or national or international legislation. For instance, the Initiative for Responsible Mining Assurance (2014) suggests specific standards for the mining sector. In other cases, thresholds can be developed through stakeholder involvement or expert input (Kelly *et al.*, 2013; Gotts *et al.*, 2018).

Probability assessments must consider all the factors that are likely to trigger one or more risk events. The estimation of probability is often integrated into several risk assessment methods and tools of variable complexity depending, for instance, on the level of technical detail required and the available data. A great number of physical, numerical, or statistical models might be used to determine the probability of a system’s failure, and the chosen method depends mainly on the amount of data required. For instance, when few data are available, the probability of occurrence might be estimated through statistical assessments of coefficients derived from historical databases, expert-based assumptions, or empirical estimates of the “susceptibility” to system failure and risk occurrence. At this stage, the probability assessment allows to obtain the overall value of risk for each risk scenario, through risk tables or maps, which might require the coupling of GIS layers with aggregation results through non-cartographic methods (e.g. tables, lists). In such cases, the combination method considerably influences the results.

A further step aims to fully integrate stakeholder’ perspective and involves **consequence weighting** by the concerned actors. This weighting can be applied via simple qualitative data or

more complex, quantitative data gathered through different methods (e.g. surveys, questionnaires, brainstorming, Delphi method). For instance, a first approach might involve a questionnaire to estimate simple semi-quantitative scores in order to weight each consequence. This method is included in this thesis and it is detailed in Chapter 9.

During the assessment, multiple stages of **data aggregation** are performed. Concerning the vulnerability assessment, once the indicators are assessed, the methodology integrates all cartographic and non-cartographic layers representing such indicators to obtain an overall socio-ecological vulnerability value. The aggregation is performed first to combine positive and negative risks for each risk scenario and then, to combine the final scores for the RSo and RSa and obtain a **global score for each TMS**. The choice of aggregation method is extremely delicate because it influences the final results and might under- or over-estimate the consequence assessment. Current existing methods involve simple (e.g. sum, maximal value, arithmetic or geometric means) (Mehdizadeh *et al.*, 2012) or more complex aggregations (e.g. weighted means, Fuzzy Weighted Average), and sometimes integrate decision-making tools (e.g. TOPSIS, VIKOR, ELECTRE, AHP) (Mahdevari *et al.*, 2014; Govindan and Jepsen, 2016; Kasap and Subasi, 2017; Gupta *et al.*, 2018). In some cases, stakeholders are integrated as well (e.g. plurality rule by voting). Once the vulnerability layers are aggregated, the resulting outputs can be coupled with the results from impacted area assessments to obtain the final global consequence assessment, for which GIS tools are demonstrably effective.

2.5 Step 5: Comparison of different mining scenarios based on risk assessments

The final objective of our approach is to compare different TMS for land-planning purposes (Fig. 15). Hence, the utility of the methodology lies in its application and reiteration to a broader range of TMS involving different mining project types and fictional siting. After the overall scores of each risk scenarios are evaluated (RSo and RSa), they are combined to obtain the global score of the corresponding TMS: each TMS considered can then be compared and discussed based on its global level of risk (Fig. 15).

The comparison of the assessed TMSs might take different forms (e.g. from simply constructed discussions, conceptual models and diagrams, and tables, to the integration of more sophisticated decision-making tools such as TOPSIS, ELECTRE, or AHP). The number of reiterations and the number of TMSs depend on the above-defined objectives and land-planning goals.

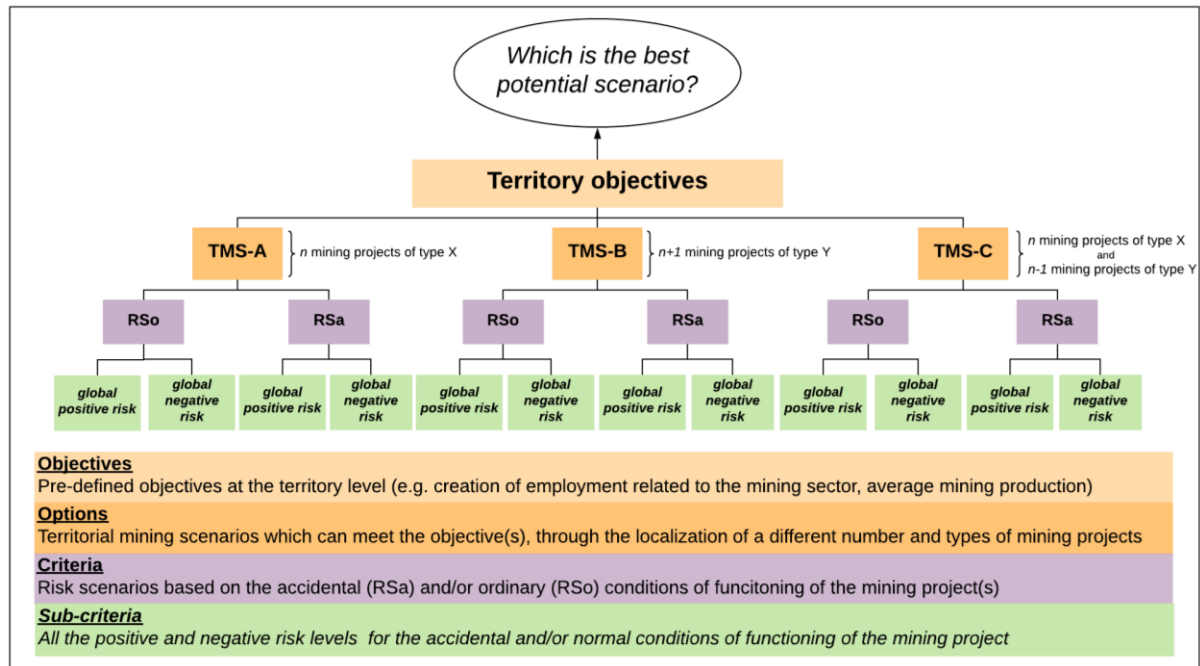


Figure 15 Conceptual flowchart of the scenarios assessed and compared by the methodology. Different options are available to meet one or more objectives, as represented by the development of different TMS. Each option is evaluated based on RSo and RSa criteria.

3. Criteria used for the selection of a case-study

In order to test our approach and refine the developed methodology, we applied it on an example case-study: the exploitation of gold in French Guiana (FG). It is important to underline that the application of this approach and its methodological framework might be extended to other cases and commodities as it will be discussed in Chapter 11.

The selection of a case-study is vital in order to operationalize the proposed approach and test its methodology, highlighting its gaps, its advantages and further improvements to be made. Therefore, the choice should follow specific criteria that allows to integrate the characteristics and the objectives that the methodology is intended to meet.

Indeed, such criteria must show the feasibility, the utility and the holistic nature of the methodology. Concerning the territory system, they are related to:

- The development of growing pression from anthropic activities due to global changes (e.g. urbanization, industrial activities, land-use changes)
- A high and sufficiently homogeneous socio-ecological vulnerability of the territory system;
- If possible, the availability of sufficiently reliable data to describe the territory and to perform the assessment.

Finally, concerning the mining system, these criteria imply the presence of:

- a) Coexisting mining projects distributed on the whole territory, involving various sizes, forms and mining techniques;
- b) Public concerns and debates related to mining and land-planning in order to develop potential future development strategies. During the *Grand Débat National* which united Overseas authorities and French Presidency of the Republic, the President of the *Collectivité Territoriale de Guyane*, Rodolphe Alexandre, controversially declared that gold mining can be a prior driver for the development of FG and that it ought to debate and address the question of gold mining development in FG territory.
- c) If possible, sufficiently reliable and available data to describe the mining system and to perform the assessment.
- d) If possible, only for the demonstrative purposes of our study, one exploited mineral or metal in order to make the comparison easier different scenarios;

Therefore, the case of gold mining in FG has been selected. As it will be presented in the conclusion of this chapter, the chosen case-study meet multiple of the predefined criteria mentioned above because of the social, ecological and political territorial footprint of gold mining, the variability of mining techniques involved, the characteristics of this territory and the potential development strategies currently discussed. The following sections will present an overview of gold mining across the world with a specific zoom on the Guiana Shield. Finally, FG and gold mining sector in FG are described.

Conclusion

This chapter had the purpose to present the objectives of the original approach proposed in this thesis and how this approach is operationalized. The main points to consider are the following:

- **The proposed approach aims to compare different mining scenarios according to their level of risk, to support land-planning strategies of mining regions;**
- **The approach is operationalized through the development of a methodology;**
- **The methodology is applied for a demonstration on gold mining sector in FG.**

The next chapters will present and describe the mining (i.e. gold mining) and the territory systems (i.e. French Guiana at the river basin level), to show how they fit these criteria. The next parts II and III represent the test application of the methodology.

Part II – Application on gold mining in French Guiana: definition of the systems and development of the scenarios

The methodology presented in Chapter 2 is developed via a demonstrative application of a case-study which is shown in Parts II and III of this thesis. Part II begins the application of the proposed approach on the gold mining sector in French Guiana (FG). The first step of the risk assessment process is the acknowledgment of the studied system. This Part II is intended to present and define the territory and mine systems chosen for the application of the methodology. Then, these two systems are combined for the development of territorial mining scenarios (TMS) that will be compared based on their level of risk. Therefore, Part II will conclude with the identification of multiple risks and, based on them, the development of two different risk scenarios. The assessment of these risks and, thus, of the related TMS is given in Part III.

Chapter 3. The territory system: French Guiana and Mana river basin

Chapter 3 presents the territory system on which the methodology is applied. Because of the territorial dimension of our approach, a brief but general overview of FG must be given. Then, a smaller spatial unit is chosen at the river basin scale and its human and ecological features described to give a perspective of the socio-ecological vulnerability of the territory.

1. General presentation of French Guiana and its specificities

FG is a French Overseas Territory and Department located in the northern hemisphere, near the equator, on the northern Atlantic coast of South America. With a surface of approximately 84,000 km², it is the largest department of France – the only one in South America – and the larger outermost region within the European Union (EU) (Papy, 1955). FG is at approximately 7,000 km far from Metropolitan France and it is located between the rivers of Maroni and Oyapock which separate it respectively from Suriname and Northern Brazil (Fig. 16). Its features concern a transversal range of aspects which must account for:

- Its localization within the Amazon rainforest, in a sensitive region from a hydrological, geological and environmental point of view (Gallochet and Morel, 2015)
- Its colonial history that reflects a currently complex political, economic and socio-cultural context and results in a strong dependence towards Metropolitan France through public policies that address the socio-economic and ecological challenges of the territory (e.g. exponential demographic growth, land-use conflicts, high non-employment rates) (Barret, 2001; Piantoni, 2009; Oder, 2011).

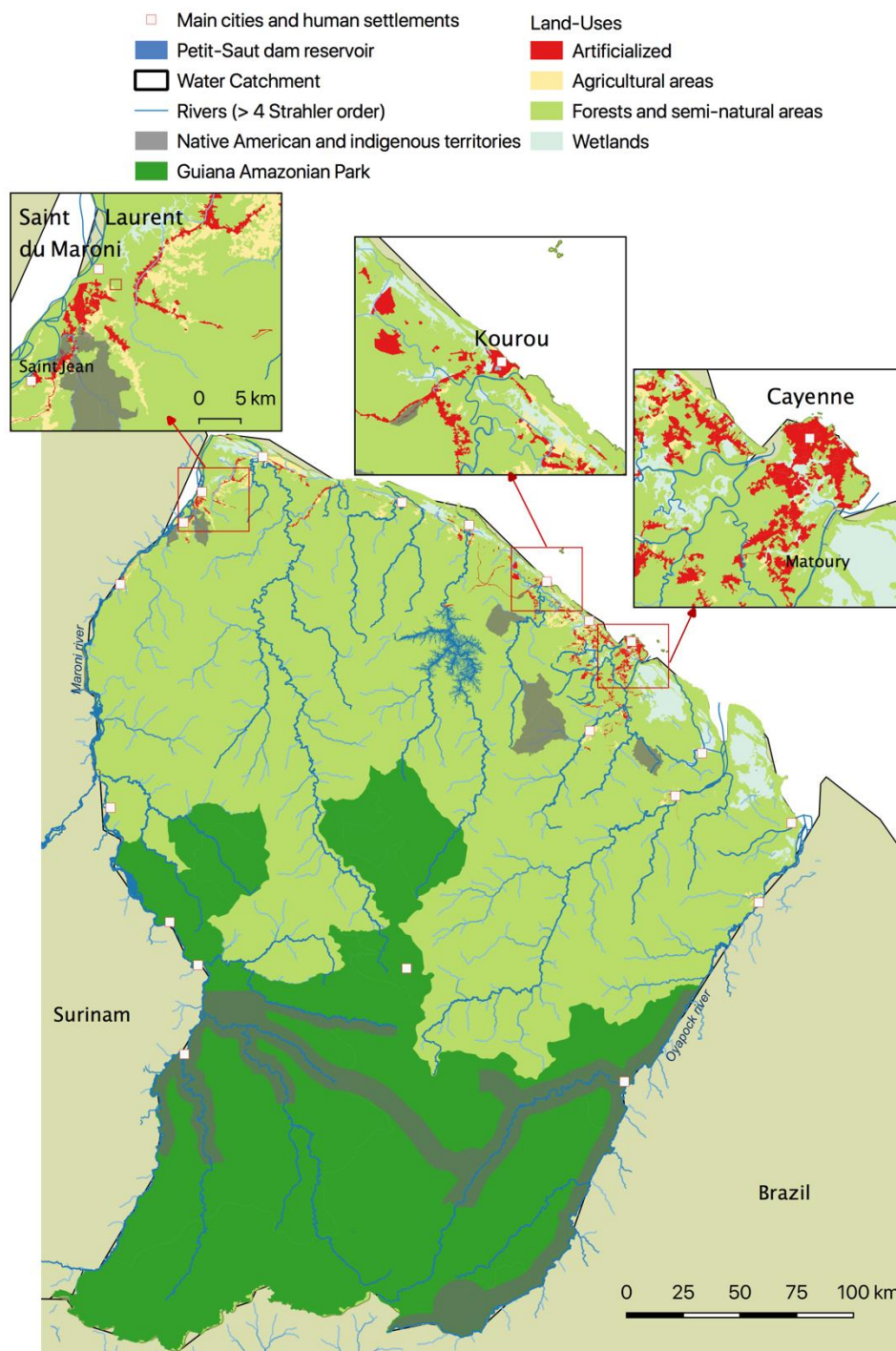


Figure 16 Simplified map of FG showing the main environmental and human features.

1.1. Environment of French Guiana

The geo-environmental context of FG is no different from its neighbouring countries and is strictly related to the geological settings of the Guiana Shield and its equatorial climate.

- **Geology** of FG is presented and discussed by a wide range of scientific literature (Delor *et al.*, 2003b; Milesi *et al.* 2003; Cassard *et al.*, 2008) and grey papers (Milesi and Picot, 1995; Degay *et al.* 1997; Théveniaut *et al.*, 2011). Two greenstone belts of low sedimentary and volcanic units cross the territory from west to east in its northern and southern regions. It is mainly in these formations that gold mineralization took place. A simplified geological map of FG is available in Appendix 4.
- An equatorial-wet **climate** due to its position within the Intertropical Convergence Zone. Because of its position, FG has (low pressures, average temperatures at ~26,5 °C and variable rainfall intensity between 1,700 to 5,000 l/m² per year). (Barret, 2001; Lecomte *et al.*, 2011). (www.meteoguyane.fr).
- A territory divided between the coastal plain, called “lowlands” (4% of the territory) and the inner regions, or “uplands” (96% of the territory) and **reliefs** globally moderate with some punctual sloping areas (the Inini-Camopi mountains, reaching 850 m, hills, inselbergs).
- **Hydrogéologic and hydrologic resources** divided in several groundwater bodies (85,000 km² in confined aquifers) and a highly dense and tufted network of surface water bodies (almost 20 000 km of length) spread across the territory (Barret, 2001; Asconit, 2013; DEAL, 2013). Actual renewable water resources (i.e. the total amount of a country’s water resources) per habitant in FG are estimated to be more than 700,000 m³/year (less than 3,500 m³/year in Metropolitan France) (OEG, 2016 www.eauguyane.fr). Surface water streams are mainly affected by the release and deposits of important quantities of total suspended solids (TSS) (Barret, 2001), due to natural or anthropic causes, including gold mining. Finally, the only plane surface water body in FG is the Petit-Saut hydroelectric dam reservoir (Fig. 16). More details about Petit Saut and its role in vectorizing, for instance, mercury-related risks can be found in Sissakian (1992); Calmont (2001); Muresan (2009), Pestana *et al.*, (2019).
- **Soils** very heterogeneous, with a great range of properties. The predominant soil types, as shown by a simplified soil map provided by Blancaneaux, (2001) (Appendix 4), concern poorly developed soils, podzols, hydromorphic soils (mainly located in the lowlands) and a great variety of oxisols and ultisols occupying ancient lowlands and mainly the uplands. The main common features of these soils zones are their high degree of weathering, their sensibility to erosion, their low fertility and a mostly acidic pH. (Turenne, 1973; Betsch, 1998). However, soil resources in FG should be more pertinently be acknowledged.
- More than 90% of the territory covered by tropical rainforest (Cassard *et al.*, 2008; De Santi *et al.*, 2016), making of FG a world-widely recognized high-biodiversity wilderness area within the Amazon rainforest region (Galochet and Morel, 2015). Indeed, **biodiversity** is maybe the environmental component the most discussed in FG, especially when it comes to gold mining-related impacts. Various compilations of the floristic and faunistic richness of FG are available (Barret, 2001; DEAL, 2014; ONF, 2015; Stier *et al.*, 2020). The ecological patrimony of FG encouraged public authorities to

create, during the years, a great number of protected areas, including three RAMSAR zones, 170 ZNIEFF areas and one Amazonian Park (Appendix 4) (Chaneac and Legrand, 2009; DEAL, 2014; Galochet and Morel, 2015; CTG, 2016).

1.2. History, society and economy in French Guiana

Gold mining affects the socio-ecological dynamics in FG and represents an activity that shaped the human component of FG, as it has been widely deepened by Jebrak *et al.*, (2020). Therefore, risks related to gold mines vary considerably based on the features of the societal context where they are performed.

1.2.1. Human societies and history

Almost all the human settlements of FG concern the coastal area, with one first main cluster in the capital Cayenne, but also Kourou or Mana – and the riverine regions of the Maroni – with the second main cluster of Saint-Laurent du Maroni – and the Oyapock. FG has one of the highest demographic growth rates in France (Millet, 2018). According to a report of the French National Institute of Statistics and Economic Studies (Insee), population increased from 27 863 in 1954 to 269 352 in 2016 (Raimaud, 2018) and may reach more than 500 000 people in 2050 (Léon, 2010; Demougeot and Baert, 2019). Cayenne more than tripled its surface between 1946 and 1998 (Barret, 2001).

Because of its history, FG population is extremely diversified. It mainly includes Creoles (i.e. people born in the colonial territory), French Metropolitans, *Bushinengue* (i.e. descendants of black slaves carried from Africa to the colony), six groups of indigenous people of America but also important communities of Brazilian, Hmong (mainly from Laos), Chinese, Javanese, Lebanese and Indo-Caribbean people (Joshua Project, 2015). Such multi-culturalism is discussed by several authors (Papy 1955; Jolivet, 1971; Collomb, 1999; Fouck, 2000; Elfort, 2010) and it poses important challenges for the uniform application of public policies and land-use regulations (Grenand *et al.*, 2006). The cohabitation of these different cultures might be on occasions the source of social tension concerning land property rights. Indeed, French administration historically took over the Native Americans and progressively transformed the territory into a “plantation model” where a process of “francization” of local people was performed through Christianity and property rights (Barret, 2001). At the same time, the slavery system shaped the population into “white” Europeans, Native Americans, African slaves and Creoles. Such dynamics must be considered at the scale of the three Guianas, since it produced internal migration flows of Native Americans and African slaves. For instance, the rebellions of Africans against slavery led to the development in FG and Suriname of new black communities (the *Bushinengue*). In 1848, slavery was abolished, and French administration continued the francization of the newly-freed slaves as sort of “social promotion” (Barret, 2001). If FG was a well-known destination for political prisoners since the French Revolution, under the 1854 “deportation decree” by Napoleon III, FG became officially a penal colony,

leading to the construction of several labour camps, called “*bagnes*”. Massive groups of people from France were sent from the Metropolis to FG, as deported or as part of the colonial administration. After the beginning of gold exploitation in 1855, the first “gold rush” added more migration flows across the region and the reduction of Native Americans at the beginning of 1900. IIWW and the economic crisis generated the worsening of living and social conditions in FG. Finally, FG became a French department in 1946 (again, after the short period in 1797) as integral part of French Republic and submitted to the same regulatory framework of the Metropolis.

The demographic rate and the high diversification of FG society is due as well to these historical conditions (Piantoni, 2009). For instance, in 1999 more than one third of the population was foreigner. Two main factors are related to such migratory flows: firstly, the physical fuzziness of FG boundaries with Surinam and Brazil (Barret, 2001), leading to massive flows, especially of illegal miners. Secondly, the gross domestic product (GDP) is a half lower than in Metropolitan France (Piantoni, 2009; Insee, 2017). As the other French Overseas territories, FG relies on public transfers from Metropolitan France which create an “artificial prosperity generating internal freezing and exacerbating nationalist identity reactions” (Barret, 2001). Therefore, FG has higher living standard and regional GDP than the neighboring countries (IEDOM, 2014) making it more attractive to the neighboring communities. Moreover, several European aids are provided for the region (IEDOM, 2016). Therefore, FG is the destination for several migrants seeking for better opportunities, including illegal gold mining.

1.2.2. Short overview of the main economic activities

In 2016, gold mining was representing approximately 1% of the GDP of FG, with 500 declared employees while the informal gold mining sector is up to 10 000 estimated workers (IEDOM, 2016). The presentation of the other different economic activities in FG is available on the portal of French institute for the statistical and economic studies (www.insee.fr). A general overview is also presented by Barret (2001), IEDOM (2016) and in a recently published report by Deloitte (2018) that compares different future scenarios of economic development in FG.,

The unemployment rate in FG was up to more than 23% in 2016 (IEDOM, 2016), one of the highest in France. If most of the jobs opportunities are provided by the public administration sector, representing 41% of the total employment and 35% of the global GDP, other several activities play an important role in the economic dynamics of FG. A short list will present the main sectors:

- Agriculture and farming: more than 30 000 hectares in FG are destined to agriculture (Deloitte, 2018). The traditional “slash-and-burn” agriculture is still the most practiced and covers almost 80% of the total agricultural surface (Demaze and Manusset, 2008; Deloitte, 2018).

- Fishing is also an important sector even if currently illegal fishing activities produce three times more than the legal ones (Deloitte, 2018).
- Wood production provides around 500 direct jobs (CTG *et al.*, 2018) and represent an important potential for FG.
- Construction represents 8% of the total value added in FG (IEDOM, 2016).
- Industrial activities, other than gold mining, cover a wide range of sectors such as the chemical transformation, food production, transport, energy, etc.
- After the development in 1968 of the Guiana Space Centre (CSG), space industry has been representing a boosting factor both for the city of Kourou, where the population raised from 3000 to more than 25 000 people in 50 years but also for the entire region (Charrier *et al.*, 2017).
- The energetic sector as well provides important outcomes since more than 64% of the total electricity is produced through renewable resources (CTG, 2016).
- Tourism counts approximately 100 000 visitors per year in FG, mostly for business purposes (Deloitte, 2018).
- Research and education count different structures in FG (INRAE, CNRS, IRD, SEAS) and one University in Cayenne, with more than 3 000 students in 2012 (Insee, 2014).

2. Selection of the spatial scale: Mana river basin

Our study is conducted at the scale of a river basin (RB), the area where all streams drain to a common terminus (Molle *et al.*, 2007). A RB is considered in this study as a territory system, thus as a socio-ecological functional unit that has the capability to provide ecosystem services and regulate human life through the meeting of societal needs (see Chapter 1).

The choice of this scale is due to the significative importance of water management at the river basin in FG where the hydrographic network is considerably dense and plays a key role in the daily life of local population. Furthermore, there is a tight relationship between mining activities – particularly gold mining – and water management, especially under the climatic conditions of FG. The structure of the basin and of the hydrographic network have a strong influence on the functioning of a mining project, starting with the localization of the mine site, its construction and water and waste management (ICMM, 2015). For instance, Kossoff *et al.*, (2014), suggest that the parameters to assess the consequences of a tailings dam failure and the remediations measures to implement, depend on the features of the RB.

Furthermore, the 2015 Carthage database – developed by the French Agency for Biodiversity (*Agence Française pour la Biodiversité*, AFB) and other services such as SANDRE and the DEAL of FG – distinguishes four spatial units (i.e. region, sector, sub-sector, zone) responding to the needs of hydrographic codification (circular n°91-50, 1991) to support Water Planning and Management Schemes (SDAGE) at the catchment scale. This meets the operational purposes at the territory level proposed by the approach presented in this thesis. The chosen geospatial unit is the hydrographic sector – corresponding to the actual river basins

– which represents a sufficiently wide area to locate multiple mining project types to test and refine the methodology.

2.1. The Mana river basin and its potential representativeness

FG counts 14 different river basins (RB), which almost correspond to municipal boundaries (Fig. 17). From the West to the East:

- the Maroni RB, the biggest in FG, which exceeds FG regional boundaries and covers an important part of Surinam,
- the Mana RB,
- nine RB usually named “river basins of the central coastline (Organabo, Iracoubo, Sinnamary, Malmanoury, Kourou, Macouria, Cayenne, Mahury, Kaw),
- the Approuague, Ouanary
- the Oyapock RB, which, as the Maroni basin, crosses FG borders and covers a part of the northern region of Amapà, in Brazil.

The choice of the river basin on which applying the approach proposed in this study is based on multiple criteria that consider the geological nature of the basin and the presence of gold deposits, the quantity and quality of mining activities, the presence of important human settlements and environmentally sensitive areas. These criteria aim to select a river basin that shares its features with the other basins and might be representative of FG territory. Hence, our study is focused on the Mana RB which has been chosen since it hosts:

- i) One of the most important surfaces of greenstone belt formations, approximately of 4100 km², after the Maroni river and the central coastline basins;
- ii) More than 50 documented legal primary and secondary gold deposits, according to the data collected in 2018 (provided by the PTMG) and more than 2000 illegal gold miners which have a considerable impact on water-related resources;
- iii) One of the most important clusters of legal mining permits and authorizations currently active;
- iv) At least 6 main urban areas, among which, the city of Mana, the 4th most important city of FG by surface, the 8th by population and the 14th by density;
- v) Multiple ecological habitats that are common to the whole region of FG, as it can be observed in the catalogue developed by ONF, (2015).



Figure 17 Main river water basins in FG (Office de l'Eau, 2015)

The choice has been mainly driven by discussions with local actors (e.g. public authorities, mining operators and local associations) during the missions that covered the first year and a half of the thesis. Mana RB represents a simple example for the demonstrative application for the methodology developed in this study. By our knowledge, this basin could be considered as representative of FG territory because of the common features previously mentioned. For instance, the application on the Sinnamary basin would have implied a specific focus on the Petit Saut pond, which plays an important role in sediment transportation and Hg methylation. Also, the most upstream zone of the Maroni river is not crossed by greenstone belts and does not represent a mining area. For this reason, it cannot be considered representative. Or else, the selection of the Maroni or Oyapock RB would have imposed the consideration of their transboundary dimension and, thus, a further assessment of gold mining sector in Surinam or in Brazil.

2.2. The socio-ecological components of Mana RB

Hereafter, we present the human and ecological specificities of the Mana RB. If such specificities are here only overviewed, they are needed for the assessment of the socio-ecological vulnerability of the basin according to the risk scenarios, developed in Chapter 6. Vulnerability assessment is detailed in Chapter 7. Data have been collected through free interviews and exchanges with the actors presented in Section 1 – which provided multiple spatialized data – field observations, mine visits and surveys, literature reviews, etc. The information has been gathered under various forms: tables, conceptual and descriptive data,

photos, geospatial data for GIS processing (e.g. raster, vector files) etc. The collected data are resumed in Appendix 5.

2.2.1 Ecological component

The Mana RB has a surface of approximately 12,200 km² and it is located on the west part of FG. As mentioned, its geology is characterized by the same units of the Guiana Shield. In Fig. 18a, a simplified geological map of Mana RB is provided, with a specific focus on the greenstone belt formations, since gold deposits are mainly localized in these areas.

The ecology of Mana RB is highly diversified as shown and detailed by the habitats catalogue provided by ONF, (2015) (Fig. 18b). Different types of forests are located within the RB and their diversity depends considerably on the relief and type of soils. The relief of Mana RB is moderately low, with a progressive increasing of the elevation towards the uplands and some high “peaks” located in its central-western region, near the Massif Dekou Dekou and in the south (Fig. 18c).

Mana coastal area is the driest with precipitations inferior to 2 meters per year, which supports rice culture, while the rainfall intensifies towards the uplands, with lower values on the western side of the RB (Fig.18d). Also because of the climatic conditions, the ecological habitats of the basin shelter an important biodiversity and several protection measures have been implemented in order to protect these areas (Fig. 18e): the coastal wetlands classified under the Ramsar Convention, several ZNIEFF areas, a large biological reserve in the north-western part of the RB and finally a part of the Guiana Amazonian Park (PAG) in the south.

Finally, as it is shown in Fig. 18f, the main ecological and protected areas have been integrated within the Departmental Mining Plan (SDOM) which, as mentioned, provides a zoning whether mining is authorized or forbidden.

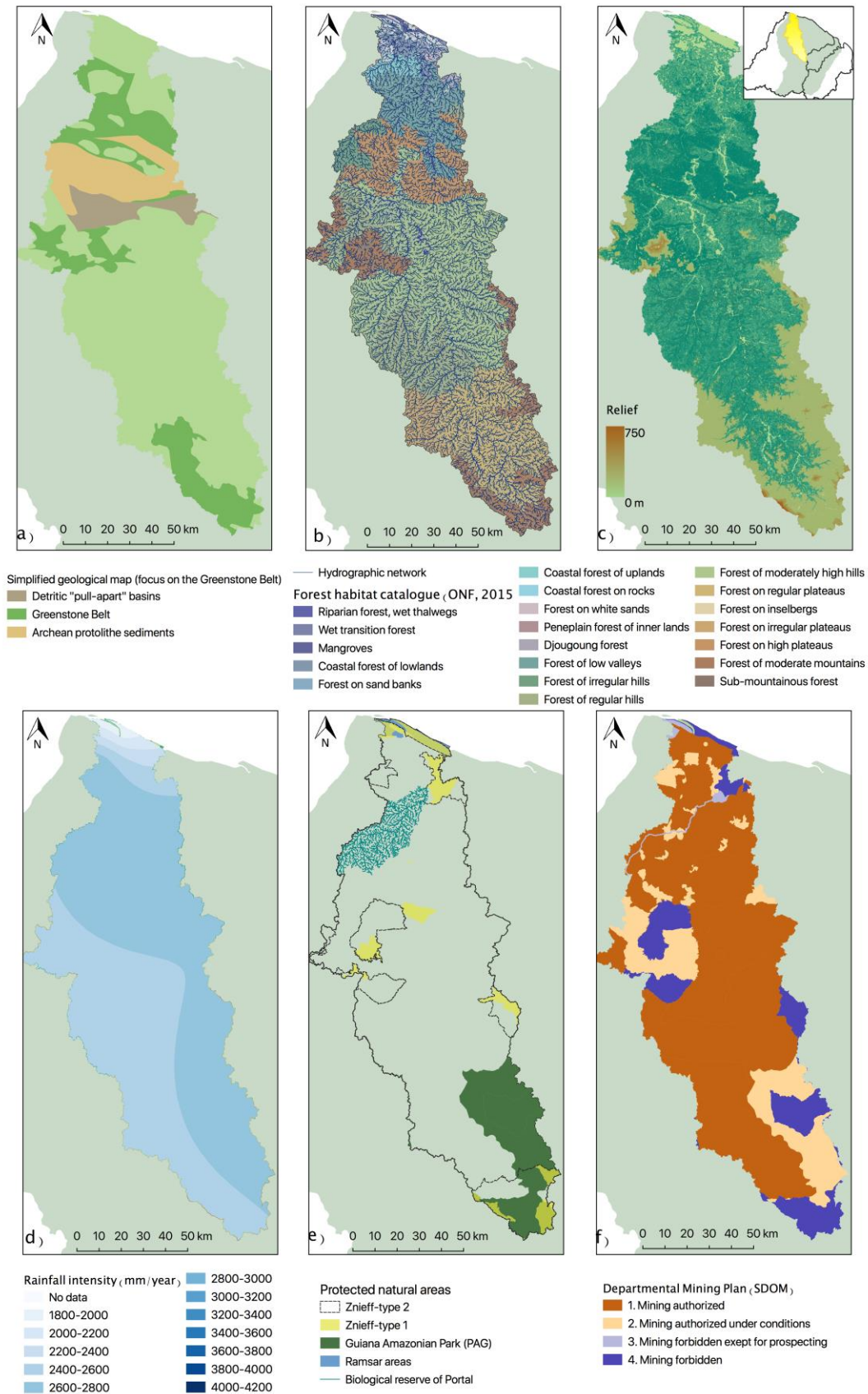


Figure 18 Six maps overviewing the ecological components of Mana RB related to the: a) Rainfall intensity; b) Relief; c) Hydrographic network and the main forest ecological habitats classified by ONF (2015); d) Environmental protection measures; e) Simplified geological maps focusing on Greenstone belts formations; f) The Departmental Mining Plan (SDOM)

2.2.2 Human component

The Mana RB intersects four different municipalities (Fig. 19): Awala-Yalimapo, Mana, Saint-Laurent-du-Maroni and Saül. These municipalities belong to the Community of Western Municipalities of FG (CCOG), along with other municipalities such as Apatou, Maripasoula, Papaïchton, Grand-Santi.

The areas of Saint-Laurent-du-Maroni and Saül, crossed by the RB, are entirely covered by rainforest. The human settlements located within the RB belongs mainly to the municipalities of Mana and, in a very residual part, of Awala-Yalimapo. Therefore, the study of the human components of Mana RB has been focused essentially on the municipality of Mana, which led us to the study of urban planning documents, observations and discussions with local authorities. Most of this general overview is presented by the report of the Agency for Urban Planning and Development of FG (AUDEG, 2018).

From a general point of view, Mana municipality has a surface of 6,520 km². In 2020, almost 12,000 inhabitants (plus approximately 2 000 illegal gold miners) – against less than 5,000 in 1990 (<https://www.insee.fr/fr/statistiques/3635065?sommaire=2414232>) – are distributed among two main urban clusters: the Bourg of Mana, located at the estuary of Mana river, and the village of Javouhey, more upstream (Fig. 19). As shown by Fig. 19, the rest of the urban agglomerations concerns peri-urban areas, distributed along the main national and departmental roads. This type of unplanned and spontaneous urbanization is an important characteristic of Mana RB which can be peculiar to other municipalities in FG. Nevertheless, it represents an important issue for risk assessment and analysis that will be detailed further.

Mana population is very varied with important rates of Metropolitan French and foreigners (mainly from Surinam). The total of human settlements and activities represents a footprint of approximately 10% of the territory. As shown by Fig.19, the main part of Mana municipality is covered by rainforest. The urban clusters are surrounded by agricultural areas that cover considerable surfaces along the coastline. Indeed, the agricultural potential is relatively important for two main reasons:

- The heterogeneous geopedological context, that will be furtherly detailed,
- The low slopes of important surfaces, which allow the mechanization and access to several areas.

Nevertheless, this potential is restrained to the northern part, leaving the rest of the area to possible forestry activities.

Mana energetic supply is provided by the EDF net installed along the main urban areas, with the potential development of the hydroelectric power plant of Saut Maman-Valentin which would supply approximately 20,000 inhabitants. Several constructions, often illegal, and mainly in unplanned urban areas do not dispose of electricity.

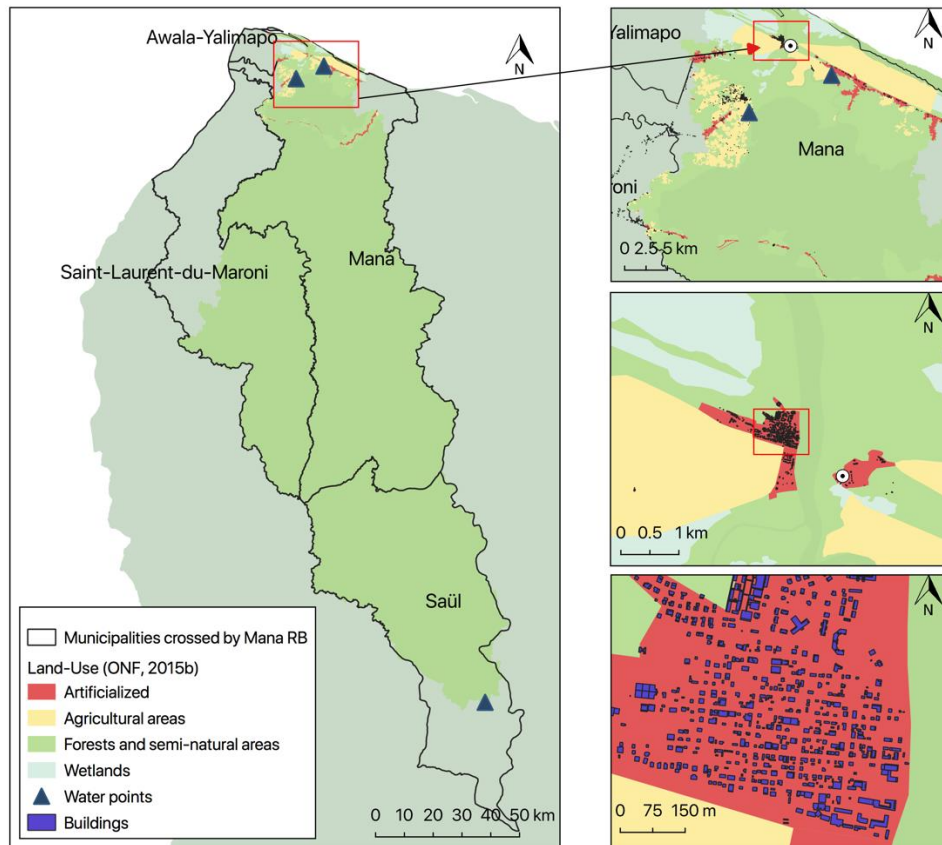


Figure 19 The human components associated with Mana RB. The maps show the overlaying municipalities concerned by the considered RB, with a particular focus on Mana municipality and its land-use. The last three maps focus on the urban areas of Mana (Mana Bourg).

3. Actors considered and temporal dimension of the application

3.1. Presentation of the stakeholders considered in the study

The multi-perspective dimension of our approach involves the integration of as many stakeholders concerned by gold mines in FG as possible. Participation of stakeholders has played a key-role mainly for data gathering and the further definition of risk-weighting coefficients (see Chapter 9).

The actors considered hereafter can be divided in three main categories that are detailed in Table 5: gold mining operators, public authorities and civil society. Continuous and ongoing exchanges with them took place during the whole thesis and concerned particularly: the general acknowledgment of FG and the collecting of semantic and spatialized data for the assessment, the development of gold mine-types, the selection of the river basin for the fictional localization of these projects, risk identification (Chapter 6), the development of the risks scenarios that will be assessed (Chapters 7 and 8) and the multi-perspective weighting of the assessed consequences (Chapter 9).

Table 5 Stakeholders contacted during the thesis. Some actors have been participating to the development of the thesis during all the three years.

Actor	Actor Type	Category
Artisanal and Small-scale mining operators	Legal miner	Mining Operators
Medium-scale mining operators		
Large-scale mining operators		
National Forestry Office (ONF)	Public Institution	Public administration
Regional Health Agency (ARS)		
French Geological Survey (BRGM)		
French Guiana Water Office (OEG)		
Research for Development Institute (IRD)		
National Institute for Scientific Research (CNRS)		
Amazonian Park of Guianas (PAG)	Association	
Urbanism and Development Agency of French Guiana (AUDeG)		
Territorial Collectivity of French Guiana (CTG)		
Technical and Mining Pole of French Guiana (PTMG-CTG)	Decentralized Governmental Services	
Prefecture		
Directorate for Environment, Development and Housing (DEAL)		
Defence and Armed Forces	Centralized Governmental Services	
French Ministry for the Ecological and Inclusive Transition		
Or de Question	Association	Civil Society
Guyane Nature Environnement		
World Wildlife Fund (WWF) France	NGO	
Private Engineering consultants	Private Engineering consultants	
Citizens participating to the <i>Montagne d’Or</i> Public Debate	Citizens	

3.2. Temporal dimensions considered in this study

In this thesis, the defined temporal boundaries chosen for the assessment concern:

- the mining system and its phasing (Chapter 1): the risk assessment is applied to the mining “operational phase” (from the excavation of the ore to the recovery and waste management), since it is considered as the most critical in terms of impacts (Fig. 6)
- the temporal dimension at the territory level: the assessment is performed through the development of territorial mining scenarios (TMS) based on the information corresponding to the actual current state of FG and its gold mining sector (2017-2020).

Conclusion

Because of its characteristics, FG seems an appropriate region where to test our methodology. This territory shows important challenges (e.g. demographic growth, human and technological development) that must be addressed in a region shaped by gold mining and with high socio-ecological vulnerability, due to its localization in the Amazon and its history. **This study focuses on the river basin scale of Mana,** as smaller spatial scale. Available and structured data for our purposes are limited, as it will be shown in Chapter 7 and 8 and Appendix 5. Finally, the different stakeholders considered in this study are presented along with the temporal dimension of the application, which focuses on the mining operation phase.

Chapter 4. The mine system: overview and classification of gold mining in FG

This chapter presents and describes the specificities of gold and its exploitation across the world and then, specifically in FG. Gold mining systems in FG are detailed, described and classified in order to obtain standardized gold mine-types for the development of territorial mining scenarios (TMS) that will be compared based on their level of risk. All the georeferenced and non-spatial data used to describe both to the mining and territory systems and their sources are presented in Appendix 5.

1. Overview of gold mining across the world

Before describing the main features of FG, it is important to have a brief focus on gold mining across the world. Indeed, rather than a simple mineral resource like other commodities, gold is considered as a “foreign exchange reserve asset” with unique features. The exploitation of gold involves a great range of techniques and it has been the historical driver for colonizations and migrations for the pursuit of fortunes.

1.1. Gold demand: uses and applications of gold commodities

The exploitation of any natural resource involves a preliminary questioning of its concrete needs and, thus, the understanding of its uses and applications. Therefore, before an overview of gold mining functioning, the main uses of gold resources are briefly presented: in order to apprehend the offer through mining, it is critical to be aware of the existing demand and needs. The World Global Council (www.gold.org/goldhub) provides updated data concerning gold price trends, gold offer and supply and all the related information. As shown in Fig. 20, of a total demand of approximately 4,500 tons of gold in 2019, more than 90% are destined exclusively for jewelry (48%), investment (29%) and Central Banks (15%). Investment includes the production of physical gold bars (approximately 580 tons of gold per year), Exchange Traded Funds, medals and coins. The demand from National Central Banks is explained by the necessity of maintaining sizeable stocks of gold as part of their international reserves (Ghosh, 2016; Gopalakrishnan and Mohapatra, 2018). Finally, the rest of the total gold demand concerns the applications in the technological and industrial sectors with 262.6 tons in electronics, 13.9 in dentistry and 50 in other industrial sectors.

China and India accounts for more than 60% of the worldwide gold jewelry consumption, which is considerably driven by cultural factors and festivities (Schmidbauer and Röscher, 2018). However, if China assures an important internal supply, as first gold producer, India remains the biggest importer of gold (Mukherjee *et al.*, 2017).

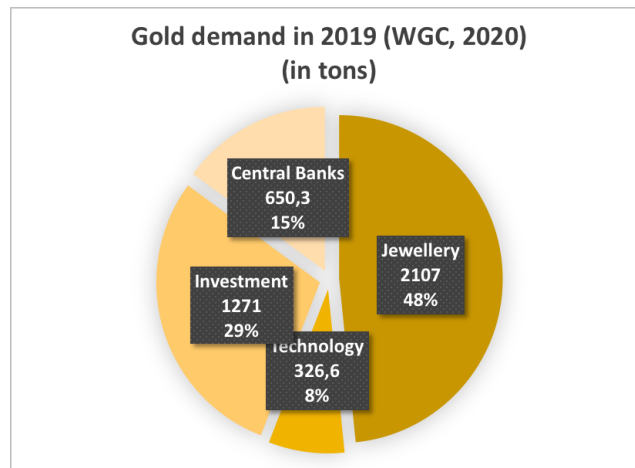


Figure 20 Main sectors contributing to the worldwide total gold demand in 2019 (www.gold.org/goldhub/data/demand-and-supply)

1.2. The specificities of gold

It is vital to apprehend the main unique features of gold involving its exploitation and its environmental, economic and social dimensions, in order to have a preliminary view of the outcomes and concerns that gold mining might raise.

- 1) Gold is rather a financial speculative asset than a simple commodity. It is easily sold and not influenced by the government's instability (Hinton *et al.*, 2003). Moreover, Because of its geological scarcity, gold has a higher market value-to-volume ratio than many other minerals, which implies that even small deposits can generate important profits (Verbrugge and Geenen, 2019). Therefore, the financial trends of world-wide gold demand have historically driven the development of new gold mines and the formal and informal rapid quests of fortune seekers to mine sites ("gold rush");
- 2) Gold exploitation methods can take widely varying forms and sizes (Verbrugge & Geenen, 2019). In particular, the geological accessibility of some deposits enhances the development of artisanal and small-scale mining communities (Hentschel *et al.*, 2002), especially where gold deposits "are simply too small, scattered or remote for large-scale mining" (Verbrugge & Geenen, 2019).
- 3) Finally, as for other commodities, the increasing demand and the lower availability of concentrated ore, encourage miners to target low-grade deposits (Smith and Connell, 1979), generating much greater quantities of wastes. For instance, according to Lottermoser (2010), at modern gold mines, more than 99,999% of the originally mined and processed ore may finally become tailings. This must be accounted for in waste management and the related risks.

1.3. Brief overview of gold geology and mining

Worldwide gold supply accounted for approximately 4800 tons of gold in 2019, enough to cover the total demand. Around 30% of 2019 total supply are covered by recycled gold (WGC, 2020) (Fig. 21), almost entirely from jewellery. Nevertheless, currently more than 70% of gold are supplied through gold mining, including the informal and illegal sectors (Fig. 21). Informal and illegal mining can be defined respectively as “community-based mining activities that typically follows customary law” and “illegal invasive mining” occurring when “miners illegally enter the old mine workings of decommissioned mines” (Nhlengetwa, 2016).

The issues concerning gold mining have a world-wide reach and involve almost all the regions in the world. According to the S&P Global database (www.spglobal.com), around 6,000 mining projects are currently active in the world. They exploit gold as primary or secondary commodity.

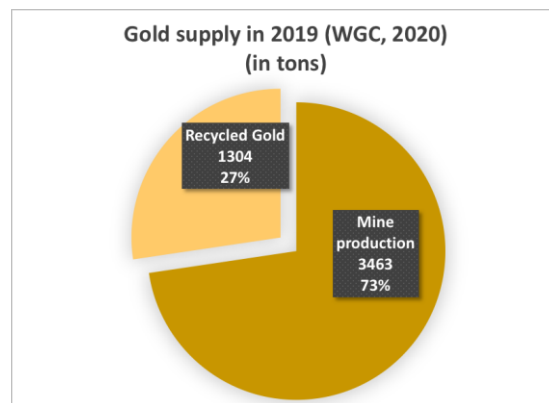


Figure 21 Main sectors ensuring the worldwide total gold supply in 2019 (www.gold.org/goldhub/data/demand-and-supply)

The geology of gold deposits and their genesis are widely discussed by scientific literature (Groves *et al.*, 1998; Macdonald, 2007; Goldfarb *et al.*, 2010). Gold deposit types are extremely diversified, affecting the mining techniques required for their exploitation and, hence, their risks. Detailed classifications of these deposits are mainly based on their geological settings (e.g. geometry, gold rate, geochemical behaviour, host-rocks, weathering, thermodynamic and tectonic conditions) (Robert *et al.*, 1997).

Gold deposits are commonly and simplistically divided in primary and secondary gold deposits, based on the weathering degree and the type of accumulation of gold particles. Primary gold deposits can imply a great range of sub-types (e.g. mesothermal and orogenic, epithermal, sedimentary, intrusion-associated gold deposits, greenstone-hosted veins) (Goldfarb, 2005). Secondary gold deposits usually refer to detrital accumulations of gold particles after weathering and displacement from primary sources (placers, paleoplacers, alluvial and eluvial deposits).

Gold deposits are evenly distributed around the globe and exploited through different techniques (e.g. artisanal, industrial). However, countries production rates are highly

heterogeneous, depending not only on the gold reserves but also on public policies, technical assets and the socio-environmental factors: the availability of gold production does not rely only on the mere occurrence of a geological deposit. Therefore, the geological parameter is not the only one who needs to be accounted for in order to understand the trajectories of gold mining countries and their production rates.

Indeed, according to the WGC (consulted on 27/05/2020) more than a half of gold supply by mining is provided by ten main gold producer countries (Appendix 6), with China, Australia and Russian Federation at the top of the list. Australia and Russia have a considerably low population density (respectively 3 and 9 people per km²) which would reduce human exposure to negative mining impacts and land-use conflicts. Australia is one of the most important mining countries in the world with an important mining history which enabled the reduction of ore grade deposits, the increasing of open cast mines and the development of a regulatory framework for each inner State. Moreover, gold production has considerably increased since the choice of the government to allow the implementation of cyanide-based techniques (Mudd, 2007). If China density is relatively higher (145 people per km²), Chinese gold mining boom is due also to increasing foreign and domestic investments into mining and to 1996 Mining Law which supported a rapid expansion of demand and supply and a high diversification of mining ownership structures (Shen *et al.*, 2009).

2. Gold mining in the Guiana Shield

The choice of FG gold mining sector for risk assessment at the territorial level needs a brief introduction to the wider geological and socio-ecological context in which FG is located in order to understand the specific types of gold deposits present in the region. FG gold deposits are hosted by two Greenstone Belts – a formation of metamorphized sedimentary and volcanic series – which are extended to a larger Precambrian geological area called the Guiana Shield. The Guiana Shield is located in the northern part of the Amazonian Craton (Delor *et al.*, 2003a) and it includes Venezuela, Guyana, Suriname, FG and Brazil (Fig. 22). The Guiana Shield is considered as the “geological cousin” of the West African craton (Milesi and Picot, 1995) and its geological history and gold metallogeny are widely detailed by scientific literature (Dardenne and Schobbenhaus, 2003; Delor *et al.*, 2003a; Daoust *et al.*, 2011; Théveniaut *et al.*, 2011). The main geological development of the Guiana Shield took place during the Transamazonian orogeny (2,26 to 1,95 Ga) (Milesi and Picot, 1995; Théveniaut *et al.*, 2011) (Fig. 22) and it is mainly within these settings that most of primary gold mineralization were formed.

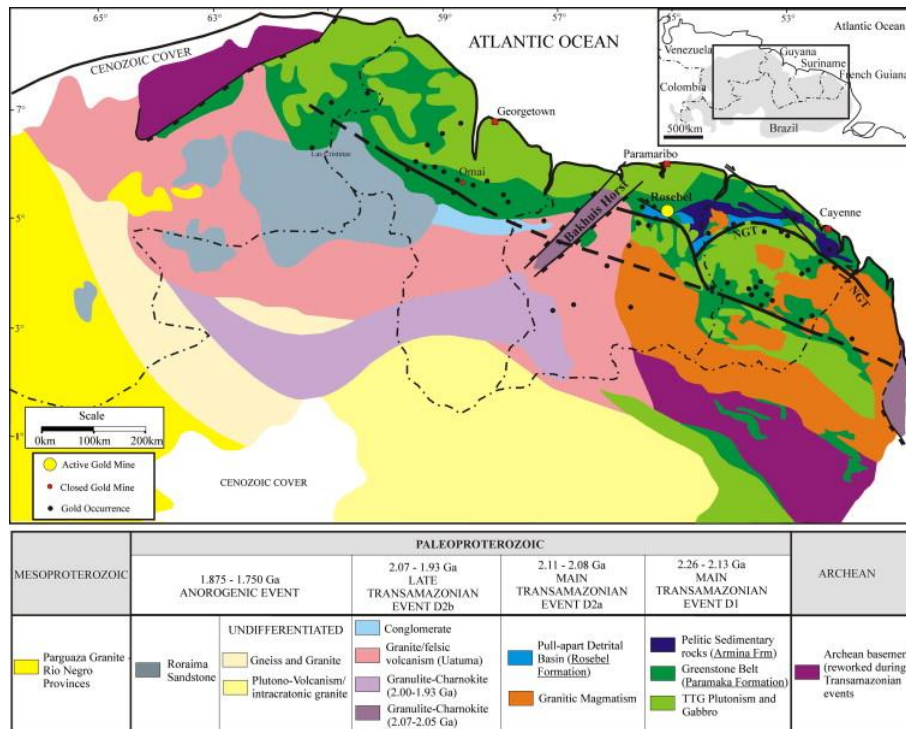


Figure 22 Simplified geological map of the Guiana Shiel (from Daoust et al., 2011)

Apart from geological affinities, the need for the comparison of FG with its neighboring countries is based on:

- The ecological and societal similarities, especially among the three Guianas (Guyana, Suriname and FG) where a cultural melting-pot with a common history inhabits a territory covered by the Amazon rainforest, in tropical and equatorial environments.
- The considerable development of the socio-technical phenomenon of informal and illegal artisanal and small-scale gold mining which moves without boundary restrictions in the three Guianas (Hook, 2019), largely contributing to informal migration flows from Suriname and Northern Brazil to FG;
- The transboundary dimension of the socio-ecosystems in these regions, with particular focus on the Maroni and Oyapock river water basins that separate FG respectively from Suriname and Brazil. For instance, most of the industrial gold mining activities in Suriname are located in the same basin shared with FG (Fig. 23).

Despite the common geological settings among these countries, mining projects take different shapes and involve various techniques (e.g. gold dredging performed in Suriname but not in FG) and mining regulations are extremely different from country to country. For instance, Suriname just recently ratified the Minamata Convention concerning the interdiction of mercury, including for gold mining purposes (www.mercuryconvention.org), while mercury has been banned in FG in 2006.

Fig. 23 shows the distribution of the main existing mining projects in the three Guianas. Data concern all the commodities exploited by mining activities (excluding quarrying). However, only for FG and Suriname, the distinction among primary and secondary gold mining was possible according to the available data. Despite such affinities, gold production is considerably divergent among these countries as shown by the diagrams in Fig. 24. Unlike gold production of Brazil, Suriname and Guyana shown in Fig. 24 (WGC, 2020), FG gold production in 2014 was estimated to be around 2 tons of gold per year and 1,3 tons of exported gold in 2017, for a total turnover of 48 millions of euros (Deloitte, 2018). The same figure normalizes gold production values with the surfaces (km²) of each country according to the World Bank data. As it is understandable, the ratio shows highest values for Surinam and Guyana while Brazil has the lowest rate. In comparison, according to its surface and gold production per year, FG, would present the same values as Brazil. However, the normalization cannot be limited to the surface and should integrate as well further parameters (e.g. the number of active gold mines per year, the surface or size of the geological deposits within country borders)



Figure 23 Modified satellite-derived map of the Guiana Shield and its main countries. The map shows most of the approximate gold mines located in the area in 2017, according to the governmental databases of Guyana (GGMC), Suriname (GMD), and FG (confidential collecting from CTG).

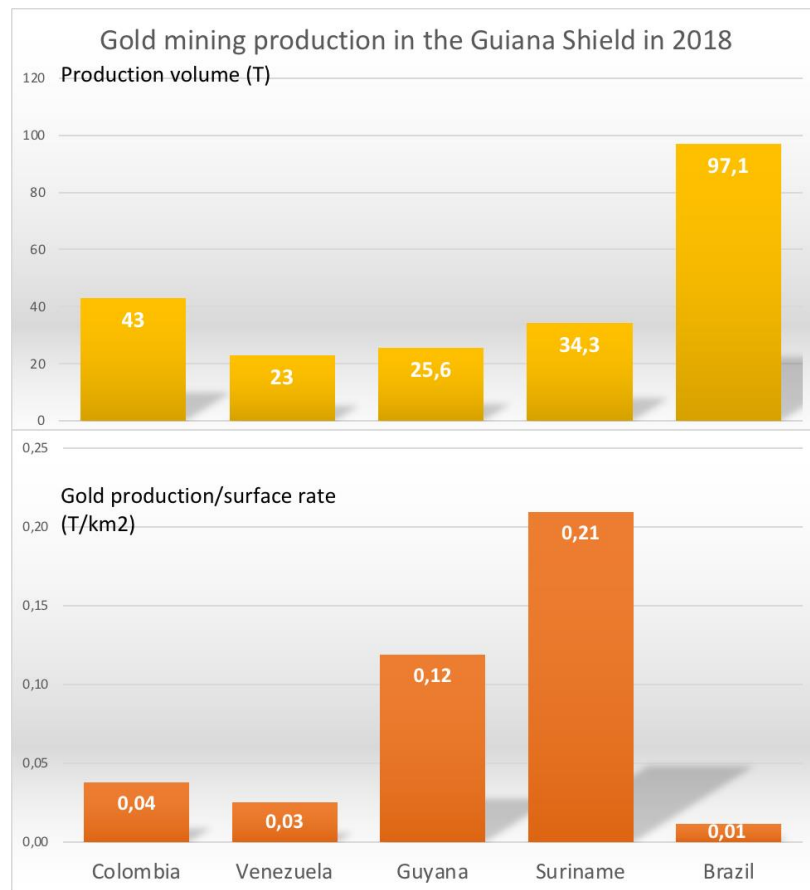


Figure 24 Gold production in 2018 of all the countries belonging to the Guiana Shield, except FG, according to the WGC (www.gold.org/goldhub/data/historical-mine-production)

3. Gold mining in French Guiana

The extraction of gold in this territory has been active only since 1855 (Moulet *et al.*, 2006; Oder, 2011). As described by Oder (2011), gold mining history in FG is composed of three periods:

1. From 1855 to 1930: the newly discovered deposits attracted more Creoles from the Caribbean and coastal areas to mining sites for personal enrichment.
2. From 1930 to 1990: due to the economic crisis of 1929, the depletion of gold deposits, the WW2 and the limited mining techniques, gold mining declines considerably. Furthermore, the 1946 departmentalization encouraged more people to choose safer and more stable jobs along the coast.
3. From 1990 to date: a second gold rush due to several phenomena:
 - New and more effective gold mining techniques and equipment developed in Brazil
 - The publication of the gold deposits survey in FG realized by the BRGM (1975 – 1990), an incentive for both legal and illegal gold miners.
 - The rising of gold prices since the end of the Bretton Wood Agreements in 1968 (Cassard *et al.*, 2008).

However, this late period differs considerably from the first “gold rush”, since it takes place within a “sustainable-development” context where environmental protection and social enhancement are the main issues of the international political agendas, especially in FG (Oder, 2011). Therefore, gold mining activities have progressively integrated socio-environmental performances to address such issues.

This section presents a brief overview of gold mining in FG, detailing the main factors that might influence the occurrence and the intensity of specific risks. The section is directly provided by a fragment of Scammacca *et al.*, (2020a).

According to the database provided by the Technical and Mining Service of the *Collectivité Territoriale Guyane (CTG)*, on December 31st 2017, around 131 valid gold mining permits and authorizations have been delivered in FG: 85 authorizations for mining exploitation (AEX), 29 mining concessions, 14 prospecting permits (PER) and 3 exploitation permits (PEX) (Appendix 4 and Table 6).

During these last decades, FG has been facing a real “gold mining paradox”: gold value increases, legal mining permits decrease, and illegal gold mining explodes (Oder, 2011). Indeed, illegal gold mining is one of the main issues related to the extractive sector in FG. It represents a way out from poverty, and it attracts hundreds of legal and thousands of illegal miners. At least 10 000 illegal gold miners (Moulet *et al.*, 2006) are active all over the territory in FG, including the PAG area. These miners, or “*garimpeiros*”, come mostly from the northern Brazilian State of Amapà, Suriname and Guyana where there is lack of opportunities.

However, if legal mining represents 1% of the GDP (IEDOM, 2016), illegal gold mining is the main sector of informal employment and of highest production rates, producing ten times more than the legal gold mining sector (WWF, 2018).

3.1. Gold mining regulatory framework in FG

In FG, mining permits are delivered according to two complementary frameworks. The Mining Code, which establish the size and the duration of the mining permit depending on the mining phase (Table 6), and the Departmental Mining Plan (“*Schéma Départemental d’Orientation Minière*” or SDOM), which states where mining is authorized or not and under which conditions it might be performed (Appendix 4). Finally, a number of European dispositions are applied in FG.

At least 10 000 illegal miners – or *garimpeiros*, when they come from Brazil – operate outside such frameworks and occupy 500 to 900 mine sites in FG (Moulet *et al.*, 2006; Tudesque *et al.*, 2012). Despite of multiple military operations, illegal mining produces ten times more than legal gold mines: the total illegal production of the last decade is estimated to be about 10 tons of gold per year, while legal production is around 1-2 (WWF, 2018).

Table 6 Synthetic scheme of the regulatory framework concerning mining permits and authorizations in FG (adapted from DEAL, 2015)

Type of	ARM	AEX	PER	PEX	Concession
French description	<i>Autorisation de recherches minières</i>	<i>Autorisation d'exploitation minière</i>	<i>Permis exclusif de recherche</i>	<i>Permis d'exploitation</i>	<i>Concession</i>
Nature of	Exploration	Exploitation	Exploratio	Exploitation	Exploration
Max.	3	1	Free	Free	Free
Max.	4 months	4 years	5 years	5 years	50 years
Max.	1x4 months	1x4 years	2x5 years	2x5 years	∞ x25 years
Spatial scale of	Regional	Regional	National	National	National

3.2. Types of gold deposits in FG

The type of geological deposit determines the techniques employed for mining, and thus, the associated impacts. Two main categories of gold deposits are generally considered in FG (Thomassin *et al.*, 2017). Primary gold is mainly found in quartz veins (type 1) or in oxidized (type 2) and residual (type 3) deposits depending on the weathering degree. On the contrary, secondary gold deposits are made of gold particles that have been subjected to an important displacement from the primary source along the lateritic profiles (type 4) or by the gravimetric concentration in streams (type 5) (Dardenne and Schobbenhaus, 2003) (Fig. 25). For instance, the phenomenon of acid mine drainage (AMD) is typical of primary gold deposits rich in sulfides and it occurs when operational and specific environmental conditions are met (e.g. oxidizing conditions, absence of carbonates, high temperature, acid pH, microbial activity) (Miramond *et al.*, 2006; Simate and Ndlovu, 2014).

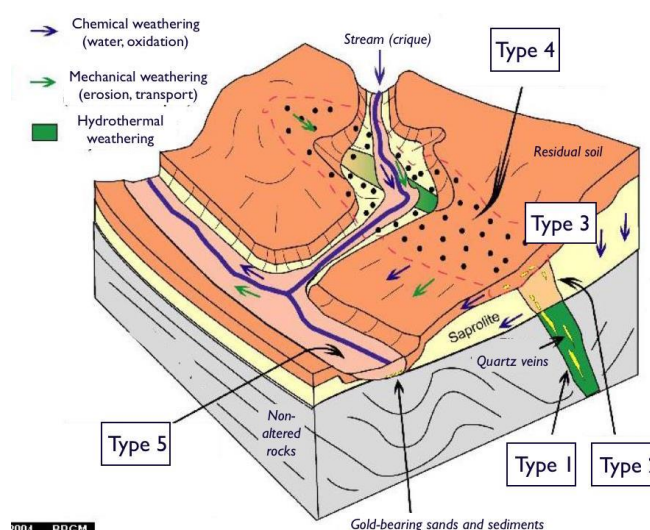


Figure 25 Conceptual image of gold mining deposits in French Guiana (adapted from BRGM, 2004)

3.3. Mining techniques for gold exploitation

Depending on the geological deposit, gold exploitation methods can take a wide range of forms and sizes (Verbrugge and Geenen, 2019). Since primary gold exploitation requires a certain amount of logistics limited by the restrained accessibility within the rainforest, current gold exploitation in FG concerns predominantly secondary deposits (types 4 and 5) through artisanal and small-scale techniques (Moulet *et al.*, 2006; Cassard *et al.*, 2008; Matheus, 2018).

In FG, secondary gold mining is usually based on surface mining techniques (“placer mining”) documented by technical reports of the French Geological Survey (Laperche *et al.*, 2008; Barras, 2010; Bourbon and Mathon, 2012; Cottard and Laperche, 2012; Aertgeerts *et al.*, 2018). The site is prepared through excavators and mechanical diggers (Laperche *et al.*, 2008). The exploitation of the deposit begins with the creation of a pond (called “*barranque*”) through the diversion of streams and the scouring of riverbanks and removal of sterile soils using hydraulic monitors to reach the secondary deposit at a depth of 2 to 8 meters (Fig. 26 and Fig. 27). Here, gold-enriched sediments from the mineralized clay layers of the “flat” (sedimentary volume of the alluvial plain) are left in suspension collected. The wastes from this first operation are released within the pond and checked again manually by panning. A second pond is opened by hydraulic monitors towards the upstream and the process is reiterated as long as it is allowed by the permit, in the case of legal mining projects. The fine-sized slurry (< 20 mm) – containing water, sediments, gold and other materials – is pumped or moved manually on terraced sluices with metal carpets or other settling tables (e.g. shaking tables, trommel machines) in order to trap gold particles by gravity. The abandoned exploitation pits are used as decantation ponds and they are interconnected through a communicating spillway system. Therefore, the mine site consists in a sequence of “*barranques*”, interconnected through channels which support the gradual decantation of the water from the newer ponds – where sediments settle – to the oldest – where water is decanted and re-pumped to the hydraulic monitors (Fig. 26 and Fig. 27). Once separated from the other materials through the settling tables, concentrates of gold-enriched “black sands” are transported to the laboratory area for recovery. A more accurate concentration of gold particles is then done either manually through the *couy* (i.e. pan) and traditional panning methods or more frequently through more sophisticated equipment such as the Knelson concentrator, shaking tables (e.g. Gemini or Goldfield types), wave tables or laboratory sluice boxes (Thomassin *et al.*, 2017; Aertgeerts *et al.*, 2018) (Fig. 28). Finally, they are transported to the smelter and then refined (Matheus, 2018). The revegetalization of these mine sites is addressed by a specific guide in FG (DEAL *et al.*, 2016).

In the case of illegal gold mining of secondary deposits, the process is quite the same, except for the non-respect of any safety and environmental regulation. Moreover, the extension of the site is quite variable and, obviously, does not depend on any permit delimitation (Fig. 29). The exploitation process of illegal gold mining involves as well a first use

of mercury (Hg) which is either spread on the ground or on riffled sluice box (Hinton *et al.*, 2003).

Only few legal mining projects concern primary deposits (types 2 and 3), while type 1 primary gold still is mainly untouched (Massoud, 2008). Primary gold exploitation in FG is performed following two main techniques. The most current is open-cast mining, which implies the excavation of a pit (20-25 meters deep) and the transfer of waste materials on waste rock piles (Fig. 30). The ore is crushed, grinded and then pulped on sluices to separate gold particles by grain-size. A second grinding and centrifugal phases are performed to trap fine gold particles (Thomassin *et al.*, 2017; Matheus, 2018).

Recently, primary deposits, including type 1 deposits, have also started to be exploited through underground mining techniques by illegal miners (Bourbon, 2014; Bourbon, 2015). Miners reach the mineralization through the excavation of pits and/or vertical shafts whose depth varies between 10 and 40 meters (Fig. 31 and Fig. 32). The equipment is rudimentary, and the stability of the tunnels is assured by simple wooden planks on the pit walls. Nevertheless, illegal primary gold mining is one of the main responsible of the degradation of Amazon ecosystems.

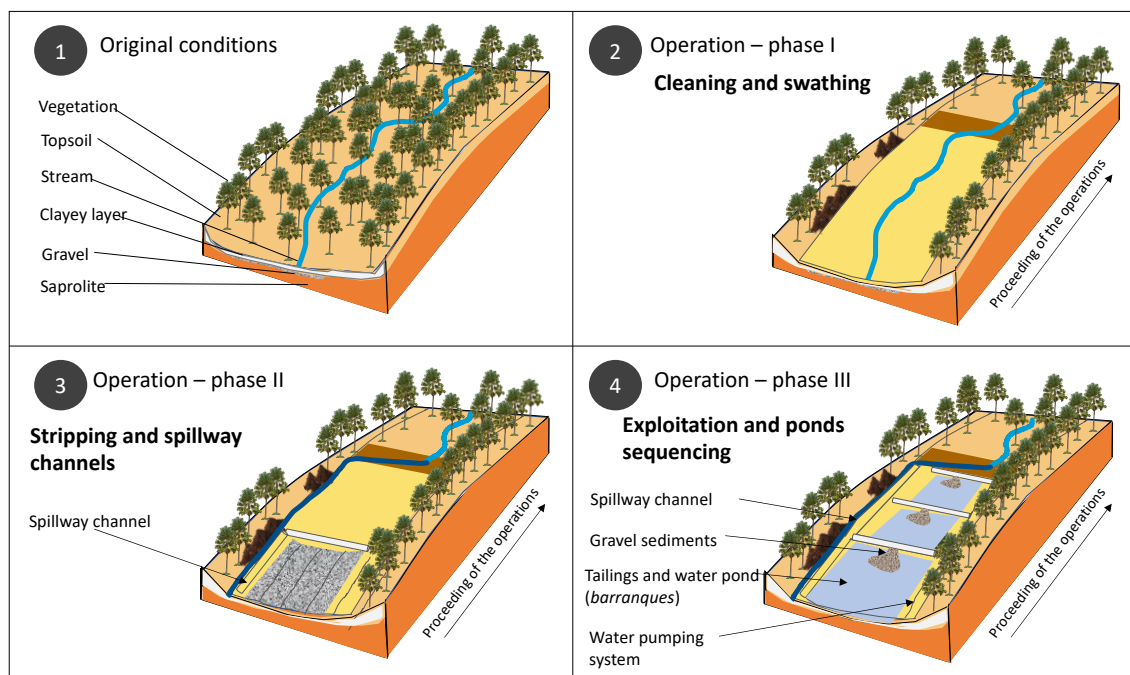


Figure 26 Simplified flowsheet of secondary-gold mining (original edition after Oder, 2011)



Figure 27 Legal secondary gold mine site in FG (photo supplied by ONF - Alexandre David)



Figure 28 Settling-table for the first trapping of gold particles and the filtering of materials by grain-size. Location: western French Guiana



Figure 29 Illegal secondary gold mine site in FG. As it is shown, the exploitation is much more irregular compared to legal mine sites (photo supplied by ONF - Alexandre David)



Figure 30 Primary gold mining site in FG (photo supplied by ONF - Alexandre David)



Figure 31 Tunnel entrance for illegal primary gold mining in FG (Bourbon, 2015)

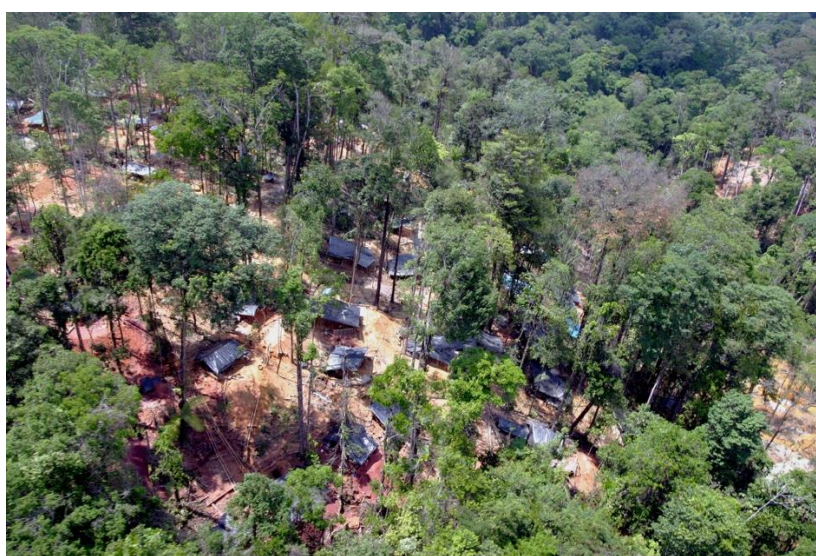


Figure 32 Illegal primary gold mine sites in FG. As it is shown, it is very difficult to acknowledge the notion of "mine site" when it comes to illegal mining. The site is a widely spread sequence of mining pits ((photo supplied by ONF - Alexandre David)

3.4. Gold recovery methods

In FG, gold is recovered mainly through three techniques: gravimetric methods, cyanidation, and gold-mercury (Au-Hg) amalgamation (UNEP, 2012) (Table 7). Legal mining of primary and secondary deposits uses gravimetric methods: gold particles are mechanically separated from the matrix first, during the exploitation phase, to reduce the grain-size of recoverable ore, then, during the recovery phase, to concentrate the gold particles. Moderately sophisticated equipment (e.g. concentrators, laboratory sluice-box) are used in addition to traditional panning (Aertgeerts *et al.*, 2018) (Fig. 33). When the wastes are badly managed, stream water turbidity is the main risk. The main risks associated with gravimetry concern mainly the increase of total suspended solids (TSS) in water streams, leading to silting. This occurs especially when water and tailings management at mine site is not properly performed.

Table 7 Simple and synthetic comparison of the three main gold recovery methods in FG

Processing method	Gravimetry	Cyanidation	Mercury amalgamation
Recovery rate (%)	20-40	~95	> 95
Costs	\$	\$\$\$	\$
Required skills	Medium skills	Very high skills	Medium skills
Biodegradability in the environment	-	Yes	No
Main risks	Silting and sedimentation Land degradation Erosion Hg remobilization	Explosions Chemical spills Transport accidents Health-related risks Ecosystem degradation	Methylation Hg emissions and pollutions Health-related risks Contamination of the food chain

The use of cyanide-based methods for gold recovery in FG is discussed in several reports (Moisan and Blanchard, 2012; GeoPlus Environnement, 2017; Menard, 2018; Urien, 2018). Nevertheless, they address cyanidation only at larger industrial and semi-industrial scales. Cyanidation is not used in FG at the moment, but one semi-industrial operator developed a plant and the infrastructures to perform it (Thomassin *et al.*, 2017). The utilization of cyanidation allows high recovery rates (> 90%) and it implies specific risks that involve mainly cyanide transport (INERIS, 2018) and storage before gold recovery (e.g. explosions) or after processing (e.g. dam failures). In this case, failures might generate catastrophic consequences (WISE Uranium) and the dispersion of free cyanide ions would add severe eco-toxicological impacts (Donato *et al.*, 2017).

The cyanidation process involves six main steps and it is furtherly detailed by GeoPlus Environnement, (2014); GeoPlus Environnement, (2015):

- i) The preparation of the cyanide slurry adding sodium cyanide, solid lime and water to the excavated crushed materials and the tailings;
- ii) The slurry is conveyed to a circuit where it passes through a series of leach tanks. Gold is adsorbed to an activated carbon from tank to tank and then washed of the slurry;
- iii) The elution phase during which carbon is eluted to obtain a gold-enriched solution, then transferred for electrolysis. Resulting gold-enriched fluids are dried and mixed with specific substances for gold refining and ingot production.
- iv) Activated carbon cleaning from inorganic pollutant;
- v) The regeneration of activated carbon from organic matter contamination (e.g. grease, lubrication oils);
- vi) Cyanide destruction at the exit of the last tank in the leaching circuit through a complex process. The detoxified residues are then thickened into a centrifuge to decrease their residual water content.

Since gold recovery rate by gravimetry is low and that cyanidation is not often technically and financially accessible, illegal miners use mercury (Hg) – and legal miners as well before Hg was banned by French Government in 2006. It allows a recovery up to 90% in some cases (Hinton *et al.*, 2003). Gold particles are concentrated and amalgamated with Hg in a simple napkin to obtain a soft nugget. Since Hg melting point is lower than gold's, the amalgam is roasted using a retort or a simple spoon. Hg-related risks in FG are well discussed (Grimaldi *et al.*, 2015) and they are at the origin of specific concerns about the health conditions of miners and local communities. Besides soils and water, air is the most impacted media from Hg-based techniques: 20% of Hg are lost during amalgamation while 70% evaporate during the roasting phase (Moullet, 2006). With an annual production of 10 tons of gold, approximately 13 tons of Hg are also supposed to be released into streams in FG (WWF, 2018). Contaminated hotspots have been localized in areas far from mining sites (Marchand *et al.*, 2006) and the impacts on biodiversity are well documented (Fréry *et al.*, 2001; Godard *et al.*, 2006; Sebastiano *et al.*, 2016; Gentès *et al.*, 2019). The most important risks occur when Hg is transformed in methylmercury (MeHg) (Guedron *et al.*, 2011a). Illegal or ancient legal gold mines are suitable locations for the formation of MeHg and its seasonal transfer across the watershed (Guedron *et al.*, 2011b). MeHg contamination might affect the food chain and lead to severe endocrine disorders on local populations (Fréry *et al.*, 2001) and on the environment. Human exposure to MeHg depends also on the receptors and their socio-cultural habits (Grandjean *et al.*, 1999; Boudan *et al.*, 2004; INVS, 2007; ARS, 2013).



Figure 33 One of the several machines used for gold recovery of secondary gold mines by gravimetry. Location: eastern French Guiana

4. Gold mining in the Mana RB

According to the new GIS-based platform CAMINO (<https://camino.beta.gouv.fr>), an on-line mining registry developed by the French Government, in June 2020 approximately 110 permits and authorizations are active in FG, excluding all the expired permits and authorizations and 18 “historical concessions”. Almost 20% of these 100 mining permits and authorizations concern the municipality of Mana alone which is the most important cluster of permits along with Roura municipality. Furthermore, if the permits and authorizations valid within the municipalities intersecting Mana RB are counted (e.g. Saul, Saint-Laurent-du-Maroni municipalities), this basin is one of the most important clusters of legal active mining permits and authorizations. These activities involve prospecting (Fig.34a) and exploitation (Fig.34b), including few historical concessions supposed to expire at the end of 2018. At the moment, most of the permits concern secondary gold mines while only one permit is related to a primary gold mine (Fig. 35). The remaining permits concern prospecting authorizations and permits and 9 historical concessions (Fig. 35). Finally, exchanges with local authorities pointed out the existence of approximately 2 000 illegal gold miners in Mana municipality. Indeed, besides to these legal mining activities, illegal gold mining is significant within Mana RB, as shown by the deforested areas in 2015 provided by WWF (Fig.34c). However, it is difficult to have a detailed estimation of the current number and surfaces of illegal activities, since spatial data are acquired through remote-sensing and, thus, leaving a considerable uncertainty concerning the actual land-use.

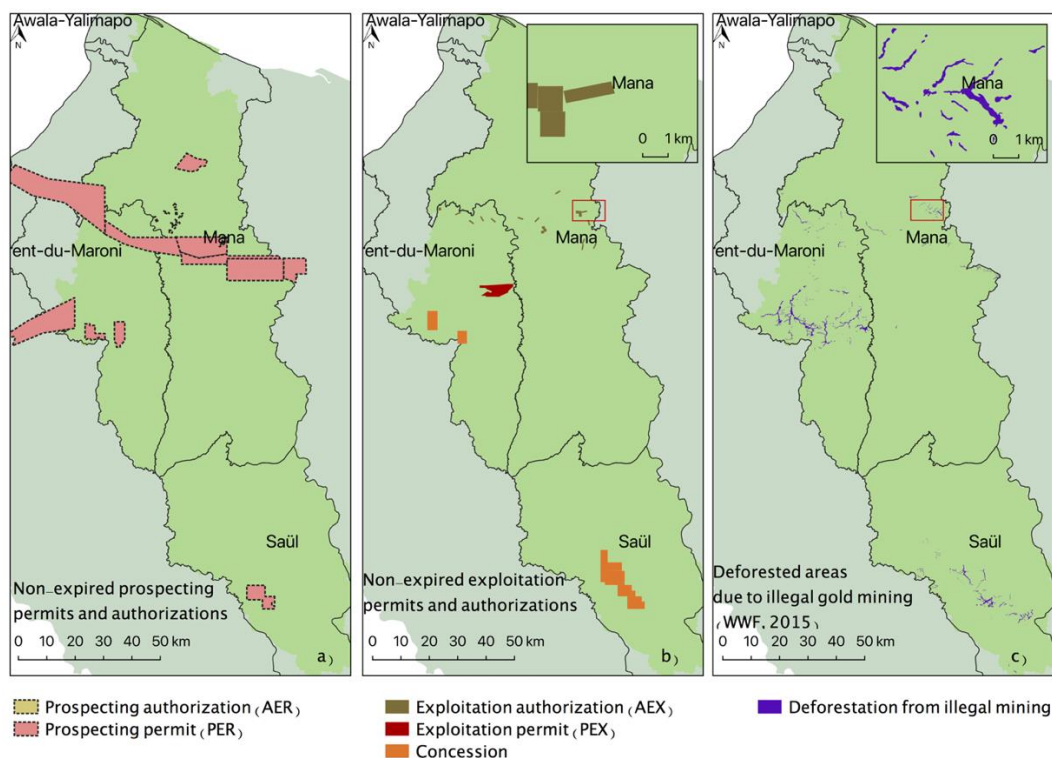


Figure 34 Map of legal mining activities within Mana RB according to the on-line mining registry consulted in June, the 15th 2020. Fig.34a and Fig.34b shows respectively current active permits and authorizations for prospecting and exploitation. Fig.34c shows the estimated deforested areas by illegal gold mining

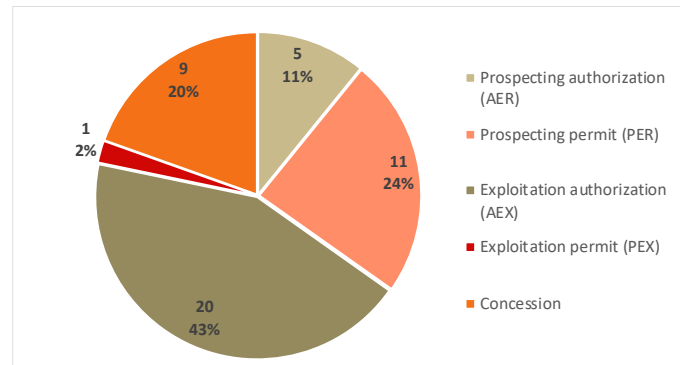


Figure 35 Distribution of legal mining permits and authorizations located within Mana RB (processed from Camino, 2020)

5. Classification of gold mines and development of standardized project-types

Mining risks vary considerably depending on the intrinsic features of the mine and the techniques used for exploration, ore exploitation and processing, as well as for remediation. Nevertheless, the great heterogeneity of, sometimes coexisting, mining projects is often difficult to be acknowledged during risk assessment, particularly for gold, which is exploited both by artisanal miners, medium and large companies.

Therefore, the definition of the gold mining activity in FG is achieved through the development of an operational classification of gold mines types for risk assessment purposes. The utilization of standard project types with standardized features is vital to develop and compare different TMS for decision-making support and perform risk-assessment on gold mining sector rather than a standalone gold mine.

The following sections present the reasons behind the development of a classification of gold mines types and highlight the present gaps and needs. The methodology used for such classification will be presented and each gold mine type defined for FG is detailed.

5.1. The need of a project-type classification for risk assessment purposes

As mentioned, risk assessment of mining projects at the territory scale implies both the holistic understanding of the territory where multiple different mines coexist and the need to foresight potential future scenarios that might come in support of decision-making. Therefore, the development of standardized gold mine types is a significant tool which would allow to consider mining projects types like “boxes” with common or different fixed parameters.

This need is more significant in FG, where gold mining takes multiple variable forms and where, at the moment, there is a lack of precise information concerning this variability. Apart from some technical reports and grey literature, no structured and systematic description of gold mines, their functioning and the induced risks, is available in scientific literature. If we

move to the existing classifications outside FG, to our knowledge no structured definition and classification of gold mines is available at the moment. Gold mine types are often defined individually, on a project-basis – and not categorized – and their detailed specificities neglected. If artisanal and small-scale gold mining are abundantly discussed (Hilson, 2002b; Seccatore *et al.*, 2014) often without the explicit distinction between legal and illegal mines (Table 8), the definition of such activities varies from country to country (e.g. Brazil, Ethiopia, Ghana, Mexico, Suriname) (Hilson, 2002b). According to Ghanaian law, for example, small-scale gold mining is “performed by *any* method not involving substantial expenditure by an individual or group of persons not exceeding *nine* in number or by a cooperative society made up of *ten or more* persons” (Graham Sustainability Institute, 2015). However, the legal or illegal artisanal and small-scale sector is defined on a country-basis and its unanimous definition represents quite a challenge nowadays (MCSA, 2019).

Illegal gold mining is widely discussed, especially for their socio-environmental consequences and their governance impasses. However, no explicit distinction between primary and secondary gold illegal mining is usually made (Table 8), although the type of deposit implies considerably different methods. Illegal gold mining is mostly described as a social phenomenon rather than a proper industrial sector composed of individually recognizable projects, where mining is performed outside any existing regulatory framework and without formal trained skills (Bansah *et al.*, 2018; Zvarivadza, 2018b). Such activities rely mostly on the global market variations of gold price, the abundant and mobile workforce, a free circulation of products for gold recovery and finally the laundering networks which bind the informal and formal sectors of gold production (Heemskerk, 2010).

On the opposite, gold large-scale mining activities are usually considered as any project involving large-capital multinationals and corporations. Finally, medium-scale mining is rarely discussed (Ribeiro-Duthie and Castilhos, 2016). Such “semi-industrial” activities are specific to some territories, such FG, where small and medium enterprises target primary deposits in order to evolve towards more industrial operations.

The existing reports usually oppose large-scale to artisanal and small-scale mining, and/or legal to illegal mining (MCSA, 2019) (Table 8). However, they do not represent structured classifications that cover other types of projects, especially in the gold mining sector, where they are highly variable in size, forms and techniques. Moreover, distinctions between the project-types are based on few factors, such as the annual gold production, degree of mechanization, size of the company, etc. The only exhaustive classification found in the literature is proposed by a report of the Brazilian Geological Survey, which includes artisanal, small, medium and large-scale gold mines (Ribeiro-Duthie and Castilhos, 2016). However, such categories are not structured specifically for risk assessment purposes and gold productivity is used as the only distinguishing criterion (Table 8) between the project-types. This criterion stands only for a project-centered – rather than sector-centered – approach. Indeed, the gold production of one large mine can’t be compared to the production of one artisanal mine. On

the contrary, the gold production of the large-scale mining sector could be compared to the production of the entire artisanal sector.

Risk assessment at the territory level and the development of TMS must involve a first step of structured classification that accounts for the range of various coexisting gold mines. This proposed classification aims to fulfill the gaps of the described existing classifications of mining projects.

Table 8 Examples of existing definitions of gold mines in literature

Used Name	Definition	Reference
ASM	Individuals, groups, families or cooperatives mining with minimal or no mechanization, often in the informal (illegal) sector of the market	Hentschel <i>et al.</i> , 2002
ASM	Any single mining operation having an annual production of unprocessed materials of 50,000 metric tons or less at the entrance of the mine	UN, 1972
SSM	Any operation producing between 10,00 t/a and 100,000 t/a of ore	Vale, 2000
	Mining operations both labour intensive and low-tech	Barry, 1997
ASM	Activities involving the exploitation of marginal ore deposits unprofitable to mine on a large-scale., using rudimentary tools (e.g. picks, shovels, wheelbarrows, panning dishes)	Zvarivadza, 2018
Small-scale mining	Any operation with intense labor activity located in remote and isolated sites using rudimentary techniques and low technological knowledge, low degree of mechanization, and low levels of environmental, health and safety awareness	Hilson, 2002b
	Micro-miners who pan the riverbanks to produce 0,1 to 0,5 g of Au per day	Veiga, 2013
ASM	ASM is a subset of SSM (mining activity producing less than 100,000 t/d ROM* for profit) where operation does not follow the conventional ecological and engineering principles of mining and uses rudimentary or basic simple techniques	Seccatore <i>et al.</i> , 2014
SSGM	Mining projects with rudimentary methods and limited mine planning, by a workforce that is not formally trained in mining engineering or geology and operates entirely or partly in the informal economy	UNDP, 2011
ASM	Mining operations with a production <100 000 oz/year	Ribeiro-Duthie and Castilhos, 2016
ASGM	Legal or illegal gold extractions conducted by individuals or groups with limited capital investment, manual labor, simple and basic machinery	Graham Sustainability Institute, 2015
MSM	Projects which may assure long or short-term operations. They might also associate with other MSM or be merged to or acquired by other major corporation groups. They produce >100 000 < 1 000 000 oz/year	Ribeiro-Duthie and Castilhos, 2016
LSM	Projects usually involving a company “with many employees which exploits the deposit until the ore is completely excavated”	Kricher, (1997)
LSM	Mining operations performed by multinationals companies well-known in the market and generally on the long term. They usually report corporate social responsibility goals and certifications. LSM operations require trainings, investments and expertise in environmental management. Their production is >1 000 000 oz/year	Ribeiro-Duthie and Castilhos, (2016)
LSM	Projects that can influence the development trajectory of nations, alter the social fabric of local communities and disrupt the environment on which livelihoods depend	Kemp <i>et al.</i> , (2016)
LSM	Complex and highly demanding endeavors carried by multinationals which require large investments, systematic management structures, in-depth geological and economic analyses	Vergara, (2009)

*Ton per day in the Run-of-Mine production

5.2. Methodology used to classify gold mines types in FG

As shown in Fig. 36, the methodology used for the current classification of gold mine types in FG followed different steps:

- i) In a first step, the foreground data concerning the technical and operational parameters of the existing and potential gold mines were collected based on a thorough bibliographic review (scientific literature, technical reports), on free interviews of local experts between December 2017 and November 2018 and on mine field visits. Further data have been gathered through the participation to the public debate on the *Montagne d'Or* project (CNDP, 2018) and the information found in several technical reports regarding industrial projects within the Guiana Shield (Allain *et al.*, 2008; Theveniaut *et al.*, 2011; SRK, 2016; SRK, 2017).
- ii) Gold mines in FG were classified based on different criteria (e.g. geological, juridical, operational). For each typology, standard flowsheets of the mines have been developed to show the mine functioning. These conceptual models are based on the following questions: what is the function of a gold mine? What are the objectives and performances which lead to the achievement of this function? What are the components of a mining project that support such objectives?. The conceptual models and their detailed features have been discussed with local experts for validation.
- iii) For each project type, a series of standard qualitative and quantitative features (e.g. number of workers, tailings dam's height, pit depth, etc.) have been specified based on mine site visits, interviews and FG-related literature (Table 9).
- iv) In a fourth final step, both positive and negative potential consequences of each project type were identified based on the same data sources presented above. The results of this last step are presented in Chapter 6.

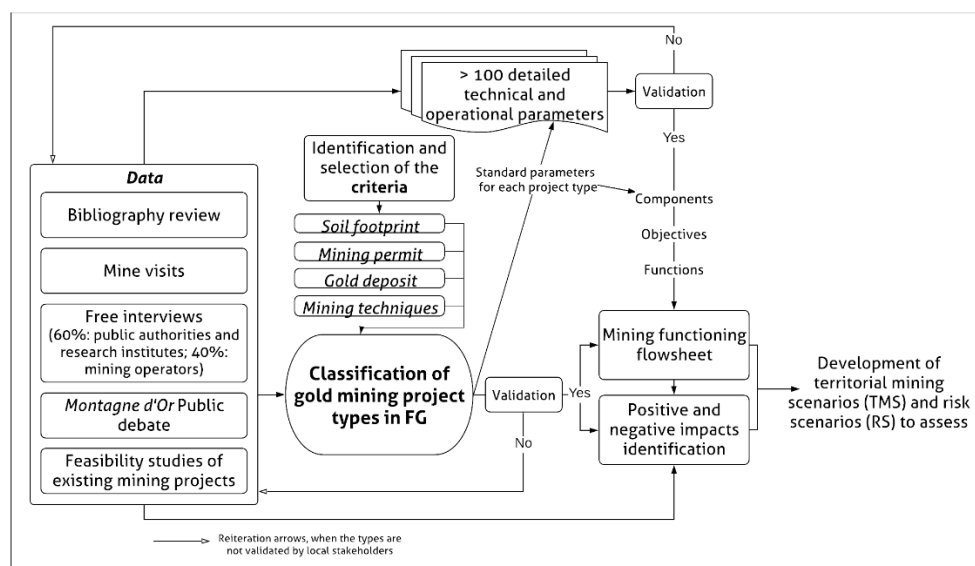


Figure 36 Conceptual flowsheet of the methodology used for the classification of gold mine types in FG and their correspondent impacts

5.3. Result of the classification: types of gold mines in FG

As it is shown in Fig. 37, four main gold mine types (i-ASM, ASM, MSM, LSM) have been distinguished according to 5 selected criteria intrinsic to the mining projects themselves (legal status, type of gold deposit, etc.). The five main criteria are chosen based on the fact that they can be generalized to the current gold mines in FG and on the technical and operational features they integrate (e.g. juridical, technical, environmental). For instance, the type of geological deposit is a useful common denominator which allows to categorize current gold mining activities in FG. It would not be the case if currently, gold mining was performed only on secondary gold deposits and a potential future primary gold exploitation was not considered at all by public authorities. On the contrary, project localization can't be a common criterion for the classification since it obviously changes on a project-basis. Therefore, the five criteria chosen are the following and they have different natures:

- i) Geological: the type of geological deposit predominantly exploited;
- ii) Legal: the possession or not of a mining permit or authorization;
- iii) Operational: the techniques used for ore exploitation;
- iv) Operational: the gold recovery methods;
- v) Geographical: the surface occupied by the mine site.

Illegal artisanal and small-scale gold mining (i-ASM) in FG can involve underground or surface (placer) mining respectively for the exploitation of primary (subtype i-ASMp) or secondary (subtype i-ASMs) gold deposits. The main feature of i-ASM is the utilization of Hg-gold amalgam for gold recovery.

Legal mining is divided in three main categories: ASM, MSM and LSM. Legal artisanal and small-scale mining (ASM) involve placer mining activities with gravity-based recovery methods. Medium-scale mining (MSM) and large-scale mining (LSM) involve the predominant exploitation of primary deposits, but secondary gold is exploited as well depending on the morphology of the deposits within the site of the mining permit (Fig. 37). MSM is divided in two subtypes, depending if the project involves gravimetric (MSMg) or cyanide-based (MSMc) methods for gold recovery. Thus, the main distinction here between MSMg and LSM is in terms of surface footprint (Fig. 37) and, therefore, in workforce, infrastructures and mining engines needed.

The specific features of each type of gold mines in FG is presented in Table 9. These specificities are furtherly detailed in Appendix 7; they concern the representative characteristics for each gold mine type. All the detailed features can be grouped into:

- The targeted geological deposit and its features;
- Regulatory and socio-environmental constraints;
- Company information;

- Mine related infrastructures, related to: excavation and exploitation, mineral processing, waste-rocks and tailings management, waste and process-water management, embankment structures, additional infrastructures;
- Total mine production;
- Direct and indirect employment;
- Capital expenditures (CAPEX);
- Operational expenditures (OPEX);
- Taxation and royalties.

Despite a considerable effort, the unavailability of data still left some gaps to be filled in the future. However, the presented characteristics confirm that the horizontal variability between each typology (“*inter-class*” variability) is higher than the vertical variability between the characteristics of each project type (“*intra-class*” variability). Thus, these criteria suffice to clearly distinguish the types of gold mines in FG and validate the proposed clear-cut classification. The presented data represent the inputs of the mining systems that will be used to develop the different TMS and assess the corresponding global risk.

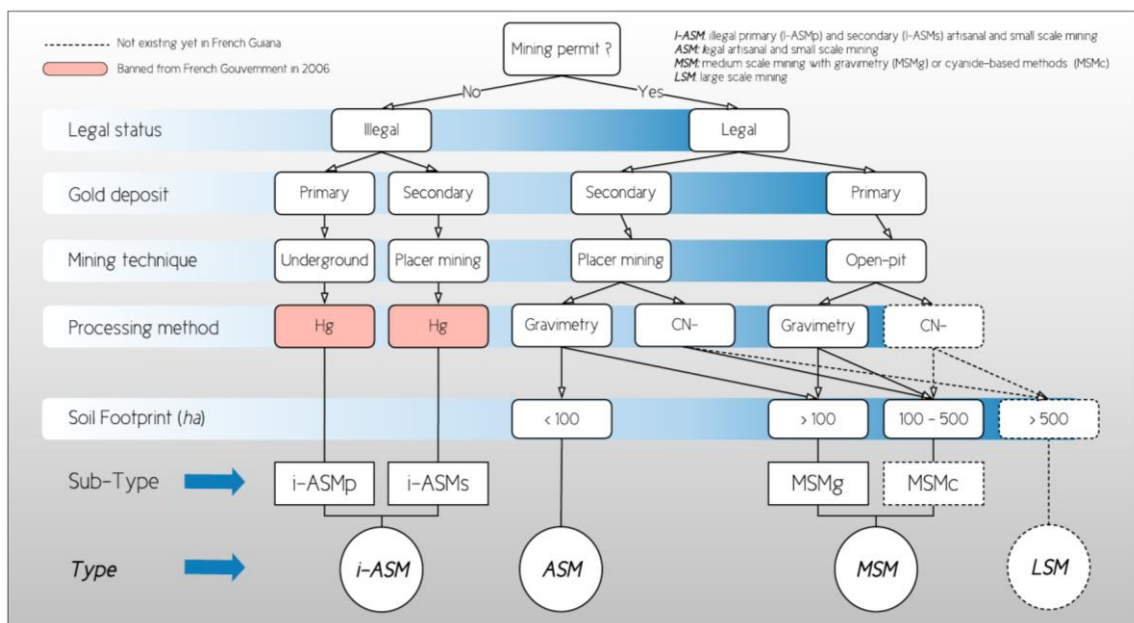


Figure 37 Conceptual tree showing the main criteria used for the classification of the main gold mine types in FG

Table 9 Synthesis of the main specificities of each legal gold mine type in French Guiana. In grey, the classification criteria. The complete table is available in the Appendix 7

Main characteristics of each mine-type	ASM	MSM		LSM
		MSMg	MSMc	
Predominantly exploited gold deposit ¹	Secondary (type 4-5)	Primary (type 2-3)		Primary (type 1-2-3)
Mining permit or authorization	yes	yes		yes
Soil footprint of the mine site (ha)	<100	>100		> 500
Main exploitation technique	Placer mining ponds (barranques)	Pit		Pit
Gold recovery methods	Gravimetry	Gravimetry	CN-	CN- (+ gravimetry)
Total OPEX (k€)	> 100	> 1,000	> 3,000	> 1,000,000
Average revenues per year (k€/yr)	< 1,000	> 1,000	> 1,000	> 200,000
Maximal produced gold per year (kg/yr)	< 150	150 - 300	> 400	> 5,000
Number of direct employees	10-15	>50	50 - 350	> 350
Gold resources (t)	< 10	10	10	> 50
Extracted materials (waste-rock and ore) (kt/yr)	5 - 35	>150	>150	5,000 – 25,000
Exploitation pit/pond depth (m)	2 - 8	> 10 < 100	> 10 < 100	> 100
Processing plant type	Gravimetric	Gravimetric	Gravimetric + Cyanidation	Gravimetric + Cyanidation
Cyanidation plant surface (ha)	- ²	-	< 1	> 10
Processed materials by cyanidation (t/day)	-	-	100	> 5,000
Gold recovery rate (%)	20 - 30	20- 40	> 90	> 90
Decantation and storage system (wastewater and tailings)	Barranque (TSF and waterpond)	Gravitary TSF, water pond	Gravitary TSF, Cyanide TSF, Decantation ponds	Cyanide TSF
Total surface of gravitary tailings pond (ha)	0.5 - 2	10 - 20	> 20	n/a
Total capacity of gravitary TSF (m3)	< 500,000	250,000 – 600,000	250,000 – 600,000	-
Total surface of cyanide tailings storage facility (TSF) pond (ha)	-	-	5 - 15	> 150
Cyanide tailings per year (m3/yr)	-	-	> 60,000	> 10,000,000
Total capacity of cyanide TSF (m3)	-	-	250,000 – 600,000	> 150,000,000
Maximal height of TSF dam (m)	2 - 3	15 - 20	15 - 20	> 50
TSF dam elevation method	-	Upstream	Upstream	Downstream
Life-camp surface (ha)	< 1	~ 1	> 2	> 10
Equipment (e.g. hydraulic monitors, bulldozer)	< 10	10 - 50	> 50	> 100
Total electrical power	~ 40 KVA	> 250 KVA	1178.4 (kW)	~ 20,000 (kW)
Fuel stockage capacity (l)	5,000 – 10,000	15,000 – 30,000	15,000 – 30,000	> 100,000

1. Refer to section 3.2 for the detailed definition of gold deposit types

2. The empty cases ("-") concerns the features "not applicable" to the corresponding project-type

5.3.1. Legal gold mine types: ASM, MSM and LSM

The classification of the defined gold mine types is illustrated through the development of functioning flowsheets which give a conceptual representation of the different functioning of each mine type and to be furtherly developed and detailed to be used as quantifiable model (for example, to perform LCA). In our study, the presented flowsheets have only the purpose to give a conceptual overview of the functioning of legal gold mines in FG, from the secondary

gold mining techniques in ASM (Fig. 38) to the exploitation of primary gold deposits with MSM (Fig. 39) and LSM (Fig. 40). The components of a mine are here grouped into three different categories whether they are related to:

- ore excavation, exploitation and related waste management infrastructures (e.g. mining pit, waste rock dump);
- mineral processing and related waste management infrastructures (e.g. processing plant, settling ponds);
- mine basic infrastructures (e.g. life camp, electric equipment).

Fig. 39 and Fig. 40 are specifically related respectively to MSMg and MSMc. For LSM-types, the same flowsheet of a MSMc can be suggested, but with different parameters values, as described in Table 9 (e.g. height of the TSF, pit capacity, number of workers).

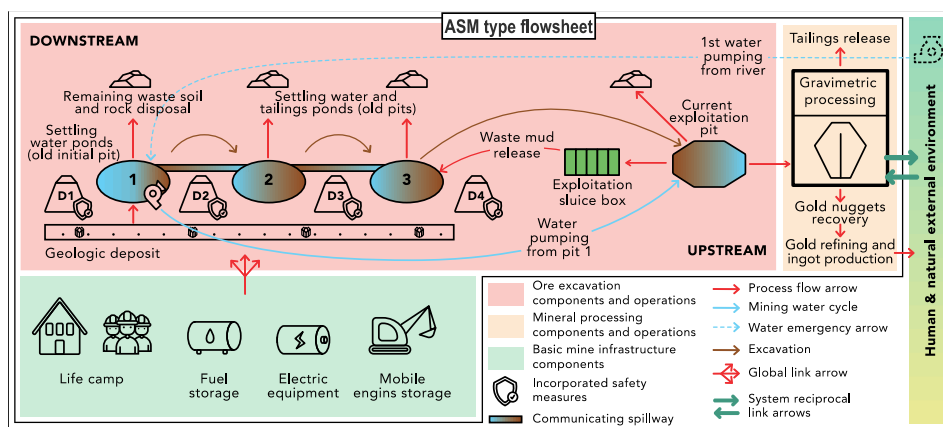


Figure 38 Conceptual flowsheet of ASM project-types in FG. The conceptual model includes different steps during the operational mining phase. Edited and designed by © Charlotte Travaillé.

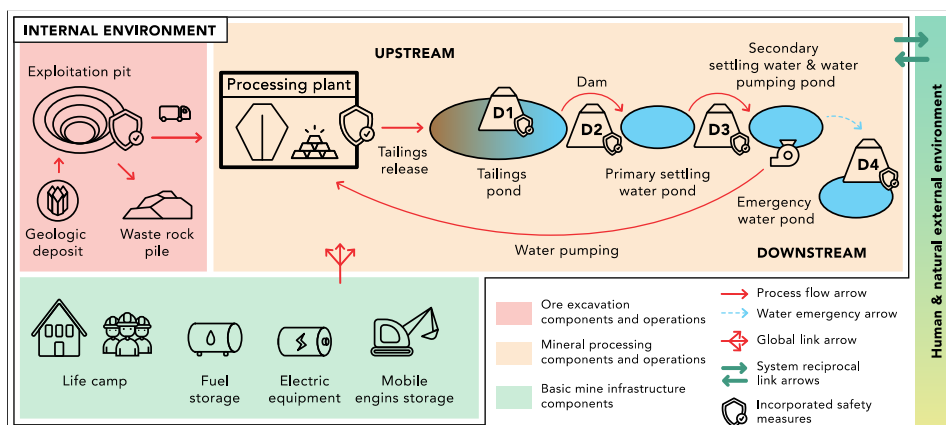


Figure 39 Conceptual flowsheet of MSMg project-types in FG. The conceptual model includes different steps during the operational mining phase. Edited and designed by © Charlotte Travaillé.

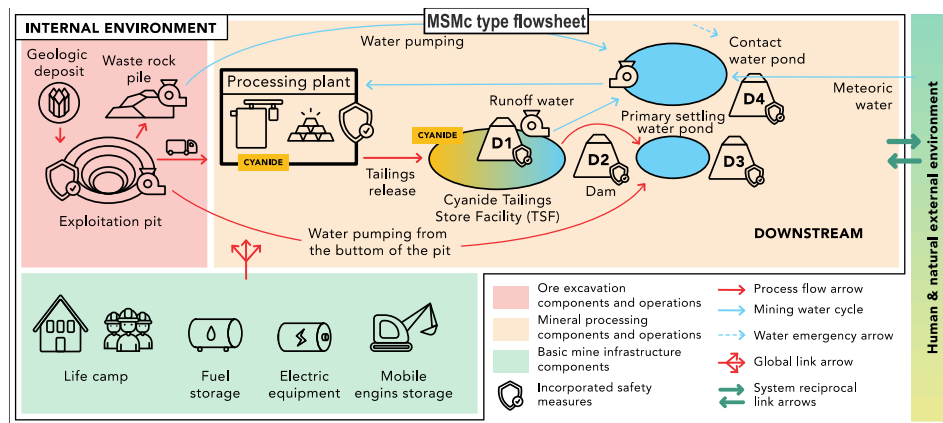


Figure 40 Conceptual flowsheet of MSMc project-types in FG. The conceptual model includes different steps during the operational mining phase. Besides the utilization of cyanidation, the functioning differs from the MSMg presented in Fig.39. Edited and designed by © Charlotte Travaillé.

5.3.2. A special mention for i-ASM and the complexity of a project-centered analysis

If the present study does not focus specifically on the assessment of illegal gold mines in FG, a special mention should be given to i-ASM types since the availability of data presented for legal gold mines (Table 9) is significantly different for illegal activities. Seccatore *et al.*, (2014), try to estimate worldwide gold production of i-ASM, reporting some information from literature concerning the technical and operational parameters of i-ASM (Table 10). As mentioned, illegal gold mining should be considered as a social phenomenon – rather than a proper mining project – which is peculiar to gold and other few commodities (Hentschel *et al.*, 2002). The main characteristics of both i-ASMp and i-ASMs in FG are related to:

- The non-respect of legal constraints. i-ASM project types lack of standards with important consequences for the safety, health and security of i-ASM miners and local communities and the environment (Hentschel *et al.*, 2003; Smith *et al.*, 2016).
- The highly variable number of miners on site. The French National Forestry Service (ONF) discovered a primary i-ASM life-camp with approximatively 1800 inhabitants. Personnel can be low or medium-skilled (Bansah *et al.*, 2018; Zvarivadza, 2018), lacking specific trainings (Ledwaba and Mutemeri, 2017).
- A wide variety of mining methods ranging from simple extraction methods (e.g. digging and panning) to chemical treatments (recovery through gold-Hg amalgam) (Pokorny *et al.*, 2019). Since most of the gold is not recovered through gravimetry, mercury (Hg) – banned by French Government since 2006 – allows a recovery rate up to 90% (Hinton *et al.*, 2003). Gold flakes are concentrated thanks to gold density and then amalgamated with Hg in a simple napkin to obtain a soft nugget. Since Hg melting point is lower than gold's (Brooks *et al.*, 2011), the amalgam is then roasted using a retort or a simple spoon. The typical value in the amalgamation process varies from 1 to 5 g of Hg per gram of gold (Kahhat *et al.*, 2019). Recent gold tailings of ancient legal and illegal mine sites can be re-processed as well.

- I-ASM communities are supported by an important supply chain for Hg and fuel, electrical generators, steel rods (IEDOM, 2016; WWF, 2018).
- A wide variety of means of transport and access to the mine site. These may involve quads, off-road vehicles and canoes, allowing illegal miners to easily move across different areas of the forest through the hydrographic network (WWF, 2018).

Table 10 Summary of production and investment features that could define i-ASM (Seccatore *et al.*, 2014)

Source	ROM ^a (t/y)	Daily ROM (t/d)	CAPEX (\$)	Revenues (\$/y)	Human resources
ONU	< 50 x 10 ³	< 200	< 1 x 10 ⁶	< 1.5 x 10 ⁶	40
DNPM (Brazil)	10 x 10 ³ < ROM < 100 x 10 ³	-	-	-	-
Ley de Minería (Ecuador)		< 300 (metallic ore) < 800 (nonmetallic ore)			

^a Run-of-Mine means the raw unprocessed or uncrushed material in its natural state obtained after blasting or digging, from the mineralised zone of a lease area.

The difficulty in defining these kinds of projects relies on the fact that they are extremely heterogeneous, and that data are usually not available. Annual production rates highly differ from country to country (Seccatore *et al.*, 2014) and from site to site. The notion it-self of “site” is complex to apply to the illegal sector since it is often impossible to determine where one ends and the next one starts. Moreover, there is a critical permeability between legal projects and i-ASM in FG which might question the proposed classification and, generally speaking, local strategies for mining governance in FG. Since it is a social phenomenon, i-ASM heterogeneity relies on technical, operational and socio-environmental parameters. It may be more appropriate addressed them as “I-ASM communities” (Van Bockstael, 2019) which represent a particular challenge for the regional development of gold mining territories of the African continent, Central and South America.

For the mentioned reasons, it has not been possible to detail the specific features of i-ASM on a project-basis as for the legal mining sector in Table 9. The only acknowledgment on this issue is based on the assessed spatial data through satellite imagery and remote-sensing provided by WWF in 2015 which report a total of 1783 “sites”. According to these data, more than 98% of such “sites” perform secondary gold mining while the rest (27 sites) concern i-ASMp. In 2008, 3396 gold sites have been reported, and more than 75% represented illegal workings for which minimal information is gathered, generally limited to their location (Cassard *et al.*, 2008).

Table 11 shows some specificities concerning the existing and current illegal gold mining sector in FG, without any distinction on a project basis. Indeed, as mentioned, the notion of mining *site* is questionable in the illegal sector, and thus, it is not possible to have the same level of specificities such as for legal mining projects (Table 9). The right column presents some assumptions on a project-basis analysis for the illegal sector based on the ratio between the

real values estimated and presented by existing bibliographic and cartographic sources and number of reported sites in 2015 by WWF. Spatialized data are provided by WWF, estimated through remote-sensing processing (Fig.34c). The number of “sites” and the surfaces estimated have been used to estimate “standardized” per-project features for the illegal sector (Table 11, right column). However, unfortunately no distinction between primary and secondary gold illegal mining projects can be quantitatively expressed at this stage.

Table 11 Estimated current features for the entire illegal gold mining sector.

Illegal gold mining sector (i-ASM) (i-ASMp + i-ASMs)	Total	Source	Illegal gold mine (no distinction between i- ASMp and i-ASMs)
Soil footprint (ha per year)	1,000 – 2,000	Rahm, 2017	20.0
Maximal produced gold per yera (kg/year)	~ 9,071	WWF, 2018	6.6
Number of employees (direct and indirect)	~10,000		10.0
Hg consumption for the recovery of 1 g of gold (g/g of gold)	1-5	Kahhat <i>et al.</i> , 2019	1-5
Water consumption (l/g of gold)	n/a		n/a
Total capacity of the water pond (m3)	n/a		n/a
Maximal height of dams	n/a		n/a
Total number of illegal gold mining sites estimated in 2015	1,379	WWF, 2015	n/a

6. Data used in this study for each gold mine-type

The brief fragment of the available data shown in Table 9 and 11 presents a wide range of values for each project-type. In the current study, the main specific project criteria and parameters that will be used are chosen among these ranges of values and shown in the Table 12. We present them here in a synthesized table in order to facilitate the understanding of the following chapters. These data are for the assessment of both the RSa (Chapter 7) and RSo (Chapter 8) scores. It is important to consider the potential uncertainty concerning data related to i-ASM since the notion of “mining site” is fuzzy, unlike in legal mining. This would imply the collection of further data related to the illegal gold mining sector in FG.

Table 12 Selected values for the parameters used in the current study based on Table 9 and 11 per project type

Project types	i-ASM		ASM	MSMg	MSMc	LSM
Base Parameter	(i-ASMp + i-ASMs)					
Annual gold production (kg/year)	6.6 ^a	6.6 ^a	150	300	800	5000
Direct jobs	10 ^b	10 ^b	15	75	200	500
Soil footprint (ha)	20 ^c	20 ^c	100	300	300	550
TSF height (m)	n/a	4	4 ^d	15	20	54
TSF storage capacity (Mm ³)	n/a	0.5	0.5 ^d	1.5	2	100
Total royalties (k€) ^e	-	-	125,611	251,223	669,928	4,187,050

^a Approximate ratio between 10 tons of gold produced per year by a total of 10 000 reported illegal miners (WWF, 2018)

^b Approximate ratio between 10 000 reported illegal miners in total and the 1379 mining sites they are distributed (1 (WWF, 2015; WWF, 2018)

^c Approximate ratio between 1379 illegal “sites” reported and a total surface of 25386 ha consumed (WWF, 2015).

^d Value extrapolated from ASM and applied to i-ASMs.

^e Royalties are calculated based on the amount of annually produced gold per-project. They represent the sum of Municipal (137,9 €/kg Au), Departmental (27,5 €/kg Au) and Regional (672,01 €/kg Au) taxes (SRK, 2017).

Conclusion

This chapter presented gold mining from the worldwide scale to the specificities of the example chosen for this study, where gold is the main extracted metal. Despite gold deposits are still underexploited, gold mining plays a critical role in the historical and current socio-ecological dynamics of FG. In some cases, human settlements have been developed on ancient mining sites, shaping the territory as it is nowadays. Despite gold is a speculative commodity, the presentation of FG gold mining sector allowed to acknowledge:

- The coexistence in FG of multiple coexisting gold mines of different types and techniques, distributed on the whole territory;
- Public concerns related to the development of gold mining sector in FG, discussed by mining operators, public administration and civil society. The public debate in 2018 over the industrial gold mine *Montagne d'Or* highlighted the panel of views and the potential conflicts around gold mining activities. More recently, the potential development of another large-scale project called *Esperance* has been presented by two important mining companies. Land-planning strategies need to be discussed in order to address socio-economic and environmental issues related to mining on a wider scale.

Based on these observations, gold mining in FG confirms to be a pertinent case-study to test our approach. Gold deposits, mining techniques and legislation in FG have been presented in order to develop a multi-criteria classification of gold mine-types in FG. In the next chapter, these gold mine-types, whose features are detailed, will be combined to the territory system for the development of territorial mining scenarios (TMS). The TMS are assessed and compared in Part III of this thesis.

Chapter 5. Development of the Territorial Mining scenarios (TMS)

The previous chapters described the territory and the mining systems, showing the pertinence of our case-study and its features. The approach is applied at the river basin scale and a classification of gold mines in FG has been developed to standardized mine-types. In this chapter, the territory and mine systems – represented by the gold mine-types – are combined to develop territorial mining scenarios to support land-planning strategies at the territory level. Only for the demonstration of the approach in this thesis, the gold mine-types are located in fictional spots, instead of real existing mining projects.

1. Territorial objectives and Territorial Mining Scenarios (TMS)

Our study aims to foresight and compare potential future scenarios of mining development, based on risk assessment at a territorial level. The territorial mining scenarios (TMS) we will consider are defined to fulfill specific pre-defined objectives. For the current demonstrative application, three main objectives are selected at the scale of Mana river basin (Table 13). Each potential TMS may satisfy totally or partially one or more of these objectives. At this stage, the territorial objectives are arbitrary and have not been decided with local stakeholders. They concern:

- i. A total gold mining production approximately of 5,000 kg per year;
- ii. A total direct employment related to gold mining sector of 3,000 jobs;
- iii. A total surface consumed that should not exceed 2,000 ha.

Hereafter, it is assumed that each scenario meets only one of the mentioned objectives. As shown in Table 13, a set of 11 TMS is proposed:

- 5 TMS for the first objective (annual gold production at 5 000 kg Au/year), one of which relies only on illegal mining;
- 3 TMS for the second objective (3000 direct jobs);
- 3TMS for the third objective (soil footprint of 2000 ha).

Table 13 Development of TMS for each objective. On the right part of the table, the number and types of gold mine are specified in order to meet each considered objective (left columns, in green). The remaining two objectives not underlined in green represents the corresponding values calculated based on the number and types of projects of the considered TMS and the parameters presented in Table 9 and 11. For this demonstrative application, only the TMS related to the 1st objective are furtherly assessed.

	Territory objectives				Territorial Mining Scenario (TMS)						
	Annual gold production (kg/year)	Direct jobs	Soil footprint (ha)		Scenario Code	i-ASM _p	i-ASM _s	ASM	MSM _g	MSM _c	LSM
Objective 1	5,000	500	550	→	TMS-A						1
	5,000	1,250	1,875		TMS-B					6	
	5,000	500	3,333.3		TMS-C			33			
	5,000	800	3,500		TMS-D			20	4	1	
	5,000	-	-		TMS-illegal	758					
Objective 2 (example)	30,000	3,000	20,000		TMS-E			200			
	12,000	3,000	4,500		TMS-F					15	
	24,000	3,000	9,266.7		TMS-G			67		5	2
Objective 3 (example)	3,000.0	300	2,000		TMS-H			20			
	18,181.8	1,818.2	2,000		TMS-I						4
	4,166.7	2,000	2,000		TMS-L			10		3	

For each TMS, a specific number of gold mine-types are selected based on the characteristics presented and discussed in Tables 9 and 11. The TMS can be simple or complex, depending on whether they involve the combination of one or multiple mine-types.

In this study, the “Objective 1” of gold production of 5 000 kg Au/year can be met by one LSM (TMS-A), by 6 MSM_c (TMS-B), or by 33 ASM (TMS-C) but also a mixed scenario involving different types of gold mining project types, such as 20 ASM, 4MSM_g and 1 MSM_c (TMS-D). If we assume a scenario where legal gold mining is absent and i-ASM is the only gold producer, the same objective might be met by 758 i-ASM (TMS-illegal).

For each set of TMS, the considered objective is underlined in green (Table 13), while the other two columns represent the corresponding secondary values based on the number of project-types of the TMS. For instance, in TMS-C, the objective 1 is met by 33 ASM-type. In the same TMS, these 33 ASM projects could also provide 500 direct jobs for a total consumed surface of 3,333.3 ha. These values are calculated based on the number of project-types per TMS and the corresponding values chosen in Table 9 and 11.

Above the mentioned 3 territorial objectives, only the TMS related to the first objective (i.e. annual gold production of 5 000 kg per year) are assessed hereafter. This choice is arbitrary, but it is justified by the possibility to compare different scenarios based on the main business objective of a mining project, which is mining production. Therefore, among the 11 TMS, this study focuses on five TMS: TMS-A , TMS-B, TMS-C, TMS-D and TMS-illegal (Fig. 41). The proposed TMS will then be compared and ranked based on their level of risks, their coherence with all the defined objectives, and by considering different perspectives and expectations of the involved actors.

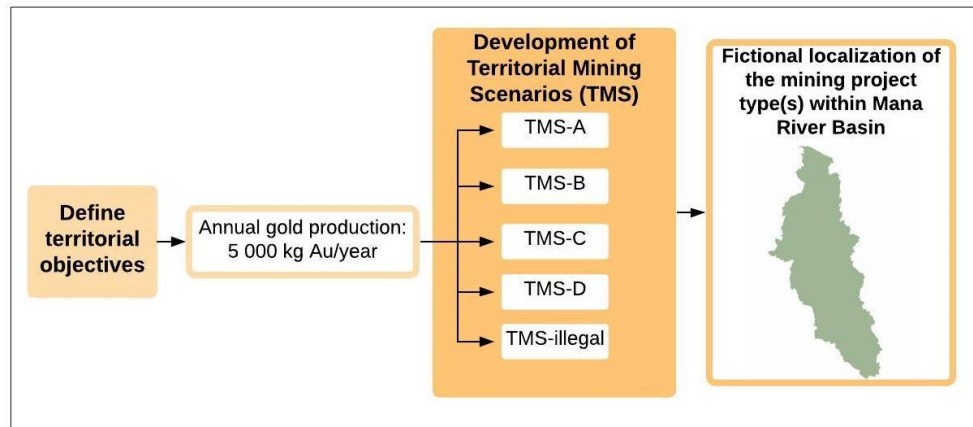


Figure 41 Selected objectives and related Territorial Mining Scenarios (TMS) for each objective. Once the TMS are developed and characterized, the corresponding number and types of gold mine are fictionally located within Mana river basin.

2. Fictional localization of the gold mining projects

For each TMS, the corresponding gold mines of each type, constituting a “mining system” will now be localized within the selected territory system (i.e. Mana river basin) (Fig.41).

The fictional localization is based on multiple criteria. If the existence of the geological deposit is the first criterion for project localization, other factors play an important role in mining siting. For instance, regulatory frameworks state where mining is or isn’t authorized. As mentioned, the Departmental Mining Plan (SDOM, *Schéma Départemental d’Orientation Minière*) divides the FG region in four zones where mining is fully or partially authorized or forbidden.

We use three simple criteria for the fictional siting of mines in each proposed TMS according to the geological, juridical and geotechnical suitability within the Mana river basin (Fig. 42). By definition, in the case of i-ASM, only the geological and geotechnical suitability are considered.

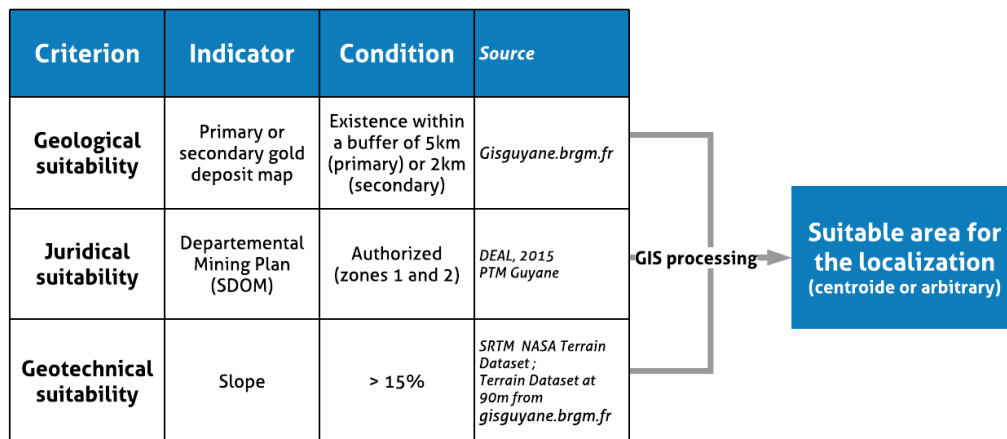


Figure 42 Methodology, criteria and indicators used for the identification of the suitable areas for the fictional localization of the mining project types in FG

The first criterion concerns the **geological suitability** of the area, indicated by the map of the primary and secondary gold deposits in FG. Since the dataset acquired from the GIS service of French National Geological Survey (BRGM) is point-shaped, two buffer zones (of variable radius) have been created on QGis respectively for primary and secondary gold deposits. Primary gold deposits will be used for i-ASMp, MSM and LSM while secondary gold deposits will be used for i-ASMs and ASM.

The second criterion is the **juridical suitability**. The SDOM zoning for mining activities (DEAL, 2015) is used as indicator. In order to simplify the cartographic rendering, the SDOM has been divided through a binary approach in: zone 1 (including the original zones 1 and 2 where mining is allowed) and zone 2 (including zones 3 and 4 where mining is forbidden).

Finally, we added a **geotechnical suitability** criterion, assuming that not all terrains would be adapted for the development of the mining site and the operation of human workforce and machinery. Some authors estimated that waste dumps and tailings facilities could not be located on areas with a slope superior to 15% (Oosthuizen, 1999; Suleman, 2017). Hence, this indicator has been used to map the geotechnical suitability of the area.

Fig. 43 presents the intersection of the three criteria (Fig.43a, b and c). As a result, the suitable areas for the fictional localization of the mines are presented in Fig.43d. Once the criteria used to determine mining suitability are defined and mapped, for each TMS, the corresponding mines of each type are fictionally located (Fig. 44). The localization within the suitable areas is concretely performed in this study using the geometrical centroid of the polygon or randomly, using aleatory GIS-based algorithms.

However, for operational applications, the aleatory localization of the mine within the suitability area should be retrieved in order to analyze the influence of the localization on the results. This could be a helpful tool to support decision-making, for instance testing multiple localizations and assessing which ones represent the lowest risk level. Furthermore, it is important to underline that other criteria should be considered for a more reliable siting of the

mining projects. For instance, physical accessibility is a key parameter for the feasibility of a mining project, depending on the existence of road access in order to develop the mine site.

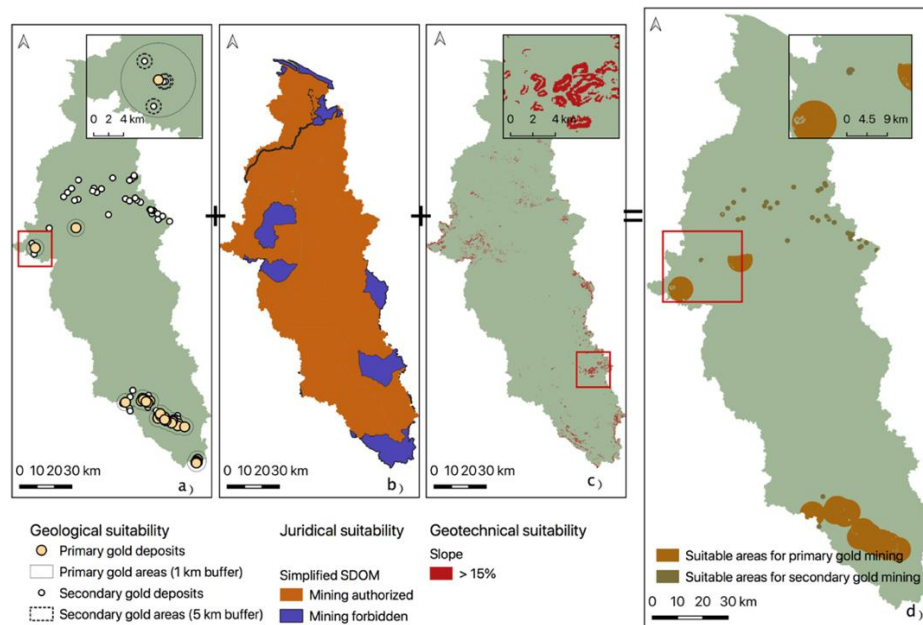


Figure 43 Cartographic application of the proposed methodology for the identification of the suitable areas for the fictional localization of gold mine types based on the geological (a), juridical (b) and geotechnical (c) suitability. On the right, the final result with the suitable areas in Mana river basin (d).

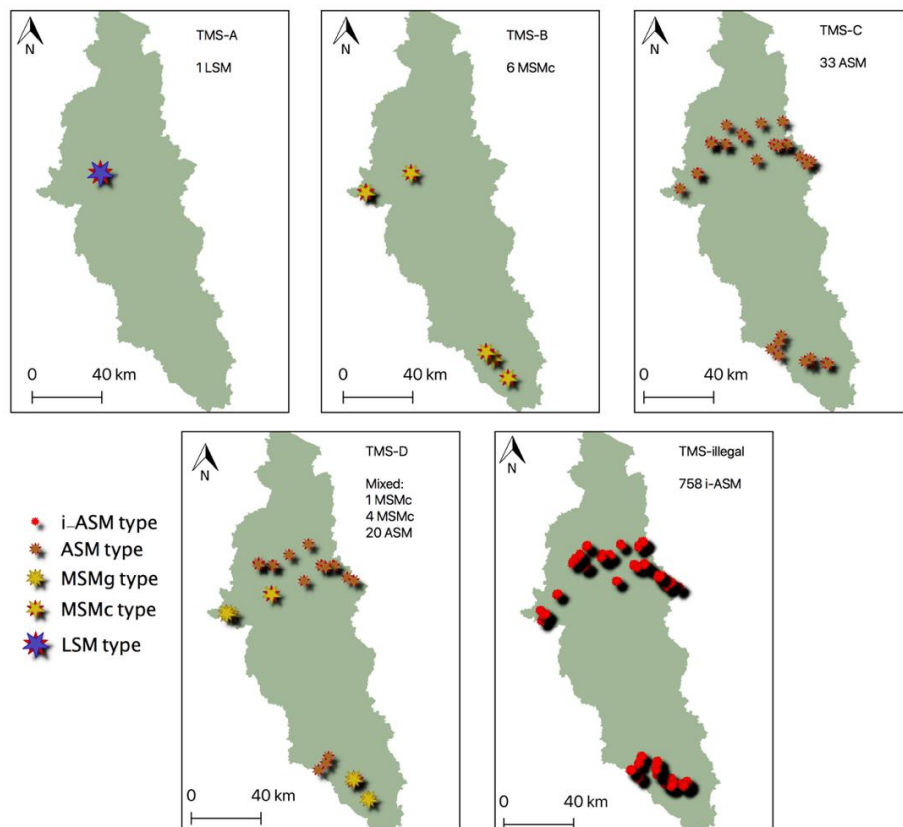


Figure 44 Final fictional localization of the gold mine types in Mana river basin according to the selected TMS. Therefore, 3 TMS based on project-type (TMS-A, B, C), one mixed TMS (TMS-D) and one illegal-TMS

Conclusion

The development of the TMS represents a key-step in the approach proposed in this study since they represent potential strategies for mining development and land-planning. TMS are developed based on pre-defined objectives that stakeholders set at the territory level. Each TMS will be compared according to its level of risk which will be assessed at the territory-level and not only at the mine-site.

Chapter 6. Risk identification and risk scenarios development

1. Risk identification for each gold mine-type in French Guiana

Risk identification aims to develop a reliable database of risk events, on which multiple risk scenarios will be developed for each TMS. Risk are identified according to different sources. In this chapter, the methods and sources used for risk identification are presented. The main positive and negative risks related to each gold mine-type are overviewed. Finally, two distinguished risk scenarios are developed for each TMS. These risk scenarios will be the object of the assessment and the final scoring of the TMS, presented in Part III of this thesis.

1.1. Methods and sources of identification

In this step, two complementary databases of risks have been developed: a risk database specific to FG gold mining sector, and a database of worldwide historical accidents in the mining sector (all commodities included). Both databases aim to structure existing positive and negative risks related to FG gold mining and worldwide mining at the same time, in order to consequently select the risk events and build the risk scenarios to assess for each TMS (Fig. 45).

The first database provides several information concerning the date, type, causes and consequences of *accidents* (see the Glossary) of different natures occurred in mining projects worldwide, and gives complementary data for each case such as: the exploited commodity, the name and location of the project, the type of mining techniques used, etc.. This database is not exhaustive, and it is being filled with new cases and complementary information gathered from different sources (e.g. newspaper, online articles and media, institutional reports), including existing databases. The general structure of the database is presented in Appendix 8.

The second risk database (Appendix 9) has been developed after collecting the foreground data through a bibliographic review (scientific literature, technical reports), mine site visits, free interviews directed to public authorities, mining operators and civil society. An important amount of data has been gathered through the participation to the public debate on the *Montagne d'Or* gold mining project, (CNDP, 2018).

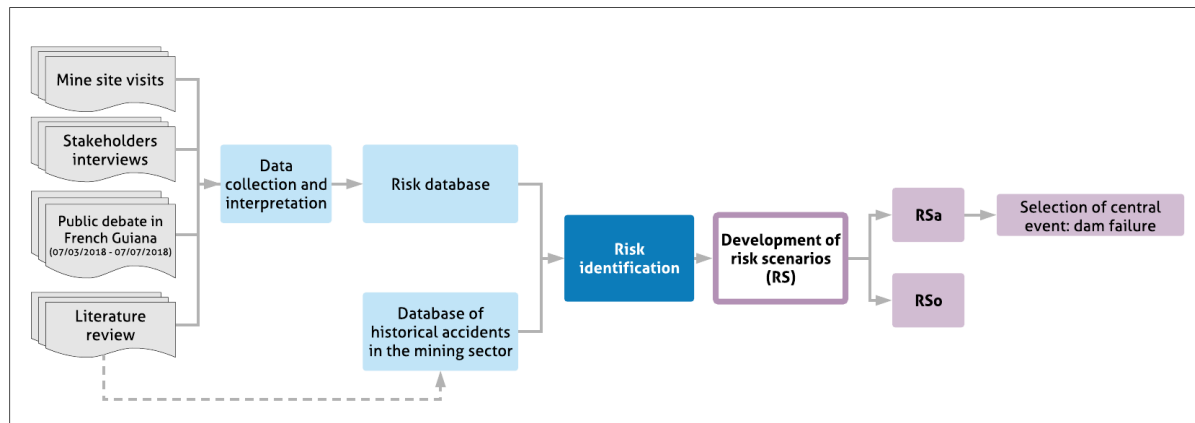


Figure 45 Materials and methods used for risk identification. Once the identification is sufficiently reliable, the risk scenarios (RS) are developed based on the identified risks. For the Rsa, the central event of tailings dam failure has been selected

1.2. Worldwide historical accidents in the mining sector

Despite not peculiar to the FG case, since it includes the occurred accidents related to mining worldwide, an historical database can be an important tool in risk assessment to support the identification of risk events and inform project management. The historical database developed in this study remains still unfinished (415 accidents listed) and under development, mainly because of the great variety of specific existing databases that need to be integrated within it (Table 14) and because not all the accidents are publicly reported. Appendix 8 gives a conceptual view of the type of information contained within the database and its general structure.

However, this database is biased, since 80% of the 415 reported accidents is related to existing databases of tailings dam failures and cyanide spills that concerns accidents occurred during the operational phase, particularly related to waste and tailings management. This is due to the fact that, unlike more current but less catastrophic events (e.g. spills, landslides, transport accidents, other malfunctions), major dam tailings failures are the most reported and mediatized accidents in the mining sector and thus, their identification is more accessible. For instance, Figure 46 shows the evolution of the reported accidents between 1850 and 2020. The figure shows a general significant increase of accidents from 1960s, which can be due to the increasing of mining activities, especially through the exploitation of low-graded ores, leading to wider exploited surfaces and a considerably higher amount of wastes to be stored (Martin and Davies, 2000; Strachan and Goodwin, 2015). However, this tendency can be explained as well by the higher mediatization of such accidental events starting from the 1960s, the increase of mainstream communication (e.g. radios, televisions) but also to the strengthening of institutional monitoring, reporting and controls from public authorities. Indeed, during this period, the raising of “sustainable development” issues exacerbated national and international regulatory frameworks (Martin and Davies, 2000; Rico *et al.*, 2008a), especially in relation to specific industrial activities such as the mining sector. The highest peak is due to a series of

earthquakes that hit Chili in 1965, triggering the failure of several tailings' dams of mining projects across the country.

Table 14 Example of existing databases of historical accidents in the mining sectors. These databases, most of which are related to tailings dam failure, need to be integrated within the unfinished database of historical accidents in the worldwide mining sector

Type of accident	Database reference	Number of accidents	Period	Location	Sector
Tailings dam failure	WISE, as of June 6, 2020	141	1960 - 2020	Worldwide	Mining
Tailings dam failure	Bowker and Chambers, 2017	289	1915 - 2016	Worldwide	Mining
Tailings dam failure	ICOLD and UNEP, 2001	221	1917-2000	Worldwide and US	Mining
Tailings dam failure	do Carmo <i>et al.</i> , 2017	308	1915 - 2016	Worldwide	Mining
Tailings dam failure	https://worldminetailingsfailures.org as of March 1, 2019	357	1915 - 2019	Worldwide	Mining
Tailings dam failure	Bowker and Chambers, 2015	226	1917 - 2009	Worldwide	Mining
Tailings dam failure	Rico <i>et al.</i> , 2008a	147	n.a.	Worldwide	Mining
Dam failure	Zhang <i>et al.</i> , 2016	1,443	1799-2006	Worldwide	All
Cyanide spill	Rainforestinfo.org as of February 28, 2018	36	1994 - 2006	Worldwide	All
Various	http://mineaccidents.com.au as of February 28, 2018	77	1882 - 2000 and 2013 - 2014	Australia	Mining
Various	https://www.cdc.gov	726	1839 - 2010	US	Mining
Various	https://www.msha.gov	445	2007 - 2020	US	Mining

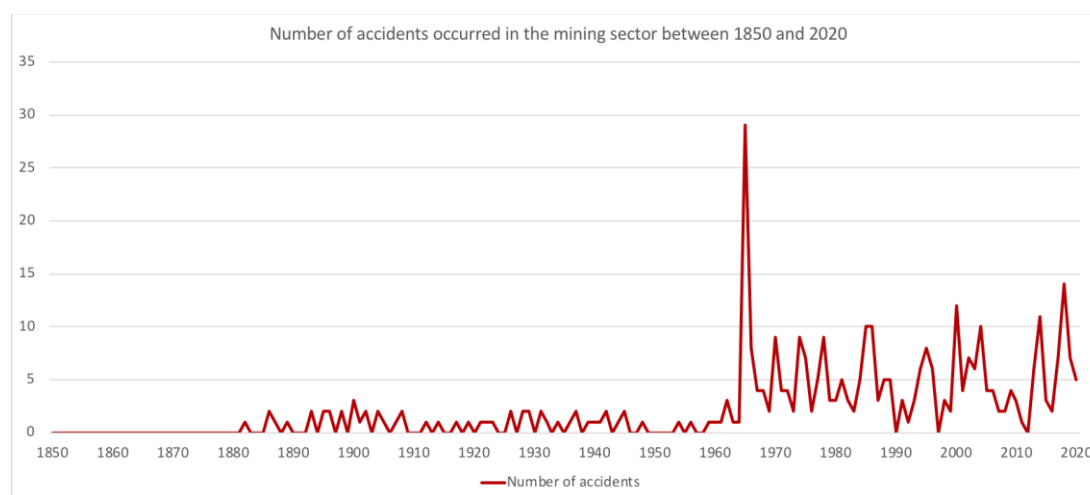


Figure 46 Evolution of the number of reported historical accident in the mining sector worldwide according to the events currently reported by our database between 1850 and 2020

Even though these types of databases give some significant information concerning historical mining accidents, statistical results might still considerably be influenced by the partial data used. Indeed, some bias should be pointed out for the fact that:

- Each country has a different number of tailings dams (Martin and Davies, 2000).

- Not all the types of accidents are reported worldwide. Existing databases concern essentially tailings dam failures and, less frequently, explosion or subsidence accidents. Therefore, only the mediatized accidents with greater consequences are currently easy-to-find, leaving also minor accidents, with “less” significant consequences but higher probability of occurrence, still underreported.
- Not all the countries offer the same level of transparency and communication, both through media, reports and scientific papers. In some cases, institutional databases are provided (e.g. US, Australia) while in other cases no reliable information is found. Also, some failures are not reported due to risks of bad publicity and legal ramification, depending on the country and on the company (Rico *et al.*, 2008a; Kossoff *et al.*, 2014).
- Not all the types of mining projects are listed. More specifically, existing databases usually focus on industrial large-scale projects leaving small-scale and artisanal mining accidents still underreported because they might be more difficult to monitor. In some cases, the same type of “catastrophic” accidents (i.e. dam failure) in large-scale mines might have much less significant “catastrophic” consequences – even if occurring more often – classifying it as a minor unreported accident.

Despite these biases, this first database will be particularly used in this study for the selection of the central risk event for the development of the accidental risk scenario (RSa) (see Section 3). The RSa is based on tailings dam failure, which, if not the most common accident in the mining sector, is surely one of the most reported.

1.3. The identified risks per project-type

Fig. 47 shows the distribution of actors according to whom the risks have been identified in the second risk database, related to FG gold mining sector. The chart underlines the number and percentage of risks mainly mentioned by each actor category, not individually, which means that some risks have been considered by multiple actors at the same time. For instance, the risks related to the use of cyanidation are mentioned by all the three considered groups of stakeholders. A considerable fraction is represented by civil society since the public debate for the LSM project *Montagne d’Or*, provided the identification of a great range of risks. Among them, the main concerns of local communities against LSM-type projects, were related especially to: the utilization of cyanidation for gold recovery and to the management of wastewater and tailings, the potential formation of acid mine drainage, the environmental consequences and the potential security issues related to deep exploitation pits, the impacts of the mine site on deforestation, the impacts of the project on local economy and job opportunities. A detailed synthesis of the public debate and their results is available in a report (CNDP, 2018). It is important to point out that the three groups of stakeholders considered in this study are not equally represented during risk identification.

The main identified negative and positive consequences related to gold mining in FG have been listed in Table 15 for each mine type. Whether these events are positive or negative depends on their effect on the objectives and performances of the mine and territory systems, which can be respectively enhanced or worsened. The table shows the type of source used for their identification of each consequence. The color code aims only to help reading the table in order to understand how many sources are used for the identification.

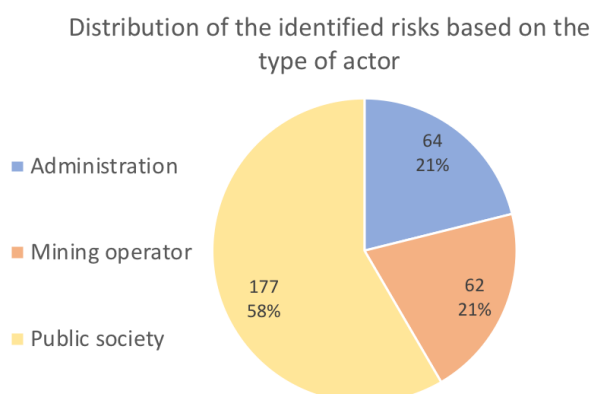


Figure 47 Distribution of the identified risks related to FG gold mining sector according to the different stakeholders

Table 15 Typical potential positive and negative consequences of the gold mining sector in FG, according to each mining project type. As explained in the legend below, the symbols in each case represent the source of identification for each consequence per gold mine-type. The colors instead aim to help the reading of the table and they indicate how many sources that have been used mentioned each consequence per project-type,

Main potential consequences		i-ASMp	i-ASMs	ASM	MSMg	MSMc	LSM	Source
Negative	Destruction of ecological habitats and biodiversity	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Laperche <i>et al.</i> , 2007
	Deforestation	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Galochet and Morel, 2015
	Surface water turbidity	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	ONF, 2017a ; ONF, 2017b ;
	Heavy metals contamination in water and soils	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Rahm <i>et al.</i> , 2017
	Direct Hg pollution and contamination (e.g. gold recovery techniques)	○ ●	○ ●	○			○	Tudesque <i>et al.</i> , 2012
	Indirect Hg contamination due to the remobilization of ancient Hg	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Gallay <i>et al.</i> , 2018
	Dam failure related flood, contamination and turbidity	○	○	○	○ ●	○ ●	○ ●	Laperche <i>et al.</i> , 2008
	Cyanide spills	○	○	○	○	○ ●	○ ●	Marchand <i>et al.</i> , 2006
	Soil erosion	○	○ ●	○ ●	○ ●	○ ●	○ ●	Guedron <i>et al.</i> , 2011b
	Physical alteration of riverbeds (hydromorphological impacts)	○	○ ●	○ ●	○ ●	○ ●	○ ●	Kahhat <i>et al.</i> , 2019
	Acid mine drainage (AMD)	○			○ ●	○ ●	○ ●	Guedron <i>et al.</i> , 2011a
	Atmospheric pollution	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Gentès <i>et al.</i> , 2019
	Landscape degradation	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Bourbon and Mathon, 2012
								Ineris, 2018
								Moisan and Blanchard, 2012

Positive	Mine subsidence	○ ●						Bourbon, 2014 Bourbon, 2015
	Pit instability	○ ●			○ ●	○ ●	○ ●	Bourbon and Mathon, 2012 Bourbon, 2015
	Landslides	○ ●	○	○ ●	○	○	○ ●	Laperche <i>et al.</i> , 2008 Bourbon and Mathon, 2012
	Health problems and serious epidemiological diseases (e.g. malaria, HIV)	○ ●	○ ●	○ ●	○			de Santi <i>et al.</i> , 2016 Douine <i>et al.</i> , 2018
	Migration of legal and illegal miners from bordering countries ("gold rushes")	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Mouillet <i>et al.</i> , 2006 Hook, 2019
	Work injuries	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Hentschel <i>et al.</i> , 2002 Amirshenava and Osanloo, 2018
	Crimes and insecurity for local communities (e.g. drug, arm dealing, prostitution, child labor)	○ ●	○ ●	○	○	○	○	Hentschel <i>et al.</i> , 2002 WWF, 2018
	Social disruption (e.g. opposition, conflicts)	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Hentschel <i>et al.</i> , 2002 Moisan and Blanchard, 2012
	Resource dispossession (e.g. land, water, crops)	○	○	○	○	○	○	Keovikignavong, 2019 Pokorny <i>et al.</i> , 2019
	Direct economic outcomes (e.g. taxes, royalties)			○ ●	○ ●	○ ●	○ ●	Amirshenava and Osanloo, 2019
	Direct jobs opportunities	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Amirshenava and Osanloo, 2019 Pokorny <i>et al.</i> , 2019
	Raw material supply	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Amirshenava and Osanloo, 2019
	Development of local business as services providers	○	○	○	○ ●	○ ●	○ ●	Amirshenava and Osanloo, 2019
	Expansion of social infrastructures (e.g. roads, energy, services)					○ ●	○ ●	Amirshenava and Osanloo, 2019
	Support of local education, research and skill development				○ ●	○ ●	○ ●	MDO, 2018
	Support to ethnic minorities	○	○	○	○	○	○	MDO, 2018
	Fight against illegal mining				○ ●	○ ●	○ ●	WWF, 2018

○ General literature	▲ Expert interviews and site visits		No impact or no data	2 sources (other than "○")
● FG-related literature	■ Public Debate of MDO		1 source (other than "○")	3 sources (other than "○")

1.3.1. The positive risks

The typical positive risk (i.e. opportunity) associated to mining concerns the **increase of employment rates** and the **creation of local wealth**. Indeed, this is the most important argument when it comes for gold mining operators to counterbalance the negative outcomes that may be generated. However, some authors emphasize that the perception of inhabitants might be concerned as well not only on how many people might be directly or indirectly employed by the mining project but also, who these people are. In some cases, especially LSM projects, tend to import short-term technical expertise which consequently limit the most qualified job offers often for non-local staff (Pokorny *et al.*, 2019). For instance, in FG, MSM and LSM often employ foreign miners, mainly Brazilians, because of their wider and greater mining experience compared to local workers. In several exchanges with local stakeholders, it often came up that

FG does not have a “mining culture”. Moreover, in i-ASM and legal ASM, work conditions are often volatile (Pokorny *et al.*, 2019).

The potential **economic outcomes** of mining activities are also among the most important opportunities often proposed to underline the importance of gold mining for territorial development (Betancur-Corredor *et al.*, 2018). For instance, Hilson and Laing, (2016) discuss the case of gold mining in Guyana showing how even a modification of gold prices “is capable of drawing valuable financial and human capital from other sectors of the economy”. These aspects are considerably related to the priorities of local population and public authorities, but also mining operators, concerning the enhancement of the territorial development on the short and long run. Economic consequences of gold mining can result in the form of **taxes and royalties** that mining companies pay to local administrations. For instance, in FG the Fiscal Code states that, among others, mining companies should pay a royalty of 137,9 €, 27,00 € and 672,01 € per kilogram of gold produced, respectively to municipalities, departments and the region (SRK, 2017). The reallocation and reutilization of these incomes for local administration might support the **enhancement of local infrastructures and services**, (Oyarzo and Paredes, 2019). However, this depends on who is the actual beneficiary of these incomes and on how trustful is the relationship between citizens and the government for the reallocation of economic resources. Moreover, some stakeholders criticized the fact that such services (e.g. infrastructures, education) should be supplied by the State and not by potential substitutes incarnated by private mining corporations. Indeed, in the case of LSM, a potential risk often claimed especially by local communities is the imposition of “export-led models” that leads public authorities to “privilege foreign companies and enrich host governments” (Hilson and Laing, 2016). In other cases, the development of road infrastructures due to new gold mining project is seen in FG as a potential facilitation for illegal gold miners to access new mine sites.

The “natural” outcome of gold mining is also the **supply of gold**. Hence, where there is a need for raw material supply for the uses of gold mentioned in Chapter 4, gold mining fills such needs. The questionability of gold needs and applications is not a matter of discussion in this thesis. Legal gold mining sector production in FG is currently overthrown by illegal operations which produce a considerably higher amount of gold annually and export it through laundering networks which bind the informal and formal sectors of gold production (Heemskerk, 2010). However, a part of local community states that illegal gold mining would be reduced by the increasing of legal mining activities, since the latter would “dispossess” the first ones of profitable lands. On the other hand, some stakeholders state the opposite, suggesting that legal mining might also – willingly or unwillingly – “attract” illegal mining activities that would exploit and re-process legal tailings and residues with more viable but destructive methods (i.e. gold-mercury amalgam). If this may be questionable for MSM and LSM-types, it can be particularly true for legal ASM, which do not seem to play a key role in reducing the illegal mining phenomenon. This is because, in the current framework of FG, small-

scale activities do not have the means to fight illegal mining and risk to be overwhelmed by the phenomenon (e.g. land claims, robberies and hold-ups).

1.3.2. The negative risks

The potential negative social and environmental consequences of gold mining should be discussed taking into account their considerable interactions. Indeed, the degradation of environmental components inexorably leads to the degradation of ecosystem services supplied by these components and that satisfy the needs of local communities. For instance, Keovilignavong (2019) discusses that the negative environmental consequences of gold mining in a region of Laos degraded considerably the quality of life of inhabitants, resulting in “declining their ability access to and use of these resources for their livelihood benefits”.

In FG, the main typical identified negative risks related to gold mining concern the consequences of such activities on the different environmental components (e.g. soil, water, biodiversity) of the region and the health and well-being of its inhabitants (Table 15). This might be explained by three main reasons:

- because of the intrinsic vulnerability of FG local ecosystem, due to a dense hydrographic network, the large surfaces occupied by Amazon rainforest, its biodiversity and the sensitivity of its water, soil and forest ecosystems;
- The contamination of soils with anthropogenic mercury (Hg), due to gold processing techniques in legal – until 2006 – and illegal gold mines;
- The remobilization of the anthropic and natural Hg presents in soils, water and sediments.

Hg-related risks in FG’s gold-mining sector have been widely discussed (Grimaldi *et al.*, 2015), and are linked to specific concerns about the health of miners and welfare of local communities. Soil, air and water are all affected: 20% of Hg is lost during amalgamation, while 70% evaporates during the roasting phase (Moulet *et al.*, 2006). Such emissions depend on the technological level of the operator and would be significantly lower if the use of retort were common among i-ASM (Seccatore *et al.*, 2014; Kahhat *et al.*, 2019). The remobilization of natural or anthropogenic Hg due to soil removal during mining is considered as relevant as direct Hg emissions from recovery process in i-ASM (Kahhat *et al.*, 2019). With an annual gold production of 10 tons, approximately 13 tons of Hg are also released into streams in FG (WWF, 2018). Contaminated hotspots due to runoff have emerged in areas located kilometers far from mining sites (Marchand *et al.*, 2006) and the impacts on biodiversity are well documented (Fréry *et al.*, 2001; Godard *et al.*, 2006; Sebastiano *et al.*, 2016; Gentès *et al.*, 2019). However, since Hg in water is bioavailable for only few organisms (Laperche *et al.*, 2007), the most significant risks for health occur when Hg is transformed in methylmercury (MeHg) (Guedron *et al.*, 2011a). Since methylation depends on anoxic conditions, organic matter rate and other

physical and biological factors, illegal and ancient legal gold mines are the locations of high concentrations and seasonal cross-watershed transfers of MeHg (Guedron *et al.*, 2011b). Contamination might affect the food chain by biomagnification and lead to severe endocrine disorders among local populations (Budnik and Casteleyn, 2019). Human exposure to MeHg depends also on the receptors and their socio-cultural habits (Grandjean *et al.*, 1999; Boudan *et al.*, 2004; ARS, 2013). For instance, Frery *et al.*, (2001) suggest that Wayana population in FG has a high exposure to Hg related to fish consumption and that 90% of the population in the Haut-Maroni in 2015 had a rate beyond the standard thresholds (WWF, 2018).

Deforestation is another potential consequence often associated to gold mining, particularly in rainforest regions (Polidori *et al.*, 2001). Rather than a risk, deforestation is almost the inexorable consequence of any activity leading to land anthropization. In gold mining, the deforested surfaces increase during the development and exploitation phases, when mining operators clear the mine site, develop and build mining roads and infrastructures. This phenomenon is particularly worsened in the case of i-ASM, where it occurs without control or monitoring from local authorities (Rahm, 2017). Among the measures to compensate and re-enhance local vegetation and soil quality, land rehabilitation practices and revegetalization are often performed during and after mining (DEAL *et al.*, 2016).

Because of deforestation and of the peculiar structure of local soils (Roose and Sarrailh, 1990), **erosion and sedimentation** are natural phenomena in FG, exacerbated by gold mining activities. This level of perturbation increases the release of total suspended solids (TSS) (Gallay *et al.*, 2018), and thus, silting, water turbidity, heavy metal release (Tudesque *et al.*, 2012; Labriere *et al.*, 2015; Venturieri *et al.*, 2017), consequentially affecting biodiversity, soils and freshwater resources (Laperche *et al.*, 2008; Asconit, 2013; Da Silva, 2014; Galochet and Morel, 2015; ONF, 2017a). Indeed, TSS release is a major driver of soil and water pollution and it is exacerbated during mining development and operations, even in ASM types.

As shown also by the final report of the public debate concerning the *Montagne d'Or* project (CNDP, 2018), the utilization of cyanidation for gold recovery is a major concern among local communities and associations, but also public authorities. Indeed, the dispersion of free **cyanide** ions on the human and natural environments would cause severe toxicological impacts (INERIS, 2012; Donato *et al.*, 2017). However, unlike Hg, cyanides are biodegradable in the environment and they are not bioaccumulated by humans (Hylander *et al.*, 2007; Laitos, 2013). Moreover, the occurrence and intensity of the potential health disorders generated vary according to the type of cyanide compound used (INERIS, 2011). Cyanide-related risks depend as well on the technical performances of the mining operators. For instance, industrial cyanidation relies nowadays on the international Code for Cyanide Management (ICMI, 2016). Nevertheless, cyanide should be stored on the long-term in appropriate conditions to avoid its oxidation and liberation of toxic acid elements (Mudder and Botz, 2004). At the moment, only one MSM-type in FG developed a cyanide plant for gold recovery. Information of gold

cyanidation in FG is available in several published reports (Moisan and Blanchard, 2012; INERIS, 2018; Urien, 2018).

Another risk often identified concerns the potential consequences of **acide mine drainage (AMD)**. By our knowledge, the occurrence of this phenomenon in FG is specifically addressed by only one report in 2006 (Miramond *et al.*, 2006). AMD depends on the geological deposit and the physico-chemical nature of the hosting rocks. Usually, AMD is specific to primary gold deposits (metamorphic or magmatic) – rich in sulfides such as FeS_2 – and it occurs when operational and specific environmental conditions are met (e.g. oxidizing conditions, altered mineralogy of the substratum, absence of carbonates, high temperature, acid pH, microbial activity) (Price, 2005; Miramond *et al.*, 2006; Lottermoser, 2010). Despite in FG, AMD risk might be relatively low in some superficial rocks, it becomes higher when deeper materials are excavated and exposed, for instance, in the non-oxidized area of the substratum. AMD contains high concentrations of acid and dissolved metals that may be released into soils, groundwater, streams, leading to high toxicity for aquatic organisms and ecosystems, infrastructures corrosion and freshwater contamination (Simate and Ndlovu, 2014). Finally, in some deposits, other metalloids might be exposed leading to specific toxic risks. For instance, in the case of *Montagne d'Or* project, the potential presence of arsenic-enriched hosting rocks was at the origin of concerns for local population.

A great range of **risks concern the i-ASM sector** in FG. Indeed, the noncompliance with the obligations legally required by mining permits, results in the amplification of the common consequences generally related to mining. According to WWF, (2018), almost 1 800 km of water streams were integrally degraded in 2015 by i-ASM and approximately 12 000 hectares were deforested – of which nearly 3 000 are located within protected areas (Rahm, 2017). Also, the hostile living conditions at mining sites lead to poor health caused by infectious and non-infectious diseases, which spread beyond mining borders (Douine *et al.*, 2018). Malaria but also digestive and cutaneous disorders, anemia, HIV transmission might affect local miners, communities, undocumented immigrants and even French soldiers deployed on the territory (Douine *et al.*, 2016; de Santi *et al.*, 2017; Douine *et al.*, 2018; Jones *et al.*, 2018). Moreover, i-ASM leads to the development of “segregated economic enclaves” (Pokorny *et al.*, 2019) which in FG might find a good example in the village of Saint-Elie.

2. Accidental Risk scenario (RSa) development

The two databases resulting from risk identification are used to develop two different risk scenarios for each TMS. The first considered risk scenario evaluates gold mines operating in accidental conditions, i.e. outside the normal functioning of the project. A central event is

selected and integrated within a Bow-Tie to identify its causes and consequences. The assessment of this RSa has been one of the main focus of this thesis.

2.1. Selection of an initial central event: dam failure induced by overtopping

In the current study, only one accidental risk event could be considered to develop the RSa. Based on the two risk databases previously exposed, the failure of the tailings dams has been chosen as the initial central event for the development of the RSa. This event will be the core of the Bow-Tie diagram. The choice of tailings dam failure is due to the fact that, as shown by the historical database, it is the most reported historical accident in the mining sector. Furthermore, this risk event has been repeatedly reported during the public debate concerning the gold mining project of *Montagne d'Or*.

Indeed, mining wastes and tailings management is today a major concern for mining operators because of their quantities and short and long-term impacts on human health and on the environment (Martin and Davies, 2000; Kossoff *et al.*, 2014). In order to characterize the risk of tailings dam failure, a thorough bibliographic review, along with discussions with experts have been carried out. In the following sub-sections, a short synthesis of this review is presented in order to detail tailings dams and their utilization in FG, so to apprehend the triggering factors of tailings dam failures and their consequences. More details can be found in Appendix 10. The acknowledgment of the root causes and the consequences of the dam failure will support the development of the Bow-Tie diagram.

2.1.1. Overview of mining dams: definition and application in the mining sector

Mining dams are retaining and protection embankments that are used for mine sites and/or metallurgical plants (Bourbon and Mathon, 2012) (Fig. 48). They have two main functions:

- to create sedimentation impoundments for the storage and settlement of fine waste materials coming from mining operations or mineral processing (called “tailings”). In this latter case, they are referred to as tailings store facility (TSF) (Lottermoser, 2010; Kossoff *et al.*, 2014; Ponce-Zambrano *et al.*, 2014).
- to create decantation ponds to hold and clarify water that may be returned for the mine to operate in a closed-circuit, after settlement in dam via penstocks and piping (Babbitt and Graham, 1996).

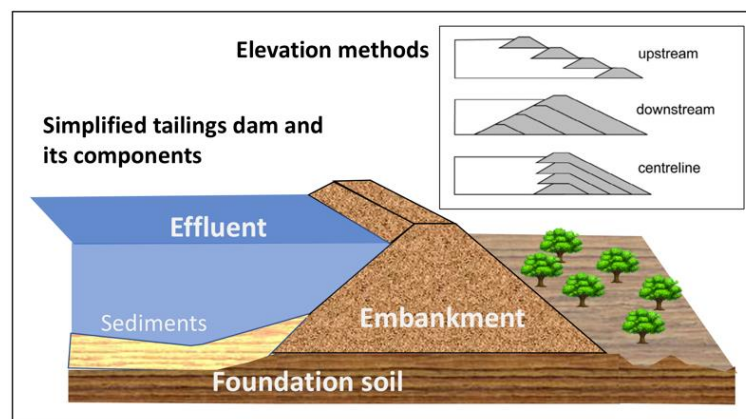


Figure 48 Simplified figure of a mining dam and its main components. On the higher right side of the figure, the three main methods used to raise the dam are shown

In order to fulfill the mentioned functions of storage and decantation of mine tailings and operation waters, three main *performances* are defined for a TSF (Bourbon and Mathon, 2012; Li *et al.*, 2018; USSD, 2018):

- i) Physical stability, which is the capacity to support the applied stress for a long time without suffering any significant deformation or movement;
- ii) Impermeability, which is the capacity of the mining dam not to allow the transfer of fluids under specific pressure conditions, except when needed;
- iii) Sufficient storage capacity which represents the aptitude of the embankment to contain the required volume of materials and fluids, without reducing stability and impermeability.

2.1.2. Overview of tailings management and gold mining dams in French Guiana

Several technical reports give an insight about the specificities and the utilization of TSF in FG gold mining sector (Laperche *et al.*, 2008; Barras, 2010; Bourbon and Mathon, 2012; Cottard and Leperche, 2012; INERIS, 2014; SRK, 2017; GéoplusEnvironnement, 2017;

Aesteergts, 2018; Urien, 2018). These TSF differ considerably depending on whether the exploitation concerns primary or secondary gold deposits. In both cases, they are usually built from local soils and materials, because of the difficulties of access and transport of heavy materials. If here they are only overviewed, some technical features of mining dams in gold mining exploitations in FG are detailed in Appendix 10.

In **primary gold exploitations**, the arrangement of mining dams consists in one or several ponds designed to stock mine tailings in a slurry (10 to 30% of solid fractions), having a sandy to clayey texture (Bourbon and Mathon, 2012) (Fig. 49-50). These ponds are embanked by two or more dams, usually built with the anciently or recently excavated materials available on site (Cottard and Laperche, 2012). In FG, the most common elevation technique is the upstream method because it is easier to perform and economically more viable. Nevertheless, because of the increasing world-wide accidents also due to this construction technique, the upstream raising method is currently being debated to avoid further uses.



Figure 49 Simplified scheme of the tailings and water ponds in a MSMg-type in FG based on a satellite image. Source: Modified from Google Map, 2020 Maxar Technologies



Figure 50 A mining dam in a MSM-type in FG

In secondary gold exploitations, the arrangement of mining dams consists in a sequence of ponds used both for tailings storage and water settlement as long as the exploitation progresses (Fig. 51; Appendix 10). As it was explained in Chapter 4, these structures embank the *barranques* and, as the exploitation progresses along the riverbed, the previous extracting ponds are used to stock turbid water and the tailings of the “active” upstream *barranque* (Barras, 2010; Bourbon and Mathon, 2012). Once extracted, the minerals are processed by grain-size, a first time through gravimetry directly in the current exploitation pond, and then sent into the downstream ponds to settle (Fig. 51; Appendix 10). No chemical additives are used.

Therefore, the main differences between the dams in primary and secondary gold mining are:

- 1) A greater storage capacity and height of primary gold mining dams, due to the difference of surface exploited, the financial and technical equipment available and the production rate.
- 2) The systematic distinction, for primary gold mining projects, between tailings dams and water settling ponds.
- 3) The localization of the ponds which depends on a progressive downstream-to-upstream sequencing for secondary gold mining and are essentially topography-driven for primary gold exploitations.
- 4) The potential storage of decyanated tailings outcoming from processing plants and the utilization of dry storage for some primary gold exploitations.

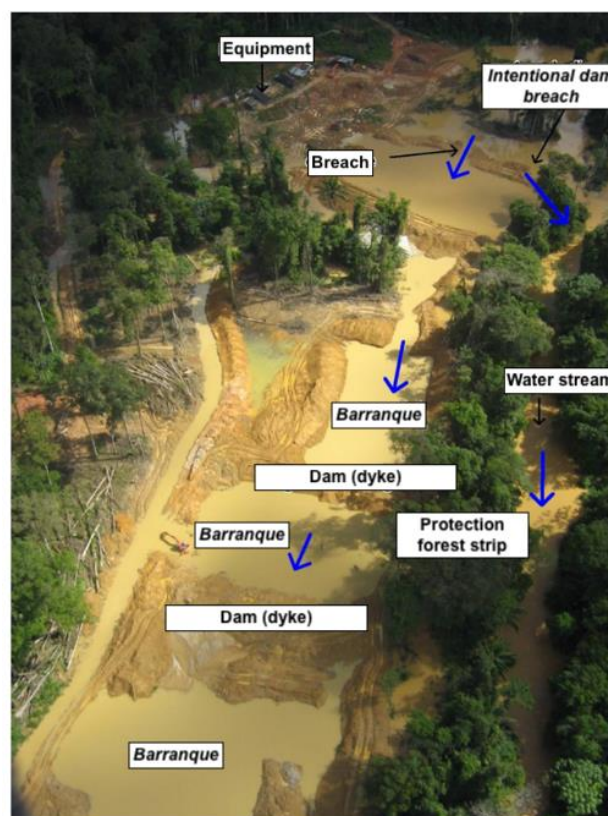


Figure 51 Example of a mining dam system in a secondary gold mining site (ASM-type) in FG (Barras, 2010)

2.1.3. Mechanisms of failures of mining dams, causes and consequences

In May 2020, approximately 23 000 tons of oil products were spilled into the environment in a nickel mine in Russia due to the possible collapse of a fuel reservoir (Kim, 2020 for NPR News). In March 2020, in Heilongjiang Province (China), more than 2.5 million cube meters of tailings contaminated the environment, threatening drinking water provisioning of almost 70 000 people. In January 2019, more than 12 million cubic meters were released after the collapse of a tailings dam in an iron mine near Brumadinho (Brazil), killing more than 250 people. These were only the major among the 21 big tailings dam failures that have been reported by WISE, 2020 after the 2015 Samarco failure. Indeed, the greatest challenge for mining is the treatment and storage of mine waste, estimated to 5 – 14 000 Mt/year (Kossoff *et al.*, 2014; Schoenberger, 2016). Tailings ponds represent the most significant environmental liability associated with mining operations (Martin and Davies, 2000), being more vulnerable than conventional dams (Rico *et al.*, 2008a).

Several definitions of failures are given by Smith and Connell (1979); FEMA (2004); Caldwell *et al.*, (2015), but none applies to all the contexts. In this study, a **mining dam failure** is referred to as the effect of the potential occurrence of single or multiple events which reduce one or more performances of a mining dam (e.g. stability, impermeability, storage capacity), leading to the alteration of its functions (i.e. tailings and water storage and settling).

Multiple failure mechanisms are described by authors, such as mine subsidence, slope instability, foundation failure, overtopping or seepage (Kossoff *et al.*, 2014; INERIS, 2014; Ponce-Zambrano *et al.*, 2014; Strachan and Goodwin, 2015; UNEP, 2017) (Fig. 52). Among them, overtopping is estimated to be the currently leading mechanism of failure (Bowker and Chambers, 2017; UNEP, 2017) (Fig. 52). Moreover, it seems that overtopping events are increasing, which may show deficiencies in design and water management (Concha Larrauri, 2017). For this reason, overtopping is chosen for this study as failure mechanism for the development of the RSa here presented.

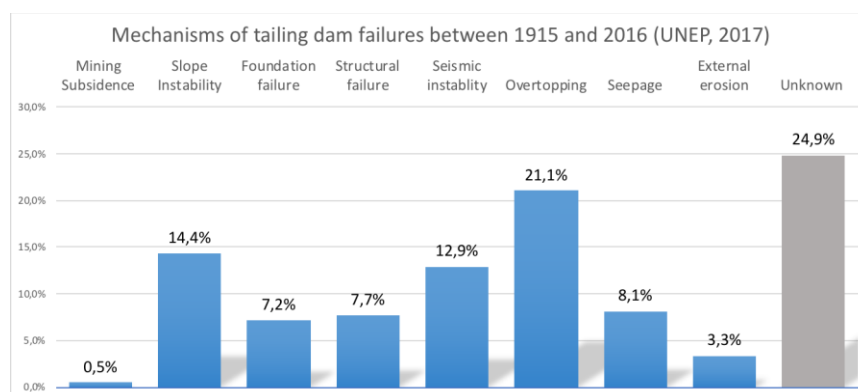


Figure 52 Most common mechanisms of tailings dam failures occurred worldwide between 1915 and 2017 according to UNEP (2017)

Overtopping is defined as the event during which water flows over the top of the dam, sometimes causing the erosion of the embankment (UNEP, 2017). The probability of occurrence of such events is influenced by a very wide range of interacting causes related both to the internal management of the mining project and its infrastructures (e.g. construction methods, water balance monitoring), and the external environment of the mining project itself (e.g. meteorological conditions, topography but also socio-political and economic causes). Despite rare in some cases, dam failures generated by overtopping do happen, and their consequences are extremely variegated, from limited overflows at mine site to catastrophic large floods. These consequences might affect the surrounding environment (e.g. silting and erosion, water pollution, deforestation), local population (e.g. deaths and injuries, flooded houses) and infrastructures (e.g. reduction of drinking water provision, limited road access). These consequences have always a negative effect that rebounds on mining companies, who may consequently face high financial and reputational costs (Franks *et al.*, 2011; Concha-Larrauri and Lall, 2018). Moreover, they may generate a widespread controversy and projects' opposition (Caldwell *et al.*, 2015), leading to clean-up, compensation and litigation costs, the non-willingness of governments and communities to support new mining operations and, thus, lost future opportunities for mining operators (Franks *et al.*, 2011). The causes and consequences of the dam failure generated by overtopping are detailed in Appendix 10.

2.2. Conceptual structure of the scenario: the Bow-Tie diagram

The RSa chosen for this study is developed based on a mining dam failure due to overtopping. The RSa is presented through the Bow-Tie diagram, detailed in Chapter 1. Fig. 53 shows the simplified diagram with the main causes (on the left) and consequences (on the right) selected for a further assessment. It is important to point out that, at the moment, the safety measures – that the mining operator can implement to reduce the probability of occurrence and/or the consequences of a dam failure – have not been included within the Bow-Tie. This implies a bias that need to be accounted for in results interpretation and that must be addressed in further studies. This aspect will be discussed at the end of the thesis. Nevertheless, because of the demonstrative purposes of the current application, the diagram is used simply as a conceptual scheme to present the selected scenario and to understand the interactions among the different causes and consequences related to a dam failure event due to overtopping.

Among the causes, two main factors are considered: the occurrence of a landslide within the pond causing the formation of a wave, and the increasing of water level. The consequences, as it will be furtherly detailed, concern the events triggered by the overtopping at the mine site (e.g. destruction of the dam, degradation of mining infrastructures, direct impacts on workforce) and socio-environmental consequences at the territory level, both within and outside the potential flooded area (e.g. degradation of drinking water, impacts on soils and surface waters, social struggle due to the loss of revenues for local households dependent on the mine site). The consequences end up to the “financial loss of the operator”

to show the feedback loop where the consequences affect the mine site, the territory and, finally, they strike back the mining operator.

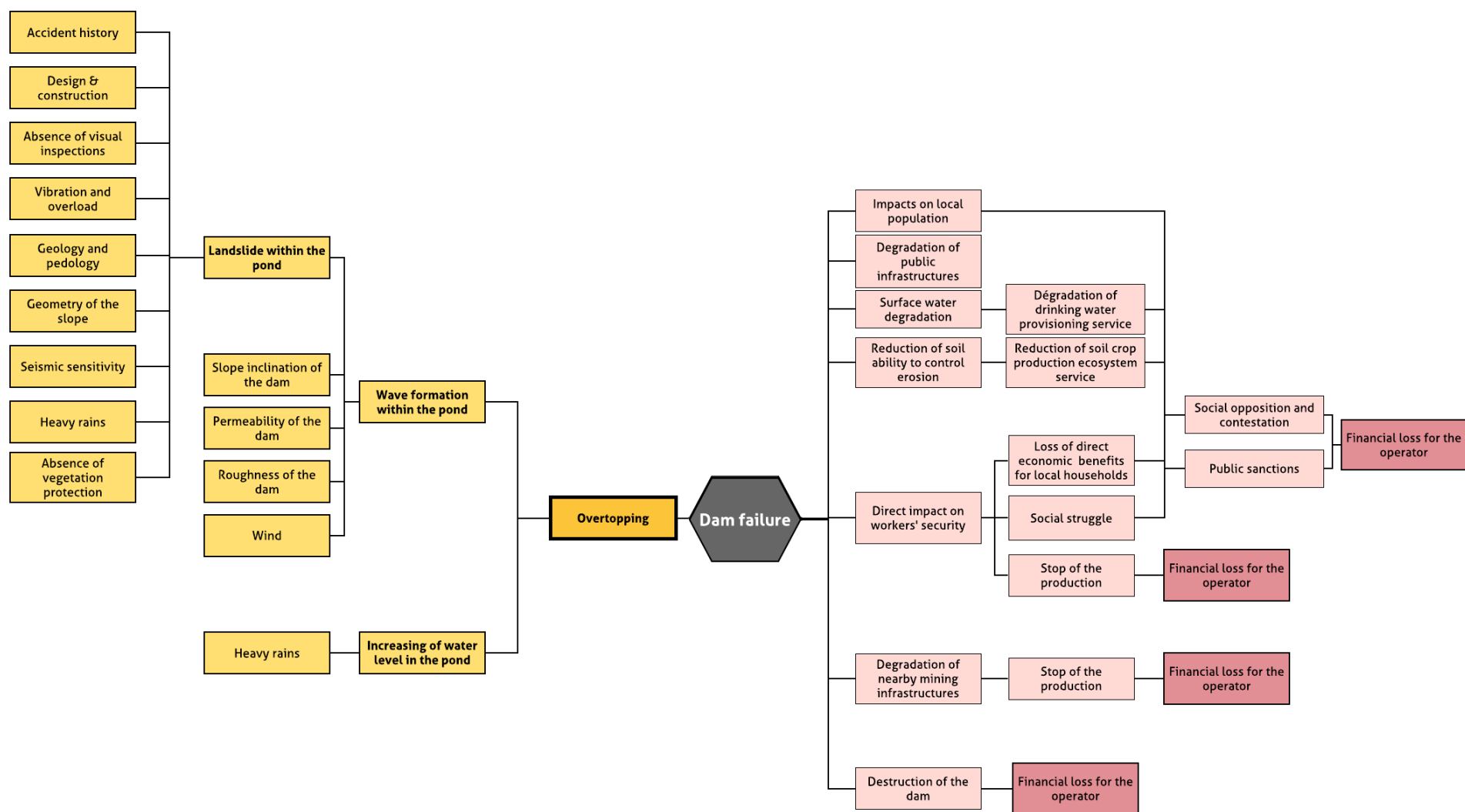


Figure 53 Selected causes and consequences of the tailings dam failure due to overtopping. The whole bow-tie diagram represents the selected accidental risk scenario (RSA) for this first application of the proposed methodology.

3. Ordinary Risk scenario (RSo) development

The second risk scenario evaluates gold mining projects under *normal operating conditions* (see the Glossary), representing as closely as possible the level of performance that can be reasonably expected by the project. In this case, the operation of the mine coincides with the occurrence of *ordinary* risks. Unlike the RSa, the occurrence of these risks is almost certain when the projects are in operation. Thus, during the assessment, the probability of occurrence of these risks will be considered equal to one.

The assessment of the RSo has not been the main object of this thesis and hence, it has not been significantly detailed (e.g. no Bow-Tie and limited assessment as shown in Chapter 8). Nevertheless, we decided to include it at this stage, since it is fundamental to obtain the final TMS scores and compare them.

The ordinary risk scenario (RSo) is composed both of positive and negative consequences (Table 16) selected among the identified risks in Table 15. Hereafter, only four positive socio-economic and one negative consequences (i.e. landscape degradation and the surfaces deforested by the development of the mine site(s)) have been selected.

In this scenario only the triggered consequences are considered, neglecting the consequences suffered by the mine(s). This aspect will not be considered neither for the second risk scenario, which means that the final scores of the TMS will both result from the assessment of risks generated – not suffered – by the mining project. The integration of both suffered and triggered risks related to mining projects based on their level of socio-environmental performances will be discussed in the fourth Part of this manuscript (Chapter 11).

Table 16 Selected positive and negative consequences for the ordinary risk scenario (RSo)

Positive consequences:
Raw material supply (Gold)
Direct jobs opportunities
Expansion of social infrastructures (e.g. roads, energy, services)
Support of local education, research and skill development
Negative consequences:
Landscape degradation

Conclusion

The current chapter presents the development of two risk scenarios for each TMS based on two databases of identified risks.). Tailings dam failure has been selected as the main central event of during accidental operating conditions of the mining project and will be detailed in Chapter 7. The risk scenario in normal operating conditions has only been introduced in our study and will be briefly assessed in Chapter 8. This risk scenario must be the object of further studies (for instance, through a bow-tie approach). The assessment and combination of these RSo and RSa will allow the scoring and comparison of the TMS.

As shown in Chapter 4, for each mine type, a range of values is given to each technical and operational parameter. Table 10 presented the parameters used according to each mine-type for the assessment of the risk scenarios.

Part III – Application on gold mining in French Guiana: assessment of the risk scenarios and TMS scoring

Chapter 7. Assessment of the accidental Risk Scenario (RSa)

This chapter presents the assessment of the accidental risk scenario (RSa) developed in Chapter 6. The scenario we selected is based on the failure of a mining dam caused by overtopping, considered as the initial central event. In this case, a “failure” is defined as the loss of the storing capacity of the dam.

The next sections (1 to 4) detail the vulnerability indicators and then expose the estimation of the impacted area, as well as the different consequences at the scale of the territory. Consequences at the project scale will only be shortly discussed, since we intend to focus on the territorial level. Fig. 54 illustrates the steps followed for the assessment of the RSa in this study. The assessment focuses on the estimation of the area impacted by the dam failure (Fig. 55b) and the identification of the socio-ecological components directly or indirectly impacted by the flood (e.g. local population, infrastructures, water, soil) and the assessment of their vulnerability (Fig. 55c). This allows to obtain a consequence map (Fig.55e) that is then combined to probability scores to assign a final score to each TMS. Probability scores depend on the financial and technical means of the mines and their aptitude in implementing safety barriers, which only qualitatively assumed in this study.

Finally, an alternative way to estimate the RSa score is just proposed in order to integrate the probability scores from the beginning of the assessment.

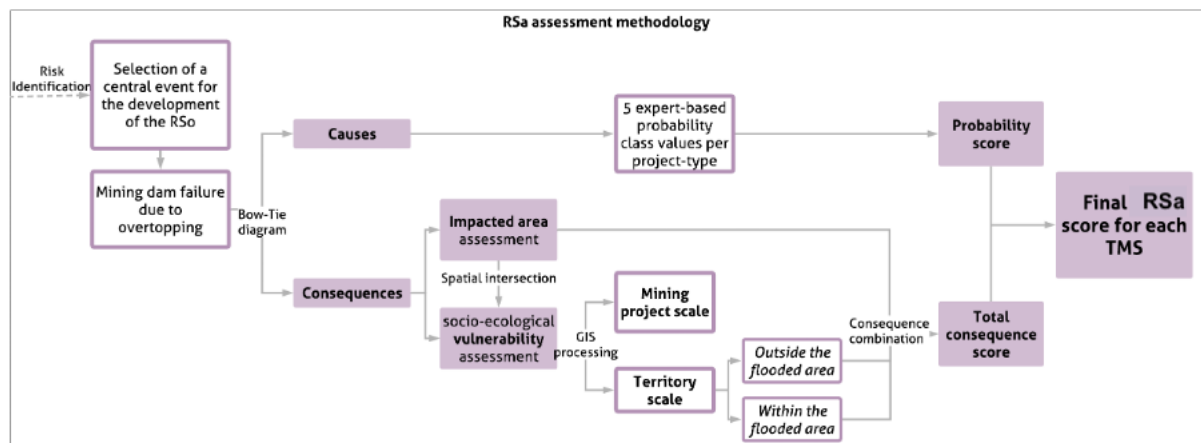


Figure 54 Simplified conceptual flowsheet of the methodology used for the assessment of the RSa. As it is shown and furtherly detailed, the "mining project scale" consequences are not considered in the overall score

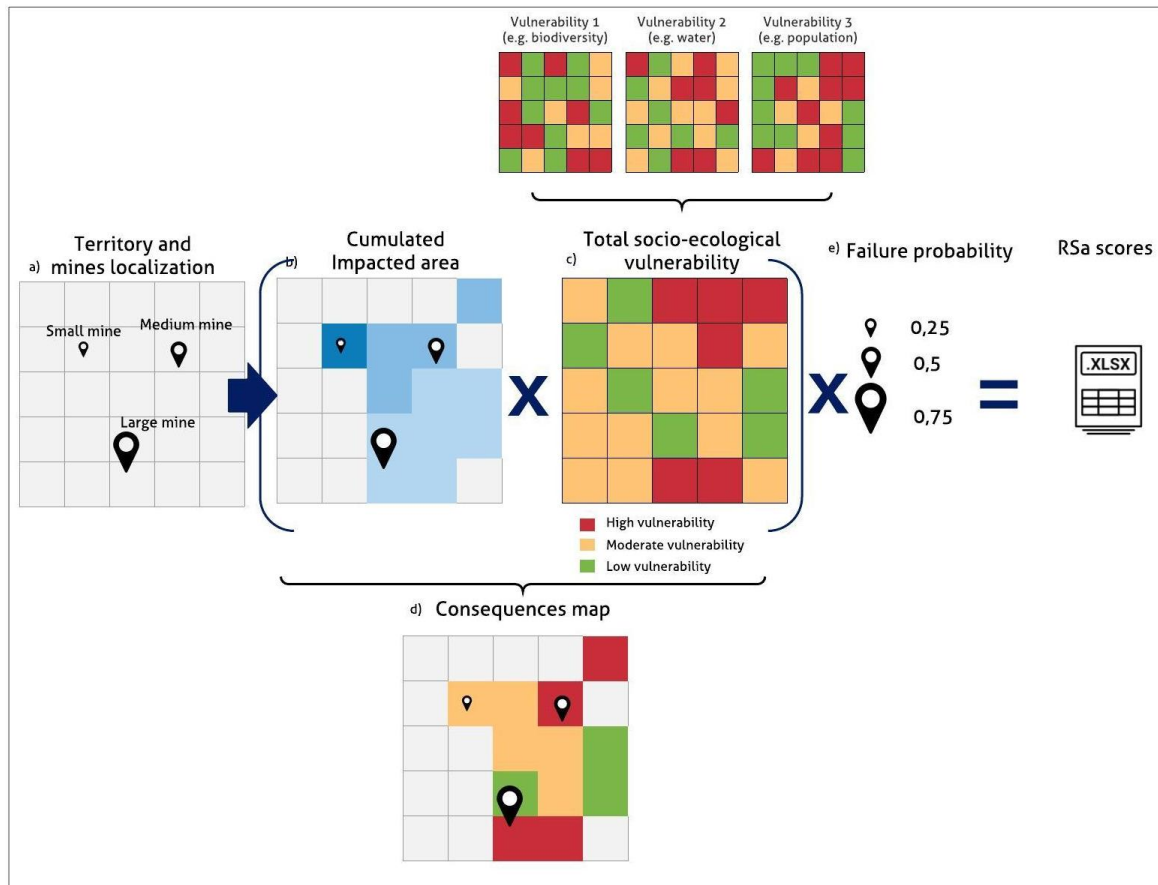


Figure 55 The assessment of the RSa is the result of the combination of different components. After the localization of the mine types on the territory (a), the estimation of the impacted area (b) and the assessment of the socio-ecological vulnerability of the territorial system (c) to obtain a consequences map (d). Finally, the integration of probability assumptions (e) to obtain a risk score for each TMS.

1. Assessment of dam failure consequences through vulnerability indicators

1.1. The spatial variability of the dam failure consequences: from the project to the territory

Direct and indirect consequences of dam failure (see the Glossary) can be both physically tangible and intangible. As mentioned, a consequence is the combination of the existence of an impacted areas and the vulnerability of the socio-ecological assets within this area.

Mining dam failure represents a good example of how an accidental event generated at the mine might physically overcome the mine site limits and impact the surrounding socio-ecological system. As shown by the Bow-Tie diagram previously presented in Chapter 6, the consequences of the failure affect the mine site, including the potential destruction of its infrastructures and the potential injuries of mine workers. These consequences affect mining operators, who might have to reduce or stop their activity. However, they might affect as well the local communities that rely on the normal functioning of the mine site for instance, as service providers, and on the revenues provided by local miners. If and when the flood exceeds the mine perimeters, it may have severe consequences on local population, public

infrastructures, soil and water resources, biodiversity and thus, the ecosystem services provided by them and the derived socio-economic services covering the needs of local population.

Concerning this territory level, two areas are distinguished, based on the type of consequences generated by dam failure. One impacted area is related to the direct consequences of the risk events and it is spatially represented by the flooded area due to the dam failure. The second impacted area is related to the indirect consequences that are caused by the occurrence of the flood and that might affect areas outside the flooded area. Finally, these negative consequences rebound on mining operators which, at last, can be charged of reparatory, compensation and reputational costs, legal proceedings, popular contestations that might jeopardize the mining activity, the success of the mining company and its shareholders and finally potential future business opportunities.

Because of the territorial dimension of our approach, the assessment of the RSa focuses on the consequences at the territory level. The estimation of project-scale risks is an important point of discussion that will be pointed out in the last part of this thesis.

1.2. Flood consequences and the corresponding indicators

The consequences considered for the current RSa are listed in Table 17. Six consequences are at the mine scale (c1, c2, c3, c16, c17 and c18). These six consequences are not georeferenced because either they occur at the mine site (c1, c2, c3) – in which case no spatialized description at the scale of the mine site is available in this approach at this stage – either they could not be spatially assessed in this study because of unavailable data (c16, c17, c18)

The remaining consequences are at the territory level, i.e. outside the mine site. As mentioned, and they can be direct or indirect and might overcome the flooded area. As shown in Table 17, consequences are structured in a chain of events and they have different natures (e.g. social, environmental). In this study, consequences are assessed through the estimation of the flooded area and the level of socio-ecological vulnerability of Mana river basin, defined as its susceptibility, based on its social and biophysical conditions, to experience damage from a given event, in this case, the failure of the dam (Muller *et al.*, 2011; Behanzin *et al.*, 2016).

Territory vulnerability to flood can be assessed based on different methods, as reviewed by (Nasiri *et al.*, 2013) and existing frameworks (Graham, 1999; FEMA, 2012). In this study, an indicator-based approach has been adopted. Table 17 presents vulnerability indicators that have been identified and selected for each consequence, based on scientific literature (Appendix 3) and on the currently available data for the Mana river basin. These indicators can be quantified through different methods, such as numerical modeling, direct measure surveys, remote observations, etc.. For instance, population vulnerability to floods has been assessed and discussed by Muller *et al.*, (2011)–based on empirical methods or throughout surveys. Kumar, (2002) pointed out that floods due to mining dam failures might contribute to the

outbreaks of typhoid – and other water-borne diseases as cholera, jaundice and dysentery – especially due to pollution of domestic water by domestic and industrial waste. Thus, health-related consequences of a tailings dam failure can be indicated by the number of typhoid cases in a territory. Vulnerability of public infrastructures and roads has been estimated based on buildings characteristics (Kreibich *et al.*, 2009; Muller *et al.*, 2011) or roads serviceability (Benedetto and Chiavari, 2010; Balijepalli and Oppong, 2014; Singh *et al.*, 2018).

Socio-ecological vulnerability related to water quality can be assessed analyzing the amount of specific heavy metals that can be remobilized in sediments and surface water resources (Gallay *et al.*, 2018; Goix *et al.*, 2019; Niane *et al.*, 2019), water turbidity Rudorff *et al.*, (2018) or the impacts on aquatic biodiversity (Brosse *et al.*, 2011). Soil erosion can be commonly estimated based on the revised universal soil loss equation (RUSLE) (Renard *et al.*, 1997; (Ganasri and Ramesh, 2016; Almagro *et al.*, 2017; Hermann *et al.*, 2018; Karan *et al.*, 2019) or through parameters such as infiltration/ runoff balance as indicator of soil erosion control (Scammacca, 2017).

These were just few examples to show the great variability of indicators that can be used to estimate the selected consequences. The indicators selected in this study are given in Table 17, along with the already available data used for their estimation., No supplementary field surveys or particular numerical investigations have been realized.

Table 17 Consequences for the RSa in this study, the source and target actor, their spatial dimension and the indicators selected for their assessment. In italic, the consequences not assessed in the demonstrative application. In particular, RSa_nc1 to 3 and 16 to 18 are at the scale of the mining project and it has been chosen to do not include them

Code	Consequence description	Source actor	Target	Spatial scale	Vulnerability indicator	Source of the data used for the assessment	
<i>c1</i>	<i>Destruction of the dam</i>	<i>Operator</i>	→ <i>Operator</i>	Project	<i>Dam cost</i>	<i>Appendix 5</i>	
<i>c2</i>	<i>Direct death and injuries of workforce</i>	<i>Operator</i>	→ <i>Operator</i>		<i>Maximal n° of workers at mine site</i>	<i>Appendix 5</i>	
<i>c3</i>	<i>Destruction of mining infrastructures</i>	<i>Operator</i>	→ <i>Operator</i>		<i>Total CAPEX</i>	<i>Appendix 5</i>	
c4	Direct impact on local population	Operator	→ Civil Society	Territory	within FA	Population density per land-use type	Insee, 2015; Audeg, 2016; ONF 2017; Audeg, 2018; 2013, private data; https://data.gouv.fr consulted the 11.04.2019
c5	Degradation of public infrastructures (buildings, roads)	Operator	→ Civil Society		within FA	N° and type of buildings and roads	Adapted from https://eauguyane.fr
c6	Reduction of surface water ecosystem services	Operator	→ Ecosystem		within FA	Expert-based ecological and chemical status of surface water	Georeferenced from Blancaneaux, 2001; Marius, 1966; Marius, 1969; Blancaneaux <i>et al.</i> , 1973; Turenne, 1973
c7	Run-off and soil degradation	Operator	→ Ecosystem		within FA	Soil permeability	Balland <i>et al.</i> , 2005; Parizot, 2011; WWF, 2013; SISE and ARS, 2015 (private)
c8	Reduction of drinking water public provisioning service	Operator	→ Civil Society		outside FA	N° of people dependent from the public water points	ARS, 2013; ARS, 2016
c9	Reduction of drinking water provisioning service (other than public)	Operator	→ Civil Society		outside FA	Number of households without available public drinking water	Adapted from ONF, 2015
c10	Reduction of biodiversity-related ecosystem services	Operator	→ Ecosystem		within FA	Biodiversity potential (ONF, 2015)	Adapted from ONF, 2015
c11	Reduction of forest-related ecosystem services (wood production)	Operator	→ Ecosystem		within FA	Wood quality (ONF, 2015)	Adapted from ONF, 2015
c12	Reduction of esthetic ecosystem services (landscape degradation)	Operator	→ Ecosystem		within FA	Landscape quality (ONF, 2015)	Adapted from ONF, 2015

c13	Reduction of crop production service	Operator	→	Civil Society	within FA	Soil agronomic potential	Georeferenced from Blancaneaux, 2001; Marius and Arthur, 1966 ; Marius, 1969; Blancaneaux <i>et al.</i> , 1973; Turenne, 1973
c14	Health Impacts	Operator	→	Civil Society	outside FA	Typhoide vulnerability (ARS, 2012)	Georeferenced from ARS, 2013
c15	<i>Social struggle</i>	<i>Operator</i>	→	<i>Population</i>	<i>outside FA</i>	<i>Avg worker salary (= potential loss of incomes for local families)</i>	<i>Not available</i>
c16	<i>Social opposition</i>	<i>Civil Society</i>	→	<i>Operator</i>	<i>outside FA</i>	<i>N° of participants in opposition groups</i>	<i>Not available</i>
c17	<i>Public sanctions</i>	<i>Public authority</i>	→	<i>Operator</i>	<i>outside FA</i>	<i>Maximal sanctions stated by law</i>	<i>Not available</i>
c18	<i>Financial loss for the operator</i>	<i>Operator</i>	→	<i>Operator</i>	<i>Project</i>	<i>i12+ refused permits + compensation measures</i>	<i>Not available</i>

2. Calculation of the flooded area

A consequence is the combination of two elements: an impacted areas (i.e. a flooded area) and the vulnerability of the socio-ecological components of the territory system within this area. This section presents the assessment of the estimated impacted areas. First, a general presentation of existing current methods is presented. Then the methods selected for this current application and the results are presented and discussed.

2.1. Literature review of existing methods to estimate the flooded area

Dam failure is a complex phenomenon to analyze and the methods to assess and map flooded areas are widely diversified (Razack, 2014). From a general point of view, these methods are usually based tools that are not specific to mining and involve the coupling of hydrological (e.g. rainfall-runoff balance analysis) and hydraulic modeling (e.g. water level, flood velocity and propagation, dam break outflow assessment), based on fluid mechanics (Pilotti *et al.*, 2014; Liu, 2018) and uncertainty analysis. These methods might involve the assessment of floods generated by different types of dams. Sometimes they are inspired from natural flood management practices. For instance, specific national guidelines have been realized to address dam flood management in U.S. (Wahl, 1998; FEMA, 2012; FEMA, 2016), India (CWC, 2018), Australia (DNRME, 2008) and they could be applied to mining dam failures.

Most of the methods used to estimate the area flooded by a dam failure are synthetized in the bibliographic review presented in Appendix 11. One of the most used models is HEC-RAS, developed by the U.S. Army Corps of Engineers, that allows detailed computation to identify the flooded area (Duressa and Jubil, 2018). Also, DMBRK, FLDWAV or MIKEFLOOD (Razack, 2014) allow precise assessment based on the characteristics of the study area and on the geometry of the dam. A simplified and performant version of these models is SMPDBK, which requires less input data (e.g. stream centerline, cross sections, and information regarding the storage and failure of the dam being modeled). Globally, such methods might demand a considerable amount of data such as dam characteristics, dam break parameters and its geometry, land use and coefficients for soil roughness (i.e. Manning values), and boundary conditions (e.g., discharge, water level) ((Zhu, 2004; Dorn *et al.*, 2014).

Besides computational models, even more detailed analysis might involve experimental modeling for fluid-dynamics and rheological studies, in order to understand the movement of the flow on the terrain, especially in the case of tailings dam failure, where the outflow is not only composed with water (Liu, 2018). Blight *et al.*, (1981) suggest a mathematical model to describe flow of tailings slurry from a breached dam. In other cases, specific physical and experimental modeling are developed to address failures caused specifically by overtopping (Wu and Qin, 2018; Larese *et al.*, 2019).

All these methods might be very complex, time-consuming, based on precise information of the dam and they are often performed at the scale of the dam itself. New broader-scale models and modules have been developed over the years directly in GIS softwares (Schauble *et al.*, 2008). Tools such as FloodGIS (Albano *et al.*, 2019) , FloodRisk (Mancusi *et al.*, 2015), Geomorphic Flood Area Tool (Samela, 2018) or the specific module for GRASS GIS called *r.damflood* (Marzocchi *et al.*, 2013) can be used in substitution to the computational models mentioned before, especially for assessment at larger scales. These GIS-based tools are often open-source and in some cases, they might allow as well the assessment of the consequences of the flood on population and the environment. Other modules might be used to obtain information in order to assess the flood-prone areas, such as the module Maximum Flow Path Length (Lindsay, 2016) based on direction equations. Among GIS-based models, for instance, El Morjani *et al.*, (2007) suggest an interesting and easy-to-apply framework to estimate an index at the country level based on a statistical approach requiring broad-scale data concerning land use and cover, DEM, soil type and texture, lithology, flow accumulation volume and distance from the accumulation path and rainfall data.

Concerning the specific application to mining dams, Concha Larrauri, (2017) and Concha Larrauri and Lall, (2018) propose a method for estimating the reach of a mining dam failure using only terrain data, the capacity of the pond and the height of the dam. This method uses algorithms based on the updating of the empirical equations by Rico *et al.*, (2008b) using historical dam failure accident data. To our knowledge, it is the only method specifically developed for tailings dam failures that have been found so far in the literature and that allows the large-scale assessment of flooded areas. Furthermore, the method can be applied on multiple coexistent mines.

Since the purpose of this study is to test the feasibility of our approach, no detailed information is needed. Therefore, considering the limitations of the mentioned models requiring important input data, we decided to use the method proposed by Concha Larrauri, (2017) for the estimation of the flooded area.

2.2. The method used to estimate the flooded area

In this study, two methods are used, based on empirical equations derived from historical tailings dam failure databases, relief, and expert-based GIS processing of flow accumulation areas. Both of the methods represent easy-to-use and GIS-based tools relying on few input data such as dam height and storage capacity (available in Table 10) and the Digital Elevation Model (DEM), available by NASA's SRTM. They are not to be considered as substitutive of more precise and detailed hydrological and hydraulic methods for flood-prone areas identification.

Fig. 56 presents a simplified conceptual flowsheet of the two methods used in this study to estimate the flooded areas due to a mining dam failure. The first selected terrain-based method is proposed by Concha Larrauri, (2017) and Concha Larrauri and Lall (2018). It involves the estimation of the volume released by the failure and the maximal run-out distance of the tailings per quartiles (Q50, Q25, Q75) (Fig. 57). The required input data concern both the technical features of the mine and, thus, of the mining dam (i.e. stored volume and dam height) and the characteristics of the surrounding environment (i.e. DEM). The mining dam parameters (e.g. dam height and storage capacity, as from Table 18) have been directly input on the web application <https://columbiawater.shinyapps.io/ShinyappRicoRedo/> in order to obtain the released volume and the run-out distance. The quartile used for this study is the Q50, which represents the median, which is considered as more solid than the simple average in the case of asymmetric distributions. The spatialization of the resulting outputs consists in a buffer area whose centroid is the mining project and whose radius is the maximal run-out distance of the tailings. Finally, the zones within the buffer with higher elevation than the total elevation of the mining dam are erased. The total elevation of the dam is the sum of the dam height and the elevation value of its localization. Since the selected dam failure mode is overtopping, dam freeboard has not been subtracted by the total elevation of the dam. However, since elevation is the only external factor influencing the surface of the flooded area, this method allows only to obtain a very large area potentially flooded. Furthermore, no distinction between upstream and downstream is done, which makes difficult to understand the flowpath followed by the flood and, hence, the areas actually impacted. Therefore, the large flood area obtained from this first method is coupled to a second method in order to furtherly precise the flooded area.

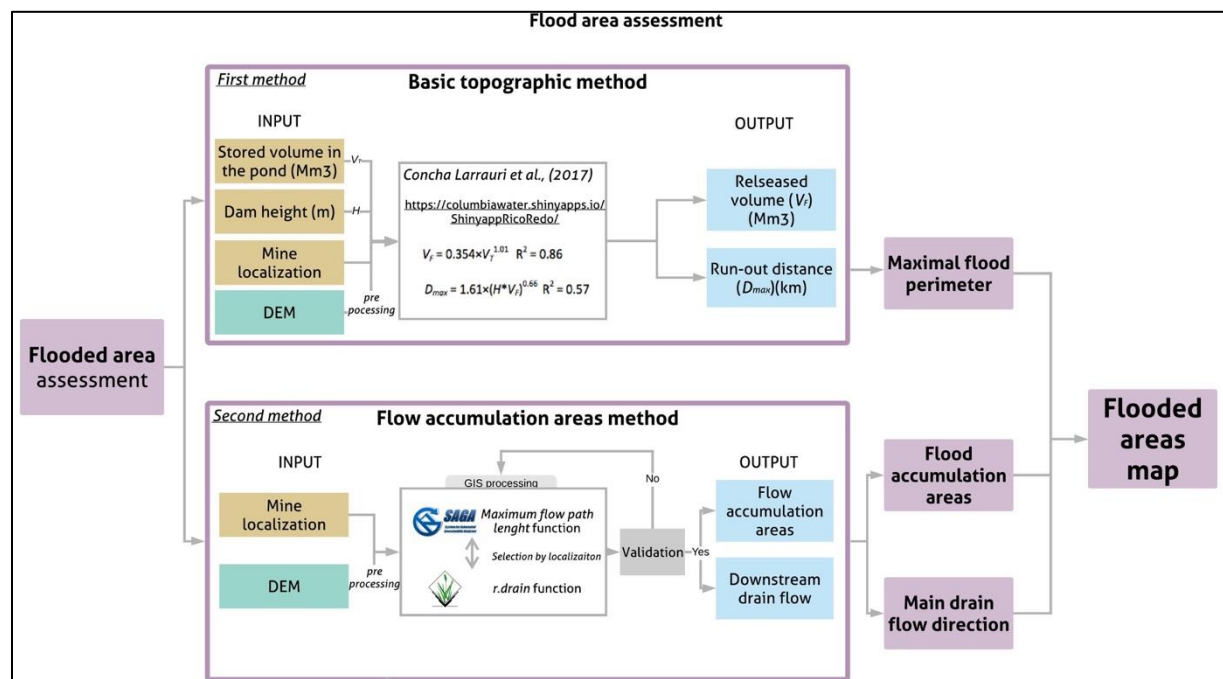


Figure 56 Simplified conceptual flowsheet of the coupled methodologies used in this demonstrative application to estimate the flood-prone areas due to a mining dam failure by overtopping.

Predict volume of released tailings

Input volume of tailings in million m³

100

Predicted released volume in million m³

Q50	Q25	Q75
27.00	15.70	46.30

Predict run-out distance

Input Height in m

54

Predicted run-out distance in km. This is calculated with the median predicted value of VF

Q50	Q25	Q75
79.00	26.20	237.90

Figure 57 Screenshot of the results obtained for the estimation of the flooded area for the TMS-A, based on the first method (Concha Larrauri et al., 2017) on the website: <https://columbiawater.shinyapps.io/ShinyappRicoRedo/>. The predicted values are estimated in quartiles (Q50, Q25, Q75). We use the average value of the Q50.

Table 18 Input and Output per gold mine-type for the estimation of the released volumes and maximal run-out distance of the tailings based on Concha Larrauri, (2017)

Mining dam features	Code	Unit	Mining project types				
			i-ASM	ASM	MSMg	MSMc	LSM
Input							
Dam height	H	m	4	4	15	20	54
Storage capacity	Vt	Mm ³	500,000	500,000	1.5	2	100
Output							
Released volume	Vf (Q50)	Mm ³	0.2	0.2	0.5	0.6	27
Maximal run-out distance	Dmax (Q50)	km	1.4	1.4	4.9	6.6	79

We developed a second method through GIS processing using open access GIS modules from Qgis and Whitebox Geospatial Analysis (WGA) tools. This method is relief-based as well, but it allows to identify the downstream path of the flood and the areas of flow accumulation, based on the DEM. The only input data used, except the localization of the mining dam, consist in the DEM. The main steps of GIS processing performed are the following:

1. The *Maximum Flow Path Length* (MFPL) SAGA module is used in QGis to calculate, based on the DEM, the maximum downstream/upstream distance or weighted distance along the flow path for each map cell based on “Deterministic 8” (D8) flow directions (O’Callaghan and Mark, 1984) (Fig. 58a). The module’s output is a raster whose values describe the upstream/downstream flow path length from a cell to the outflow.

However, because of the initial data used, the module does not give any information concerning water level. In the current application, repeated tests and observations of elevation profiles (through the module *Profile Tool*) suggest fixing a specific value to the output values of the MFPL module in order to obtain flow accumulation areas. These accumulation areas represent the flood-prone zones. Since the MFPL module is only based on the DEM, these accumulation zones are not dependent on the localization of the mining dam, dam height or the run-out distance of the tailings.

2. The output of the MFPL is then coupled to the maximal flood perimeter obtained from the first method (Concha Larrauri *et al.*, 2017) (Fig. 58b). This allows to integrate the data related to the mine-type used for the first method, which concern technical features that vary according to each gold mine. Thereby, the extension of the flood areas can be differentiated according to each mine-type and, thus, to each TMS.
3. The third step involves the estimation of the preferential flow direction of the flood using the WGA tool or the GRASS *r.drain* function already available on QGis (Fig. 58c). The estimation is based on the localization of the mine site (as a point layer) and it results in a flow direction polyline.
4. Finally, all the accumulation zones which are not adjacent, crossing, intersecting and touching the polyline of the preferential flow direction (fig. 58c) are erased. This step is monitored through the *Profile Tool* module and it allows to filter and select only the accumulation areas along the estimated direction of the flood (Fig. 58d).

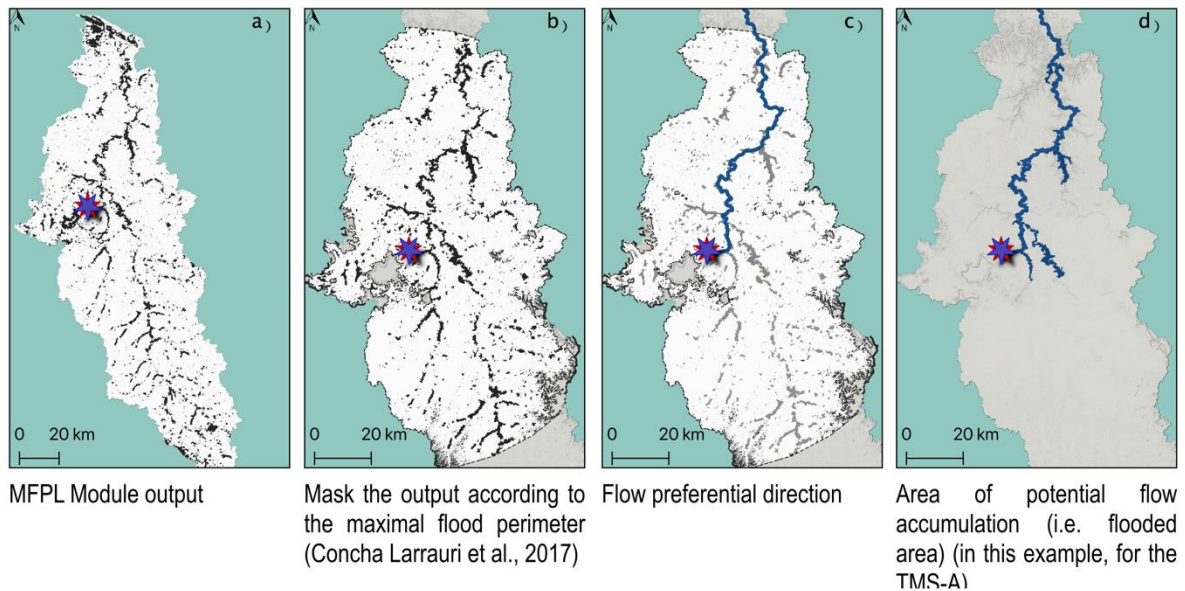


Figure 58 Example of the steps followed for the estimation of the flooded area according to the second method here presented

2.3. Validation by comparison with the Brumadinho tailings dam failure

The combination of the two methods used in this study have been tested before on the tailings dam failure of the Córrego do Feijão iron ore mine, near Brumadinho (Brazil). It has been mentioned that at this stage, our purpose is to show the feasibility of the approach proposed in this thesis with the data currently available. This means that the level of precision of the assessment and of this comparison with a real tailings dam failure event is subjected to uncertainties that must be quantified in further studies.

The tailings dam concerned by the failure is the *N°1* with a height of 86 meters and a total capacity of 11,7 million cubic meters of tailings. The dam was not active at the moment of the failure. The failure occurred on January 25th, 2019, releasing almost its complete holdings and killing more than 250 people. The slurry wave traveled approximatively 7 to 10 km downhill until Rio Paraopeba (Du *et al.*, 2020; Rotta *et al.*, 2020; Thompson *et al.*, 2020). Among recent studies concerning the failure, Raman and Liu, (2019) simulated the failure with the HEC-RAS model, obtaining a great similarity between observed and modelled inundation patterns.

Table 19 shows the outputs estimated from the first method used (i.e. Concha Larrauri, 2017) compared to the real failure event characteristics (Fig. 59a). The estimated values concerning the run-out distance traveled by the tailings are much greater than the actual ones. For instance, based on the real parameters of the dam, the released volume (Q50) is underestimated at 3.5 Mm³, instead of 11,7 Mm³. On the contrary, the run-out distance is highly overestimated (131.6 km against 7-10 km). Even if we assume, as suggested by the model, that 3.5 Mm³ of slurry are released, the estimated run-out distance appears much higher than the real one (35.2 against 7-10 km). However, despite the immediate run-out distance is about 7-10 km, considering the physical accumulation of tailings, the impacts have been recorded over longer distances by recent studies (Thompson *et al.*, 2020)

Table 19 Input and outputs based on the method proposed by Concha Larrauri, (2017) on the case of Brumadinho tailings dam failure and comparison with the real values of the failure.

Mining dam features	Code	Unit	No.1 Corrego de Feijao tailings dam (ESTIMATED)	No.1 Corrego de Feijao tailings dam (REAL)
Input				
Dam height	H	m	86	86
Storage capacity	Vt	Mm ³	11.7	11.7
Output				
Released volume	Vf (Q50)	Mm ³	3.5	11.7
Maximal run-out distance of 3.5 Mm ³ assumed released	Dmax (Q50)	km	35.2	7-10
Maximal run-out distance of 11.7 Mm ³ assumed released	Dmax2 (Q50)	km	131.6	7-10

Concerning the second method, Fig. 59 shows the cartographic results of the estimated accumulation zones (Fig. 59b) overlapping the actual flooded area (Fig. 59c). DEM has been downloaded by NASA's SRTM.

The validation of the proposed method is object to discussion. Indeed, first of all, the comparison between the estimated and the real flooded areas should be based on preliminary criteria (e.g. surface of the flood area, direction and flow geometry). Also, in terms of surface, the difference between the real ($\sim 2\,500\text{ km}^2$) and the estimated flooded areas ($\sim 1400\text{ km}^2$) corresponds to more than 50% of the real flooded area. The direction of the flow is obviously driven by the terrain and it is well considered by the proposed method.

The surface difference can be partly justified by the fact that the proposed method does not account for the topographic depressions due to the alterations induced by the development of the mine site which represent an immediate sink of flood accumulation (Fig.59c). Moreover, the underestimation of the real flooded areas is due as well to the fact that the proposed method does not include flow speed and flood water level, which might be greater than the aptitude of the topography to contain the flood. Finally, although the flooded area is underestimated, its length is overestimated since initial water level is not used as input data.

Despite such considerations, it has been said that the purpose of this study is to show the feasibility of our approach. The methods combined in the thesis to obtain the flooded area do not substitute more solid existing methods. Yet, they allow to obtain the values for the estimated area of a flood that is sufficiently reliable for the objectives of our current study.

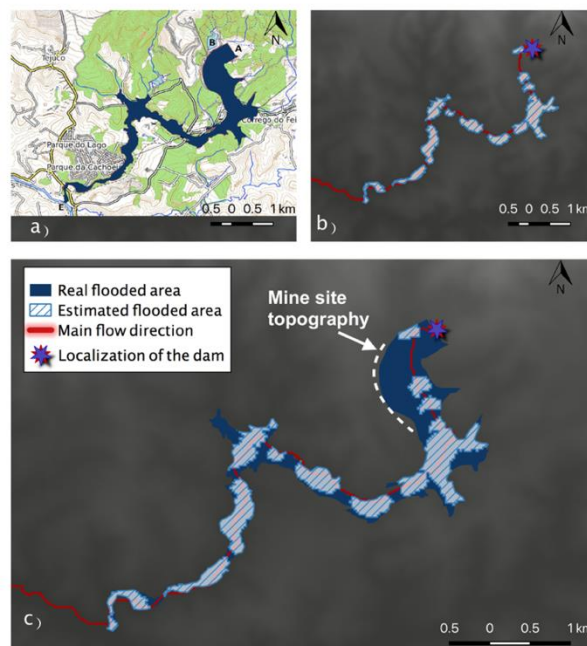


Figure 59 Comparison between the real flooded area from the Brumadinho tailings dam failure (a) and (b) the area estimated based on the second simple method proposed in the current demonstrative application of the methodology. Finally, the overlapping of the real and estimated areas allows a full comparison, emphasizing the limits of the method here used (c).

2.4. Practical estimation of the flood area

Table 18 shows the input and the outputs of the first method (Concha Larrauri, 2017) for each mine-type. Clearly, the outputs of the first method – used to determine the maximal potential perimeter of the flood – increase proportionally to the mine-type and its size. However, it must be pointed out that this method has been developed based on data of historical failures of LSM mines. Therefore, its suitability to smaller mining projects (e.g. ASM, MSM) must be quantified with its uncertainty. Furthermore, the increase of the results for each mine-type is not proportional to the increase of the values of the inputs. This means that, despite it is not the purpose of this study, the interactions between the parameters and their influence on the results must be quantified, for instance, through a sensitivity analysis. The values of the maximal run-out distance represent the radius of the maximal perimeter impacted by the flood for each gold mine type.

The maps of Figure 60 represent the application of the two methods used for the estimation of the flooded areas for each TMS. The methods for the estimation of the flooded area are applied to each mine in each TMS independently, and then the identified areas are merged on Qgis. Thereby, the flooded area considered for each TMS is represented by the total area flooded by the dam failures generated by the corresponding gold mine-types. Finally, for each TMS, the flooded area is classified (1 to 5) based on its surface (Table 20). This latter step is important because it will be integrated for the assessment of the final score of the RSa.

Among all the TMS, the TMS-A presents the largest flooded surfaces, while the artisanal scenario (TMS-C) has the smallest. In terms of potential consequences, there is no comparison between LSM and ASM mines, even when the ratio of their distribution is 1:33, such as in this study. TMS-B, TMS-D and TMS-illegal present approximatively an equivalent total flooded area, despite the great difference in the number and the distribution of the mine-types.

Despite, LSM (TSM-A) have the greatest flood area, it must be pointed out that, because of their often significant financial and technical resources compared to the other gold mine-types, they are susceptible to implement better and more efficient safety measures. This has not been integrated in the application of our approach at this stage and it will be discussed in Chapter 11 of this thesis. Indeed, safety measures may reduce the probability of occurrence of the failure, reducing the global RSa score.

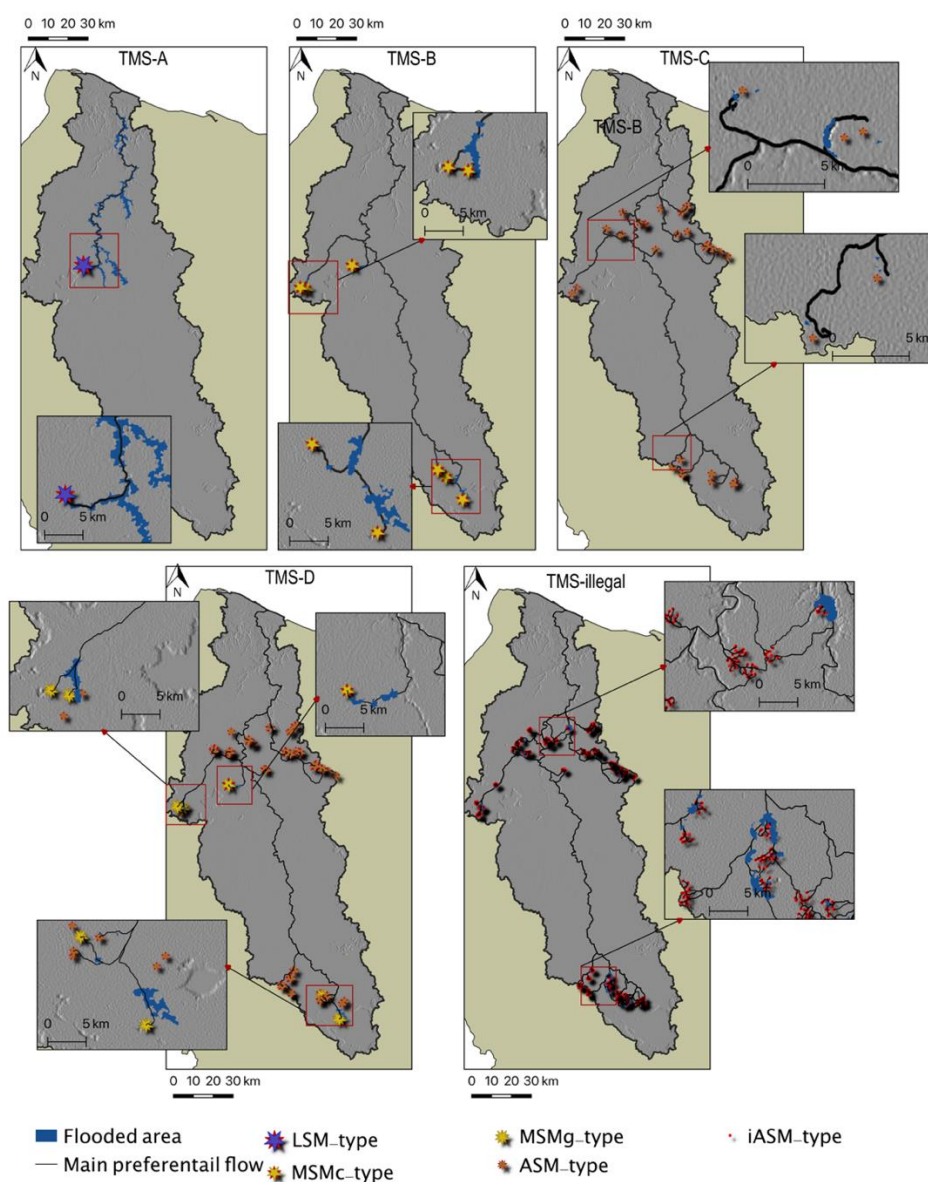


Figure 60 Assessment and cartography of the flooded area per each TMS based on the mentioned methodology here used

Table 20 On the left, the thresholds and ranges used to classify the level of consequences for each TMS according to the surface of the flooded areas. This parameter will be integrated at the end of the RSa assessment to obtain the global RSa score per TMS

Classification thresholds		Scenarios	Flooded area (km ²)	Class
Class	Range (km ²)			
1	< 1.00	TMS-A	227.76	5
2	1.00 – 5.00	TMS-B	32.89	3
3	5.01 – 50.00	TMS-C	4.35	2
4	50.01 – 100.00	TMS-D	22.71	3
5	> 100.00	TMS-illegal	35.76	3

3. Mapping socio-ecological vulnerability to flooding

The second component of consequence assessment is the estimation of the socio-ecological vulnerability of the territory where the gold mines are located. Socio-ecological vulnerability is here the susceptibility of the territory to experience damage from a given event (Muller *et al.*, 2011; Behanzin *et al.*, 2016). It is assessed through the quantification of specific indicators for each consequence, as presented in Table 17.

The following sub-sections present the general frameworks, with few examples, developed for the quantification of the vulnerability indicators both within and outside the flooded area. The assessment is based on the semantic and spatialized data concerning soil and water quality, population density etc., provided by local stakeholders or collected through bibliographic reviews and field visits, as presented in Appendix 5.

3.1. Assessment of each vulnerability indicator

Because of the territorial scale of the assessment and the limited available data, already existing thresholds adapted to mining activities in FG have not been found. Furthermore, the few existing thresholds currently available (e.g. water and soil quality) to estimate the potential socio-ecological consequences of mining activities are in some cases qualitative, expert-based and not suited for our purposes. Therefore, specific methods have been purposely built for the assessment of each vulnerability indicator, in adaptation to the FG context. Fig. 61 shows the general framework used for each assessment method. The set of data (which is presented in Appendix 5) involves both semantic and spatialized information in order to allow a GIS-based representation. The assessment of each indicator is performed both quantitatively or qualitatively, depending on the initial data. In this chapter, just few examples of the developed methods to estimate of each vulnerability indicators are given (Fig.62, 63, 64, Appendix 12).

The results of the assessment are normalized and then, the vulnerabilities are converted to a set of scores from 1 to 5, where 1 refers to low vulnerability, and thus, lower potential consequence and 5 refers to higher vulnerability and thus, higher potential consequence. In some cases, few assumptions have been made. For instance, in the case of surface water quality (c6), it has been assumed that the hydrological zones with a global good quality are susceptible to be more vulnerable: hence, in this application, surface water vulnerability is assumed as directly proportional to his quality. The conversion from the estimated values for each indicator to vulnerability scores is based on a matrix with thresholds specifically adapted to the FG case for each indicator.

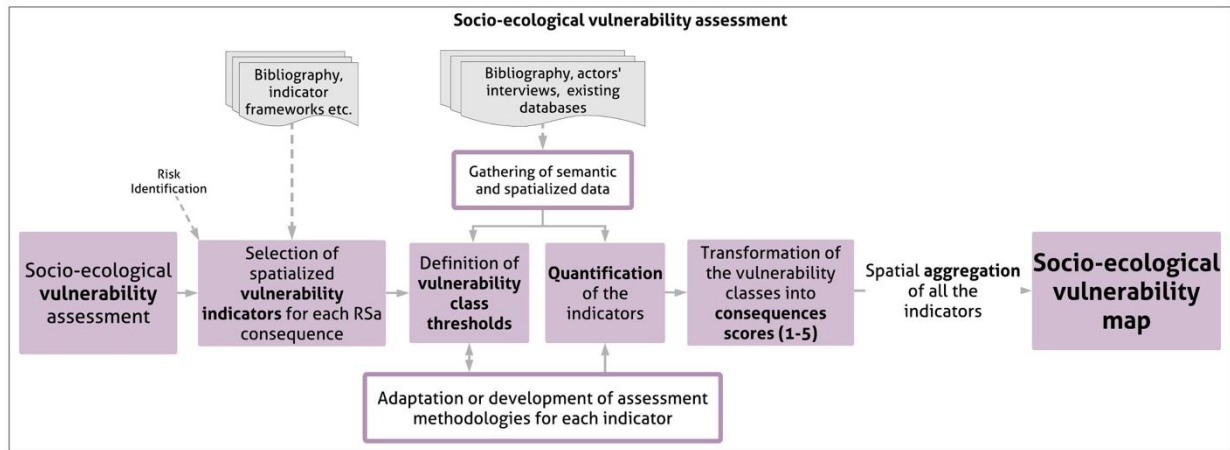


Figure 61 Simplified conceptual flowsheet of the methodology used for the assessment of socio-ecological vulnerability

For instance, the consequences of a dam failure-induced flood on local population might be here assessed based on population density and land-use, divided in three main categories: urban, agricultural, natural (Fig. 63). In other cases, when more data are available, this might be assessed knowing the population at risk but also warning time and evacuation measures different methods (Brown and Graham, 1988). However, no procedure is currently available to accurately predict the consequences of a dam failure on population. According to (Ge *et al.*, 2020), “such estimates are often no better than guesses”.

Another example may concern the consequences on soil-related ecosystem services (Fig. 64 and Appendix 12). These are estimated based on a method specifically developed in this study based of both georeferenced and semantic data from scientific literature. Concerning the first type of data, soil surveys and the related soil maps are limited in FG and concern mainly the coastal areas. Soil resources of the region are less documented also because of the difficulty of access for field surveys and sampling. The only map found on a regional level is a simplified soil map realized by Blancaneaux, (2001) that has been specifically georeferenced on Qgis. Synthetized and adapted semantic data have been associated to each corresponding soil map unit. The original semantic data (e.g. soil depth, texture, C/N ratio, pH) were collected through a throughout bibliographic review of the studies realized over the past 60 years through direct measurements, field surveys, numerical modeling (Marius and Arthur, 1966; Léveque, 1967; Marius, 1969; Blancaneaux *et al.* 1973; Turenne, 1973 ; Veillon, 1986; Bravard *et al.*, 1990 ; Veillon, 1990; Betsch, 1998; Leprun *et al.*, 2001; Ferry *et al.*, 2003; Guedron *et al.*, 2009; Grimaldi *et al.*, 2015; ONF, 2015).

In other cases, original data were already quantified and converted into semi-quantitative classes. For instance, Fig. 62 shows the semi-quantitative and spatialized data concerning the households without direct public drinking water provisioning (c9), according to ARS, (2013) and then adapted according to ARS, (2016). As it is shown, these data are directly converted into vulnerability classes. As another example, the original data used for the assessment of the socio-ecological vulnerability related to biodiversity, landscape quality and

wood production (*c10*, *c11*, *c12*) are based on the Catalog of forest habitats developed by ONF, (2015) which is briefly presented in Appendix 13.

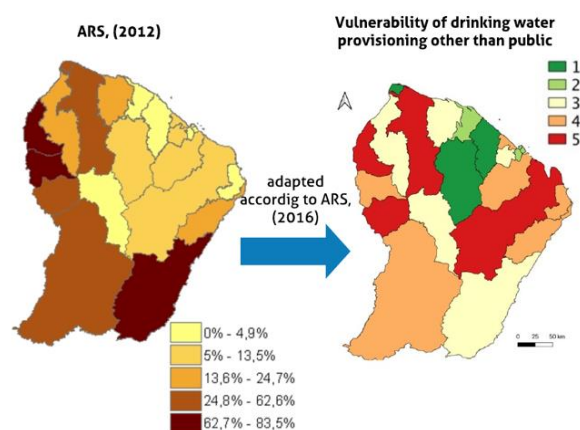


Figure 62 Example of extrapolation of data from already existing information. In this case, ARS, (2016) provides a cartography of the households without current drinking water on a municipality basis. The map has been georeferenced and adapted for the current demonstrative application of the proposed methodology

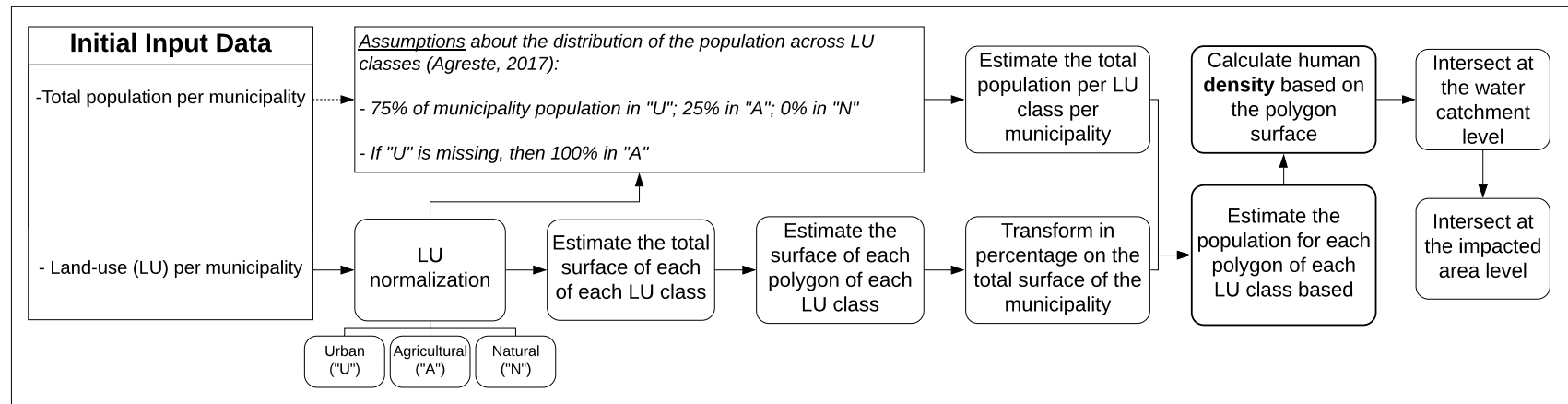


Figure 63 Flowsheet of the methodology specifically developed for the assessment of the "population density indicator" used for the estimation of social vulnerability related to the consequence "Impact on local population"

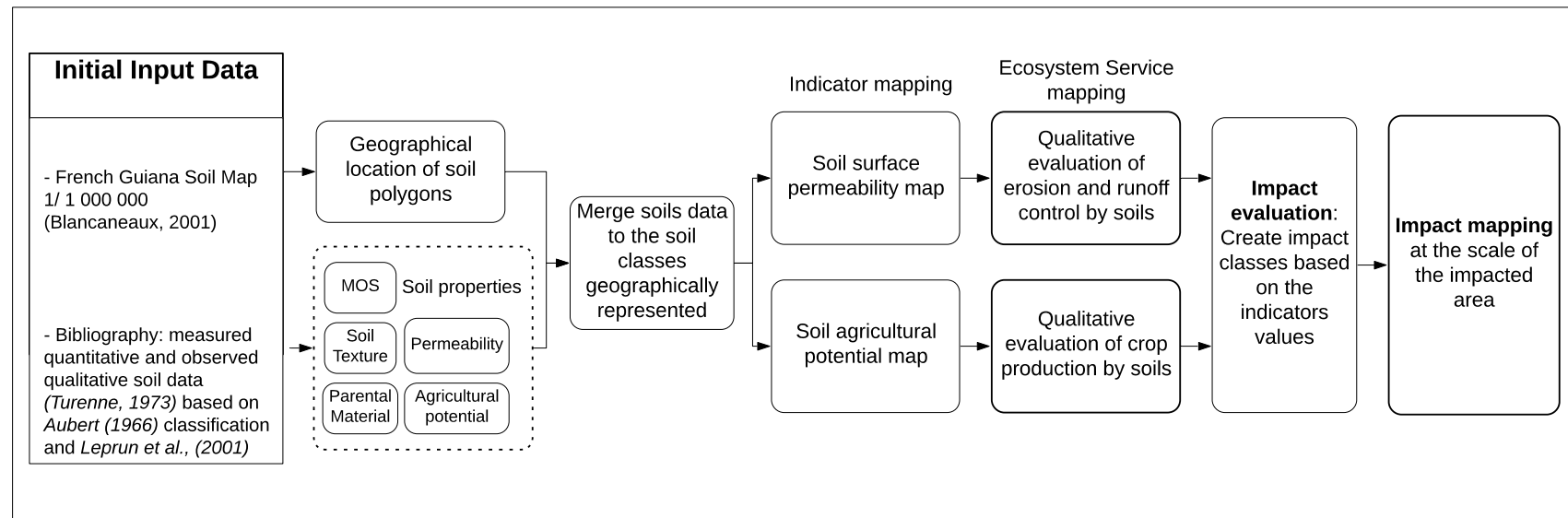


Figure 64 Flowsheet of the methodology specifically developed for the assessment of the "soil permeability" and "soil agronomic potential" used respectively for the estimation of socio-ecological vulnerability related to the consequences "Run-off and soil degradation" and "reduction of crop production service".

3.2. Mapping of the territorial vulnerability within the flooded area

Once each indicator has been assessed and converted into vulnerability classes spatially explicit, 11 maps are obtained (Fig. 65). As shown by the Figure, each map represents the corresponding vulnerability at the scale of Mana river basin, based on each indicator presented in the previous Table 17. All the maps are normalized on a scale from 1 to 5, where 1 refers to a lower vulnerability, and thus, lower potential consequences, while 5 refers to higher vulnerability and potential consequences.

The limits between each polygon depend on the spatial scale chosen for each indicator assessment – or the scale at which the original data were already set – and thus, its resolution. For instance, *c4* estimation is based on a simplified land-use map while *c8-9-14* are mapped based on the administrative boundaries of the municipal areas in FG. *c10-11-12*, on the contrary, have a higher resolution since they are based on a precise mapping realized by the ONF, (2015) through remote observations and local surveys.

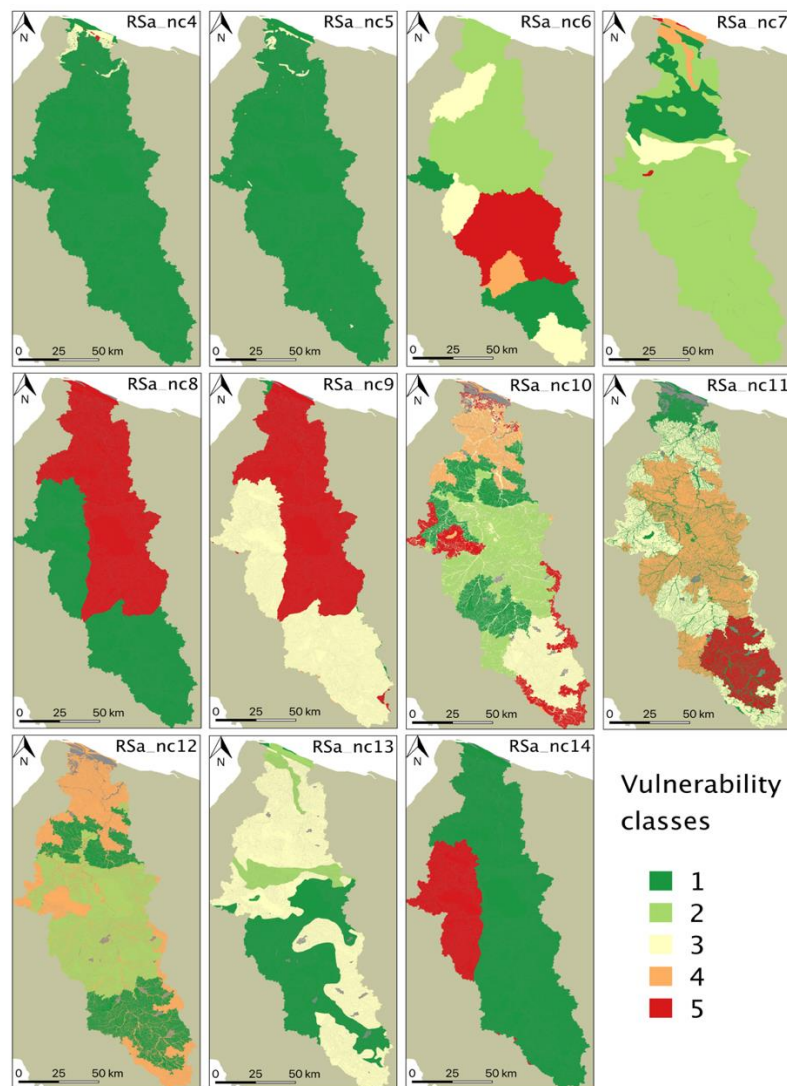


Figure 65 Assessment and mapping of each socio-ecological vulnerability indicators based on 5 vulnerability classes. These maps are independent from the mining system and on the TMS. Therefore, their applicability is extended to all TMS.

4. Estimation of the consequence scores of the RSa

The consequences of the RSa are assessed through the combination of a flooded area, which strongly depends on the mining system, and socio-ecological vulnerability of the territory system (Fig. 66). This process is achieved through geoprocessing methods in GIS software (e.g. intersection, vector masking).

The vulnerability scores are intrinsic to the territory system and, thus, do not change depending on the TMS. This means that the same vulnerability maps are applied to each TMS. On the contrary, the impacted area (i.e. the flooded area in this case) varies according to technical and operational parameters related to the gold mine-type and thus, for each TMS. This section presents the steps followed to obtain a global RSa consequence score from the simple individual vulnerability layers as presented in Fig. 65.

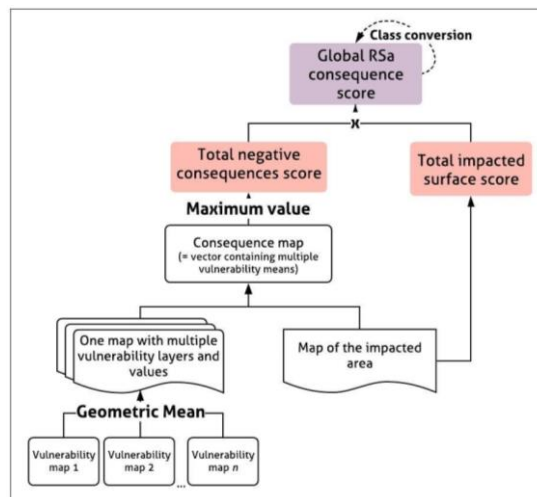


Figure 66 Aggregation methods used for the estimation of the global RSa score

4.1 Aggregation of the vulnerability scores to obtain total vulnerability map of the territory and combination with the flooded area maps

After their assessment and mapping (Fig. 65), the vulnerability maps are merged on Ggis to obtain an overall vulnerability map of the territory. The result is one map where each polygon represents the intersection of all the merged vulnerability layers (Fig. 67). Then, the geometric mean is calculated. This means that each polygon of the global vulnerability map contains the geometric mean of the vulnerability scores of all the used layer (Fig. 67a). Hence, at this stage, the vulnerability territory is given multiple different scores for each polygon of the map.

Fig. 67b shows the difference in results if the maximal value of each layers would have been calculated instead of the geometric mean.

The total vulnerability map (Fig. 67a) is combined on Qgis with the map of the flooded areas each TMS, as presented in Fig. 60. These represent consequence maps that contains a series of values according to the corresponding polygons. In order to be able to compare the TMS between them, these results must be reduced to a single score for each TMS.

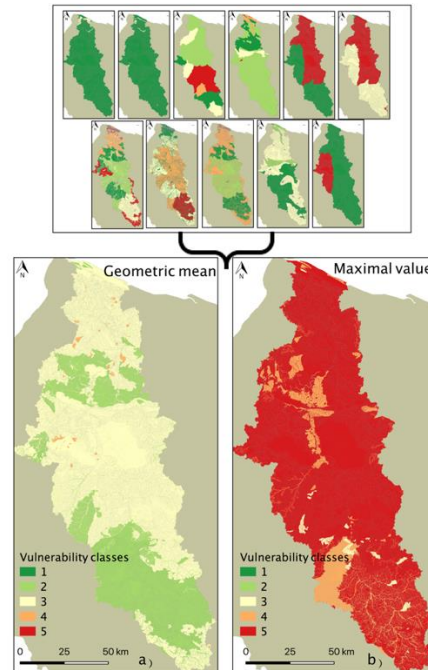


Figure 67 Aggregation of all the socio-ecological vulnerability indicators based on the simple methods of the « geometric mean » (a) and the « maximal value » (b)

4.3. Estimation of a final consequence score for the RSa

As shown in Fig. 68, the global RSa consequence score is obtained by combining the total impacted surface score and the total negative consequences score. The first one is given in Table 20. The second, on the contrary, is obtained reducing all the values of the geometric means contained in the maps that combine territorial vulnerability with the flooded areas for each TMS. Indeed, as mentioned, the fact that each consequence map is represented by multiple value makes it difficult to compare the TMS. Therefore, these are reduced to a single score by extracting the maximal value of all the geometric means (indicating the *worst* of the mean scores).

Since there is no need to have a spatial representation of this unique score, the final consequence score is calculated in sheets (Table 21). The total RSa consequences score is combined with the total impacted surface score – shown in the previous Table 20 – in order to obtain the global RSa consequence score for each TMS (Table 21). This score is then converted according to the following equation in order to compare the TMS based on a final score where 5 represent the best territorial scenario and 0 the worst.

$$\text{Converted score} = (\max - v) + \min$$

Equation 1

Where *max* is the maximum value of the negative score (i.e. 5), *v* is the corresponding value to convert and *min* is the minimum value of the negative score (i.e. 1 or 0 depending if the conversion is on the vulnerability or risk scores) (Table 22).

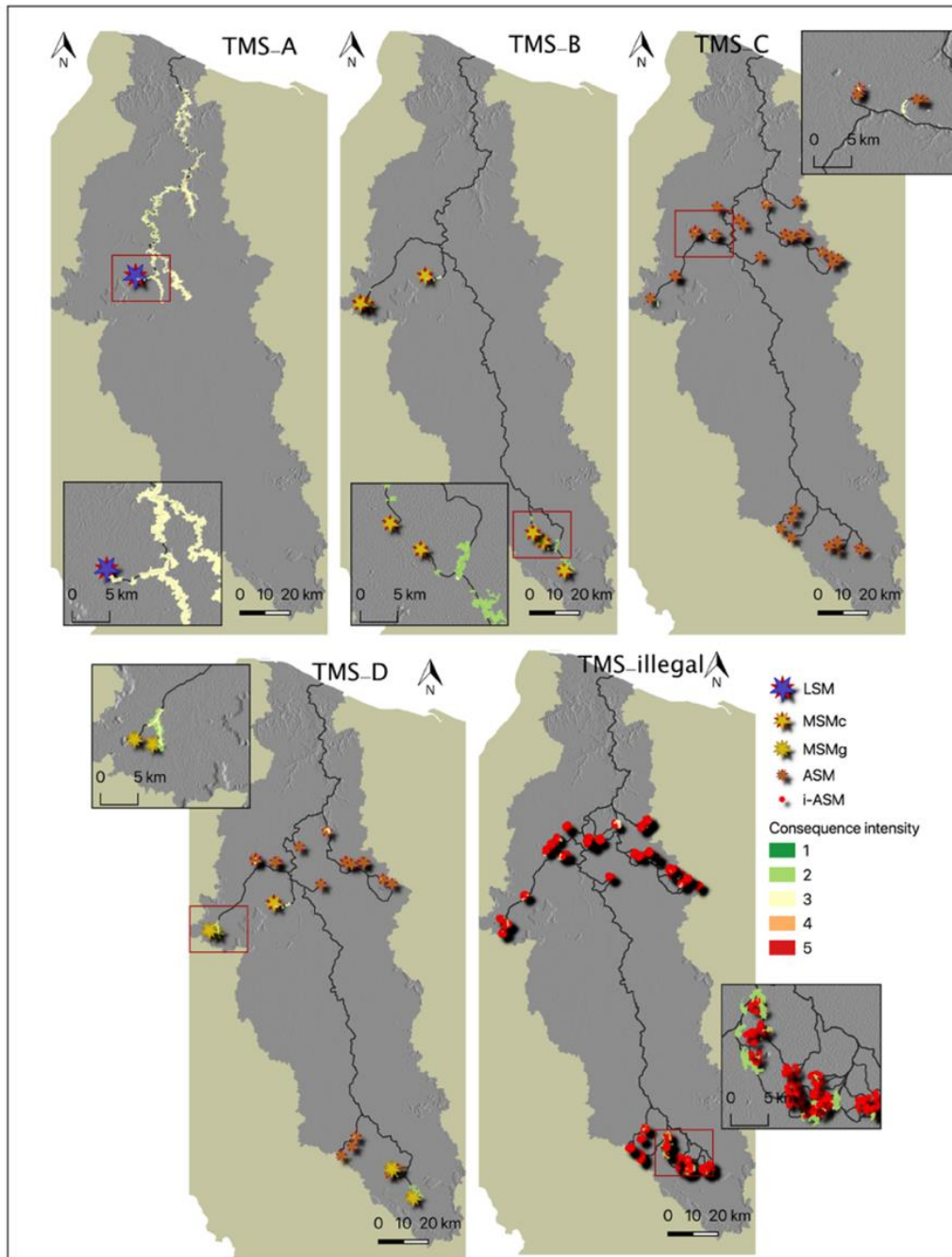


Figure 68 Assessment and mapping of the consequences generated by the dam failure caused by overtopping for each TMS. It is the result of the combination of the flooded area maps and the socio-ecological vulnerability map

Table 21 All the consequence scores combined to obtain the converted global RSa score for each TMS.

	Scores per Territorial Mining Scenarios (TMS)				
	TMS-A	TMS-B	TMS-C	TMS-D	TMS-illegal
Total RSa impacted surface score	5	3	2	3	3
Total RSa consequences score	3.3	2.5	2.5	2.5	2.7
Global RSa score	3.3	1.5	1	1.5	1.6
Converted global RSa scores	1.7	3.5	4	3.5	3.4

Table 22 Conversion rules of the negative consequences

	Original negative classes	Converted negative classes
Less negative	1	5
	2	4
	3	3
	4	2
Very negative	5	1

5. Probability assessment and risk estimation

As mentioned, a risk is considered as the combination of the consequences of a risk event and its probability to occur. The evaluation of the RSa level now implies the estimation of the dam failure probability. In the case of the RSa, the integration of the probability is more complex compared to the RSo. Since it is an accidental scenario, a fundamental step is to identify the factors triggering the dam failure by overtopping, to analyze their interaction and assess the actual probability of occurrence. As mentioned in Chapter 6, the failure rate of tailings dams (1.2%) is much higher than water dams (0.01%) and it is estimated that approximately “three of the world’s 3,500 tailings dams fail every year” (Lyu *et al.*, 2019). However, these data refer often to large-scale mines, because of their potential catastrophic consequences and their mediatization, but also because of the easier traceability compared to medium and small-scale mining projects.

Probability assessment of dam failure can be performed through multiple models, as detailed in Chapter 1. During this thesis, a parallel project has been carried with two students in order to develop a methodology to assess the probability of failure by overtopping based on the combination of multiple triggering factors (e.g. landslide within the pond, wave formation within the pond, impact of the wind on the wave) (Sauer *et al.*, (2019). The methodology is presented but it is not readily applicable, and it needs a further optimization (Appendix 14).

In this study, the probability is assessed base on a simple scale of five classes shown in Table 23, ranging from a value of 0, corresponding to the impossibility for the consequence to occur, to 1, meaning that the consequence is certain (Populaire *et al.*, 2002). For the RSa, we decided to estimate the probability of occurrence of the tailings dam failure based on different

assumptions. It is assumed that the potential efficacy of safety measures and means to reduce the probability of dam failure event to occur depend on gold-mine types and their size in terms of potential technical and financial resources. The larger the gold mine – in size, productivity and financial resources – the better are the safety measures potentially implemented to prevent dam failures. Therefore, one scenario can be imagined where an overall higher probability of occurrence of the dam failure event is assumed (RSa1) (Table 24).

Table 23 Probability classes between 0 (i.e. "impossible") and 1 (i.e. "certain")

Probability class	Value
Impossible	0
Uncertain	0.25
Even chance	0.5
Expected	0.75
Certain	1

Table 24 Probability assumptions used for this study for the assessment of RSo and RSa scores.

Probability scores						
RS	Assumptions	i-ASM	ASM	MSMg	MSMc	LSM
RSo	Certain occurrence of the risk events	1	1	1	1	1
RSa_1	Overall higher probability of occurrence of the event	1	0.75	0.5	0.5	0.5

This probability assumption has been integrated to the geometric means contained within the “consequence map” (Fig. 68). The probability scores have been multiplied to the consequence score of each layer and then, the maximum value has been extracted. This means that the process followed is the same as the one presented in the previous sub-sections, with the only difference that the geometric means have been weighted with the probability scores.

As example, Fig. 69 shows the comparison between the consequence map of TMS-A without the probability (Fig. 69a) and with the assumed probability scores (Fig. 69b). The overall risk is much lower since the dam failure occurrence is assumed to be uncertain (i.e. probability score equal to 0.75).

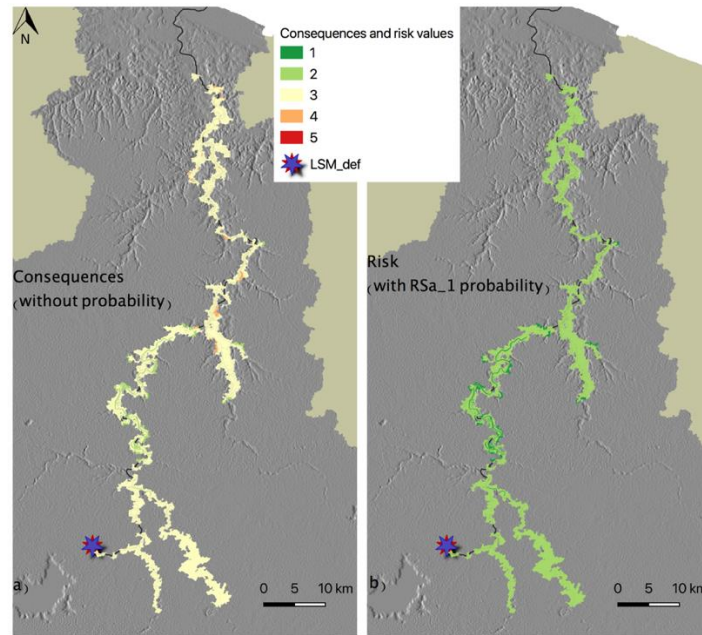


Figure 69 Comparison of the cartographic results with and without probability (RSa_1) for the TMS-A

6. Calculation of the RSa risk score for each TMS

At this stage, the potential flooded area by the dam failure and the vulnerability of the territory system have been estimated. These two components have been combined in order to obtain a global RSa consequence score. Finally, since the probability assessment has not been detailed during this thesis, a probability assumption has been given in Table 24.

As shown in the following Table 25, the probability assumption has been integrated in the assessment in order to obtain a risk score for each TMS. Table 25 shows, first, the total impacted area scores and the total consequences scores. The total consequences scores are presented with and without the integration of the probability assumption presented in Table 25a. Then, the global scores of each TMS are obtained combining the total impacted surface and total consequences scores. These are shown with and without the probability assumption (Table 25b). Finally, since the scores represent negative consequences scores, they are converted to allow their further combination with the RSo scores (which represent positive values) (Table 25c) (Chapter 8) and obtain the final global TMS scores (Chapter 9). As mentioned, the conversion rule is given by Eq.1 and Table 22. The lower the final score, the higher is the risk level.

Table 25 Final scores of the current RSa. The table shows the scores of the impacted area based on the surface and of the mapped consequences combined with the probability assumption. Then, the global scores are obtained combining the impacted surface scores and the total consequences scores.. Finally, the converted scores are shown in order to combine them with the RSa score and obtain an overall TMS score (Chapter 9).

Scores per Territorial Mining Scenarios (TMS)					
	TMS-A	TMS-B	TMS-C	TMS-D	TMS-illegal
<i>Number and types of mines</i>	<i>(1 LSM)</i>	<i>(6 MSMc)</i>	<i>(33 ASM)</i>	<i>(1 MSMc + 4 MSMg + 20 ASM)</i>	<i>(758 i-ASM)</i>
Total impacted surface score	5	3	2	3	3
Total consequences score :					
a) Without probability	3.3	2.5	2.5	2.5	2.7
Risk score RSa_1)	1.6	1.3	1.9	1.9	2.7
Global scores:					
b) Global RSa score (no probability)	3.3	1.5	1	1.5	1.6
Global RSa score (RSa_1)	1.6	0.8	0.7	1.1	1.6
Converted global scores:					
c) Converted global scores (no probability)	1.7	3.5	4	3.5	3.4
Converted global scores (RSa_1)	3.4	4.2	4.3	3.9	3.4

7. Alternative estimation of the RSa score for each TMS

The method proposed until here can be twisted and complex to perform. Nevertheless, it allows to synthesize all the information directly into one score, especially when initial data might not be always spatialized. Furthermore, at this stage, the surface of the impacted area is integrated within the final score.

Another easier way to proceed to the estimation of the RSa score would be to assign the probability scores directly to the flooded areas before consequences assessment following the approach shown in Fig 70. In this case, the flooded area of each gold mine-type incorporates the scores of probabilities of occurrence given in Table 24. Once the flood map is combined with the vulnerability map for each TMS— containing, as mentioned, the geometric means of the vulnerability scores of each polygon – only the maximal values of these means within the flooded area are considered. Then, the maximal scores are multiplied with the vulnerability scores to obtain a final risk score, which is not spatialized. In the case of the mixed scenario (TMS-D), since multiple gold mine-types are present, three maximal values are obtained. In this case, the geometric mean of these values is extracted and then converted into positive scores according to Table 22 and Eq.1.

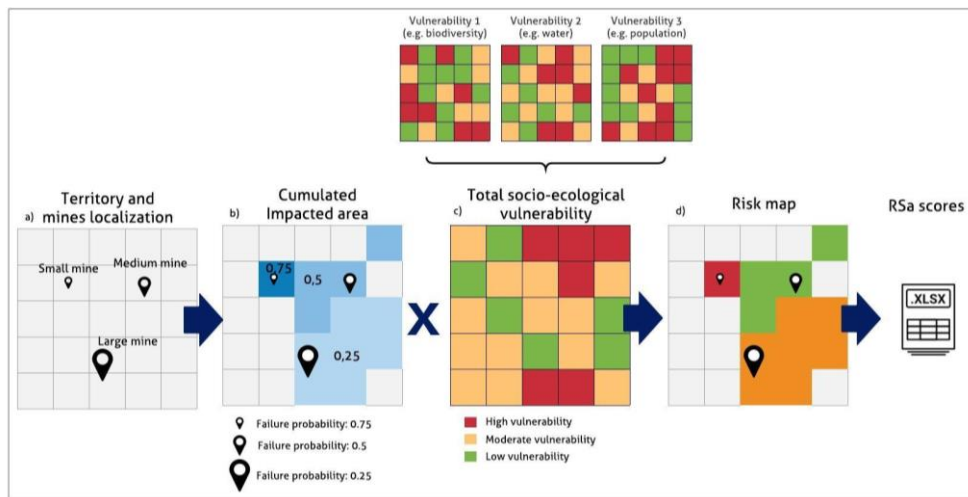


Figure 70 Conceptual flowsheet of the second alternative way to integrate probability for the estimation of the RSa scores

The obtained results are given in Table 26. As it is shown, compared to the method previously used (Table 25), the scenarios presenting the “best” and “worst” scores do not change, them being respectively the TMS-B and the TMS-illegal. However, the ranking of the TMS changes between the remaining scenarios. TMS-C, which in the first method is the second “best” scenario, is now the second “worst”. TMS-D obtains the second place in the second method and the TMS-A, which was one of the worst in the first method has now a score superior to 4.

In this case, the changes in the results are given essentially by the fact that in this second method, more importance is given to the probability scores – which are assumed based on the potential safety measures implemented in each gold mine-type. Here, the scores related to the impacted area are not considered. Hence, TMS involving LSM or MSM types present a better score while the artisanal types the worst ones. This was not the case in the previous method where the surface of the impacted area outweighed the probability of failure. This explains why, for instance, the TMS-A, which has the biggest surface area despite its lower probability of failure, is ranked 4th on 5 in the first method.

Table 26 RSa scores of each TMS based on a second alternative way to proceed to the assessment

TMS	TMS-A	TMS-B	TMS-C	TMS-D			TMS-illegal
Number and types of mines	1 LSM	6 MSM _c	33 ASM	1 MSM _c	4 MSM _g	20 ASM	758 -iASM
Maximal value of the geometric means of the consequence scores	3.26	2.52	2.49	2.52			2.71
Probability scores	0.5	0.5	0.75	0.5	0.5	0.75	1
RSa scores	1.63	1.26	1.86	1.54 (= geometric mean)			2.71
Converted RSa scores	4.37	4.74	4.13	4.46			3.29

Conclusion

Chapter 7 aims to assess the RSa score. The RSa is based on the central risk event of a tailings dam failure caused by overtopping. The assessment has been based on the combination of multiple components: a flooded area and the socio-ecological vulnerability of Mana river basin. The flooded area has been estimated through the combination of two basic methods according to the available data. Specific indicator-based methods have been developed and adapted to FG for the estimation of territorial vulnerability (Table 17). After the aggregation of all the components and the integration of assumed probability scores, the final RSa scores for each TMS scores have been obtained.

The estimation of the RSa has been the main focus of this study. The assessment has been adapted to the lack of data and the wide resolution of our approach. Despite a significant level of uncertainty that must be quantified in the future studies, the estimation of the RSa scores has been rapid, simple and adapted to the existing information. It allowed the obtention of final scores that, combined with the following RSo score – that has been only introduced in this study – will enable to compare the TMS based on a global score.

Chapter 8. Assessment of the ordinary risk scenario (RSo)

In this thesis, the main focus was given to the RSa assessment. Nevertheless, it has been explained that our approach aims to compare and score multiple territorial mining scenarios (TMS) based on the assessment of the risks related to two different operating conditions. Since this wouldn't be possible based on the assessment of the RSa only, this chapter has the purpose to present the assessment of the risk level of the ordinary risk scenario (RSo) for each TMS developed in this study. Only an example will be exposed hereafter, following the steps presented in Fig. 71.

The RSo includes both positive and negative risks, that are evaluated through the selection of specific indicators and the definition of thresholds, in order to obtain consequences classes. The assessment of the level of this RSo focuses mainly on the consequences presented in Table 16 and the following Table 27. Indeed, the probability of occurrence of the risks in the RSo is considered to be certain (section 2.2.), because such events occur inexorably when a mine operates. As mentioned in Chapter 2, despite their occurrence is certain, these events are here considered as “risks”, to distinguish between the “normal” and “abnormal” operating conditions of a mining project.

Once the selected consequences are assessed individually, they are combined all together and then integrated with the probability, to obtain a global RSo score for each TMS. Since no spatialized data are used for the RSo in this study, its assessment does not have a cartographic rendering, unlike the assessment presented in Chapter 7.

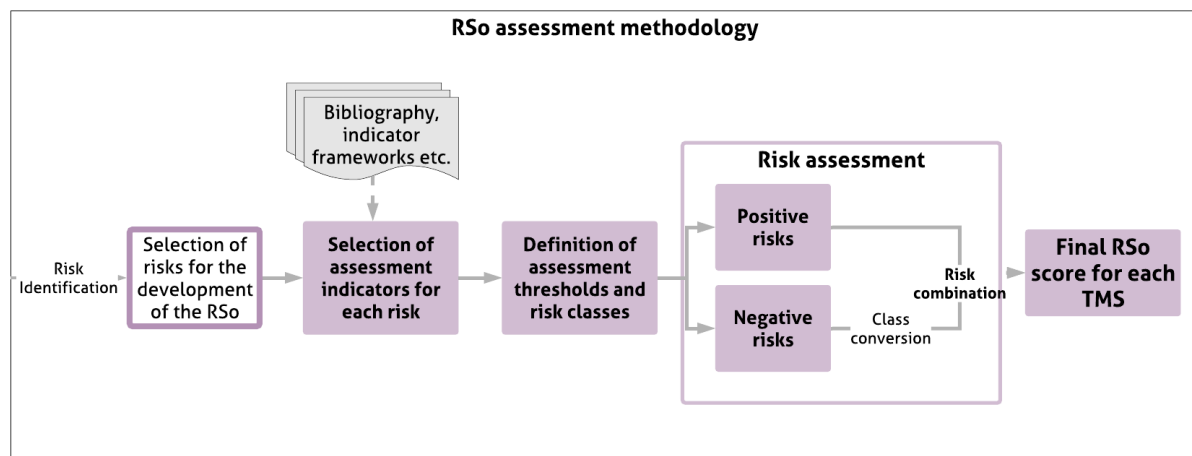


Figure 71 Conceptual simplified framework of the methodology used for the assessment of the RSo

1. Evaluation of the positive and negative consequences for each TMS

1.1. Selection of consequences indicators

Table 27 presents 4 positive and 1 negative consequences chosen for the current RSo based on the risk databases presented in Table 16, Chapter 6. The only negative consequence selected is landscape degradation, considered as a overall negative environmental footprint of

the mining project. As it will be discussed, this dissymmetry has a significant impact on the final scores.

The first step consists in the selection of specific indicators representing each consequence. The selected indicators are the result of a thorough bibliographic review both. Most of the indicators have been chosen based on:

- the current frameworks developed for social impact assessment in the mining sector reviewed by Mancini and Sala, (2018),
- the indicators proposed by the EO-Miners project (Falck and Spangenberg, 2014),
- the Global Report Initiative (GRI, 2013, and by Azapagic, 2004).

The proposed indicators are specific to the mining sector and cover a great range of consequences, both positive and negative, sometimes accounting for the different sizes and types of mining projects (Falck and Spangenberg, 2014).

Table 27 Consequences chosen for the current RSo and corresponding consequence indicators that have been chosen

Type of consequences	Code	Consequences	Consequence Indicator
Positive	RSo_pc1	Gold production (Raw material supply)	Annual gold production (kg/yr)
	RSo_pc2	Direct jobs opportunities	Number of miners or Total direct jobs/Annual gold production ratio
	RSo_pc3	Expansion of social infrastructures (e.g. roads, energy, services)	Total royalties (k€)
	RSo_pc4	Support of local education, research and skill development	Total royalties (k€)
Negative	RSo_nc1	Landscape degradation / deforestation	Topographic footprint of the mine site (ha)

1.2. Definition of consequences thresholds

The choice of the consequence's indicators is followed by the definition of thresholds, that help classifying the level of each consequence. This means to divide the range of possible values for the TMS – and not for the project-types individually – in different classes according to the intensity of the consequence. For instance, according to our parameters, one ASM mine employs approximatively 15 miners (see Table 12). This means that the TMS-C, implying 33 ASM mines, can create direct jobs for 495 people. At the same time, for the same amount of gold produced – which is the territorial objective on which the TMS were created in Chapter 5 – the TMS-B (six MSMc) can create direct jobs for 1,200 people. Therefore, for each consequence, the range of possible levels cumulated in the TMS has been divided into 5 classes (Table 28). Nevertheless, this classification has been realized just for the demonstrative purposes of the study, since no references have been found for FG gold mining sector.

Since the consequence's indicators are evaluated five classes have been defined based on the consequence level considered within the threshold, where "1" is equal to the minimum value (i.e. least positive for the positive consequences and least negative for the negative ones) and "5" to the maximum one (very positive for the positive consequences and very negative for the negative ones) (Table 28). Therefore, for positive risks, class "1" means that the positive consequence is very low, or that the output is "not positive at all" while for class "5", the consequence is highly positive. On the other hand, intensity of negative risks is inverted: a negative risk assessed as class "1" is considered very low, while a class "5" is considered highly negative.

Table 28 Class thresholds defined for each range of values of each considered consequences in the RSo.

Consequence	Unit	Class thresholds				
		1	2	3	4	5
Gold production	Kg/year	< 10	10 – 100	101 – 1,000	1,001 – 10,000	> 10,000
Direct jobs opportunities	n	< 50	50 – 200	201 – 500	501 – 1,000	> 1,000
Expansion of social infrastructures	k€	< 500	500 – 1,000	1,001 – 10,000	10,001 – 25,000	> 25,000
Support of local education, research and skill development	k€	< 500	500 – 1,000	1,001 – 10,000	10,001 – 25,000	> 25,000
Landscape degradation	ha	< 100	100 – 500	501 – 1,500	1,501 – 8,000	> 8,000

1.3. Final assessment of each consequence

As mentioned, the risk assessment does not focus on each single project but on the given TMS. For instance, the RSo assessment of TMS-A, which includes one LSM, is performed based on the values resulting from this one project-type alone. For the TMS-C (i.e. 33 ASM), the assessment corresponds to the cumulative level of consequences of 33 ASM types. In this study, the cumulative level of consequences is given by the sum of the values per gold-mine types in each TMS, as shown in Table 29. This table presents the evaluated consequences based on the assessment of their indicators for each TMS. The levels of consequences are then classified (Table 30) based on the classes of thresholds presented in Table 29.

As shown by Table 29 and Table 30, the values and scores of the first positive consequence (i.e. gold supply) do not differ for each TMS. This is actually normal since the indicator chosen to assess the gold supply is annual gold production, which is the same parameter used to define the "territorial objectives" and to build the TMS in Chapter 5. The indicators used to evaluate the level of expansion of local infrastructures and of support to local education and research by the TMS are represented by mining royalties. These, are calculated based on the rates defined by the French Fiscal Code per kilogram of gold produced by a mine,

as mentioned in Chapter 4. Therefore, since their level depends on annual gold production, these values do not change very much for all the legal TMS (i.e. TMS-A to D). However, the difference is drastically noticeable when it comes to the illegal scenario, since i-ASM are supposed not to create wealth through tax payments and, thus, the “royalties” indicator is equal to 0.

Table 29 Consequences assessed for each TMS according to the indicators presented (Table 27) and the thresholds classes (Table 28)

Consequences	Unit	Values				
		TMS-A	TMS-B	TMS-C	TMS-D	TMS-illegal
		(1 LSM)	(6 MSMc)	(33 ASM)	(1 MSMc + 4 MSMg + 20 ASM)	(758 i-ASM)
Gold production	kg Au	5,000	4,800	4,950	5,000	5002.8
Direct jobs opportunities	n	500	1,200	495	800	7,580
Expansion of social infrastructures	€	4,187,050	4,019,568	4,145,179.5	4,187,050	0
Support of local education, research and skill development	€	4,187,050	4019568	4,145,179.5	4,187,050	0
Landscape degradation	ha	550	1,800	3,300	3,500	15,160

Table 30 Conversion of the values of the indicators assessed in Table 29 for each TMS in classes based on the defined thresholds (Table 28)

Consequences	Risk class				
	TMS-A	TMS-B	TMS-C	TMS-D	TMS-illegal
	(1 LSM)	(6 MSMc)	(33 ASM)	(1 MSMc + 4 MSMg + 20 ASM)	(758 i-ASM)
Gold production	4	4	4	4	4
Direct jobs opportunities	4	5	3	4	5
Expansion of social infrastructures	3	3	3	3	1
Support of local education, research and skill development	3	3	3	3	1
Landscape degradation	3	4	4	4	5

2. Aggregation of the risks and final score for each territorial mining scenario (TMS)

The final score of a given TMS is obtained through the combination of all the consequences previously evaluated, along with their probability. Data aggregation can be performed through different methods, as mentioned in Chapter 2. Fig. 72 presents the aggregation steps we followed in order to obtain a final RSo score. At this stage, the consequences are not weighted, and they are aggregated by calculating their geometric mean.

Two aggregation steps are considered. Firstly, the aggregation of all the consequences of each type is used to obtain a total negative and positive consequence scores (Fig. 72). In the current RSo, for example, this step is not required for the negative consequences as only one negative consequence has been selected. The second aggregation step, consists in the combination of the total positive score and the total negative score to obtain the global value of the RSo. This is done after the re-classification and conversion of the classes from negative to positive scores to obtain the global value of the RSo the previous Table 22 and Equation 1 (Fig. 72).

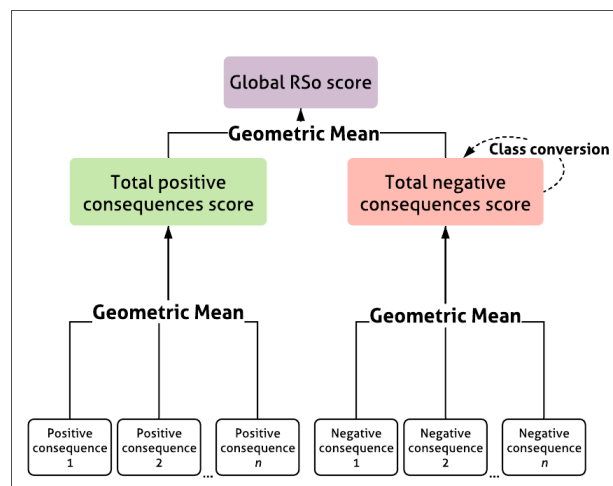


Figure 72 Conceptual simplified framework of the aggregation method used to combine the different positive and negative consequences in order to obtain a final global score for the RSo of each TMS

2.1. Aggregation of the positive and negative consequences

As mentioned, the negative consequences of the current RSo do not need to be aggregated, since only one is considered: landscape degradation. On the other hand, the positive consequences have been aggregated using their geometric mean. Table 31 gives the total final score for each type of consequence. Each considered TMS has a total positive and a negative scores resulting from the geometric mean of their consequences classes. As mentioned, in order to obtain a final RSo score, the total negative scores are converted based on the same rule presented in the Eq.1. and on Table 22 in Chapter 7. The last line of Table 31 presents the converted negative classes.

Table 31 Assessment of the final positive and negative consequences' scores based on the geometric mean of each consequence and converted total negative score based on Table 22.

Consequences	Values per Territorial Mining Scenarios (TMS)				
	TMS-A (1 LSM)	TMS-B (6 MSMc)	TMS-C (33 ASM)	TMS-D (1 MSMc + 4 MSMg + 20 ASM)	TMS-illegal (758 i-ASM)
Gold production	4	4	4	4	4
Direct jobs opportunities	4	5	3	4	5
Expansion of social infrastructures	3	3	3	3	1
Support of local education, research and skill development	3	3	3	3	1
Total positive score	3.5	3.7	3.2	3.5	2.1
Landscape degradation	3	4	4	4	5
Total negative score	3	4	4	4	5
Converted total negative score	3	2	2	2	1

2.2. Aggregation of positive and negative consequences and final score

Once the total negative and positive scores are calculated, a global score can be determined for the entire RSo, for each considered TMS. The combination of the total negative and positive scores is based on the geometric mean (Fig. 72). The result is then multiplied by the probability of occurrence of such consequences (see Table 24). Since the RSo concerns the functioning of the mine site in ordinary and normal conditions, the probability of occurrence of its consequences is assumed to be certain (i.e. "1") (see Table 23). The global score of the RSo for each TMS is given in Table 32. As for the RSa, the higher the global RSo score, the better is the corresponding TMS in ordinary functioning conditions

Table 32 Assessment of the final global score of the RSo for each TMS based on the geometric mean of the total positive and negative consequences and the probability of occurrence. Since the assessment concerns the RSo, probability is fixed at 1 (i.e. "certain")

Consequences code	Values per Territorial Mining Scenarios (TMS)				
	TMS-A (1 LSM)	TMS-B (6 MSMc)	TMS-C (33 ASM)	TMS-D (1 MSMc + 4 MSMg + 20 ASM)	TMS-illegal (758 i-ASM)
Total positive score	3.5	3.7	3.2	3.5	2.1
Total converted negative score	3.0	2.0	2.0	2.0	1.0
Total consequences score	3.2	2.7	2.5	2.6	1.5
Probability of occurrence	1	1	1	1	1
Global RSo score	3.2	2.7	2.5	2.6	1.5

Conclusion

The purpose of this chapter was to include the risk assessment of the TMS during the normal operating conditions of the mine. Despite it is not the main focus in this thesis, a simple risk scenario has been developed based on few positive and negative risks. The levels of these risks have been assessed and combined to obtain a final score for each TMS (Table 32).

As shown in Table 32, the illegal-TMS presents the lower global score. Indeed, although this scenario presents the best jobs opportunities, emphasizing the role of illegal gold mining as a social phenomenon driving informal jobs opportunities, the low score is due to the absence of formal payments of royalties filling the public budget and to the considerable surfaces consumed. The latter explication is aggravated by the fact that illegal gold miners do not respect the mining perimeters of the concessions and the environmental protection measures imposed by the law. On the other hand, the best score is performed by the TMS-A. This is explained by the fact that this scenario involves only one large-scale gold mine (LSM). Therefore, at the end, despite the higher surface consumed per-project by a LSM compared to the other gold mine types, this is still less significant than the cumulative surfaces consumed on a scenario-basis with multiple smaller projects (TMS-B, TMS-C, TMS-D), while having almost the same values of positive consequences. Finally, the scenarios TMS-B, TMS-C and TMS-D presents approximately the same average global scores. This can be mainly explained by the fact that the score highly depends on the chosen indicators and their thresholds. Moreover, the lower variability is due as well by the fact that some parameters related to MSMc and MSMg-types – respectively present in TMS-B and TMS-C – are the same (e.g. soil footprint of the mine site). Therefore, a better and more accurate global assessment should integrate more detailed and variable data concerning these projects.

These results depend significantly on the choices made during the assessment, the selected actors, the aggregation methods and the defined thresholds. For instance, although it is less sensitive to different scales and only applicable to positive numbers, the geometric mean is preferred when synthesizing judgment for decision-making purposes (Kreĵci and Stoklasa, 2018; Doré-Ossipyan and Sareh, 2020). Indeed, the geometric mean is directly based on all the observations and usually the presence of a few extremely small or large values has no considerable effect on the result.

As mentioned, the RSo in this study needs to be furtherly detailed and deepen, also through the integration of territorial vulnerability which may vary according to project localization. The gaps related to the RSo assessment in this study will be furtherly discussed in Chapters 10 and 11. Here, it is important to point out that the assessment does not account for some specificities, such as the identification of one or more impacted areas (e.g. the mine site perimeter or a wider area within Mana river basin) and the territorial vulnerability of these areas. Also, the aggregation method does not consider the number of studied consequences. Therefore, the combination of five positive consequences and – only – one negative consequence is not normalized, misleading the results. Even if the negative consequence had the lowest value, this would be compensated by the presence of 5 positive impacts. As discussed in Part IV, more complex aggregation methods should be proposed, such as the AHP, in order to evaluate the final score.

Despite such gaps, the presented assessment allows to evaluate the second risk score for each TMS. Hence, in the next Chapter, both the RSa and the RSo scores will be combined in order to obtain a final global score for each TMS. This allows the comparison of the different territorial scenarios and their weighting based on the perspective of the different stakeholders.

Chapter 9. Global risk score of the territorial mining scenarios and multi-actor weighting

This chapter presents the last steps of our the application of our approach. At this stage, for each territorial mining scenario (TMS), the corresponding RSa (Chapter 7) and RSo (Chapter 8) scores have been assessed independently. The risk scenarios integrate social, environmental and technical aspects, and they have been assessed by following an “expertise” approach that requires only limited data.

For a given TMS, once the risk scores of the RSa and RSo are obtained, it is possible to combine them in order to obtain a global risk score for the given TMS. This facilitates the comparison between the different TMS, enhancing the analysis of potential strategies for land-planning in mining regions. Finally, since our approach aims to the involvement of stakeholders during the whole application, a questionnaire survey has been carried out in FG to develop coefficients in order to weight the final TMS scores according to stakeholders perception.

1. Assessment of the global risk score of each TMS

1.1 Aggregation of RSo and RSa scores

Two risk scenarios have been considered for each TMS: the RSa, which has been the main focus of this thesis (Chapter7), and the RSo, which has been only introduced here (Chapter 8). The assessment of their risk scores has the objective to finally obtain an global score for each TMS, in order to compare the various TMS for operational purposes to support land-planning decision-making. Fig. 73 summarizes the steps followed until now to get to the global score for each TMS. As mentioned in the previous chapters, the aggregation methods used for this thesis must be furtherly improved but they were chosen to enhance the rapid and simple demonstrative application of the approach proposed in this study.

1.2 Global scores of the Territorial Mining Scenarios

The global score of each TMS is presented in Table 33. Each score is the result of the geometric mean of their corresponding RSo and RSa scores. This seemed the aggregation method the most suited in this case. For instance, selecting the maximal value would have reduced the importance of the RSo within the final TMS score. Indeed, RSo scores are globally lower than RSa because of the choices made during RSo assessment. This is due particularly to the stringent thresholds defined for the RSo that results in consequences scores whose global average does not exceed a medium score (~ 3) with a standard deviation of 1.4 (Table 28). Hence, further studies need to focus exclusively on the normal functioning of gold mine types in FG in order to improve the assessment of the RSo. Further points of discussion are detailed in Chapter 10.

Except for the TMS based only on illegal mines, which displays the lowest global score, the other TMS, which rely on legal mining, present very similar scores. The “best” scenario is represented by the TMS-B, mainly because it seems to assure – according to the data, thresholds and the assumptions used for this assessment – important employment rates with lower surface impacts (in the RSo) and smaller flooded areas in case of dam failure (in the RSa). However, these results must be taken carefully and cannot be fully considered for operational purposes without quantifying their levels of uncertainty. Furthermore, the current methodology does not integrate the use of cyanidation and the chemical nature of the tailings which would potentially alter the final scores of TMS-A and TMS-B. A better estimation of the impact on surface waters – for instance, using water turbidity as indicator – due to the distribution of a great number of ASM (i.e. TMS-C), might also worsen significantly the scores of TMS-C and TMS-illegal. All these considerations are furtherly detailed in Chapter 10.

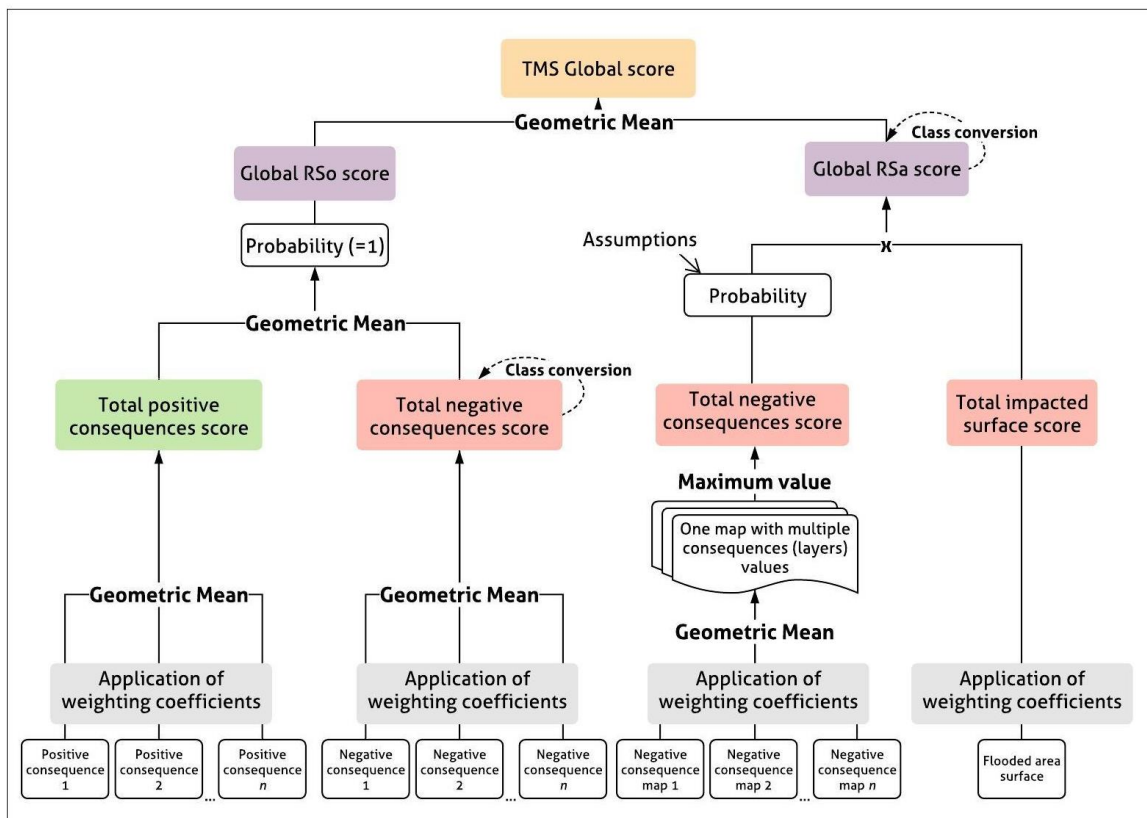


Figure 73 Conceptual flowsheet of the aggregation methods used in this study and the integration of weighting coefficients to the RS scores

Table 33 Global risk scores of each TMS

Territory objectives	→	Territorial Mining Scenario (TMS)							→	Risk Scenario scores		TMS Global score
Annual gold production (kg/year)		Scenario Code	IAS M	IAS M	AS M	MSM g	MSM c	LS M		RSo	RSa	
5000,00		TMS-A						1		3.2	3.4	3.3
		TMS-B					6			2.7	4.2	3.4
		TMS-C			33					2.5	4.2	3.2
		TMS-D			20	4	1			2.6	3.9	3.2
		TMS-illegal	758							1.5	3.4	2.3

2. Multi-actor assessment of the relative importance of each consequence

As mentioned in Chapter 2, our approach aims to involve stakeholders all along its application, starting with the definition of the territorial objectives and the development of the TMS. Therefore, a crucial step of our approach is the weighting of the global TMS risk scores according to stakeholders' perspective. The weighting is based on the interests and the perceptions of the stakeholders considered in this study (e.g. civil society, public administration and gold mining operators) (see Table 5). More precisely, this means to evaluate the importance that each stakeholder group gives to the socio-ecological assets affected by the risks considered in the RSo (Table 16) and the RSa (Table 17).

In this section, a quick introduction aims to emphasize the utilization of a questionnaire survey for the purposes of this study and to point out the method used to develop, distribute and analyze the questionnaire in this study. Finally, the results are shown, and the weighting coefficients are estimated and applied to the RSo and RSa scores previously assessed.

2.1 Questionnaire used to evaluate stakeholders risk perception

Among all survey methods, questionnaires are commonly used for risk analysis for data gathering, stakeholder's definition, assessment, preferences or behavioral analysis and risk weighting (Carpino *et al.*, 2019; Robinson and Botzen, 2019; Zhuang *et al.*, 2019). For the purposes of the current application, a simple questionnaire has been developed based on existing studies not related to the mining sector (El-Sayegh, 2008; Rosenthal, 2016) and distributed among local stakeholders. The method used for the development and the use of the questionnaire (Appendix 15) is shown in Fig. 74 and furtherly detailed below.

We have developed a semi-structured questionnaire, divided in two sections. The first section is intended to gather information about respondents' profile. Six general questions

address general information of each respondent (e.g. age, birth and residence place, professional activity). The answers are anonymous, thus, no information concerning the identification of the respondent is demanded.

The second section is intended to get the perception of the *relative importance* that each respondent gives to the corresponding socio-ecological assets that are potentially impacted by gold mines. The assets concerned by the questionnaire correspond to the list of consequences listed in tables 16 and 17, respectively for the RSo and RSa assessment. To do so, 13 questions aim to obtain a score regarding the importance that the respondent attributes to a given asset (e.g. drinking water, public infrastructures, population safety and health, biodiversity), where 0 is “not important” and 4 is “very important”. Each respondent gives the score to each socio-ecological asset according to its perceived functionality, need or use. This step allows to apprehend the relative importance of that asset in the case it was positively or negatively impacted by one/multiple gold mining activities. For example, one of the questions concerns which level of importance (between 0 and 4) the respondent gives to the preservation of the physical status of surface waters, against riverbank erosion or the diversion of streams. The response gives an idea of the importance that is given to this asset if a gold mine would affect it.

Finally, few open questions concern the respondents’ identification of supplementary non-cited assets potentially impacted by gold mining – in order to enrich the risk identification database presented in Chapter 6 – but also information regarding how respondents received the questionnaire and their willingness to obtain the results of the survey. A copy of the questionnaire is available in Appendix 15.

The questionnaire has been distributed both directly and indirectly to people through personal interactions during the last mission in FG (January 2020), email distribution and local intermediaries from the University, public administrations, NGOs and mining operators all around the region. Concerning Mana river basin, the questionnaire has been personally distributed directly to the main municipal services and shared to Mana inhabitants.

Figure 74 Simplified method used to develop weighting coefficients to apply to each TMS score

2.2 Results of the questionnaire and actor-based weighting coefficients

At this stage, 39 questionnaires were returned. However, only 34 questionnaires were completed and susceptible to be furtherly analyzed to estimate the weighting scores. As mentioned, each question was answered by the respondents giving a score between 0 and 4. These scores were averaged for each asset and then normalized in order to obtain weighting coefficients between 0 and 1, where 0 represents the lowest relative importance of the respondent to the corresponding asset and 1 the highest one. The coefficient normalization is based on the following simple rule presented by Eq.2.

$$W = \frac{v - \min}{\max - \min}$$

Equation 2

Where:

W , is the normalized weighting coefficient between 0 and 1 and it can be based on all the collected answers (W_{gen}) or distinguished according to the actor-category of the respondents, whether they belong to civil society (W_{cs}) or public administration (W_{pa});

v , is the score given by each respondent on a scale from 0 to 4;

\min , is the minimum value of the non-normalized score (i.e. in this case, 0);

\max , is the maximal value of the non-normalized score (i.e. in this case, 4)

While W_{gen} refers to the weighting coefficients related to the totality of the respondents, few values have been extrapolated distinguishing the different stakeholders groups, only to give a demonstrative example of a multi-perspective assessment related to society (W_{cs}) and public administration (W_{pa}) (Table 34). The stakeholder's category "mining operators" could not be considered since only one respondent belonged to this category.

Table 34 Socio-ecological assets evaluated in the questionnaire survey and the corresponding RSo and RSa consequences code. On the right columns, the weighting coefficients derived from all the complete answers (W_{gen}), or from the respondents belonging to the "civil society" (W_{cs}) and "public administration" (W_{pa}) categories

Assets	Corresponding consequences		Weighting coefficients (0 – 1) (W)		
	RSa	RSo	W_{gen}	W_{cs}	W_{pa}
Non drinkable water	Reduction of surface water ecosystem services	-	0.81	0.76	0.88
Drinkable water	Reduction of drinking water public provisioning service; Reduction of drinking water; provisioning service (other than public);	-	0.95	0.93	0.96
Water physical quality	Reduction of surface water ecosystem services	-	0.79	0.79	0.84
Mining infrastructures	Destruction of the dam	-	0.40	0.32	0.48
Public roads	Degradation of public infrastructures	Expansion of social infrastructures	0.69	0.64	0.75
Public infrastructures	Degradation of public infrastructures	Expansion of social infrastructures	0.69	0.67	0.73
Biodiversity	Reduction of biodiversity-related ecosystem services; Reduction of forest-related ecosystem services	-	0.88	0.89	0.86
Soil erosion	Run-off and soil degradation	-	0.78	0.78	0.77
Soil fertility	Reduction of crop production service	-	0.79	0.78	0.82
Air quality	-	-	0.85	0.88	0.82
Mining job opportunities	-	Direct jobs	0.57	0.55	0.59
Public health	Direct impact on local population; Health Impacts	-	0.88	0.87	0.88
Miners' health	Direct death and injuries of workforce;	-	0.69	0.68	0.66
Landscape quality	Reduction of forest-related ecosystem services; Reduction of esthetic ecosystem services; Impacted surface	Landscape degradation	0.87	0.89	0.84
Economic outcomes	-	Raw material supply; Direct jobs ; Support of local education	0.43	0.43	0.38

Table 34 shows the normalized weighting coefficients deduced from the survey, for each socio-ecological asset (first column). The second and third columns represent the corresponding consequences, related to the RSo (Table 16) or RSa (Table 17), to which a given weighting coefficient is applied. The weighting coefficients used in this study are those in the W_{gen} column and they are related to the global results from all the average of all respondents.

Although insufficient data do not allow an actor-based distinction, an example of multi-perspective weighting coefficients is just presented in the last two columns (W_{cs} and W_{pa}) for civil society and public administration. However, these coefficients will not be applied since, not enough data have been gathered from the current survey to capture the weight variability of each actor category.

At this stage, the highest weighting coefficients are generally given mostly to ecological assets (e.g. soil fertility, air quality, landscape quality) with a specific peak to water resources for both its social and ecological functions and to public health. Assets related to gold mining activities have the lowest values here (e.g. mining infrastructures, mining job opportunities, miner's health) according to both civil society and public administration. The economic outcomes from mining activities represent the lowest peak of the presented coefficients.

2.4 Global TMS risk scores after risk weighting

Once the weighting coefficients are calculated (Table 34), they are applied to the scores of each risk scenario as shown in Fig. 73. Each weighting coefficient is applied to the corresponding consequence in the risk scenario, as presented in Table 34. Table 35 shows the application of the general weighting coefficients to obtain weighted RSa (Table 35a) and RSo (Table 35b) scores and finally the global TMS scores (Table 35c).

The application of the coefficients does not alter significantly the original ranking of the non-weighted TMS. According to this demonstrative application, the potentially TMS with the highest score responding to the objective of a total annual gold production at 5,000 kg at the Mana river basin scale are the TMS-B, which involves six MSMc and TMS-A, with one LSM. Then, 33 ASM (TMS-C) and the mixed scenario (TMS-D) present the same scores. Moreover, the worst RSa score is obtained by the TMS-A, mainly because of the score given to the "surface area" component (i.e. the flooded area), which is the largest one in the TMS-A. However, the reduced surface of only one mine site, used as indicator for "landscape degradation" in the RSo tends to increase its position in the final TMS scores ranking. Finally, the illegal scenario obtains the worst scores which is due especially to its very low RSo score and to the fact that the probability score applied is equal to 1, since no safety measures are assumed implemented by illegal miners. However, the difference between the scores of the legal TMS are very low and the assessment must be integrated with uncertainty analysis to fully apprehend which might be the most suitable alternative for a land-planning strategy.

It has been mentioned already in the previous section that the scoring does not take into account the cumulative impacted areas. For instance, the length of impacted surface waters could be more important in TMS-C and TMS-illegal. These scenarios involve smaller mines but in a much higher number. This higher distribution of mining activities compared to the other TMS must be quantified more precisely in its cumulative dimension. Moreover, the products used for mining processing and the chemical nature of the tailings must be integrated as well, since they would considerably alter the current scores for all the TMS, including the final score of TMS-B.

Table 35 Final TMS scores with the application of the general weighting coefficients

Territorial Mining Scenarios scores with W_{gen}		TMS- A	TMS- B	TMS- C	TMS- D	TMS- illegal
Weighted RSa score (W_{gen})						
	Impacted surface score	5	3	2	3	3
	Weighted impacted surface score	4.34	2.6	1.74	2.6	2.6
	Consequences weighted score	2.88	1.98	2.33	2.33	2.33
a)	Consequences weighted score with probability	1.44	0.99	1.75	1.75	2.33
	Total weighted score	2.5	1	0.8	1.2	1.2
	Total weighted score with probability	1.2	0.5	0.6	0.9	1.2
<i>Conversion</i>						
	Total converted weighted score	2.5	4	4.2	3.8	3.8
	Total converted weighted score with probability	3.8	4.5	4.4	4.1	3.8
Weighted RSo score (W_{gen})						
b)	Total weighted positive	1.81	1.91	1.68	1.81	1.10
	Total weighted negative	2.60	1.74	1.74	1.74	0.87
	Total weighted score	2.17	1.82	1.71	1.77	0.98
Global weighted TMS score (W_{gen})						
c)	Global non-weighted score (with probability)	3.3	3.4	3.2	3.2	2.3
	Global weighted TMS score (with probability)	2.9	2.9	2.7	2.7	1.9

Conclusion

The current chapter presents the final steps of the demonstrative application of the approach proposed in this thesis. After the RSa and RSo are respectively assessed in Chapters 7 and 8, the final scores for each TMS are here estimated and weighted based on stakeholder's perception.

The multiple limitations encountered during this test-application (e.g. lack of data and assessment methods, threshold references) are furtherly discussed in Part IV (Chapters 10 and 11). Nevertheless, despite the high level of uncertainty that must be quantified in future studies, our approach was fully applied, through a rapid and simple assessment based on the information currently available.

Therefore, further studies should ameliorate the current application not only integrating new data but also developing and applying more solid methods for risk assessment and for uncertainty analysis. In this way, the comparison between the TMS might have a higher reliability. Furthermore, the integration of existing decision-making tools (e.g. TOPSIS, AHP) could improve considerably the operationalization of our approach and support public authorities, civil society but also mining operators for the definition of land-planning strategies.

Part IV – Discussion of the approach proposed in this study and its application

This thesis proposes an original approach to integrate mining into land-planning strategies through risk assessment at the territory level. This approach has been operationalized through the development of a methodology (Part I) via an application-test on gold mining in FG (Parts II and III). The current thesis shows the feasibility of the proposed approach and the achievement of many of the objectives presented in Chapter 2 (e.g. the integration of territorial and technical-operational features of mining activities, stakeholders' involvement). The first goal of this thesis is to show what can be accomplished through a territorial and pluridisciplinary approach, that includes things usually treated differently and separately. Nevertheless, Despite the feasibility of the methodology and, hence, of the proposed approach which allows a better view of mining projects at wider scales, this approach and its application present some important points of discussion. These aspects will be considered in this last part of the thesis. Discussion concerns both the case-study that has been the object of this thesis (e.g. the choices made, the data used) (Chapter 10) and the general philosophy behind our approach (e.g. the adaptability to other cases, the improvement of its operationalization) (Chapter 11).

Chapter 10. Discussion on the application of our approach to the French Guiana gold mining sector

Chapter 10 discusses the application of our approach to gold mining in FG. More precisely, it addresses the analysis of the results of what has been realized in Part II, also pointing out the gaps and the potential improvements.

1. The influence of system definition on the final scores

In Chapters 3 and 4, the systems to which our approach is applied have been presented and defined. For a more practical development and comparison of the territorial mining scenarios (TMS) a multicriteria classification of gold mines in FG has been proposed (Scammacca *et al.*, 2020a; Scammacca *et al.*, 2020b) in Chapter 4. Section 1 of Chapter 10 discusses the representativity or the limits of the territory and mining systems chosen in this study and how these choices influence the results.

1.1. *Mana river basin: a representative territorial unit of French Guiana?*

The territory system considered for this study is the Mana river basin. The choice of the river basin as territorial unit and the specific selection of Mana river basin have been justified in Chapter 4, according to the geology of the basin (especially the distribution of gold deposits), the types of gold mines, as well as the presence of human settlements and environmentally sensitive areas. For its features, Mana river basin seems a representative sample to describe and analyze gold mines in FG, their risks and the average level of socio-ecological vulnerability.

As described in Chapter 4, common parameters and vulnerability factors existing for all the other basins in FG are found in Mana river basin. The representativeness of the studied area is important because it allows to have an idea about the generalization of the application and the adaptability of our approach. This would have been biased if the territory system chosen would have presented socio-ecological features that were not found elsewhere in FG.

If the methodology is extendible to other river basins in FG, further applications should account for peculiar characteristics that deserve more precise assessments. For instance, if the Kaw river basin was chosen (Fig. 17), the unique ecological vulnerability of this area should have been considered in risk analysis, weighting, mine site localization. Kaw hosts an important protected wetland reserve but also a significant gold deposit that has been targeted by different projects. In 2007, the large-scale gold mining project of Camp Caiman, proposed by the Canadian company Iamgold has been the object of important concerns. Finally, the project has been suspended by the French Government for environmental concerns and to underline its engagement towards the key-regulations of French political Agenda (i.e. *Grenelle de l'Environnement*).

Also, if the Maroni or the Oyapock river basins were selected, the application should have necessarily included the description and assessment of gold mining activities respectively in Suriname or in Brazil, the related regulatory frameworks and their risks. This also would have implied the gathering of data in different countries. Also, in the latter case, another parameter should have been considered. These two river basins hosts a large part of the Guiana Amazonian Park, where multiple sites of Native Americans are also located. Together with the Tumucumaque National Park in neighbouring Brazil, the Guiana Amazonian Park represents the biggest rain forest protected area in the world. These factors would significantly increase the socio-ecological vulnerability of the area and the related data would be difficult to be detailed.

To support the choice of representative basins and their features, detailed hydrological modeling of water catchment systems in FG and their specificities could be performed. A comparison tool might be coupling the ONF catalog (ONF, 2015) – which gives spatialized information about the biophysical assets of forest ecosystems in FG (e.g. soils, biodiversity quality, type of vegetation, landscape quality) – and the delimitations of the hydrographic sectors representing the river basins.

1.2. The variability gold mine types in FG and the limits of their classification

1.2.1. Gold mine-types vs real mining projects

Our study focuses on standardized mine types that have been developed via a multi-criteria classification of existing or potentially existing mining projects in FG. The classification has been detailed in Chapter 4. The replacement of real gold mining projects and their specific characteristics by standardized prototypes represents a methodological choice also to

emphasize the operationalization of an approach that can be performed also for potential future strategies and other TMS than the ones selected in this thesis. Furthermore, this choice was driven by the current concerns regarding real projects that might have limited the process of data gathering and risk assessment. The existence of a range of characteristics for each project type is a useful tool for the acknowledgement and the evaluation of risks related to each gold-mine type. Furthermore, the development of such classification allowed to structure the gold mining sector in FG, with the further possibility, as it will be discussed in the following sub-sections, to include new gold mine types that might – or might not – see the light in the region.

1.2.2. The variability of mining projects and the normalization of the gold mine-types

The classification of gold mines given in Chapter 4 is based on multiple criteria (e.g. geological, juridical, technical) and it is presented along with an extract of the main characteristics of each project type. These criteria manage to comprehensively include the existing gold mines in FG. However, few considerations should be added. First of all, the “soil footprint” criterion varies according to the employed mining techniques. For this reason, it is rather a parameter rather than a distinguishing criterion. For instance, no project in FG were currently performing large-scale underground mining at the moment the classification was being developed. According to some recent prospections, the new mining company Orea – which includes the *Montagne d’Or* project – is considering underground techniques for the project *Maripa Gold* shared with Iamgold near the Kaw wetland (Orea, 2020). Therefore, these mine-types should be included in the classification. A gold mine classified under the LSM-type using underground techniques would have a lower soil footprint than a MSM-type operating surface mining techniques. Also, underground mining might help reducing the potential volume of mine wastes. Therefore, at this stage the “soil footprint” criterion might help to distinguish more importantly MSMg from MSMc and MSMc from LSM-types.

Therefore, the development of TMS varies according to the actual evolutions of mining projects and their techniques but also on where the assessment is performed. For instance, we said that if the Maroni river basin was chosen, the classification should have focus as well on gold mining in Suriname. A mining technique currently used in Suriname or in Guyana is gold dredging along the Maroni river (Kioe-A-Sen, *et al.*, 2016, Hook, 2019). This technique involves dredges that extracts gold from sand, gravel, and dirt using water and mechanical methods and it would represent a supplementary specific gold mine-type with specific risks. Therefore, in the case of application on the Maroni river basin, these activities should be identified and detailed and can be integrated on updated classifications of gold mine-types.

Hence, the identification and comparison of risks specific to each project type should be based on *a priori* normalization of such risks to the specific features of the project, which influence risk nature and intensity. The normalization allows to obtain pertinent ratios between

the features of the gold mine-types and the risks that such activities generate. Table 36 lists some examples of information that can be derived from Tables 9-11. For instance, the ratio between annual extracted gold and the surface footprint of each project type might be a global socio-environmental indicator to compare positive economic production outcomes and negative environmental consequences of a mining activity before any further detailed assessment. Since they use cyanidation for gold recovery, MSMc and LSM seem to assure a better ratio but only because the normalization did not consider the potential impacts related to this process. The inclusion of water consumption might add as well considerable information about the overall environmental performance of a project. The ratio between direct employment and soil footprint provides further information about the comparison of the positive outcomes of mining, in terms of employment, to the loss of surface due to the development of the mine. For instance, the difference between MSMg and MSMc is mainly due to the fact that the construction and the operation of the cyanidation plant involve a higher number of specialized workers and technicians. The ratio between the maximal dam height and the annual extracted gold might be as well an indicator comparing the potential impact of a dam failure indicated only by the height of the dam, and the annual gold production. However, the use of the dam height as simple indicator might be not pertinent. As already explained, if higher and larger dams' failures generate much more considerable impacts than smaller dams, they might be also the less likely to fail because of specific monitoring programs that could be more effective in large mines, because of higher investments and training. On the other hand, the content of the tailings pond and possible chemical additives (e.g. cyanide, thiosulfates) should be considered, for instance modeling the potential interactions between these compounds and the environment (e.g. chemical speciation) or even through the less detailed assignment of expert-based-scores to the corresponding gold mine-types.

Table 36 Examples of information that can be derived for each project-type from Tables 9-11

Examples of indirect deducible information (per-project)	i-ASM		ASM	MSM		LSM
	i-ASMp	i-ASMs		MSMg	MSMc	
Annual extracted gold/Mine soil footprint ratio (kg/ha per year)	5 - 10		~ 1.5	~ 1.5	~ 3	5 - 10
Total direct jobs/Mine soil footprint ratio (number of workers/ha)	5 - 10		~0.15	~ 0.3 - 0.6	~ 0.4 - 0.7	0.7 - 1
Total direct jobs/Annual gold production ratio (worker/kg per year)	1		0.1	0.3	~0.7	~1.4
Maximal dam height/Annual extracted gold ratio (m/kg per year)	n/a	n/a	0.02	0.07	~0.04	~0.01
Water consumption/Annual extracted gold ratio (m3/kg per year)	n/a	n/a	n/a	n/a	~6	~12

1.2.3. Difficulties of a project(s)-based approach for illegal mining (i-ASM)

The illegal gold mining sector deserves a peculiar discussion compared to the other gold mine-types. The first question concerns a terminological issue. As discussed in Chapter 4, no unanimous definition of illegal gold mining is given. Furthermore, a neat distinction must be made between *illegal* and *informal* mining. For instance, Nhlengetwa, (2016) distinguished between “illegal invasive mining” which occurs “when miners illegally enter the old mine workings of decommissioned mines” and “informal mining”, which is a “community-based mining that typically follows customary law”. These differences are often not considered by mining policies, but they do need to be addressed, especially in risk assessment and land-planning processes. This should be implemented in the approach applied in this study, in order to optimize and precise the classification of gold mine-types, through the gathering of more detailed data from local authorities that help distinguishing, for instance, two additional sub-types i-ASM (e.g. illegal vs informal gold mining) and their specific socio-technical features.

Indeed, another question concerns the quantity and quality of information related to illegal gold mining. Firstly, the difficulty in defining this type of mining activity relies on the fact that they are extremely heterogeneous. Also, because of the volatility of such activities, i-ASM are difficult to track and data are extremely variable and hardly available. Annual production rates of illegal gold mining highly differ from one country to another (Seccatore *et al.*, 2014), and from site to site. Secondly, the notions of *project* or *mine site* are extremely fuzzy for the i-ASM sector. Therefore, the integration within a project-type approach of a type of mining activities which represents rather a “social phenomenon” – where it is difficult to determine where a mine site ends and another one begin – must include the support of social and human sciences.

The information presented in Table 11 (Chapter 4) is based essentially on the global consideration of mining activities cumulatively on a sector-basis, rather than individually on a project-basis. The values shown are based on the estimation of a total annual impacted surface of 1,000 – 2,000 hectares (Rahm, 2017), a total annual produced gold reaching 10 tons and a total number of illegal miners which may reach 10,000 people (WWF, 2018). These data are effectively considered in the study but, based on what previously explained, their uncertainty might be even higher compared to legal projects and, therefore, must be quantified.

1.3. Adaptability of the proposed classification to other case-studies

The use of standardized mine types is an original approach that serves two purposes: i) the comparison of potential future scenarios of mining development and ii) the analysis of such scenarios and the related risks at the territory level. Therefore, this approach might be adaptable to other studies concerning other mining and territory systems. However, the substantial results of the classification – thus, the standard mining project types presented here for the gold mining sector in FG – can be only partly adapted to other cases. First of all, the

partial adaptation concerns the exploitation of the same commodity (i.e. gold), since each commodity involves different geological, geographical – and thus, political and socio-ecological – but also technical features.

1.3.1. Adaptation to the studied commodity: is gold a commodity like others?

As for their impacts, mine types depend also on the type of targeted commodity. “Annual productivity” is a criterion that significantly depends on the commodity and its market. For instance mining production of bauxite is not comparable to gold production rates. Nevertheless, these differences can easily be adapted within the classification. However, the exploitation of bauxite will not require the same infrastructures and techniques used in gold mines. For instance, the amounts of ore to transport can be much higher, which can play an important role for risk assessment .

Also, as mentioned, the i-ASM sector is a social phenomenon peculiar to gold and other few commodities (e.g. cobalt, diamonds and other gems) (Hentschel *et al.*, 2002). Moreover, since it is poverty-driven, it concerns often countries with particular socio-economic and political backgrounds (the so called “developing” countries). The difficulty in defining this type of mining activity relies on the fact that, as previously mentioned, they are highly heterogeneous and that data are usually unavailable.

Furthermore, some specificities of the gold commodity should be tackled since its main sectors of demand are jewelry, investment and banking, with very low industrial implications (World Gold Council): gold could be considered as a strategic product rather than a simple mineral resource. Therefore, it may not be a representative commodity for a demonstrative study. Moreover, the necessity of gold mining and its applications might be discussed in relation to its socio-environmental costs, while gold recycling rate is approximately equivalent to about 87% of reported consumption (USGS, 2020). The application of our approach to industrial commodities, for instance, could list, among the positive risks to assess, the benefits generated from the mining activity to respond to local or worldwide technological needs.

1.3.2. The variability of gold mining in different “territorial system(s)”

Even when the targeted mineral commodity in two different countries is the same, the classification is affected by the territory system where mining is performed. The particularities of each territorial system, given a same commodity, concern a great range of aspects. For instance, the nature of the regulatory framework of a State plays an important role. For example, gold mining sector in Suriname is very similar to FG. Since they both are located within the Guiana Shield, the types of geological deposits are almost the same. However, Surinamese laws do not forbid the use of Hg-gold amalgam for gold recovery. Thus, the use of Hg-based recovery methods cannot be used as a distinction criterion between legal and illegal gold mines

in Suriname. Furthermore, it has been said that gold dredging along the Maroni river is a mining technique currently used in Suriname, representing a supplementary gold mine-type to add.

In the case of gold mining, another specificity concerns the medium-scale mine-type (MSM). MSM represents a middle type between ASM and LSM that is specific to FG and very few countries, such as Brazil. In the Guiana Shield and in the nearby areas (e.g. Bolivia, Peru), similar features are displayed by “mining cooperatives” but they represent rather the entrepreneurial and institutional choice of a structured sector for small and medium-scale miners to reduce negative socio-environmental costs and maximize economic performances (Alves *et al.*, 2019).

Finally, political and regulatory challenges might affect the pertinence and the effectiveness of such a classification for risk assessment purposes. These aspects are related to:

- the permeability between legal and illegal gold mines in some areas of the world;
- situations where political decisions might take over the technical dimension of a mining project becoming the main final driver for its feasibility or suspension;
- the transboundary nature of the consequences generated by a mining project.

The first two points are extremely related to the capacity and transparency of governmental authorities in regulating their mining sector and the related decisions. Furthermore, the linkage between legal and illegal economic activities is hardly quantifiable in our approach but it must be considered when it comes to decision-making and stakeholder’s concertation. Concerning the latter point, in some areas multiple project types with contrasting regulatory frameworks might coexist. As mentioned, one of the clearest examples concerns actually FG with the Maroni river basin, shared with Suriname (Fig. 17). Maroni river basin is the largest in FG and here two legal frameworks for gold mining coexist in such area: on one side, legal gold mines using Hg-based recovery methods, and on the other, a Hg-free legal sector. These circumstances, when not properly addressed, might hinder the risk assessment process – and generally speaking land-planning strategies – requiring cross-border efforts for mining governance and policies. Also, FG is the destination of most of the migration flows present in the Guyana Shield. This is a phenomenon independent from the typology of gold mine since it is strictly correlated to the global trends of gold and local political and juridical frameworks at wider scales (Taubira Delannon, 2000).

Therefore, an extensive and detailed analysis of the territory system and the features of its mining sector must be acknowledged during the application of our approach. Since the particularities of each territory, as it is described below, are hard to quantify, they must be considered in advance, for the classification of mine-types and the development of TMS but particularly afterwards, when it comes to decision-making.

1.4. Mining phasing vs territorial variability

The temporal boundaries chosen for the application of our approach have an important influence on the development of the TMS and the final results. As mentioned, two temporal dimensions should be considered, whether they are related to the mining system or the territorial system. The first one is related to the mining phase (i.e. prospecting, planning, operation, closure) during which the assessment is focused. The second one concerns the variability in time of the parameters of the territory in which mining is performed.

This study focuses on the operation phase. Therefore, the temporal scale here considered only refers to the mining system, neglecting the changes over time of the socio-ecological characteristics of the territory in which mining is performed. These temporal dimensions should be enriched and integrated for instance, through the development of hypothetical and fictional scenarios in which the parameters of the territory and mining systems might change (e.g. new localizations of mining projects, the utilization of new mining techniques, urban intensification (e.g. 2020-2050), new environmental protection measures, the effect of climate change). For instance, on a regional scale, we can consider a first scenario where a mine is located in a catchment with no urbanization. Hence, population vulnerability, which influences the consequences of the risk event, is very low. A second scenario where urbanization is spreading and human clusters are formed in the same catchment, implies the increase of the level of risk. Such issues are vital to develop territory-based risk assessment approaches especially in FG where urbanization is expected to reach approximately 574 000 inhabitants in 2040 (Léon, 2010) (which is almost twice of the current population). Another fundamental issue is related to the impacts of climate change over the next 100 years on the socio-ecological vulnerability of FG and also how these changes might interact with gold mining activities, resulting, potentially, in the aggravation of the negative consequences (Lecomte *et al.*, 2011).

2. The influence of the chosen territorial mining scenarios on the results

We compared different territorial mining scenarios (TMS) on the basis of their risk scores. Therefore, how these scenarios have been developed and the risk events have been selected must be discussed to understand the final results of this application-test.

2.1 Territorial objectives and stakeholder involvement

Except the choice of Mana river basin as territory system and the classification of gold mines, that have been previously discussed, another main step having an important influence on the TMS is the definition of objectives at the territory level. As shown, the TMS are developed based on the combination of one or multiple mine types that, with their characteristics, could meet specified pre-defined objectives. In this study, three examples have

been given in Chapter 5, based on gold production, employment related to the gold mining sector and the limitation of deforested areas. These objectives can be an interesting complementary tool to compare the TMS before the risk assessment. Table 37 shows the different TMS developed in this study – based on the objective of gold annual production equivalent to 5,000 kg – and the assessment of their risk scores. If we look at the other two objectives mentioned in Chapter 5 which haven't been used in this study, for each TMS it is possible to estimate the corresponding values (according to the number and type of projects). This can be, before the detailed assessment, a preliminary tool to discuss and compare the TMS. Indeed, the TMS are ranked in a different order whether we consider their global scores or their employment/soil footprint ratio. This means that the “best” strategy cannot be evaluated only on some given territorial objectives but on multiple criteria which include these objectives as well as the generated and suffered risks by the mining projects (e.g. opportunities and losses).

Table 37 Risk scores and global scores of the TMS developed in this study. If the other two objectives are considered (see Chapter 5) and their ratio is given, the TMS are ranked in a different order

Territory objectives		Territorial Mining Scenario (TMS)		Risk Scenario scores		TMS Global score	Other territory objectives considered		Ratio DJ/SF
Annual gold production (kg/year)		Scenario Code		RS_o	RS_a		Direct jobs (DJ)	Soil footprint (ha) (SF)	
5,000	→	TMS-A	→	3.2	3.4	3.3	500	550	0.9
		TMS-B		2.7	4.2	3.4	1,250	1,875	0.66
		TMS-C		2.5	4.2	3.2	500	3,333	0.15
		TMS-D		2.6	3.9	3.2	800	3,500	0.22
		TMS-illegal		1.5	3.4	2.3	7,580	15,160	0.5

However, these objectives – which have been defined arbitrarily for demonstrative purposes – should be: compared with stakeholders' perspectives and detailed to see if they actually meet pertinently the real concerns related to gold mining in FG, and more precisely, within Mana river basin. Surveys and participative methods should target local authorities and civil society in order to identify and quantify more accurately a set of objectives based on which the TMS can be developed. Social sciences should be integrated through specific methodologies that help quantifying the involvement of local actors . Statistical analysis and data gathering should focus on the representiveness of the territorial objectives defined in this study, to see if they properly describe the reality. For instance, is annual gold production an objective that all the local actors would actually consider for the development of gold mining sector in FG? Some actors might give more importance to specific objectives rather than others. Local population and public authorities might weight higher the rate of employment and of

reduced deforested surfaces than the produced gold per year. At the same time, for mining operators, annual gold production could be the main objective to consider when it comes to plan strategies for mining development.

The definition of the objectives must be coherent with the spatial boundaries chosen for the application of the methodology. For instance, in the presented study, the territorial objectives concern only and exclusively Mana river basin. Further studies about the interactions among nesting territorial systems (e.g. from the river basin to the region) should be carried out and see, for instance, how this might influence the definition of the objectives and the governance related to gold mining, from the municipality to the central services of the government. For instance, different territorial objectives might be chosen by each municipality, according to their characteristics and goals. For instance, at the scale of Mana river basin the main territorial objective would be a high employment rate while at the Kaw river basin scale, the deforested surface would be a priority. Therefore, the application of our approach must not exclude the possibility of different and new territorial objectives for different territory systems and their spatial scales.

Finally, the current application is based only on the first objective (i.e. annual gold production of 5,000 kg) on which five TMS are built. However, this is rather the case when it comes to concretely purpose decision-making strategies, since public policies and objectives are built on multiple criteria of interest. Therefore, the TMS should be built on multiple objectives at the same time, based on the results of stakeholder's concertation and participative surveys especially if our approach aims to more accurate assessment and more effective decision-making support in land-planning processes.

2.2. The TMS: number and types of mining projects

The TMS took a spatialized form through the fictional localization of gold mine types within the Mana river basin. The number of projects depend on the territorial objectives but also on the intrinsic properties (e.g. mining techniques, workforce, mine site surface) for each mine-type, as defined in Chapter 4. However, the important amount of collected data concerning each mine type is dynamic and should be updated based on the changes that might affect the gold mining sector in FG. As we mentioned, recently, a new gold mining project suggested the use of underground mining techniques (Orea, 2020). Secondly, these parameters are expressed in a range of values (Appendix 7). Therefore, it is important to select a given value in order to allow a quantified assessment of the score of the TMS. The choice of a specific value within the range for each parameter of the gold mine-type should be guided by local experts and mining operators and public authorities to avoid under or overestimation of the consequent levels of risk. For instance, the illegal-TMS involves 758 illegal mines against the TMS-C with only 33 ASM. This is explained because, according to the data gathered and interpreted so far, one ASM produces approximatively 100 kg of gold per year, while one i-ASM only 6,6 kg. However, in reality the same miners in one i-ASM-type might work on multiple

projects. The higher gold production of the illegal sector is due significantly to the significant quantity of illegal mines that cover the territory. This *size-vs-quantity* issue, which will be detailed in the next section, is peculiar to the illegal sector – but not only – and its specificities, if compared to legal projects. Therefore, the assessment of the illegal-TMS does not allow the proper comparison between the legal and illegal sectors using the same common parameters. The data concerning illegal projects should be furtherly assessed and detailed, especially if specific strategies aim to address the role of this sectors into land-planning.

2.3. Fictional vs real localization of the gold mines

A final concern is related to the method used for the localization of the gold mines for each scenario. In this study, as we focused on gold mine-types instead of real projects, we used fictional localizations for the mining projects. Furthermore, the utilization of fictional localizations serves the purpose to develop potential future scenarios at the territory level, although more factors should be considered (e.g. road accessibility, electric generators nearby). This approach might be used as well by local authorities to hypothesize fictional land-planning strategies on the long term. Nevertheless, the approach proposed in this study can focus as well on the real localization of existing mining projects still under development. This would allow the analysis the mining projects that would see the light on the short term and a rapid comparison that might support decision-making for immediate operational purposes.

Concerning the fictional localization, since the purpose of this study is not to develop a method to optimize the siting of gold mines, a simple and basic methodology has been presented in Chapter 5 based on geological, juridical and socio-ecological criteria and on few assumptions (e.g. the localization of the project within a 2 to 5 km wide buffer around the localization of the geological deposit). However, despite its reliability, the localization of the mine site does influence the level of risk and, thus, the final score of each TMS. Hence, mining siting should be performed using well more developed methodologies or, when these are not available, on a higher number of reliable criteria. For instance, Amoah and Stemn, (2018) used a spatialized multi-criteria analysis for the localization of centralized processing centres for artisanal miners through an approach similar to ours but using more criteria (e.g. slope and nearness to other ASM sites, to roads, railways, settlement, tectonic zones, waterbodies). A recent research program called *APPUI-Mines* is being realized by the French Geological Survey (BRGM) that aims to the development of a GIS-based “favorability” methodology for the localization of small-scale gold mines in FG based on a significantly higher number of criteria (e.g. protected areas, terrain data, regulations). Once finalized, this could be integrated within the current application of our approach.

3. Rapidity and reliability of the RSa and RSo scores assessment

Our approach allows a rapid and easy comparison of different TMS using existing data, based on the risk scores. This study focuses mainly on the accidental risk scenario (RSa), more specifically in the case of a tailings dam failure generated by overtopping. However, in order to obtain a global TMS score, the ordinary risk scenario (RSo) has been only explored with a simple series of risks. Despite the demonstrative purposes and the transposability of the approach, the results are naturally by the choices and assumptions made during the assessment and their uncertainty still remains an important gap to fulfil. Nevertheless, these choices answers to the fact that this study aims to show the feasibility and the rapidity of our approach, especially in a context where data are lacking.

This is particularly true for the RSa which has been the main focus in this thesis. The central event of the RSa is the tailings dam failure generated by overtopping. The assessment of the RSa score involved a series of estimations, concerning the impacted area (i.e. the flooded area), socio-ecological vulnerability and probability assessment. The following sub-sections detail specific issues related to the assessment of the RSa score.

3.1. Flood area estimations: limits and perspectives

The assessment of the consequences related to the selected RSa was performed, firstly, estimating the directly impacted area by the dam failure by overtopping. As it is shown in Appendix 11, a great range of hydrological, hydrodynamic, hydraulic and rheological models is currently available and applied in different studies, for geotechnical monitoring, flood management and land-planning. However, because of their reliable and detailed prediction, these models are very time-consuming and requiring a considerable amount of data.

Therefore, the method proposed by Concha Larrauri, (2017) has been selected for a first estimation of the flooded areas due to a dam failure since it has been developed specifically for tailings dam failures, when few data are available. Also because of these advantages, this method presents a series of limitations and a rough estimatead flooded area.

Nevertheless, this method is simple, rapid to perform and it integrates few parameters related to the mining project and the structure of the dam. Furthermore, it allows a first operational estimation of the dam failure at the territory level and performed on multiple mining projects at the same time, which makes it adapted to the purposes of this study.

However, from a methodological point of view, this method is built on historical failures related to large-scale mining operation. Therefore, it might be inconsistent for the application on smaller mining projects (e.g. i-ASM, ASM, MSM). Furthermore, the resulting area is more or less represented by a buffer zone around the localization of the gold mines, without considering the downstream direction of the flood and sometimes considerably overestimating the flooded area (Table 38).

For this reason, the method has been integrated with another methodology developed directly on Qgis and presented in Chapter 7, Section 3.3. This second method is only based on DEM and the localization of the mine site. Although the delimitation of the flooded area is more precise than the first method, its accuracy of prediction is very limited to the few data used for the assessment. No considerations are given concerning the level of the water inside the dam, flow velocity, the nature of tailings and other parameters concerning the dam structure or the surrounding environment (e.g. soils permeability, presence of natural or anthropic barriers) (Table 38). Nevertheless, this approach is based on the same theory behind the methodologies usually applied to derive the hydrological network from DEM data. The method is based the choice of a threshold value of the GIS module used (i.e. Maximal Flow Path Length). The numerical outputs of this module have been interpreted and selected on a subjective observational basis. This represents as well the main grey area of this method, since the value chosen varies on a case-to-case basis and on expert-based opinion, which considerably influence the extension of the flooded area. Therefore, the uncertainty of this second method should be furtherly quantified. As for the first method (Concha Larrauri, 2017), the second method is not intended to substitute more detailed and accurate methodologies for dam failure flood assessment. Finally, the combination of the two methods is realized through limiting the accumulation zones resulting from the second method to the maximal flood perimeter obtained from the first method (Concha Larrauri *et al.*, 2017) (see Fig. 58).

This coupled simple approach has been tested on the Brumadinho dam failure, to see if the flooded area corresponds to the estimated one. It has been shown that, as mentioned, the choice of the threshold values used in the QGis module vary on a case-to-case basis. Furthermore, the maximal run-out distance of the flood is highly overestimated. Hence, it is possible that the estimated flooded areas are much greater than if they were estimated by more accurate models and using more data. The reduction of the flooded area would increase – in positive – the final score of the TMS. But it is still to discuss if such increase would operate proportionally for each TMS or only for the TMS-A, which involves only one large scale mining project and for which the maximal flooded perimeter is considerably wide.

Finally, concerning the integration of much more detailed data, a specific issue is related to fully apprehend the mechanisms of failure, which influence the quality and the quantity of the tailings release. In the case of overtopping, if the dam does not collapse, not all water comes out, and in some cases, it might not exceed the mine site. In the current study, overtopping is used as a triggering mechanism of a dam failure where the total water volume is assumed released, which is rarely the case during overtopping. In the current case, the only adaptation to failure generated by overtopping is given during the application of the first method used, where the total elevation of the dam parameter does not take into account the freeboard (i.e. the difference in elevation between the crest of the dam and the maximum water surface in the reservoir), as it would be the case during an overtopping (where the freeboard becomes equal to zero).

Table 38 Limits and advantages of the methods used in this demonstrative application for the estimation of the flooded area

Methods used	Advantages	Limitations
Concha Larrauri, (2017)	Specific to tailings dam failures	Built based on historical tailings dam failures related to large-scale mining only Does not consider flow velocity, route and direction
	Same geological context of FG	DEM as only external parameter
	Limited input data	Does not consider nature of tailings
	Based on historical tailings dam failures	Does not consider variation of water level Based exclusively on large-scale mine failures
	Can be partly adapted to the type of failure	Does not consider safety measures at the dam level Does not distinguish downstream and upstream areas
	Good rendering at large spatial scales	Does not consider potential surrounding sink or vectors (e.g. depressions, streams)
Flow accumulation area method	Based only on DEM and the localization of the mining project	Does not consider water level or flow velocity, type of failure, nature of tailings etc. Expert-based selection of the thresholds for the FLP module on GIS-tools
	Considers the downstream area and the main preferential direction of the flood	Does not consider safety measures at the dam level

3.2. Estimation of territorial vulnerability

Once the flooded area has been estimated, vulnerability indicators are assessed, mapped and combined to obtain an overall vulnerability map of territory (Fig. 67). Socio-ecological vulnerability of Mana river basin is independent from the mine-type in the flooded area since it is related to the intrinsic characteristic of the territory system.

The indicators and the methods used to quantify it have been specifically selected and developed for FG based on the available data through an expert-based approach. However, in order to be more solid, the assessment should be integrated with more reliable data and commonly recognized and validated methodologies for land-planning purposes. For instance, soil fertility could be assessed through further specific indicators (e.g. C/N ratio, cation-exchange capacity, total organic carbon) widely used in scientific literature (Drobnik *et al.*, 2018; Yageta *et al.*, 2019). Moreover, because of the territorial resolution of the assessment, some information gathered at local scales can be lost. For instance, multiple aspects of the assessment of soil-related ecosystem services can be discussed since the wide resolution of the

assessment does not consider the great horizontal and vertical variability of soils in FG. Hydromorphic soils nearby surface waters which can be greatly affected by changes in hydrological regimes are not considered. Secondly, *oxisols* and *ultisols* present a good permeability (see Appendix 12) only because the assessment focuses on the features of topsoil while deep drainage can often be stopped by clayey layers present within the subsoil. Finally, speaking of soil fertility, it would be important to assess soil agronomic potential also based on information related to currently used or potential agricultural practices.

Concerning the aggregation of the scores, the main reasons behind the final outputs given in Chapter 7 consist in the fact that, firstly, the scores have not been weighted (Chapter 9) at this stage. Secondly, the processing on Qgis of the vulnerability assessment involves a great range of spatial data only in the form of thousands of polygons and eleven indicators. The *horizontal* resolution of the results (i.e. the multiple polygons displayed) involves areas where the values of the geometric mean are at the maximum or minimum. However, these areas are “lost” within the great number of polygons (Fig.67a). This is due to the difference of spatial scales at which the original data are displayed. For instance, the spatial data provided by ONF, (2015) (e.g. biodiversity vulnerability, wood production, landscape vulnerability) have a higher resolution compared to the data used for the other indicators. Therefore, here the aggregation method chosen doesn’t seem able to consider the difference of the resolution at which the data used for the assessment were originally produced. Secondly, the *vertical* resolution concerns the number of vulnerability indicators, thus the number of vulnerability maps that need to be aggregated. Despite they are a bit more than a dozen, for every *pixel* there is at least one indicator that has a high vulnerability value (i.e. 4 or 5), which explains why the aggregation method by maximum value displays an elevated vulnerability for the whole basin (Fig. 67b). For the mentioned reason, it is vital to choose or developed other aggregation methods which tend to consider these two types of resolution and thus, that manage to normalize the final global score, taking into account the number of indicators considered and the number of data used for the aggregation. For instance, it could be investigated mono or multi-criteria decision-making methods for data combination.

Despite the methodological issues mentioned, specific considerations should focus on the data currently available used for the estimation of each indicator. This kind of information has been gathered after free-interviews and observations in the municipality of Mana during the different missions in FG, but it has not been possible to integrate such aspects under a quantitative form. For instance, it is important to consider that, in relation to the vulnerability of local population, in FG, and particularly in Mana RB, there are some areas of informal human settlements (approximately along the roads D8-9 and 10). These areas are extremely dynamic, and they rely considerably on the resources provided by the Mana river. Furthermore, more than 2,000 illegal gold miners are spread across the municipality in inner forest areas. Also, the municipal services emphasize as well the necessity to consider the potential cumulative

impacts of the upstream agricultural areas on the increasing water pollution in the area of Javouhey (Fig. 19).

Another aspect concern drinking water points. The municipality is changing during these years the method for drinking water provisioning switching from surface water to water sinks drilled near the main village. At the moment the water provisioning is starting to rely on underground wells in order to not depend on the surface waters of Mana river. Therefore, the vulnerability assessment of drinking water availability must consider the technical features related to the engineered structures used to provide drinking water and their protection measures. Furthermore, Mana municipality currently provides drinking water to another different municipality, Awala-Yalimapo (Fig. 19), which would enlarge the indirectly impacted area if this water catchment point was affected by the flooded area.

Therefore, territorial vulnerability is dynamic, and its estimation should be updated through continuous visits on the field, surveys and interviews with local stakeholders. Furthermore, new parameters should be added to detail the vulnerability of specific assets. For instance, the vulnerability of infrastructures should include data concerning the construction materials of each building, their age, etc. Also, for the assessment of surface water quality vulnerability, the length of the impacted water streams, the water flow and the width of the riverbed, the distance from the dam etc. An interesting way to do so would be to integrate and quantify the level of vulnerability based on the Strahler order, which is a mathematical tree giving the numerical measure of the branching complexity of a hydrographic network.

3.3. Size vs quantity of the gold mine-types and cumulative consequences

In this study, the main output that greatly depends on the gold mine type, its features and localization, hence, on the TMS, is the flooded area. Therefore, as it is expected, the more the gold mine has higher volumes in terms of gold processing and tailings stored in the embankment, the greater is the flooded area if the mining dam fails: the rate of gold production influences the volume of tailings processing wastes, which is proportional to the potential flooded area if a dam failure would occur by overtopping.

Thus, on one hand the great *size* of the gold mine is defined in terms of gold production, the availability of important financial and human resources (e.g. capital, workforce, technical skills) and, in the current case, by its soil footprint. If currently a “greater” gold production influences the volume of tailings and the surface of the potentially flooded area, important questions should be raised about the allocation of project resources. A better allocation of human and financial capital of a mining company could aim to increase the operator performance in managing mining wastes through reducing waste inputs, optimizing storing methods, safety barriers reducing the probability of failure of a mining dam etc. Therefore, in this case, the *size* of a gold mine might not be directly proportional to the quantity of tailings stored and potentially hazardous. For instance, the analysis would be different if underground gold mines were considered in this study. Waste management in underground mining differs

from the one during surface mining and, moreover, the surface of the mine site is likely to be much lower than the current gold mines in FG.

The other element that needs to be taken into account is the *quantity* of gold mines operating at scale of Mana river basin according to our TMS. This implies the consideration of cumulative consequences. For instance, in this demonstrative application, despite one LSM project-type has a greater flooded area in the case of a dam failure, the same scenario for smaller projects (i.e. ASM or MSM-types) results in much smaller flooded areas but a considerably higher number of surface water affected. At the scale of the water catchment, and particularly in equatorial and tropical region such FG, a fundamental issue concerns whether the distribution of a given number of mine-types is higher or lower than the density of the hydrographic network. As it has been pointed out in the sub-section 2.2 of this Chapter, the influence of the number and types of mines chosen naturally influences the level of risk. The distribution of multiple gold mines on the territory, that we called *mining density*, increases obviously the probability to have at least on failure and more important cumulative positive and negative risks than the scenarios where only one mining project is considered. What is important to apprehend is if the cumulative risks of dozens of small mines can outweigh the risks generated by one large mine. For instance, Franks *et al.*, (2013) highlight the implication of the consideration of cumulative risks into policies and management, through the necessity of decision-making that responds to the scale of the system in which impacts are aggregating and interacting, adopting participative and cooperating strategies for a management which is adapted to the studied system and its components.

The quantity of gold mines in each TMS is particularly relevant for the level of consequences in both the risk scenarios. In particular, the final score of the RSa integrates as well the cumulative consequences generated by a mining dam failure, which is an *extraordinary* event, that would occur for multiple mining projects at the same time. On one hand, history of accidental dam failures shows that is extremely rare that multiple dam failures occur at the same time. For instance, during 1960s, this happened in some South American areas, triggered by seismic events in the region (Fig. 46). On the other hand, this study shows the application of an approach to foresight and discuss potential scenarios at the territory level. Indeed, as mentioned in multiple occasions, the proposed approach does not aim to assess the detailed level of risk – for which specific methods exist already – but to compare territorial scenarios based on a certain level of risk and discuss them based on the level of detail of the assessment and its level of uncertainty. The main goal is to simulate and compare potential scenarios rather than precisely predict them. Hence, the current thesis aims to show an analytical approach – rather than a predictive one – in order to compare potential strategies for future land-planning scenarios involving (or not) mining activities of different natures.

3.4. Probability assessment and safety measures in the RSa

It has been shown in Chapter 7 that probability of occurrence has been integrated in this study based on a simple assumption that considers the probability of occurrence indirectly proportional to the size of the gold mine-type. The probability scores used in this study tend to significantly decrease the TMS scores. As mentioned, a global higher probability of occurrence of the dam failure event is assumed here (Table 24). Nevertheless, other assumptions could have been applied: for instance, a scenario (RSa_2), where the probability is proportional to the size, productivity and financial resources of the gold mine or another scenario assuming a global lower probability of occurrence of the dam failure event (RSa_3) (Table 39). Therefore, is important to emphasize the shortcomings present in the application shown in this study that might have led to the under/overestimation of the final RSa scores and how to address them.

Table 39 Assumptions concerning the probability scores in this study for the RSo and RSa_1 and other assumptions that could have been used

Risk scenario	Assumptions	Probability scores				
		i-ASM	ASM	MSMg	MSMc	LSM
RSo	Certain occurrence of the risk events	1	1	1	1	1
RSa_1	Overall higher probability of occurrence of the event	1	0.75	0.5	0.5	0.5
RSa_2	Higher probability for less equipped projects	0.75	0.5	0.5	0.25	0.25
RSa_3	Overall low probability of occurrence of the event	0.5	0.25	0.25	0.25	0.25

First of all, the Bow-Tie diagram has been used in the current application only for its conceptual advantages, since it allows to display the cause-effect relationships between the triggering factors and the consequences around a central risk event. However, if used properly, the Bow-Tie might offer an important assessing tool that allows the assessment not only of the probability of occurrence of the main central event – in this case the dam failure by overtopping – but also the probability of occurrence of each consequence generated from this event.

This is particularly useful for a territory-based approach, it is not only important to understand what is the probability of the event to occur but also which is the probability for the consequences to overcome the mining site (or, even more specifically, the area surrounding the tailings dam, in case of the dam failure). For instance, the probability of occurrence of a dam failure in a given mine could be certain, but the probability for the failure to affect local population or the downstream waterbodies is inexistent (e.g. because the region is not populated or because of the construction emergency ponds). Therefore, the probability for the consequences to occur, after the central event occurs, may depend on the characteristics of the territory system and its level of socio-ecological vulnerability (e.g. region with no population) or on the characteristics of the mining system, i.e. the implementation of technical and organizational safety measures. Proactive and reactive safety measures can be effectively

integrated within the Bow-Tie. This would enhance the results of the assessment and, thus, a pertinent comparison of the TMS risk scores and more effective decision-making support. For instance, the integration of these measures (e.g. draining or overflow devices, monitoring, alarming system) might suggest which actions should be proposed on the mining infrastructures or at the level of the river basin also to reduce their vulnerability. For instance, overtopping may occur and destroy the dam but if specific safety measures are implemented in the immediate downstream, the failure will stop at the mine site. In a certain way, the mining dam represents by itself a safety measure, at the scale of the mine site, to protect the surrounding environment from the wastes generated by mineral processing. At the beginning of the century, tailings were released directly in water streams without any consideration for their socio-environmental consequences.

Finally, concerning the estimation of the probability of failure of tailings dams and its uncertainty, an international project called IMAWARE (<https://riskinstitute.uk/imaware/>) is currently being conducted by the Risk Institute of Liverpool University in collaboration with other universities, research centers and mining operators. The project focuses on a transdisciplinary approach to address mining risks in vulnerable regions, with a specific focus of South America. IMAWARE aims to enhance multi-stakeholder governance, dam reliability assessment, through stochastic structural reliability analysis of the physical dam under its environmental conditions, but also vulnerabilities, long-term human health and ecological risks in order to consider the entire nexus of external drivers, human factors, and engineering failure. This could represent a complementary tool to our approach, especially when the RSa chosen concerns tailings dam failure.

3.5. An alternative way to integrate probability within the RSa score

The method used in this study to evaluate the RSa score (Chapter 7) can be discussed for the fact that probability scores are integrated only at the end of the assessment. This means that this method does not consider that in the TMS has different probability of occurrence of flooded areas exist, according to each gold mine-type and their related probability scores (Table 24). As mentioned in chapter 7, section 7, another way to proceed is to integrate the probability at the beginning of the assessment (Fig. 70), assigning the probability scores to each flooded area per gold-mine type in each TMS. The probability scores are then multiplied to the maximal value of the geometric means of the vulnerability scores located within the flooded areas.

This second method allows a more rapid assessment and also a better spatialization of the final results through risk maps whose values change according to the gold-mine type at the origin of the flood event (Fig. 70d). Nevertheless, all these results are then reduced to non-spatialized RSa scores, as for the first method, in order to compare the TMS.

Furthermore, this alternative might present the same level of incongruity than the first method used in Chapter 7. Indeed, the method tends to lower the values, increasing the final (positive) RSa scores for each TMS (Table 26). It is significant that, at this stage, this second method does

not consider the surface of the flooded area. For such reasons, the TMS-A, which presents the larger flooded area according to this study, has a better final RSa score (Table 26). Therefore, further improvements must prioritize these gaps and address such challenges through the development of approaches integrating in this second alternative the scores related to the surface of the flooded areas for each gold mine-type of each TMS. As mentioned already, specific aggregation methods should target the mixed scenarios, where multiple scores, related to different coexistent gold mine-types, need to be combined.

4. Final TMS scores and weighting coefficients

Once the risk scores of the risk scenarios were estimated, they were combined to obtain a final score for each TMS (Chapter 9). This score depends directly on the assessment of the risk scenarios and on how these two are aggregated but also on the weighting coefficients developed to account for the different perspectives of local stakeholders. The following sub-sections discuss the final scores of the RSa and the RSo developed in this study and the methods used for their aggregation and its weighting.

4.1. The non-weighted global scores of each TMS

4.1.1. Final risk scores of the RSa

As a demonstrative example, the most “preferable” TMS for the RSa scores assessed in this study are TMS-B and TMS-C (Table 33), while the illegal and the large-scale scenarios present lower scores. For the TMS-B and TMS-C, this is due especially because of the influence of the RSa scores, with limited surfaces of the flooded area. However, when weighted, the TMS-A score is significantly increased, particularly because of the influence of the limited surface (i.e. landscape degradation) in the RSo and the important weight associated (Table 20). This aspect is particularly interesting in FG, where at the moment, legal gold mining implies exclusively surface mining techniques that consume considerable cumulative surfaces. Could underground mining be a way to reduce such risks or they would just be replaced by new risks associated with underground mining?

In the case of the illegal scenario, such score is given by the fact that, despite the flooded area of each i-ASM individually is not comparable with the one generated by one LSM-type (*size*), the presence of 758 i-ASM mines (*quantity*) generates cumulatively a wide flooded area. Furthermore, because of the lack of safety measures in i-ASM, the probability of occurrence of the failure is more likely. Nevertheless, the TMS-A and TMS-illegal have the same final RSa score because in this study, the final RSa score is the result of the consequences (i.e. the combination of the level of vulnerable assets within the impacted area and the size of the surface area) and the probability. However, probability scores have been applied only to the level of vulnerability of the assets within the flooded area but not to the “surface of the flooded area” score. Since the probability score is very low for the LSM (Table 24), this would have actually optimized significantly its final score of the TMS-A.

The integration of the probability scores to the “impacted surface” score represents still an unresolved issue. Except implying supplementary aggregating decisions that, at this stage, would make the results more uncertain, a specific difficulty concerns particularly the mixed scenario (TMS-D) where different mine-types present different impacted surfaces and different probability of occurrence of the failure. For this reason, more pertinent ways to adapt the probability parameter to the coexistence of different mine-types within the same TMS must be developed. Qualitative and expert-based assumptions could be used to assign to each mine-type more valid scores representing the probability of failure and more composite ways to aggregate them. Or else, it could be interesting to use the alternative approach (section 2.3) to integrate the probability scores directly in the impacted area and finally, normalize the final RSa scores by the flooded surfaces corresponding to each gold-mine type.

A specific concern is related, for the application shown in this study, to the intensity of the consequences of the dam failure on surface water resources. This aspect is to be taken into account especially in regions such as FG where the hydrographic network is extremely dense and particularly for the scenarios involving gold mines of smaller *sizes* (e.g. ASM, i-ASM) but in a greater *quantity*. As mentioned, independently from their size, a higher number of mines heterogeneously located on the river basin, is more likely to be in contact with a greater number of water streams. In FG, the main negative consequence generated by ASM is the increase of water turbidity and silting through the production of sediments, due to accelerated soil erosion. While the surface of the individual flooded areas would be very low, their cumulative areas and consequences would be very relevant. Therefore, the integration of such particularisms would change significantly the final global RSa scores of each TMS. This aspect justifies again the need of studies which focus, rather than at the mine-itself, at the territory level and the cumulative dimension of risks. Specific indicators could be developed to assess such consequences, for instance focusing on stream length, water flow, Strahler order of each segment but also on the quantity of released materials in water streams and their chemical nature.

4.1.2. Final risk score of the RSo

From a general point of view, the TMS-A displays the “best” RSo score, thus showing that for the same annual gold production of 5,000 kg of gold, cumulative risks of smaller projects might outweigh the risks generated by only one LSM-type gold mine. The higher RSo score for the TMS-A is due particularly to the lower land consumption compared to the cumulative surfaces occupied by multiple MSM, ASM or i-ASM projects. Thus, it seems that, in normal functioning conditions, the production of gold generated by only one cluster of mines (i.e. the LSM in the TMS-A) could represent a better allocation of land-use, avoiding supplementary soil losses. The MSMc scenario (TMS-B) shows as well a high score, mainly

because of its employment potential which is the highest among the considered legal scenarios, based on the parameters that we have defined in Chapter 4.

However, such statements should be considered carefully because of the uncertainty related to the development of the RSo that, as mentioned, was not the main focus of this study. Compared to the RSa, the RSo used is poorly developed and it has been integrated to compare the TMS based on their global scores, in order to show the feasibility of the approach proposed in this study. Therefore, further studies must focus on the improvement specifically of the RSo development and the assessment of its level.

A first point of discussion of the RSo concerns its definition as a “risk” scenario. It has been mentioned already that the risks related to the normal functioning of a mining project are not properly “risks”, strictly speaking, since their occurrence is certain. Therefore, these “risks” represent rather “nuisances”, when negative (e.g. deforestation, noise pollution), or opportunities when positive (e.g. employment, economic outcomes) that arise as the mining project exists. However, what is uncertain is the occurrence of the positive or negative consequences that might be generated by these events. For instance, the deforestation generated by the development a mine site could be considered not as a risk, since it is certain. On the contrary, the potential effects that such deforestation has on biodiversity, CO₂ sequestration or else, can be considered as such. Therefore, the RSo should focus also on the assessment of the uncertain events that are generated by the certain nuisances or opportunities related to the mere existence of a mining project. This cause-effect analysis should be performed through the integration, within the RSo, of the Bow-Tie analysis for each risk event considered. Also, in this study, the estimation of the impacted area and territorial vulnerability have been performed only for the RSa and no mention has been done for the assessment of the final RSo score. These two aspects have been considered essential for the application of the approach proposed in this thesis. Therefore, further studies should focus on the quantification of the interactions between the events occurring during the normal functioning of mining projects and the uncertain events they might generate, the area affected by these events and, therefore, the vulnerability of the assets within it. An option could be the adaptation of LCA studies to our approach for the estimation of the risk score in normal operating conditions.

Furthermore, the distinction between what is a positive and what is a negative risk must be multi-perspective. This means that stakeholders should be integrated in order to understand if there is a unanimous consideration of the negative and positive risks related to a mining project.

Other considerations are related to the choices made to expose the development of the RSo and the assessment of its score must be discussed in order to understand the final score obtained. The RSo was developed in this study including only one negative risk (i.e. deforestation). The surface deforested due to the development of the mine site has been

considered as a global indicator to assess the overall negative environmental footprint of a gold mine. Indeed, it might represent the immediate physical effect of the development of a mining project in a given area. However, the selection of only one negative risk, compared to four positive risk events (see Chapter 8) is not considered sufficient to obtain a reliable score of the RSo. The disproportionate combination of such risks or the weights that are given to them might mislead the resulting scores. For instance, even if the negative consequence had the lowest value, this would be compensated by the presence of four positive impacts.

Unlike the present study, that focused on the available data for a rapid estimation of the RSo scores, the assessment should consider more trustful indicators. These indicators can be found in general literature not specific to the mining sector, often at the country-scale. For instance, concerning employment, the International Labour Organization proposes indicators such as the number of employed or non-employed persons, to measure employment opportunities and quality (Coderre-Proulx *et al.*, 2018). De Bustillo Llorente and Fernandez Macias, (2005) assess employment opportunities in Spain through the quantification of multiple indicators (e.g. salary, teamwork, type of contract, public or private sector, length of service, size of the workplace). Other indicators are proposed by The World Bank Group and the Organisation for Economic Co-operation and Development (Lachler and Merotto, 2020; OECD, 2020).

The initial data used for the estimation of the indicators and the thresholds classes used for their scoring are a limiting factor that influences the final results. Furthermore, the uncertainty related to such data must be accounted for. For instance, for some risks of the RSo, data are available for some gold mine-types but unavailable for others. In this case, the result would be the comparison of TMS where in some cases, the assessment is partial or even impossible to perform. A simple way to address these shortcomings could be the quantification of an index considering the number of quantifiable risks for each TMS based on the rate between the number risks with available data and the total number of considered risks. For instance, one TMS is provided with all the available information for the assessment of its RSo score (let's assume that the RSo is composed of 10 consequences), while another TMS disposes only of 8 quantifiable consequences, the index would be respectively 1 for the first one and 0.8 (i.e. 8/10) for the second one. This index would then be multiplied to the global RSo for each corresponding TMS in order to obtain a result which at least would be weighted according to the level of available information for each TMS. In any case, further studies should focus on gathering more reliable data and to develop assessment methods to define more accurately specific indicators in FG and their thresholds ranges based on participative approaches and expert-based considerations.

Finally, the methods used to aggregate these data need as well improvements to consider the number of considered risks, whether they are negative or positive, and the weights potentially given by stakeholders. For instance, if the maximum value was chosen to combine

total negative and positive scores, the best scenario would be TMS-B, since it is the most performant on the positive consequences due to its highest score corresponding to the creation of job opportunities. Indeed, in this scenario, 6 MSMc-types might generate a significant rate of employment due both to the recruiting of miners and specific technicians for the functioning of six different cyanidation plants.

4.1.3. Aggregation of the RSa and RSo scores

As shown in Fig. 73, the main aggregation method used to combine RSo and RSa scores is the geometric mean and the maximal value. The maximal value was only used in order to take into account the maximal score among all the geometric means of each spatialized layers assessed during the RSa (see Chapter 7).

The geometric mean has been chosen since, although it is less sensitive to different scales and only applicable to positive numbers, the geometric mean is preferred when synthesizing judgment for decision-making purposes (Kreĵci and Stoklasa, 2018; Doré-Ossipyan and Sareh, 2020). Indeed, the geometric mean is directly based on all the observations and usually the presence of a few extremely small or large values has no considerable effect on the result. Concretely, the geometric mean allows to reduce the influence of the highest values of the dataset and to increase the one of the lowest ones. If the modeler needed to increase such contrast between highest and lowest values, another aggregation method could have been the harmonic mean. It is important for further applications, to integrate decision-making tools (e.g. AHP, TOPSIS) allowing data combination through participative and multi-criteria approaches.

4.2. Weighting coefficients and the integration of stakeholders' perception

The multi-perspective dimension of the approach proposed in this study led to the integration of weighting coefficients to the global scores of each TMS. These coefficients have been obtained through a questionnaire survey among local stakeholders, as it is detailed in Chapter 9.

However, the number of gathered answers does not represent a sufficient sample size and have high interval coefficients. If we consider the size of the population in Mana river basin (~12,000 inhabitants), at least 1,000 answers would represent a reliable sample size that guarantees a sample error inferior to 3% at a 95% confidence interval and with a sample proportion of 50% (Israel, 1992). At this stage, the number of answers is not sufficient to integrate a correlation analysis as well to quantify the correlation between the weighting coefficients and the TMS scores (e.g. Spearman or Pearson coefficients).

Furthermore, the weighting coefficients, as shown in Table 34, tend to have the lowest values, particularly for mining-related assets, while the ecological assets were the most “important” for respondents. At this stage, this can be explained by several considerations.

- First of all – and most importantly – only one respondent belongs to the mining operator’s actor-category, which might drive and counterbalance a significant variation of the coefficients.
- Secondly, socio-ecological assets represent public goods and natural assets of general interest. In this sense, the responses to the questionnaire seem not to consider mining projects as matter of land planning and thus, at least with the same relevance that is given, for instance, to public roads and infrastructures.
- Also, as we mentioned, the gold commodity represents a particular strategic asset that does not awaken often the interest of local populations for its actual use and applications as raw material, unlike other commodities with higher technological applications (e.g. niobium, coltan, copper, zinc, nickel).
- Finally, most of the responses came from inhabitants of Mana municipality, which is currently affected by the presence of approximately 2,000 illegal gold miners, which might affect the vision of local communities towards mining activities.

Therefore, further actions should look towards the optimization of the questionnaire survey in order to gather as many answers as possible from all the different stakeholders in order to obtain reliable coefficients for a more pertinent weighting process. Despite the need for further improvements of the survey, the purpose of this weighting step is to show the methodological feasibility of the integration of stakeholder’s perception in order to normalize the results of the assessment and of the global score of each TMS based on stakeholder’s perception.

5. Comparison of the territorial scenarios: which scenario is the “best”?

The “best” scenario of this current application, according to the choices made, are the TMS-B and the TMS-A, suggesting that, for an annual gold production of 5,000 kg, the most interesting strategy based on the two risk scenarios developed, is represented alternatively by the development of 6 MSMc mines or one LSM in Mana river basin. Therefore, are these the options that a potential stakeholder should choose to develop mining strategies in the studied area?

The answer is negative because, as mentioned, the application shown in this study allowed to show the rapidity and feasibility of the approach that we propose and its adaptability to existing data. The result would be much more reliable if an uncertainty analysis would be performed, for instance through Monte Carlo simulations, fuzzy logic-based methods, uncertainty propagation, Bayesian statistics, although they might introduce subjectivity (Auwah-Offei and Adekpedjou, 2011).

Furthermore, as detailed in section 2.1., the comparison of the territorial objectives and the corresponding values for each TMS could be a preliminary tool that might allow the comparison and ranking of the different strategies (Table 37). The “best” strategy must be evaluated on multiple criteria which include territorial objectives as well as the generated and suffered risks by the mining projects (e.g. opportunities and losses) and their level of uncertainty.

Furthermore, except the illegal TMS, all the legal TMS (i.e. A, B, C, D) present very similar final weighted global scores which range between 2.7 and 2.9, as it has been explained in the previous sections. The differences between these TMS is not significant if we consider the uncertainty behind the assessment of their scores. However, the illegal scenario obtains the worst score among all the selected TMS. Indeed, the main point of force of the illegal TMS is represented by its aptitude to generate informal employment, influencing considerably the RSo score (Table 40). However, the surface impacts of the illegal TMS are the highest among all the other scenarios. Nevertheless, the social phenomenon of gold illegal mining must be considered extremely carefully since it is not subject to the same considerations that can describe legal gold mines, particularly concerning the precise delimitation of “mining sites” and “mining projects and the social – rather than technical – connotation that this phenomenon take locally in FG and in many other countries.

Table 40 Ranking of the TMS developed in this study based on their final global score with and without the integration of stakeholders’ perception

Ranking	TMS	Weighted TMS global score	TMS global score
1	TMS-B	2.9	3.4
1	TMS-A	2.9	3.3
2	TMS-C	2.7	3.2
2	TMS-D	2.7	3.2
3	TMS-illegal	1.9	2.3

Conclusion and perspectives for the application of our approach in FG gold mining sector

The approach proposed in this thesis has been tested on the gold mining sector in FG. Rather than predicting risks related to gold mines in FG, the purpose of our approach was the comparison of five territorial scenarios, involving different types of gold mining distributed over a river basin. Despite the level of uncertainty, this study answers to the purpose of presenting an original approach to look at mining activities and their risks at the territory level for land-planning strategies. Its application shows its feasibility , especially in a territory such as FG where data are often not available.

This approach is not operationalizable yet but the current application was intended to show as well the open questions and challenges that might be addressed by further studies to enhance our approach. Further improvements should focus on the characterization of the uncertainty of the results. The results of the application shown in this thesis should be integrated with the potential error and their level of uncertainty. Indeed, uncertainty and sensitivity analysis would help quantifying the confidence of the results in order for the application to be more pertinent to support decision-making and land planning.

Among other perspectives, the current application should aim to:

1. Improve the process of data gathering for the assessment of the risks and for the definition of the features of gold mines in FG and socio-ecological vulnerability;
2. Develop new TMS, for instance combining the legal and illegal sectors in the same scenario, which would be a more representative scenario in FG. This means to mobilize pluridisciplinary competences, including social and human sciences, to apprehend the technical and social features of these activities, especially for the illegal gold mining sector;
3. Improve the ordinary risk scenario with more risk events, integrating a Bow-Tie analysis, the identification of the impacted areas and socio-ecological vulnerability;
4. Test new central events for the RSa (e.g. explosions, transport accidents, spills, pit instabilities) and/or potentially combine multiple RSa at the same time.

Finally, the application of our approach in FG should integrate as well new project-types that might respond to the same territorial objectives defined for the TMS. For instance, a great number of Classified Installations for Environmental Protection (ICPE) are located in FG, among which just a few are related to the mining sector (Appendix 16). It would be interesting to test the approach integrating some of these projects, their specificities and the relative regulatory frameworks. The consideration of projects of different natures and their risks would allow to meet in a more comprehensive way the purposes of land-planning of our approach.

For instance, recent experimental studies concern the potential implementation of agromining in FG. Agromining is a practice that allows the recovery of target metals through the utilization of hyperaccumulator plants whose biomass is harvested and processed (van der Ent *et al.*, 2015). It would be a technique serving multiple purposes of production, through the extraction of strategic metals – although very limited compared to mining projects – through biogeochemical processes. Therefore, agromining might present an economic interest, since it would contribute to respond to the demand of metals such as gold, at a different ration. Furthermore, this practice might respond as well to technical and operational needs – for land reclamation, revegetalization and phytoremediation of mine sites, reducing their negative socio-environmental consequences (Chaney *et al.*, 1997; Krisnayanti *et al.*, 2016) – but also to the enhancement of ecosystem services (Pons *et al.*, 2018).

Finally, despite the approach is is specifically built for mining activities, the same framework could be applied in order to integrated mixed scenarios involving other anthropic activities that may have important socio-ecological consequences (e.g. biomass production, agricultural activities and farming) in order to: i) assess the overall level of cumulative impacts within a same territory; ii) analyze and discuss the closed interactions between mining projects and other human activities.

Chapter 11. Advantages, limits, perspectives of our approach and concluding remarks

This study represents the first effort to propose a new and original approach to integrate mining activities into wider spatial scales of decision. In this PhD thesis, this takes the form of a comparison between multiple land-planning strategies for mining regions based on risk assessment at the territorial scale. Furthermore, the proposed approach was given a formal basis and has been operationalized through the development of a methodology based on existing methods and adapted for its application to the FG gold mining sector.

We are aware that there are still important efforts to be made at this stage. These efforts should focus on the improvement of the approach and its operationalization, addressing as well the challenges that have been pointed out in the previous chapter.

1. Added value of the approach proposed in this study

1.1. Mining as part of a land-planning strategy

The application to FG is based mainly on the general procedure followed to perform risk assessment, as defined by ISO (2008), namely: system definition, risk identification, analysis, quantification, management and control. Indeed, risk is one key-elements considered in project management. As for project management, when it comes to territorial management and land-planning, risk must be accounted in the interest of public authorities, for governance, and of mining operators. However, because of the very wide spatial scales addressed by our approach and because its purpose is not the quantification of the risk it-self but rather the comparison of different scenarios based on their risk scores, the standard risk assessment process has been adapted to our needs.

Our approach meets most of the objectives presented in Chapter 2. The land-planning purpose of our approach is emphasized in one of the crucial steps shown in Chapter 5, i.e. the development of different TMS defined in agreement with pre-determined territorial objectives.

Indeed:

- i) It is structured and transversal, based on existing frameworks (such as ISO, 2008) and adapted to wider spatial scales;
- ii) It allows the integration of the coexisting mines with different characteristics.;
- iii) It integrates the socio-ecological vulnerability of the territory where mining is performed and risks of different natures
- iv) Its application is based on currently available data;
- v) It is susceptible to include the involvement of stakeholders all along its application;
- vi) It provides results which can be communicated and easily made accessible to stakeholders (e.g. maps, sheets).

1.2. The ecosystem-services approach

According to our approach, a mining project is considered as a socio-technical system operating within a territorial socio-ecological system. This requires a systemic approach where a risk – positive or negative – occurs when the performances and functions of one of these systems are – positively or negatively – altered (Fig. 7 and Fig. 13). Therefore, the “good” functioning of a mining project depends on its positive or negative contribution to the socio-ecological system where mining is performed. The operationalization of this approach can be done through the integration of the ecosystem-services framework (see the Glossary). Despite subject to multiple debates regarding its fuzzy conceptuality and its application (Schroter *et al.*, 2014) an ecosystem-services approach might:

- i) Merge into a single concept both the social and ecological dimensions of the risk. The performances and functions of a territory system aim to satisfy specific needs (e.g. water provisioning, food quality, economic welfare). When mining alters the processes that guarantee such performances and functions, the corresponding needs might be unsatisfied (e.g. the release of important amounts of heavy metals-enriched sediments reduces surface water quality, jeopardizing the supply of drinking water of nearby settlements).
- ii) Serve as an operational tool for decision-making support to help quantifying the transversal impacts of some human activities through scenario-based approaches at wider spatial scales (Furst *et al.*, 2017; Scammacca, 2017; Blanchart, 2018).

The ecosystem-services approach should be furtherly improved through specific assessment methodologies that allow to apprehend the nexus among all the different ecosystem services and the mining activities. Therefore, further studies should focus on the quantification and spatialization of ecosystem-services *flows* (the ecosystem services actually delivered) and *stocks* (the ecosystem services potentially delivered), related to different ecological components (e.g. water, air, soils, forest, biodiversity). This would allow a state of the art of the original conditions of ecosystem services supply. In this way, the influence of different territorial mining scenarios on ecosystem services supply could be quantified more consistently.

For instance, a research project called ECOSEO is being led by the International service of the French National Forestry Office (ONFI) and the WWF. The purpose is to assess ecosystem services delivery at the scale of the Guiana Shield through remote-sensing and GIS tools (ONFI and WWF, 2019). This might provide a significant amount of data that could improve the estimation of socio-ecological vulnerability and, therefore, of the potential consequences generated by mining activities.

1.3. Complementarity between our approach and SWOT analysis

SWOT (Strengths-Weaknesses-Opportunities-Threats) analyses, as mentioned in Chapter 1, are another tool for the comparison of scenarios to support decision-making and strategies for project management but also land-planning. This tool is widely used in the mining sector as well (Azimi *et al.*, 2011; Cluett, 2012; Neagu *et al.*, 2015) and allows project managers to develop business goals while understanding the viability of a project, addressing weaknesses and capitalizing on project opportunities and strengths. However, SWOT analyses do not prioritize issues or provide solutions and alternative decisions, jeopardizing the effectiveness of decision-making with a great amount of useless information. Hence, in some cases, they can be integrated with other decision-making methods. For instance, Azimi *et al.*, (2011) combined different multi-criteria decision-making methods such as the Analytical Network Process (ANP) and TOPSIS within the SWOT framework to prioritize the strategies of Iranian mining sector. The authors used SWOT analysis to assign feasible strategies and then, ANP and TOPSIS to rank different mining strategies.

These applications were performed at the scale of the mining projects, without acknowledging the territorial dimension of mining. Nevertheless, the SWOT analysis can be performed as well to suggest multiple development strategies at the territory level. For instance, Deloitte (2018) propose a SWOT analysis which compares the relevant economic sectors in FG in order to propose potential development strategies that might lean on wood production, tourism, construction, manufacturing or other sectors.

The SWOT analysis could be integrated as well within the proposed approach as a preliminary tool for the comparison and analysis of the different mine-types. The figure given in Appendix 17 gives an example of a SWOT analysis for the gold mine-types in FG, based on the perspective of mining operators. However, this analysis could be too much shallow at some occasions if not deepened with more quantitative information. Moreover, it might present further limitations regarding the assessment of the positive and negative outcomes of the classified mine types. Indeed, despite it integrates a qualitative and descriptive multi-perspective dimension, SWOT may not be sufficient to quantify and synthetize the influence of the different stakeholders' views on the final strategies, like what it has been proposed in this study through the weighting of the TMS scores (Chapter 9). Furthermore, the analysis of cumulative effects of multiple mine types on wider spatial scales is often limited in SWOT since it is often performed on the project alone. Also, spatial variability might be considered but SWOT is not based on geospatial data and, thus, it is not spatially explicit. Hence, the variability of the territorial specificities (i.e. socio-ecological vulnerability) are difficult to be integrated.

Hence, SWOT might not be appropriate to substitute alone the territorial approach proposed. Nevertheless, when integrated with sophisticated decision-making methods (e.g. ANP, AHP, TOPSIS), SWOT analysis can be important to develop and compare mining strategies.

For instance, within our approach, SWOT can be used as a preliminary complementary tool that can consistently support a first classification of the mine-types or the development of the TMS. If coupled to the analysis of the pre-determined territorial objectives and their corresponding scores (Table 33 and Table 37), SWOT can allow a preliminary comparison and discussion of the TMS, even before a detailed risk assessment.

1.4. The participation of stakeholders

Chapter 2 describes the ideal application of the current approach with a continuous participative integration of stakeholders all along the methodology. In this study, three categories of stakeholders have been identified: mining operators, public authorities and civil society (Table 5). Their integration in the current application has been pointed out at different steps, such as the selection of the territorial system, the validation of the gold mine-types and their features, risk identification, and the development of weighting coefficients.

Despite their partial integration, further efforts should be directed to involve stakeholders all along the application. Furthermore, the involvement of stakeholders and their contribution to the assessment should be more structured and quantified through transdisciplinary methods. For instance, the definition of territorial objectives should be strictly based on stakeholder's participation, since this is a crucial step for the development of the TMS. The same goes for the construction of the risk scenarios and the selection of the assessment indicators. Finally, once scored, the TMS should be publicly discussed and compared to integrate all the stakeholders at the same time into interactive exchanges, discussions and brainstorming. Further contribution of stakeholders to the application should be structured and quantified. Also, stakeholders might provide a considerable amount of data, in different forms and at different degrees of expertise.

However, it is important to point out that stakeholder's involvement must be considered carefully. From a general point of view, stakeholder's participation is a very delicate process which depends on a confidential relationship, transparency, available time, the scientific validity of their contributions and their representativeness, and on potential clashes and political implications among stakeholders (Voinov *et al.*, 2016; Gotts *et al.*, 2018).

1.5 Extendibility of the approach: other commodities, mining projects and territories

The objective of this study is not to develop a specific method for industrial risk assessment of mining projects but rather to propose an original approach to consider mining activities and their risks at the territory level. Hence, although our approach is partially operationalized through a methodology developed via its application test to gold mining in FG, the purpose of this approach is to be transposable to other commodities, types of mining activities and other territories. For instance, the development of TMS based on a standardized

mine-types might be performed in other cases and for commodities other than gold. The classification is based on the factors that the most influence risk occurrence or intensity (e.g. exploitation and processing techniques, type of geological deposit) Although the results of the classification will obviously differ from the ones presented in this study, the approach and the methodological framework should be the same, we believe.

However, the variability of the mining system and the extracted commodity is not the only parameter that needs to be taken into account. It has been shown that the specificities of the territorial system in which mining is performed – its juridical and political frameworks, its socio-ecological vulnerability – have a significant influence on the mining system itself and its negative or positive risks. For instance, the methodology proposed within this study can be extended to other territories where gold mining is performed. As mentioned, Suriname gold mining, although within the same geological settings of FG, involves different types of gold mines that might add to the ones currently operating in FG (i.e. gold dredging). Also new criteria of distinction should be applied to classify these gold mine types since gold-Hg amalgam is not used only by i-ASM in Suriname. In some regions with different climatic conditions and with almost absent population density where gold is exploited, such as the Northern Canada, the socio-ecological vulnerability of the territory will not be comparable to the characteristics of Mana river basin or other mining territories in the Amazon region.

2. Geospatial issues of the approach and its application

Because of its territorial dimension, our approach is supposed to be spatially explicit, in order to account for the spatial variability of risks and to serve land-planning support purposes. Furthermore, maps are a tool for a visual communicability, displaying and sharing information that otherwise might be inaccessible to the general public. In this study, QGIS has been used to process geospatial data for the RSa, but improvements should address the application of spatialized data (e.g. socio-ecological vulnerability, impacted area) for the RSo.

2.1. Mining siting for the development of the TMS

As mentioned, the localization of the mines during the development of the TMS might have a significant influence on the final results and TMS scores. Since it is not the purpose of this thesis, a simple methodology is proposed in Chapter 5 to identify the suitable areas for the localization of gold mine-types. However, further studies should consider:

- i) The improvement of more criteria to identify the suitable areas and reduce arbitrary or random decisions for the precise siting of the mines within these areas;
- ii) Quantify the uncertainty of criteria used for mining localization and the influence of mine localization on the final TMS score, for instance using correlation or sensitivity analysis;

- iii) When possible, the integration of existing and validated protocols for mining siting. For instance, it has been already mentioned that at the moment in FG, the French Geological Survey is developing such a methodology within the research project APPUI-Mines, which might be a useful complementary tool to the approach proposed in this study, integrating more “favorability” criteria for mining siting.

2.2. How to integrate risks at the project-scale in a territory-based approach?

Our approach analyzes one or multiple mines in each TMS, and performs a sector-based, rather than project-based, assessment. This implies necessarily the simplification of the mining system and its features, reducing the technical discrepancies between two distinguished projects that might be associate to a same mine-type. This is the very logic behind the classification of mine types proposed in this study.

Nevertheless, it is important that this simplification – realized through the standardization of the mine type – should not influence considerably the scores of the risk scenarios. Indeed, in reality, each project depends on specific topography and logistical specificities that affect the organization of the mine site and, thus, are essential to apprehend for a more precise assessment of the related risks.

Therefore, the integration, within the current approach, of the risks suffered at the project-scale might be an important challenge to address in the future, since it would need very accurate information. The same accurate information that has been lost during the standardization of mine types. Thus, it is difficult to combine the territorial purposes of our approach with too much detailed project-scale data.

The assessment at the project-scale, as individual unit, is already performed through several methods mentioned in Chapter 1. Somehow, such methods should be integrated in our approach to acknowledge the business-risk of mining operators generated by the failure of their technical and socio-environmental performances. For instance, the estimation of *cumulative risks* related to multiple mines would be then biased if the mines were not standardized and normalized. As example, the consequences for the territory due to the dam failure of an LSM or an ASM type can be significantly different. Nevertheless, the consequences of this failure event for the mining operator due to the destruction of the dam structure (after a dam failure) would be equally important in the case of an ASM (small dam) as for an LSM (big dam) operator. Their financial vulnerability (e.g. economic and human resources) would be equally impacted since an ASM would not have the same economic means of an LSM mine.

Furthermore, the territorial objectives on which based the TMS are not based at the scale of the projects but of the territory it-self. Mining operators’ perspectives – related to the performance of a mining project also as business activity – can be integrated within these objectives?. Such integration must pass through a systemic approach quantifying the

interactions and the feedback loops between the mine and the territory, i.e. the positive and negative contributions of the mining project to the performances of a territory (e.g. environmental protection, employment, economic development) and the contribution of a territory to the mining project (e.g. regulatory frameworks, political stability, mining contestation).

2.3. The problem of transboundary risks

The spatial variability of the risks related to mining projects can be discussed also with regard to the acknowledgment of their transboundary nature. Indeed, risks do not submit to administrative boundaries and their consequences – or else the triggering factors – might vary in quantity and quality go beyond the boundaries of a given territory system. For this reason, the definition of the territory in which the TMS needs to be developed is a key-issue for the methodological feasibility of our approach. However, this represents at the same time an operational gap that need to be considered for decision-making support. Indeed, the comparison of the TMS for land-planning purposes cannot overlook the transboundary nature of some risks, although these are outside the pre-defined system boundaries. This would be regrettable for governance perspectives.

For instance, the current application focuses on Mana river basin as territorial unit system. However, especially when outside the flooded area, several consequences might impact considerably and exceed the perimeter of the river basin as well (e.g. communicating roads, tourism, drinking water points etc.). Moreover, in FG, territory-based risk assessments of gold mining activities and the development of potential land-planning scenarios must consider the existence of transboundary flows of resources among different countries in the Guiana Shield. As mentioned, the focus on the Maroni river basin in FG should integrate the Surinamese gold mining sector as well, since the larger part of Maroni river basin is located in Suriname. Therefore, system definition is fundamental for the application of the methodology, but it should not be limiting factor for the interpretation of its results, especially when it comes to decision-making and governance. Each application of the proposed approach must be open to discussion and interpretations that cannot neglect such transboundary aspects, especially when it comes to develop territorial strategies.

3. Future perspectives of our approach

3.1. Uncertainty and sensitivity analysis of the methodology

Our approach and the method that has been presented in this study to apply it to FG is adapted to the amount of available data, as it has been shown in the application given in this thesis. Therefore, it is important to quantify the reliability of the results of the proposed methodology according to the level of available data. For instance, the results presented

suggest that TMS-B is the best scenario according to the risk events selected in this study. However, as discussed in the previous chapter, the scores of each TMS cannot must be considered carefully at this stage. Indeed, the pertinence of these scores for decision-making purposes must account of the potential error and their level of uncertainty of the results. Indeed, the application of uncertainty and sensitivity analysis should help quantifying the confidence of the results in order for the approach to be more appropriately used to support public authorities, land-planners but also mining operators and civil society.

Therefore, an important challenge to address to compare and rank the assessed TMS based on their scores is to improve the reliability of the such scores through ithe estimation of their level of uncertainty. Sensitivity and uncertainty analysis can be performed using stochastic modeling such as Monte Carlo simulation or, when limited data are available, fuzzy logic-based methods, uncertainty propagation, Bayesian statistics, although they might introduce subjectivity (Awuah-Offei and Adekpedjou, 2011).

3.2. The role of safety measures

Mining risks, positive or negative they might be, depend on the intrinsic characteristic of the mining project(s). Among these characteristics, an important attention must be given to the technical and organizational measures implemented by mining operators to improve mining performances limiting the risk event from occurring (i.e. proactive measures) and/o reducing its consequences once it occurs (i.e. reactive measures).

The role of these safety measures has been already pointed out in this thesis at multiple occasions. For the risk assessment to be reliable and for a correct application of the Bow-Tie, the capability of each mining project to implement safety measures must be quantitatively accounted for. Indeed, these measures might completely alter the final scores of each TM.

Table 41 shows a non-exhaustive list of some of proactive and reactive safety measures that are implemented by gold mines in FG. Future studies should focus on the identifying and detail such measures for each mine-type and their degree of effectiveness. Moreover, specific methods should be suggested in order to quantify the role of these measures. In industrial risk management, the Bow-Tie analysis might be a useful tool but it needs important amount of data for a pertinent estimation.

Table 41 List of general safety measures used for gold mining projects in FG. The information concerning the susceptibility of each gold mine-type to implement such measures is not available at the stage of this current thesis

Proactive Safety Measures (dam failure scenario)		AVOID
Technical		
Overflow device		
Vegetation cover		
Spillway system		
Bottom draining device		
Dry disposal of the tailings		
Tailings thickening		
Size-differentiated disposal of the tailings		
Cementation (increasing impoundment resistance)		
Coarse granular fill covering slopes against erosion		
Geotextiles and geosynthetics		
Freeboard control		
Downstream dam construction		
Risk and Impact assessment studies		
Organizational and Human		
Monitoring and visual inspections		
Technically formed and skilled employees		
Crisis simulation training		
Processing centers for i-ASM and ASM (Hinton <i>et al.</i> , 2003)		
Reactive Safety Measures (dam failure scenario)		REDUCE
Technical		
Emergency water pond		
Alarm system		
Containment barriers		
Addition of chemical to reduce/neutralize contaminants		
Application of OM for chemical stabilization		
Removal of spilled tailings		
Spillway system		
Organizational and Human		
Evacuation measures		
Insurance		
Restoring Safety Measures (dam failure scenario)		COMPENSATE
Revegetalization*		
Compensation measures		

3.3. Suffered risks and social acceptability of mining

For the construction of the risk scenarios, our approach wants to include all the generated positive and negative outcomes by mining but also the events suffered by mining operators themselves. However, as partially discussed in section 2.2. of this chapter, in this study the consequences suffered by the mining project(s) have not been estimated because of the mentioned geospatial issues.

Indeed, it is difficult to apprehend and quantify the risks suffered by a mining project, since they significantly depend on project-centered specificities and cannot be integrated in a territory-based approach. This means that the estimation of the cumulative risk suffered by multiple mine types in a same TMS might be very complex since it depends on the specific features of each mine type. Furthermore, the estimation of these risks often implies the possession of a series of financial and investment corporative data, hard to find or even confidential.

Nevertheless, it has been said that the performance of a mining project relies on its contribution to the performances of the territory in which its located. This means that, some risks suffered by the mining projects are the result of feedbacks from the positive and negative risks that mine themselves generate on the territory. For example, environmental degradation generated by mining can lead to contestations and conflictual situations that might represent an entrepreneurial risk for mining operators themselves (Bergeron *et al.*, 2015).

Therefore, a mining project needs to guarantee optimal socio-ecological performances in order to sustain as well its business dimension. This need has been translated into specific frameworks developed over the years such as Social Corporate Responsibility and Social License to Operate (see Chapter 1). These frameworks might – at least from a theoretical point of view – might support the realization of the sustainable development goals (SDGs). For instance, the non-acceptability of a mining project by society cannot be considered as a “suffered” consequence *per se*, but rather as a social response to the positive and negative risks that a mine might generate or that are expected to be generated. Social acceptability is not part of a risk scenario, but it is influenced by it since it might vary according to the score of the TMS.

The improvement of mining practices found a way also through the concept of “responsible” mining (IRMA, 2014). Mining responsibility is social, political, environmental and economic, and it can find operationalization through the integration of new safety measures or new *green* technologies into mining. These initiatives can also take organizational forms. For instance, as processing methods can be complicated and require great capital costs and skills, some countries are trying to develop centralized centres where artisanal miners can process their ore. These “Amalgamation Centers” or “Processing Centers” would allow a better control from authorities, a significant performance for miners and greater acceptability from local communities (Hinton *et al.*, 2003).

Hence, further improvements of our approach should focus on the combination of project-scale risk assessment methods and decision-making tools at the territory level the

integration of the risks suffered by mining activities. This implies the inclusion of both the entrepreneurial dimension of each mine-type and the transdisciplinary analysis of the social context where mining is performed and the risk of potential contestation.

3.4. Integration of decision-making tools

The approach we propose in this study serves the purpose to support decision-making in land-planning processes of mining regions. Rather than directly giving the decision, which is out of the scope of a scientific research, our approach allows to structure the territorial objectives and the related alternative strategies for land-planning. The TMS represent these strategies and they can be compared based on their risk score. Hence, ideally, public authorities should select, interpret and discuss the best suitable option(s) for a further implementation.

The proposed approach should be improved through the integration of well recognized multi-criteria decision-making methods such as Analytical Hierarchy Process (AHP), ElectrIII, TOPSIS, etc. This would allow a more symmetric integration of the negative and positive risks for each scenario through structured approaches. At this stage, the proposed approach is based in a certain way to the AHP, which has the purpose to answer to a general question (i.e. which is the best mining strategy?) offering a series of alternatives (i.e. the TMS) based on multiple criteria (i.e. the RSa and RSo scores) (Fig. 15).

Also, as already mentioned in the previous Chapter, LCA studies can improve the assessment of the interactions between the mining system and the territory system. For instance, recent studies about Territorial Life Cycle Assessment (Loiseau *et al.*, 2018) could be helpful to ameliorate the approach and quantify, for example, the *socio-eco-efficiency* of mining projects, defined as a ratio of the negative and positive risks related to a mine. The improvements concern as well the development of weighting coefficients. A method that can be applied is, for instance, the Saaty Scale (Saaty, 2008) which is widely used, especially with AHP, to generate priorities and made an actual decision according to stakeholders' perception.

3.5. The development of an automated GIS-based tool

The operationalization of the approach proposed in this study has been concretely performed through a series of separated and time-consuming tasks in order to acquire and process the data used to obtain the final TMS scores. For instance, some data have been repeatedly geoprocessed on GIS-based softwares, particularly for the localization of the mines and the estimation of the RSa score. Since the tasks for the geoprocessing and assessment of the risk scores and vulnerability are performed individually this might increase the occurrence of human errors and be excessively time-consuming for a rapid application.

Therefore, a significant perspective should be the development of automatized GIS-based tools to allow a faster, simpler and more operational application of the approach and its

methodology. The automatization of GIS-based tools is widely discussed by scientific literature (Jebamalai *et al.*, 2017; Nordin, 2017; Cao *et al.*, 2019; Rahmati *et al.*, 2019). For instance, Bhattacharya *et al.*, (2014) developed an automated tool for natural hazard zonation mapping. These kinds of studies might apply as well to the fictional siting of mining projects, without requiring for the modeler to manually locate each mining project-types for each scenario. GIS-automation can be developed through the translation of the current individual tasks into programming codes using multiple languages (e.g. C, C++, Java, Python). This can lead also to the development of interactive web-GIS tools (Aye *et al.*, 2016) that would be an interesting tool to enhance stakeholder's involvement. Therefore, such improvements would ameliorate the operationalization of the approach, its easier application and reducing processing time. They also could include uncertainty analysis and the decision-making methods previously described. However, it is important to underline that a potential automated tool (or software) should always leave the place to adaptations on a case-to-case basis and to integrate the critical analysis and discussion of the potential results.

General Conclusion

The main *ratio* of this thesis, emphasized by a growing scientific literature over these last decades, is the integration of mining into wider territorial approaches. The current thesis does not question whether mining is necessary or not, whether the industrial applications of specific commodities – and thus, their mineral exploitation – are justified or not, neither whether a given mine should be developed at a given place or not. If mining exploitation is necessary for a given commodity, technological and socio-economic development should never compromise and undermine socio-ecological integrity.

The socio-ecological dilemma does not consist in the opposition or “mining vs not mining” and cannot be resolved through a strict boolean ultimatum. Mining is globally driven by a growing demand for minerals and metals. Therefore, the main challenges are related to understanding and improving how mining is performed and, before that, the possibility of supplying raw materials at least partly through other complementary methods (e.g. recycling, agromining...or else?), or to reduce the demand to some extent.

For such reasons, our study aims to highlight the potential positive and negative contributions of mining at the territorial level, overcoming the simple perimeter of the mine site itself. Mining projects are a matter of land-planning rather than localized industrial objects. Hence, territorial management and land-planning of mining territories should be supported by tools that allow to propose and foresight potential development strategies and analyze them based on different criteria: e.g. the localization of the mine site, the level of positive and negative risks, the conflictual nature of mining projects.

It has been said that the engagement of mining into land management relies on multiple factors that involve land-use, public policies and market trends. Therefore, if and how the development of the mining sector should take place in a given territory implies political answers and political objectives. This implies a distinction between the decision-maker, citizen and the scientific researcher. In any case, the roles of these distinctive actors are significantly complementary and must be effectively taken into account when it comes to land-planning.

As researchers, in this thesis we presented the first development of an original systemic approach that compares potential land-planning scenarios for mining territories based on their level of risk. In view of the advantages and the gaps of specific risk assessment methodologies, the framework used for the application of our approach is intended to provide a structured and pluridisciplinary analysis that acknowledges both the specificities of mining projects and the socio-ecological vulnerability of the territories in which these activities are located. Because of its territorial resolution and its operational purposes, our approach and its application have proven to be adapted to the level of available data, including the involvement of stakeholders’

perception and cartographic outputs to support sharing and communication of the results and a better integration within decision-making tools.

The demonstrative application here presented focuses on gold mining in French Guiana, a French Overseas Territory located in northern South America. The results of our approach are represented by global scores given to each territorial mining scenario. The rendering of such results has been spatialized, through a GIS-based approach and under the form of sheets. In both cases, the shareability and communicability of such results is very accessible for local stakeholders and allow to have an overall value for each scenario, facilitating the comparison and discussion of these strategies and supporting decision-making. The synthetic process that leads, from a complex risk scenario (RSo or RSa), to one simple score, might imply a considerable loss of data and information. However, the transparency of the methodology allows to scan and go through each phase of the assessment process in order to analyze each used data and the obtained results. The underestimation or overestimation, uncertainty and variability of results are driven by how the method is performed and on which data is based. Despite future challenges must improve the reliability of the results, the objectives in this thesis were to show the feasibility of our approach and its rapid applicability.

Furthermore, our study was open to the identification of multiple future leads, that have been highlighted in the last chapters of the manuscript. As mentioned previously, the current thesis represents the first step of a wider research objective that aims to apprehend the socio-ecological footprint of mining at the territory level. Therefore, this studied was intended to identify as well the challenges to address in the future to improve the effectiveness of our approach and its application. Further researches for the improvement of our approach should focus on multiple challenges that concern two complementary aspects.

- i) First, the current application of our approach to the FG case, for which further studies should:
 - a. Consider the level of **uncertainty** of the final scores based on the data used, which would guarantee more reliable comparisons of the different TMS developed. This implies as well the estimation of the level of **reliability of the input data**, their **processing** and of the **final results**, in order to better operationalize our approach;
 - b. Develop and compare SMT based on **multiple territorial objectives** at the same time rather than only one, as it is the case in the current feasibility test of the proposed approach.
 - c. Improve the development and the risk assessment of the TMS during normal operating conditions (**RSo**), through the integration of more risk events, the analysis of their chain of cause-consequences and the estimation of the corresponding risk

level based on the identification of impacted areas and socio-ecological vulnerability;

- d. Collect data concerning the **safety measures** that might reduce the probability of occurrence of the dam failure or its consequences. These safety measures must be quantified and integrated within the final global TMS scores, for instance, through approaches such as the Bow-Tie, which can be a performant assessing tool, although it allows the analysis of only one failure at a time;
- e. Extend the current assessment to **new TMS** (see Table 13) and other risk scenarios. The dam failure was chosen as central accidental risk event based on two risk databases (Chapter 6). New applications might consider explosions, spills, transport accidents;
- f. Improve the **weighting** of the final TMS scores through new surveys allowing the homogeneous integration of all the stakeholders groups considered in this study (e.g. civil society, public administration, mining operators);
- g. Deepen the understanding of the socio-ecological vulnerability of the territory where mining activities are located, for instance, improving the **quantification of the ecosystem services** delivered by a territory and the potential impacts that mining can have on such services and the related societal needs. Several frameworks and indicator-based approach exist for the assessment and mapping of ecosystem services and the corresponding societal needs (Berrouet *et al.*, 2018);
- h. Improve the quantification of **cumulative risks** of multiple mining projects coexisting in a given territory. Land-planning strategies must apprehend if the cumulative risks of dozens of small mines can outweigh the risks generated by one large mine. This imply systemic approaches such as territorial LCA, and a better involvement of stakeholders;
- i. Improve the **quality and quantity of data** used for the assessment, integrating more precise information gathered specifically for such purposes and allowing a more detailed modeling and assessment). For instance, socio-ecological vulnerability might integrate quantitative data related to soil and water resources, drinking water availability, health vulnerability but also more specificities concerning local population and the characteristics of private and public infrastructures (e.g. construction materials for roads and buildings, year of construction, monitoring). Further information concern as well gold mine-types in order to enrich and complete the list of their features (Appendix 5);

- ii) Secondly, further studies must improve the general methodological framework that would ensure the reliable applicability of our approach to other case-studies, serving decision-making purposes. These are related to:
- a. A more structured and quantifiable integration of all mining **stakeholders** during the entire application of the approach, from the definition of the territorial objectives, to risk identification, risk weighting and TMS comparison;
 - b. The effective integration of **decision-making tools** (e.g. ANP, AHP, TOPSIS, ElectrIII, multi-agent system approaches) to ensure the operationalization of our approach and the ranking of the TMS to better serve decision-making purposes;
 - c. The implementation of our approach within an **automated GIS-based tool** that should be developed to guarantee a more rapid application of the approach and its suitability for decision-making;
 - d. The integration of industrial risk management methods to perform also risk assessment at the project-level to quantify the **rebound dynamics** (i.e. from the territory to the mining project) that affect the performance of a mining project. This implies as well the mobilization of social and human sciences to analyze and quantify the patterns that lead to entrepreneurial risks driven by the contestation and opposition of civil society to mining activities;
 - e. Finally, the possible integration in the future, of complementary approaches that focus on **other human activities** (e.g. forestry and silviculture, agricultural activities, urban development, industrial plants) and their interactions with mining at the territorial scale. This might allow to extend the application of our approach to holistically serve land-planning decision-making not only in relation with the mining sector.

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Résumé étendu et continu en français

L'extraction minière peut être la source et la cible de risques positifs (*i.e.* opportunités) et négatifs (*i.e.* pertes) de différentes natures, qui généralement dépassent le périmètre des sites miniers eux-mêmes et affectent le système socio-écologique dans lequel les projets miniers sont installés. De plus, les dégradations socio-environnementales possiblement liées au secteur minier (*e.g.* pollution des eaux et des sols, érosion, déforestation, impacts sanitaires) peuvent entraîner des tensions sociales et des mouvements d'oppositions ; elles représentent donc un risque entrepreneurial pour les compagnies minières (*e.g.* sanctions, retards, suspension ou révocation des titres miniers).

Le secteur minier doit ainsi répondre à une demande croissante en matières premières, tout en faisant face à des défis environnementaux et sociaux considérables. Puisque le développement socio-économique ne doit pas compromettre l'intégrité socio-environnementale, le concept de « durabilité » a été intégré au fur et à mesure au secteur minier à travers l'adoption de pratiques et de performances visant à maximiser les effets positifs de l'activité extractive, tout en réduisant ses effets négatifs. Cette évolution est rendue possible par l'intégration de nouvelles performances socio-environnementales ou de « développement durable », qui viennent s'ajouter aux performances traditionnelles des opérateurs miniers (*e.g.* faisabilité technico-opérationnelle, viabilité financière). Ces nouvelles performances sont consacrées par de nombreuses initiatives nationales et internationales, telles que le *Global Reporting Initiative* (GRI), les *Sustainable Development Goals* (SDGs), les Principes de l'Equateur ou encore le *Responsible Mining Index* (RMI).

La dimension territoriale du(es) projet(s) minier(s) et des risques qui y sont associés implique donc qu'un ou plusieurs projets miniers soient évalués en fonction de leur contribution positive ou négative au système socio-écologique dans lequel ils sont installés : ainsi, un projet minier doit être considéré comme un enjeu d'aménagement territorial plutôt que comme un simple objet industriel isolé (Figure 1). Ce changement de paradigme implique non seulement l'appréhension de la dimension technico-opérationnelle du ou des projets miniers (*e.g.* taille du projet, nombre et types d'infrastructures minières, nombre d'employés, techniques minières utilisées) mais également la description précise du système socio-écologique (*i.e.* le territoire) dans lequel ces activités sont réalisées, tant dans ses caractéristiques que dans ses fonctions. L'intégration territoriale des projets miniers soulève ainsi des enjeux d'ordre foncier, concernant les modalités d'aménagement et d'occupation du sol dans un territoire donné, et également d'ordre (géo)politique, relatif aux dynamiques de gouvernance et de marché global des ressources minières. En effet, le fait de développer ou ne pas développer un ou plusieurs projets miniers dans un territoire implique aussi des choix politiques.

Cette thèse esquisse une autre façon d'aborder cette problématique, en proposant une approche pluridisciplinaire pour comparer, sur la base de leur niveau de risque, différents scénarios de développement minier et aider ainsi la prise de décision en matière d'aménagement territorial. Pour rendre cette approche opérationnelle, nous construisons ici un cadre méthodologique permettant l'analyse des risques miniers à l'échelle territoriale.

Les risques des projets miniers sont aujourd'hui évalués par différentes méthodes d'étude d'impact ou d'analyse de risques, qui sont souvent basées uniquement sur les objectifs des projets miniers, sans considérer dans le détail la vulnérabilité socio-écologique du territoire où ces projets sont installés. De plus, elles sont souvent appliquées sur un projet à la fois, en négligeant la dimension cumulative des risques liés à plusieurs projets - de différents types et natures - coexistant sur le même territoire. Il existe néanmoins des approches « multi-projets », mais celles-ci sont basées uniquement sur les objectifs intrinsèques aux projets. Enfin, à notre connaissance, ces différentes méthodes sont développées pour le secteur industriel *lato sensu* et ne prennent donc pas bien en compte les spécificités de l'activité minière. Enfin, dans d'autres cas, comme par exemple dans les analyses de cycle de vie, les projets miniers sont considérés comme des « boîtes noires » dont on néglige la variabilité technique.

Pour ces raisons, le cadre méthodologique développé dans cette thèse vise à intégrer à la fois la coexistence de plusieurs projets miniers de différentes tailles et natures, la vulnérabilité socio-écologique du territoire d'installation, la variabilité de la nature des risques, mais également la perspective des parties prenantes dans une optique d'aide à la prise de décision.

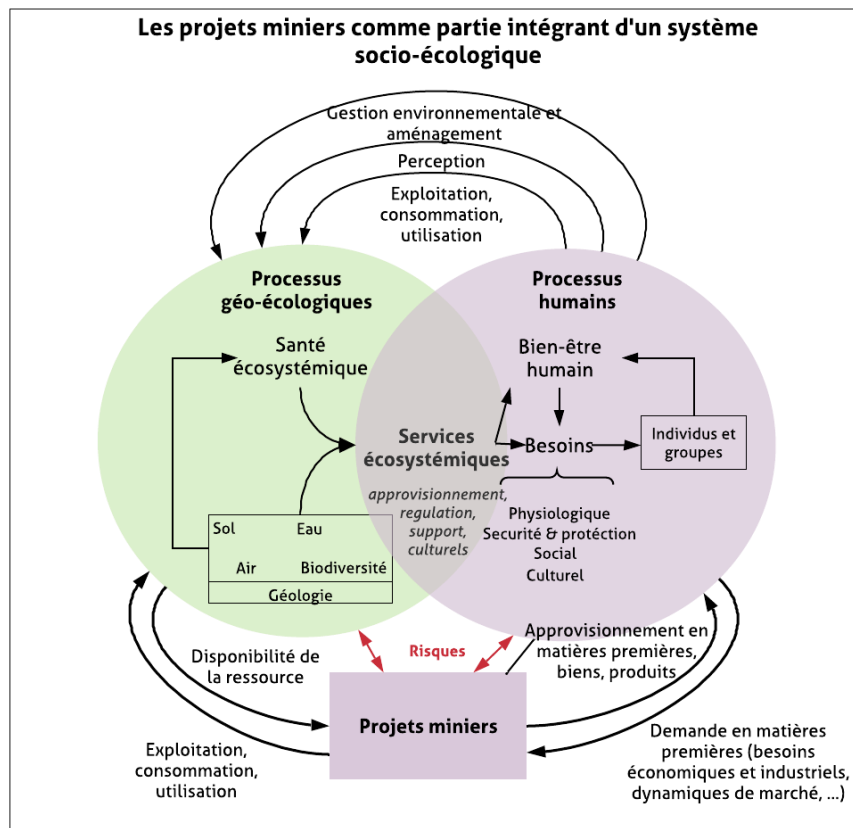


Figure 1 Les projets miniers comme enjeu d'aménagement territorial et éléments d'un système socio-écologique plus large.

La faisabilité de l'approche proposée dans cette thèse et du cadre méthodologique qui l'accompagne est testée sur le cas de l'exploitation aurifère en Guyane. Ce territoire français d'outre-mer, situé en région amazonienne entre le Surinam et le Brésil, permet de prendre en considération la coexistence de différents projets miniers légaux et illégaux de différents types, tailles et utilisant différentes techniques dans un contexte socio-écologique particulièrement vulnérable, avec un couvert forestier occupant plus de 90% de sa surface.

La méthode proposée se distingue par cinq étapes principales (Figure 2), de la création de scénarios miniers territoriaux (SMT) à l'évaluation de ceux-ci sur la base de leur niveau de risque global.

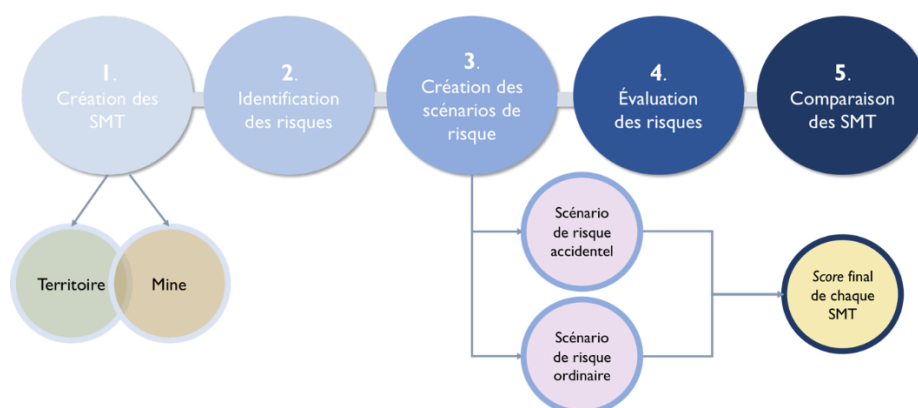


Figure 2 Cadre méthodologique simplifié de l'approche proposée dans cette thèse.

Notre premier objectif est de comparer entre eux ce que nous appelons des **scénarios miniers territoriaux (SMT)**, c'est-à-dire différentes stratégies de développement et d'aménagement territorial basés aussi sur les ressources minérales du sous-sol (Figure 3). Les SMT se composent de deux éléments qui sont appréhendés de façon détaillée pour que l'analyse des risques soit pertinente :

- Un système territorial ou socio-écologique, c'est-à-dire l'unité spatiale (*e.g.* commune, région, bassin versant) dans laquelle le système minier est localisé,
- Un système minier, représentant une combinaison de projets miniers, en différent nombre et types, installés dans le système territorial choisi.

La définition du système territorial – nous avons choisi le bassin versant du fleuve Mana à titre d'exemple dans cette thèse – est réalisée à partir d'une vaste collecte de données et de plusieurs visites sur le terrain. Quant à lui, le système minier est défini sur la base d'une classification multicritères (Scammacca *et al.*, 2021), qui distingue et détaille quatre grandes catégories de projets miniers « types » existant ou potentiels en Guyane : mines illégales primaires ou secondaires, mines légales artisanales secondaires, mines légales de taille moyenne, mines légales de grande taille. Ces « mines-types » sont distinguées sur la base de différents critères : réglementation, type de gisement géologique exploité, techniques d'exploitation et de traitement, surface du site minier, etc.

La création des SMT nécessite la définition préalable d'**objectifs territoriaux** que les SMT visent à satisfaire, par exemple : un niveau donné d'emploi lié au secteur minier, de production annuelle de matières premières, de surfaces préservées par l'activité minière, etc. Pour chaque SMT répondant à ces objectifs, un certain nombre de projets miniers de différents types est implanté dans le système territorial choisi à partir de différents critères (localisation des gisements géologiques, zones autorisées à l'activité extractive, distance aux centres urbains, etc.). Dans notre cas, un objectif de production de 5 000 kilos d'or par an au total a été choisi à titre d'exemple et cinq SMT, représentant cinq manières d'atteindre l'objectif fixé, ont été comparés (Figure 3).

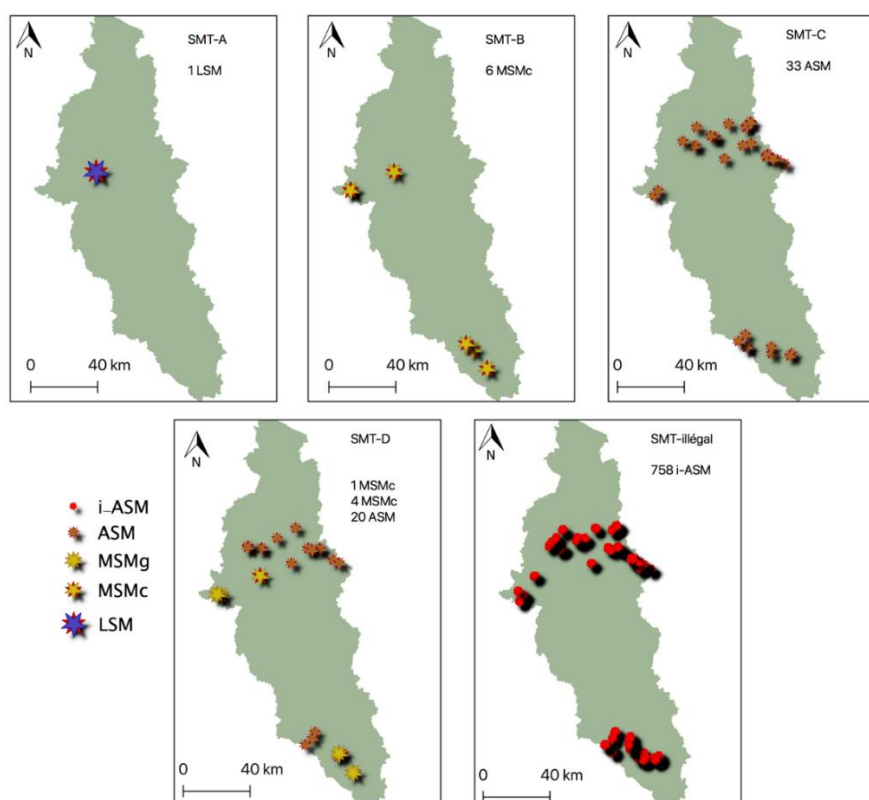


Figure 3 Représentation cartographique des cinq SMT retenus. L'objectif territorial fixé est la production aurifère de 5000 kg d'or au total.

Pour chaque SMT, les risques relatifs à l'exploitation minière ont été identifiés à partir de nombreuses sources (recherche documentaire et bibliographique, visites de sites miniers, entretiens avec les différentes parties prenantes, débats publics). Les informations récoltées ont été structurées dans deux bases de données à partir desquelles deux **scénarios de risque** ont été construits. Leur évaluation permet *in fine* de comparer entre eux les différents SMT à travers leur niveau de risque :

1. Un scénario de risques accidentels (SRa) correspondant aux conditions anormales de fonctionnement du projet minier, pour lequel la défaillance de digue minière par débordement a été choisie comme évènement central. Ce choix se justifie par le fait

qu'il s'agit d'un évènement aux conséquences potentiellement catastrophiques et d'un exemple intéressant pour tester la dimension spatiale de l'approche proposée dans cette thèse, notamment à l'aide d'outils SIG ;

2. Un scénario de risques ordinaires (SRo) correspondant aux conditions normales de fonctionnement du projet minier, qui a été intégré, bien que de manière plus rudimentaire, pour permettre l'application complète de l'approche proposée.

L'évaluation de ces deux scénarios de risque se fait en suivant différentes étapes qui visent à : i) évaluer la zone impactée par le ou les projets miniers associés à chaque SMT ; ii) estimer la vulnérabilité socio-écologique du système territorial ; iii) identifier la probabilité d'occurrence de l'évènement central ; iv) coupler tous ces éléments pour obtenir des cartes de risques et des notes finales pour chaque scénario de risque associé à chaque SMT. Avant de combiner les notes finales du SRa et du SRo, les risques sont pondérés en fonction des différents acteurs concernés par le secteur minier (société civile, administration publique, opérateurs miniers).

Les résultats obtenus dans cette thèse montrent donc la faisabilité de l'approche originale proposée, même s'ils doivent être considérés avec une certaine prudence. L'objectif principal de la thèse est en effet de démontrer ce qui peut être accompli en intégrant, dans une même approche territoriale et multidisciplinaire, des aspects généralement traités séparément. A ce stade, les résultats obtenus ne sont pas suffisamment précis pour pouvoir être directement appliqués à la définition de stratégies d'aménagement territorial. De nombreuses pistes devront être explorées et approfondies à l'avenir : l'optimisation des méthodes d'agrégation de toutes les données à chaque étape de l'évaluation des risques, une meilleure définition des « objectifs territoriaux » sur la base desquels les SMT ont été construits, l'amélioration de l'évaluation spatialisée des risques à la fois en conditions « accidentelles » (par exemple, en utilisant d'autres risques que la défaillance de digue) et « ordinaires ».

La classification multicritère des projets miniers proposée dans cette thèse a permis de montrer la pertinence de la définition de « mines-types » pour des démarches d'analyse et de comparaison de stratégies d'aménagement territorial, dans une optique prospective et sur des larges étendues spatiales. Cependant, cette classification pourrait, elle aussi, être améliorée pour tenir compte de deux aspects fondamentaux : tout d'abord, une meilleure connaissance technique des projets miniers illégaux, qui représentent plutôt un phénomène social pour lequel la notion de « site » est extrêmement vague ; en second lieu, l'intégration des mesures de sécurité disponibles pour chaque projet-type, visant à réduire la probabilité d'occurrence d'un évènement ou de ses conséquences.

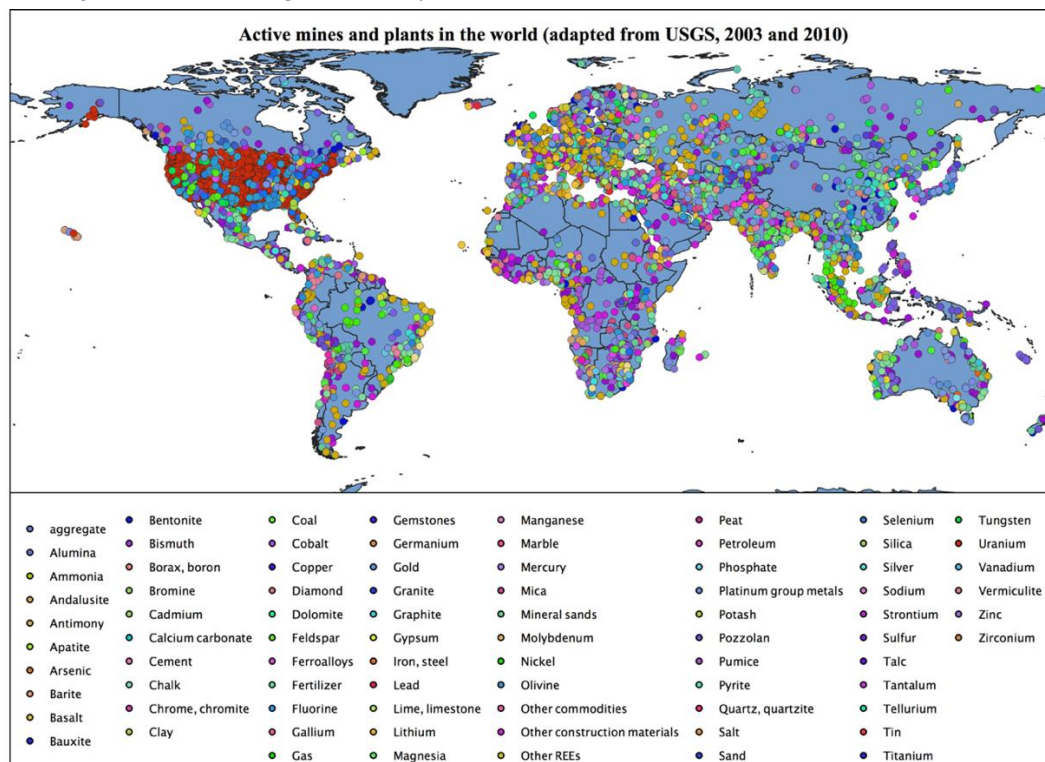
Enfin, des futures pistes de recherche devraient se consacrer également à la dimension temporelle de l'activité minière et du territoire où cette activité est réalisée. Cela implique,

d'un côté, de prendre en considération les différentes phases minières – de la prospection et exploration jusqu'à la fin des opérations, la fermeture et la gestion d'après-mine – qui comportent des risques de différentes natures et intensité. De l'autre côté, il est nécessaire d'intégrer également la variabilité, dans le temps, du territoire d'installation des projets miniers et donc de ses caractéristiques et de sa vulnérabilité (par exemple, une croissance démographique d'ici 2050, la définition de nouveaux espaces naturels protégés, l'effet du changement climatique vis-à-vis des risques miniers, etc.)

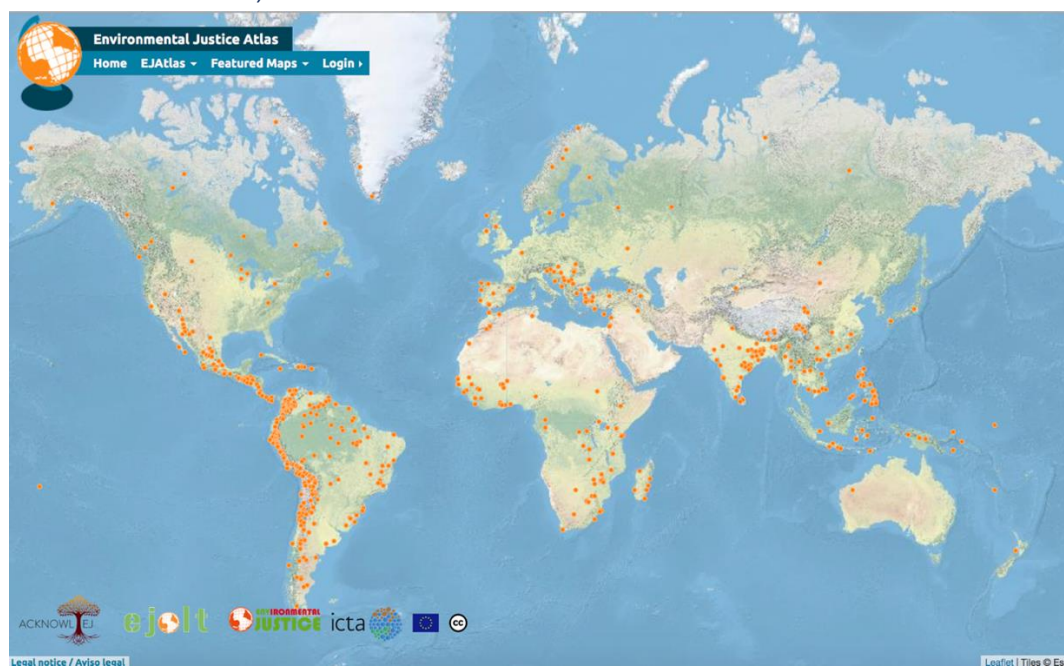
Pour conclure, l'objectif de cette thèse est celui de proposer une approche ambitieuse qui se construit à travers les yeux du géoscientifique et du géographe, du fait de sa dimension territoriale et donc de son caractère fortement pluridisciplinaire. Cette approche représente une autre façon de regarder les questions qui se posent pour les territoires miniers et leur aménagement, y compris pour la Guyane. Ainsi, cette thèse permet d'offrir un cadre méthodologique et une vision d'ensemble des risques liés à l'exploitation aurifère et de leur évaluation à l'échelle territoriale. Parallèlement, notre travail essaie de pointer du doigt ce qui doit être accompli dans les études à venir pour améliorer l'opérationnalisation de l'approche proposée et l'étendre aussi à d'autres cas d'étude.

Appendices

Appendix 1 – Active mining project and plants in the world according to the 2003 and 2010 databases of the U.S. Geological Survey



Appendix 2 – World-wide distribution of conflicts related to extractive activities (ejatlas.org, consulted the 10.04.2020)



Appendix 3 – Bibliographic review of 40 scientific papers, including review articles and case studies. This table presents the nature of the consequences represented by the indicators in each study and the main methods used to assess of those indicators. The last two columns indicate papers that refer to the mining sector or integrate the concept of sustainability

Reference	Type of paper	Nature of the assessed consequence(s)	Assessment method	Mining sector	Sustainability
Hammond <i>et al.</i> , 1995	Review	Environmental	-	X	
Azapagic, 2004	Review	Social, environmental, economic	-	X	X
Haberl et al 2004	Review	Social, environmental, economic	-		X
Bohringer et al 2007	Review	Social, environmental, economic	Monetization, empirical equations		X
Robu <i>et al.</i> , 2007	Case study	Environmental	Direct measurements (e.g. field survey, sampling), empirical equations		
Bell and Morse, 2008	Review	Social, environmental, economic	-		X
McLellan <i>et al.</i> , 2009	Review	Social, environmental, economic, technical	-	X	X
Schöber <i>et al.</i> , 2010	Review	Social, environmental, economic	-		X
Ingwesen, 2011	Case study	Environmental, economic	Direct measurements (e.g. field survey, sampling), empirical equations, observed data, existing databases	X	X
Van Erk, 2011	Case study	Environmental	Remote sensing	X	
WHO, 2011	Review	Health, social, environmental	Direct measurements (e.g. field survey, sampling), empirical equations, observed data, existing databases		
Caudeville <i>et al.</i> , 2012	Case study	Health, social, environmental	Direct measurements (e.g. field survey, sampling), empirical equations, observed data, existing databases		
Larondelle and Haase, 2012	Case study	Social, environmental, economic	Empirical equations, observed data, existing databases	X	X
Haldar, 2013	Review	Social, environmental, economic	-	X	X
Banos-Gonzalez <i>et al.</i> , 2014	Case study	Social, environmental, economic	Empirical equations, observed data, existing databases		X
Estoque and Murayama, 2014	Case study	Social, environmental, economic	Observed data		X
Legg <i>et al.</i> , 2015	Case study	Health, social, environmental	Direct measurements (e.g. field survey, sampling), empirical equations	X	
Matamin <i>et al.</i> , 2015	Case study	Environmental	Remote sensing		

Akinbiola <i>et al.</i> , 2016	Case study	Environmental	Direct measurements (e.g. field survey, sampling)	X	
Banos-Gonzalez <i>et al.</i> , 2016	Case study	Social, environmental, economic	Observed data		X
Gemechu <i>et al.</i> , 2016	Case study	Geopolitical	Empirical equations, observed data, existing databases		
He <i>et al.</i> , 2016	Case study	Environmental	Direct measurements (e.g. field survey, sampling), remote sensing		
Schreck <i>et al.</i> , 2016;	Case study	Environmental	Direct measurements (e.g. field survey, sampling)	X	
Albuquerque <i>et al.</i> , 2017	Case study	Environmental	Direct measurements (e.g. field survey, sampling), empirical equations		
Amadi <i>et al.</i> , 2017	Case study	Environmental	Direct measurements (e.g. field survey, sampling)	X	
Bui <i>et al.</i> , 2017	Case study	Social, environmental, economic	Observed data	X	
Clifford, 2017	Case study	Health, social, environmental	Direct measurements (e.g. field survey, sampling)	X	
Guan <i>et al.</i> , 2017	Case study	Health, social, environmental	Direct measurements (e.g. field survey, sampling), empirical equations	X	X
Mariet <i>et al.</i> , 2017	Case study	Environmental	Direct measurements (e.g. field survey, sampling), empirical equations	X	
Murray <i>et al.</i> , 2017	Case study	Environmental	Remote sensing		
Nguyen <i>et al.</i> , 2017	Case study	Social, economic	Observed data, existing databases	X	
Ramos <i>et al.</i> , 2017	Case study	Social, environmental, economic	Observed data, existing databases		X
Yakovleva <i>et al.</i> , 2017	Case study	Social, environmental, economic	Observed data, existing databases	X	X
Bansah <i>et al.</i> , 2018	Case study	Social, environmental, economic	Direct measurements (e.g. field survey, sampling), empirical equations, observed data, existing databases	X	X
Betancur-Corredor <i>et al.</i> , 2018	Case study	Social, environmental, economic	Observed data, existing databases	X	X
Boggia <i>et al.</i> , 2018	Case study	Social, environmental, economic	Observed data, existing databases		X
Dialga, 2018	Case study	Social, environmental, economic	Direct measurements (e.g. field survey, sampling), empirical equations, observed data, existing databases	X	X
Gallay <i>et al.</i> , 2018	Case study	Environmental	Direct measurements (e.g. field survey, sampling), remote sensing	X	
Liu <i>et al.</i> , 2018	Case study	Environmental	Direct measurements (e.g. field survey, sampling), empirical equations		
Mancini and Sala, 2018	Review	Social, environmental, economic	-	X	X
Goix <i>et al.</i> , 2019	Case study	Environmental	Direct measurements, physico-chemical analysis (Hg isotopes)	X	

Geological map of Suriname

Legend:

- "Apatoe" dolerite (145-200 Ma)
- "Tampok" dolerite (809 Ma)
- "Avanavero / Comté" dolerite (1.8 Ga)
- Late-Transamazonian event
- Meta-aluminous monzogranite (2.06-2.07 Ga)
- Transamazonian event
- Neoproterozoic granitic plutonism (2.08-2.11 Ga)
- Pull-apart detrital basin - NGT (Neoproterozoic)
- Upper Detrital Unit (Boridoro and Orapu Formations)
- Mesorhyacian TTG plutonism
- Mesorhyacian gabbro
- Mesorhyacian North and South complexes
- Metamorphic greenschist belt
- le de Cayenne Formation and Lower Volcanic and Sedimentary Unit (Paramacca and Armina Formations)
- Associated thermal aureole
- Archean protolith sediment
- Eorhyacian tholeiitic magmatism (2.20-2.26 Ga)
- Fault

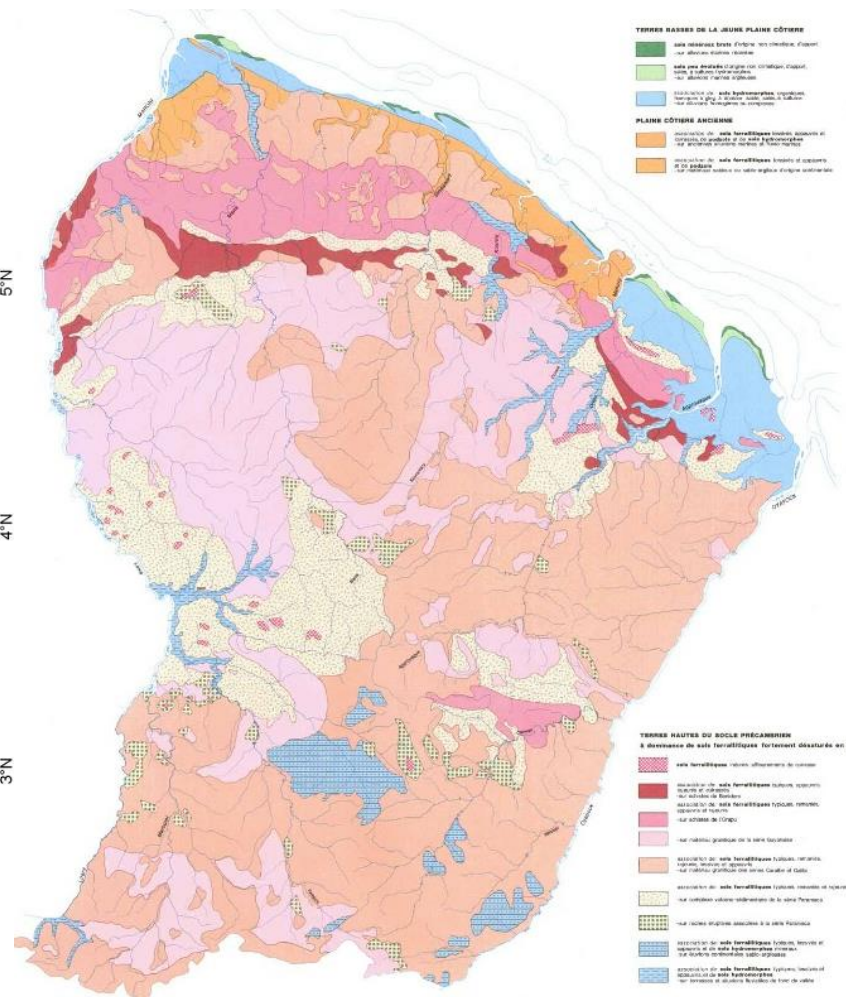
Geological Units and Events:

- Neoproterozoic granitic plutonism (2.08-2.11 Ga)
- Upper Detrital Unit (Boridoro and Orapu Formations)
- Mesorhyacian TTG plutonism
- Mesorhyacian gabbro
- Mesorhyacian North and South complexes
- Metamorphic greenschist belt
- le de Cayenne Formation and Lower Volcanic and Sedimentary Unit (Paramacca and Armina Formations)
- Associated thermal aureole
- Archean protolith sediment
- Eorhyacian tholeiitic magmatism (2.20-2.26 Ga)

Scale: 0 to 50 km

Orientation: North arrow pointing up.

Figure 76 Simplified soil map of FG (Blancaneaux, 2001)



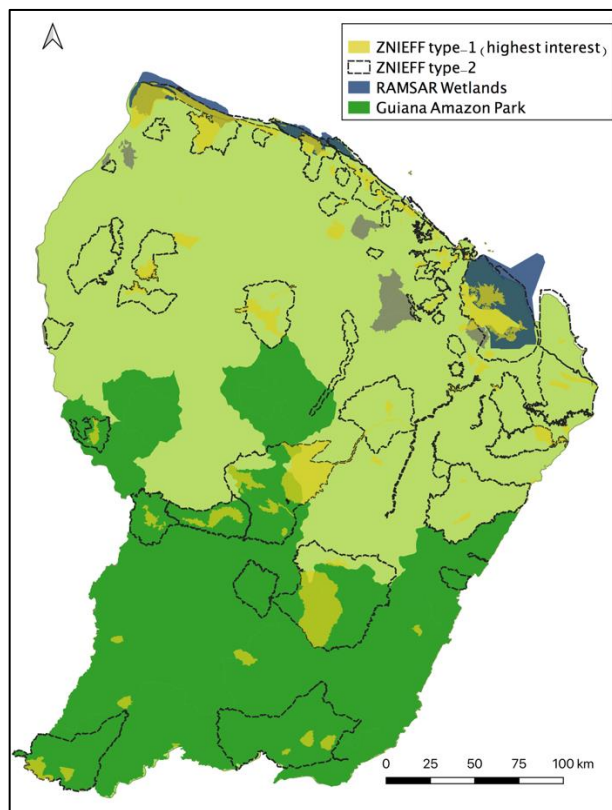


Figure 77 Main natural protected areas in French Guiana

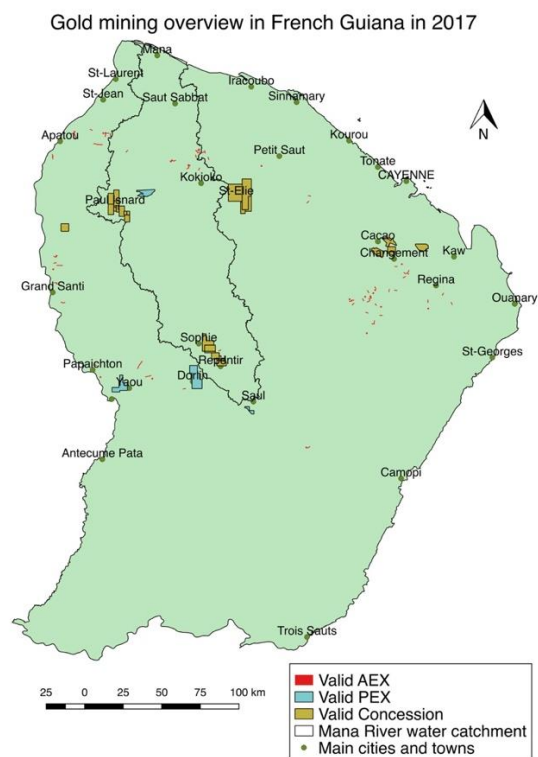


Figure 78 Gold mining permits and authorizations in FG at the date of 31/12/2017 (PTMG-CTG, confidential data collecting)

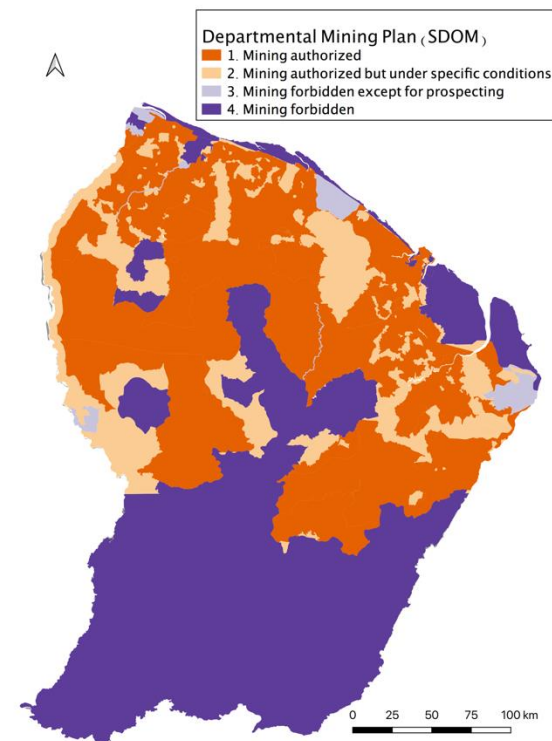


Figure 79 Cartography of the Departmental Mining Plan (SDOM) currently applied in French Guiana

Appendix 5 –Table with the main gathered data, their format and type and their sources

External Environment Type	Asset	Available Data	Format type	nom	Description	Source
Human	Population	Number of people per commune	text			Insee, 2015
		Number of people per commune	shape	COMM_Manage_impl_edit_POPULATION	population totale. Nous avons repris les données insee 2015 et écrites dans la table attributaire des communes sur la mana	Adapted from INSEE, (2015) on SIG
		Ethnic distribution per commune ?	n/a		"COMM_Manage_simpl_edit"	
	Buildings	Construction features	text	97306_PLU_MANA (dossier)	Plan Local d'Urbanisme (PLU) de Mana avec documents annexes	PLU Mana (AUDeG, 2018)
				Zonage_slm_mairie (dossier)	Plan Local d'Urbanisme (PLU) sans documents annexes	PLU SLM Données de 2013, fournies en privé par QUEGUINER J. - Mairie de SLM
		Number of buildings Types of buildings and use	shape	97352_CC_SAUL (dossier)	Carte Communale (CC) de Saul de 2014, approuvée par arrêté préfectoral en 2016 avec documents annexes	CC Saul (AUDeG, 2016)
				1gen_departement-973 (dossier)	Description of buildings in the area with their function (according to this dictionnary "Key_building_dictionn")	https://www.data.gouv.fr/fr/datasets/r/7f4559b9-08c8-4f71-97b3-625ae1a8ee11 consulted the 11/04/2019
				Strategic_assets.shp	Points d'interet: Hopitaux, écoles et enseignement, musées, archeologie prevnetive, conservatoire de jardins, monuments nationaux, police et gendarmerie, service pompiers 18, campings, points info tourisme, etablissements thermaux, maisons de retraite, colleges et lycees, ecoles maternelles, enseignement superieurs, ecole smaternemes	georef à partir de GEOGUYANE, plan de la ville de man et vecteur "buildings" du dossier 'departement' ("points" dans 1gen_departement-973 (dossier))

	Number buildings commune	of per	shape			
Roads	Roads		shape	lgen_departement-973 (dossier)	Description of roads: path, primary, residential, service, tertiary, track, unclassified	https://www.data.gouv.fr/fr/datasets/r/7f4559b9-08c8-4f71-97b3-625ae1a8ee11
Urbanized areas	Urbanized surfaces		shape	97306_PLU_MANA (dossier)	Plan Local d'Urbanisme (PLU) de Mana avec documents annexes	PLU Mana (AUDeG, 2018)
			shape	Zonage_slm_mairie (dossier)	Plan Local d'Urbanisme (PLU) sans documents annexes	PLU SLM Données de 2013, fournies en privé par QUEGUINER J. - Mairie de SLM
			shape	97352_CC_SAU L (dossier)	Carte Communale (CC) de Saul de 2014, approuvée par arrêté préfectoral en 2016 avec documents annexes	CC Saul (AUDeG, 2016)
			shape	OC_SOL_mod_MANA	Niveaux d'occupation du sol sur la bande littorale. Nomenclature: Voir Vigné, 2008	Occupation du sol, 2015 (ONF, 2017)
	Spontaneous urbanized surfaces		shape	urb_spontane_MANA	Urbanisation spontanée	l_urbaspontaneeterrain2018_s_973.shp (Audeg, 2018)
Industrial areas	Industrialized surfaces		shape	97306_PLU_MANA (dossier)	Plan Local d'Urbanisme (PLU) de Mana avec documents annexes	PLU Mana (AUDeG, 2018)
			shape	Zonage_slm_mairie (dossier)	Plan Local d'Urbanisme (PLU) sans documents annexes	PLU SLM Données de 2013, fournies en privé par QUEGUINER J. - Mairie de SLM
			shape	97352_CC_SAU L (dossier)	Carte Communale (CC) de Saul de 2014, approuvée par arrêté préfectoral en 2016 avec documents annexes	CC Saul (AUDeG, 2016)
			shape	OC_SOL_mod_MANA	Niveaux d'occupation du sol sur la bande littorale. Nomenclature: Voir Vigné, 2008	Occupation du sol, 2015 (ONF, 2017)
			shape	urb_spontane_MANA	Urbanisation spontanée	

Agricultural areas	Agricultural surfaces	shape	97306_PLU_MANA (dossier)	Plan Local d'Urbanisme (PLU) de Mana avec documents annexes	PLU Mana (AUDeG, 2018)
		shape	Zonage_slm_mairie (dossier)	Plan Local d'Urbanisme (PLU) sans documents annexes	PLU SLM Données de 2013, fournies en privé par QUEGUINER J. - Mairie de SLM
		shape	97352_CC_SAU L (dossier)	Carte Communale (CC) de Saul de 2014, approuvée par arrêté préfectoral en 2016 avec documents annexes	CC Saul (AUDeG, 2016)
		shape	OC_SOL_mod_MANA	Niveaux d'occupation du sol sur la bande littorale. Nomenclature: Voir Vigné, 2008	Occupation du sol, 2015 (ONF, 2017)
		shape	urb_spontane_MANA	Urbanisation spontanée	
Wood production	Forest zoning per utility	text	ONF, 2015 catalogue habitat foret adapté	Adaptation du catalogue des habitats forestiers de l'ONF donnant des info sur chaque habitat forestier et son importance (3 classes) en terme de présence de biodiversité, production de bois, production de biomasse. D'autres informations concernent le type de sol et les pressions présentes	ONF, 2015 adapté
		shape	zones_forest_MANA.shp	Zones forestieres definies en fonction IE, PPGM et production	WWF, 2014
Wastewater treatment points	Wastewater treatment points	shape	Assainissem_MANA.shp	Nom ville nombre habitants en 2006 capacité de l'assainissement collectif estimation qualité eaux cotières pourcentage population couverte par assainissement collectif pourcentage population non couverte indice pour representation cartographie de la population par ville	assainissement_des_villes14_prelevement_aep_BASSINGUYANE (WWF - PTMG, 2010)

Water supply points	Water supply points	supply	shape	Captage_eau_Manana.shp	Points de captage d'eau	WWF, 2013;
Electrical supply points	Electrical supply points	supply	shape	l_reseau_elec_p_973	Localisation des postes de distribution électrique publique sur lesquelles la DAAF est intervenue pour assistance technique	Morel C., - DAAF/EDF, 2015
Fishing areas	Professional fishing surfaces		shape	zones_de_peches_de_professionnelles.shp	Zones de peche professionnelle	WWF, 2011
	Leisure fishing surfaces	fishing	shape	zones_de_peches_de_loisirs.shp	Zones de peche de loisir	WWF, 2011
Quarries	Number of quarries and extracted materials		shape	Carrieres_Manashp	Carte de localisation des carrières en 2010 dans le Schéma départementale des carrières (SDC)	Georeferencé à partir de Nontanovanh and Marteau, 2010 - BRGM (Capture d'écran 2019-04-01 à 14.35.03) (shapefile "Carrieres_BRGM")
Illegal mining	Surfaces impacted from illegal mining		shape	Defor_orpail2015_Manashp		Adapted from WWF, 2015
	Communes per impacted surfaces by illegal mining in 2015		shape	Defor_orpail2015_par_comm.shp		

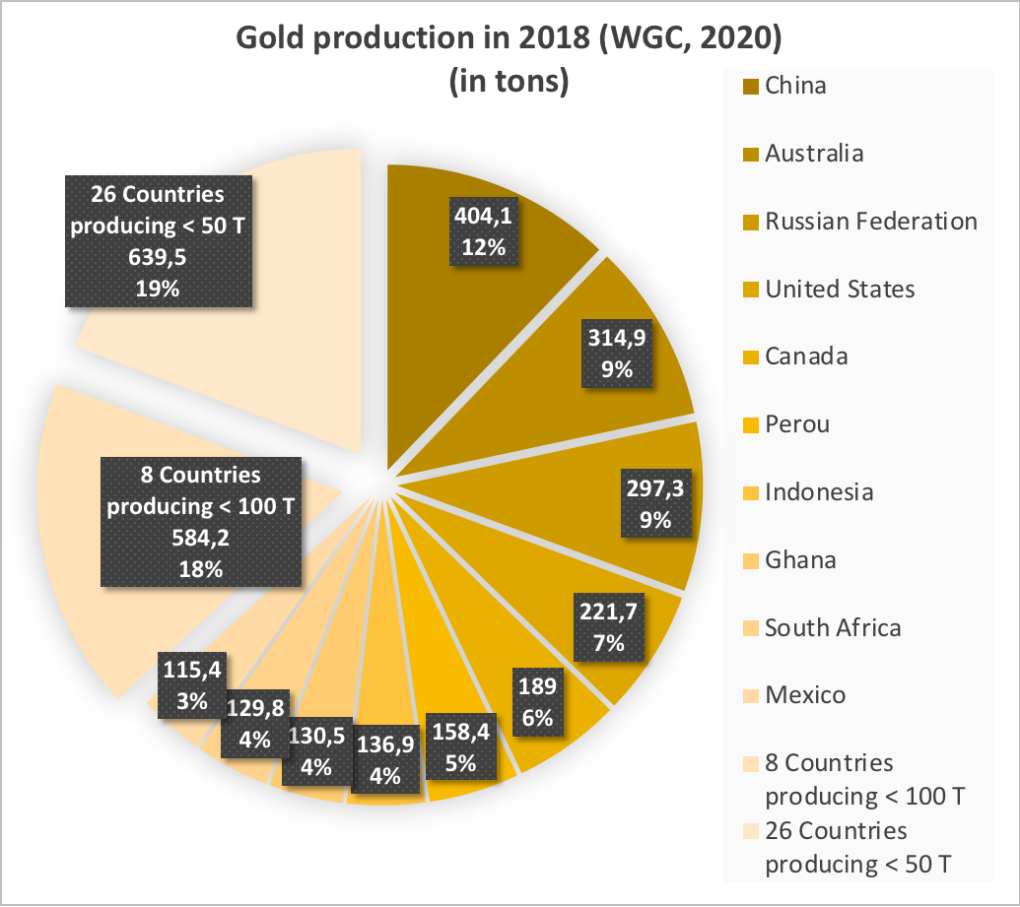
Natural	Soil	Simplified soil map	shape		Simplification (deux grandes catégories de sols) à partir de: Numéro de carte Sphaera : 760 GUYANE FRANÇAISE - - PÉDOLOGIE. 1:1000000. 1979 Pédologie : la Guyane : planche 10. (IN) Atlas des départements français d'Outre-Mer : 4. La Guyane / Philippe Blancaneaux ; G. Lasserre (éd. scientifique), Gilles Sautter (éd. scientifique), M. Boyé (éd. scientifique), Gérard Brasseur (éd. scientifique), G. Réaud (coord.), G. Cabaussel (coord.), J. Menault (coord.). - Bordeaux-Talence (FRA) : CEGET, Centre d'études de géographie tropicale du CNRS ; Paris (FRA) : ORSTOM, Office de la recherche scientifique et technique outre mer, 1979. - 1:1000000. - 3 p. : planche en coul., 9 réf. bibliogr. ; 48 x 58 cm	Adapted and created from Turenne1972a and georeferencing IRD, 1979
		Hydro ecorégions	shape	hydro_ecoregions_guyane_2005	Donnée du relief issue du SRTM à 90m	DEAL, 2005 CEMAGREF/IRSTEA,
		Soil per habitat type	text	catal_hab_forest_ONF (dossier)	Catalogue avec habitats forestiers et propriétés de chacun (sol, biodiversité, bois, biomasse etc.). Données qualitatives ont été adaptées pour notre tableau de susceptibilité (biodiversité) http://www1.onf.fr/lire_voir_ecouter/++oid++4cc4/@@display_media.html	Guitet <i>et al.</i> , 2015 - ONF; fournis en privée avec données supplémentaires spatialisées par Brunaux Olivier - ONF

					"03_etat_actuel BASSINGUYANE 05_rnabeBASSINGUYANE Asconit, 2013 report carte_etat_chimq BASSINGUYANE carte_etat_chimq-sansorp BASSINGUYANE carte_etat_ecologq BASSINGUYANE Document-d-accompagnement- 7_vdef KALITEO Environnement/HYDRECO , 2013 rapport RNAOE methodology, 2013 GUYANE SDAGE, 2014"
	Etat global des milieux aquatiques de surface text (chimique et écologique)				
Surface water					
	Reseau hydrographique	shape	Drainage_MNT_ Guy	Vecteur ligne de tous les cours d'eau et les criques en Guyane française avec le nombre d'ordre de Strahler (1-8)	BRGM
	Decoupage hydrographique	shape	"hydro_servicesa ndre_eau2012 (dossier)"	Découpage par nœuds hydrographiques, points d'eau isolés, région, secteur, sous-secteur, traits de côte, troncons, zones hydrographiques	SANDRE, 2012
	Etat global de chaque zone hydrographique de surface	shape	etat_zone_hydro _MANA.shp		Adapted and created from text documents in C41

Underground water	Etat global des milieux aquatiques souterrains	text	"04_rnabe_eaux_souterrainesBASSI NGUYANE Document-d-accompagnement-7_vdef KALITEO Environnement/HYDRECO , 2013 rapport RNAOE methodology, 2013 GUYANE SDAGE, 2014 Asconit, 2013 report "	
	Masse d'eau souterraine	shape	Division selon formations du socle ou sédimentaires SANDRE, Eau Franc-e - BRGM	
Biodiversity (flora and fauna)	Natural surfaces	shape	97306_PLU_MANA (dossier)	Plan Local d'Urbanisme (PLU) de Mana avec documents annexes PLU Mana (AUDeG, 2018)
		shape	Zonage_slm_mairie (dossier)	Plan Local d'Urbanisme (PLU) sans documents annexes PLU SLM Données de 2013, fournies en privé par QUEGUINER J. - Mairie de SLM
		shape	97352_CC_SAU L (dossier)	Carte Communale (CC) de Saul de 2014, approuvée par arrêté préfectoral en 2016 avec documents annexes CC Saul (AUDeG, 2016)
	ZNIEFF surfaces	shape	"znieff1_2001_1386686225_5399znieff1_2014_csrpn_copy1_1452604722_5108znieff2_2001_1386687071_6630znieff2_2014_csrpn_1452604840_8886"	WWF

	Zones de reproduction des tortues	shape	zcb_plages_awala_et_pontes_tortues		WWF
	Zones d'interet écologique pour oiseaux, tortues, crevettes etc.	shape	zones_de_nurseries		WWF
	Ramsar protection surface of Amana (Basse Mana)	shape	RAMSAR_limite 500_090630	Zonage RAMSAR (Marais de Kaw, Basse Mana et estuaire du Sinnamary)	DEAL Guyane
	Portal biosphere reserve surface	shape	reservoirs_biologiques		WWF - PTMG, 2010
	Biodiversity potential per area (3classes)	text	catal_hab_forest_ONF (dossier)	Catalogue avec habitats forestiers et propriétés de chacun (sol, biodiversité, bois, biomasse etc.). Données qualitatives ont été adaptées pour notre tableau de susceptibilité (biodiversité) http://www1.onf.fr/lire_voir_ecouter/++oid++4cc4/@@display_media.html	Guitet <i>et al.</i> , 2015 - ONF; fournis en privée avec données supplémentaires spatialisées par Brunaux Olivier - ONF
Other	Digital Elevation Model (DEM)	Raster (.tif)	N03W054 N04W053 N04W053 N04W054 N04W055 N05W054 N05W055		Available by NASA's SRTM

Appendix 6 – Gold production in 2018 per-country. The graph shows mainly the countries that produced more than 100 tons of gold in 2018. (www.gold.org/goldhub/data/historical-mine-production)



Appendix 7 – Database concerning all the technical and operational data gathered per gold mine type in French Guiana. An extract is cited in the text in Table 9 and 11. Data have been gathered based on different sources (Scammacca et al., 2020).

NA Not available
- Not applicable

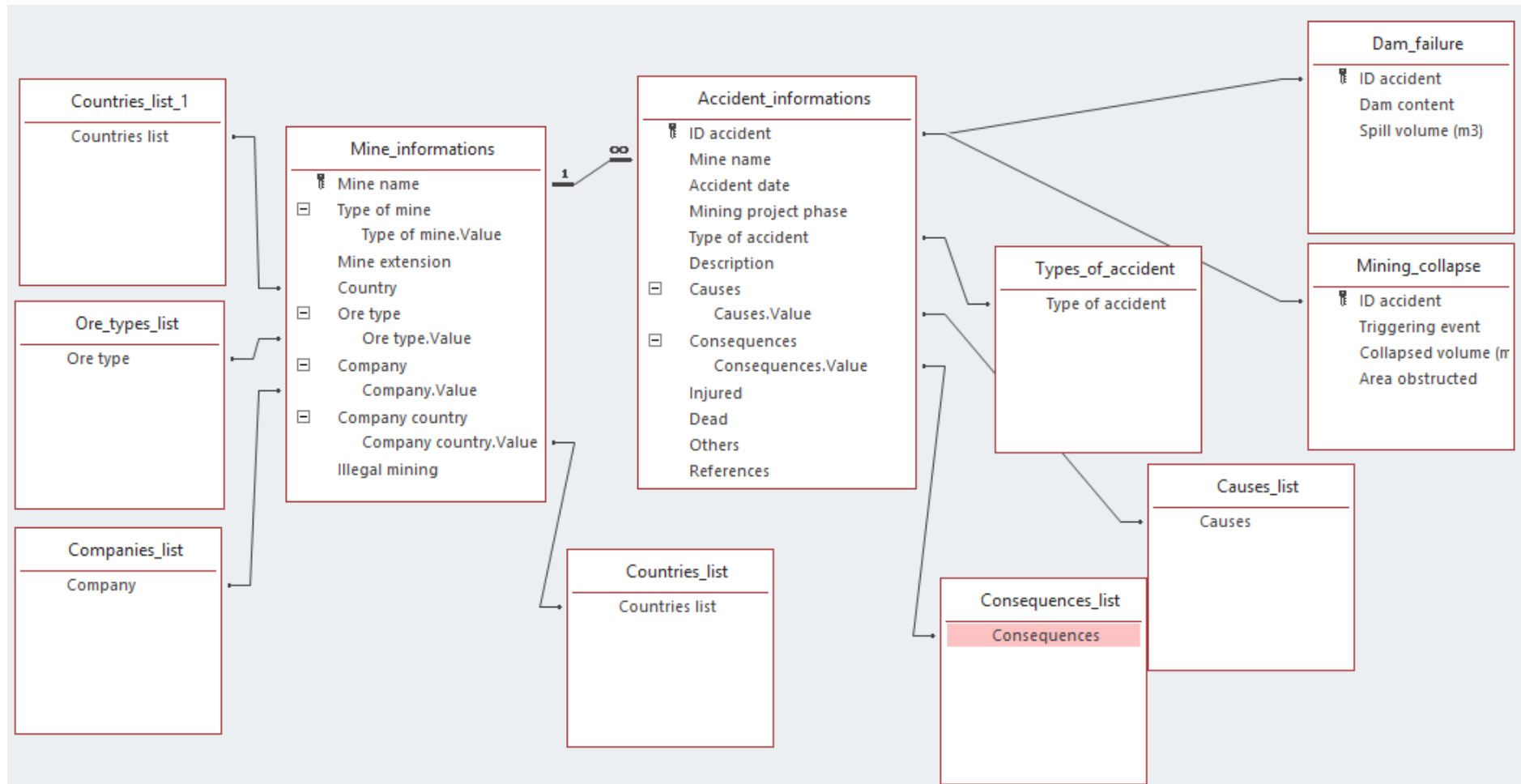
Classification criteria		Illegal Artisanal and Small-Scale		Legal Artisanal and Small-Scale	Medium-Scale		Large-Scale
	Code	i-ASM		ASM	MSM		LSM
	French name	Artisanal illégal		Artisanal légal	Semi-industriel		Industriel
I	Predominantly exploited gold deposit	Primary (type 1-2-3)	Secondary (type 4-5)	Secondary (type 4-5)	Primary (type 2-3)	yes	Primary (type 1-2-3)
II	Mining permit or authorization	no	no	yes	yes		yes
II	Soil footprint of the mine site (ha)	NA	NA	<100	>100		> 500
I	Main exploitation technique	Underground	Barranque (mining pond)	Barranque (mining pond)	Pit		Pit
V	Gold recovery methods	Hg	Hg	Gravimetry	Gravimetry (MSMg)	Cyanidation (MSMc)	Cyanidation (+gravimetry)
General characteristics of the deposit							
1	Gold resources (t)	NA	NA	< 10	10	10	> 50
2	Gold rate (g/t)	1 - 2	1 - 2	1	0.7 - 2.10	0.4 - 2.10	0.7 - 2.5
3	Depth (thickness of the materials to clean)	NA	NA	0 - 8	> 20	~ 20 (depending on the deposit)	~ 20 (depending on the deposit)
Regulatory and socio-environmental constraints							
4	Mining permit/authorization for the predominant exploitation	none	none	AEX	PEX, Concession	PEX, Concession	PEX, Concession
5	Other regulatory constraints	none	none		AOTM, AE	AOTM, AE	AOTM, AE
6	Mine surface allowed (km2)	none	none	1	free	free	free
7	Regulatory duration of the project (years)	none	none	4	5-50	5-50	5-50
8	Duration of the regulatory proceedings before the beginning of the exploitation (years)	none	none	3 - 8	NA	NA	> 8
Company informations							
8	Juridical status	NA	NA	SAS, SARL	SARL, SAS, SA à CA	SARL, SAS, SA à CA	SARL, SAS, SA à CA
9	Subsidiary of another company	NA	NA	yes/no	yes/no	yes	yes
0	Listed on the stock exchange market	NA	NA	no	no	yes	yes
1	Social Capital (k€)	NA	NA	5 - 500	< 1 000	1 000 - 8 000	> 20 000
1	Revenues (R) (k€)	NA	NA	< 1 000	> 1 000	> 5 000	> 500 000
1	Origin	local, French, international	local, French, international	local, French	local, French	local, French, international	French, International
3	Fiscal residence	NA	NA	local	local, French	local, French, international	local, international
1	Direction team origin	French, foreign, local	French, foreign, local	local, French, foreign	local, French, foreign	local, French	French
Mine related infrastructures							
Excavation and exploitation							
1	Extracted ore (mineral + waste rocks) (kt/year)	NA	NA	5 - 35	>150	>150	5 000 - 25 000
6	Extraction pit	excavation pit (square 1,5 m)	no	no	yes	yes	yes
7	Number of pits/barranques	NA	NA	Variable	Variable	Variable	Variable
1	Volume of the pit/barranque (m3)	NA	NA	(1500 – 3000)	NA	NA	> 100 000
9	Pit/barranque soil footprint (ha)	(0,0001)	NA	~0,2 (50m x 40m)	(10-20)	(> 20)	> 100
2	Pit/barranque depth (m)	10 - 40	NA	2 - 8	NA	NA	> 100
1	Use of explosives (y/n)	yes	NA	no	no	yes/no	yes
2	Type of explosive	TNT/HT, HEXAL	NA	-	-	NA	NA
2	Explosive charge (kg)	25 - 50	NA	-	-	NA	NA
Mineral processing							
2	Plant type	NA	NA	Gravimetry plant	Gravimetry plant	Gravimetry and cyanidation plant	Cyanidation plant (with gravimetry unit inside)
5	Cyanide plant surface (ha)	NA	NA	-	-	< 1	> 10
2	Total processed materials (t/day)	NA	NA	NA	> 200	> 300	> 5 000
7	Processed materials by cyanidation only (t/day)	NA	NA	-	-	100	> 5 000
2	Recoverable gold by processing (kg/year)	NA	NA	NA	100 - 300	> 400	> 5 000
2	Gold recovery rate according to the processing method used(%)	NA	NA	20 - 30	20- 40	> 90	> 90
0	Settlement and disposal system (process water + tailings)	NA	NA	Barranques	Gravitary tailings pond Exfiltration water pond	Decyanated tailings pond Exfiltration water pond	Decyanated tailings pond (No intermediary storage for gravitary residues)
Management of waste rocks and tailings							
3	Total surface of waste-rock dumps (ha)	NA	NA	NA	NA	NA	> 100

3	Volume of waste-rock for the mining life-cycle (m3)	NA	NA	NA	NA	NA	> 100 000 000
3	Tons of waste-rock for the mining life-cycle (kt)	NA	NA	NA	NA	NA	> 40 000 000
3	Volume of gravitary residues to process (m3/year)	NA	NA	NA	> 60 000	> 60 000	NA
3	Total volume of gravitary residues entering the cyanidation plant (m3/year)	NA	NA	-	-	> 60 000	NA
3	Gold rate of gravitary residues (ppm Au)	NA	NA	NA	1,5 - 4	1,5 - 4	NA
3	Moisture rate of gravitary residues (%)	NA	NA	15	15	< 15	NA
3	Texture of gravitary residues to re-process	NA	NA	Fine to coarse	Fine to coarse	Fine to coarse (< 2,5 mm)	NA
4	Solid rate of the gravitary residues (%)	NA	NA	> 80	> 80	> 80	NA
1	Solid rate of the slurry to process (%)	NA	NA	-	-	40	40 - 50
4	Solid rate of decyanated slurry after thickening (%)	NA	NA	-	-	60	50 - 60
4	Potential concentration in total cyanides in the residues (ppm)	NA	NA	-	-	1, 67	< 1
4	Potential concentration in free cyanides in the residues (ppm)	NA	NA	-	-	0, 35	< 0,1
4	Potential concentration in weak acid dissociable cyanides (WAD) in the residues (ppm)	NA	NA	-	-	0,3	< 0,1
4	Volume of the ultimate residues (m3/year)	NA	NA	NA	40 000	60 000 - 250 000	> 3 000 000 (decyanation residues)
4	Total surface of the tailings storage facility for gravitary residues (ha)	NA	NA	~0,2 (50m x 40m)	(10 - 20)	(> 20)	NA
4	Total capacity of the tailings storage facility for gravitary residues (m3)	NA	NA	< 500, 000	500 000 - 3 000 000	500 000 - 3 000 000	NA
4	Total surface of the tailings storage facility for decyanated residues (TSF) (ha)	NA	NA	-	-	5 - 15	> 150
5	Annual storage of the tailings storage facility for decyanated residues (TSF) (m3/year)	NA	NA	-	-	60 000 - 400 000	> 10 000 000
5	Total capacity of the tailings storage facility for decyanated residues (TSF) (m3)	NA	NA	-	500 000 - 3 000 000	500 000 - 3 000 000	~100 000 000
5	Moisture rate of the decyanated residues (% solid)	NA	NA	NA	NA	NA	~ 50
2	Waste and process water management						
5	Total storage capacity of exfiltration water ponds at the exit of the TSF (m3)	NA	NA	-	-	10 000 - 25 000	NA
5	Total surface of exfiltration water ponds at the exit of the TSF (ha)	NA	NA	-	-	NA	NA
5	Total storage capacity of secondary settlement water ponds (m3)	NA	NA	NA	(4 000 - 10 000)	(4 000 - 10 000)	NA
5	Total surface of secondary settlement water ponds (ha)	NA	NA	NA	NA	NA	NA
5	Total surface of the emergency water pond (clean water) (ha)	NA	NA	NA	3 - 5	5 - 10	NA
5	Total capacity of the emergency water pond (clean water) (m3)	NA	NA	NA	20 000 - 250 000	20 000 - 250 000	NA
5	Features of holding and embankment structures						
5	Priority dam for monitoring (TSF dam, upstream, downstream, external)	NA	NA	External	External/TSF(downstream)	External/TSF(downstream)	External/TSF(downstream)
6	Maximal height of the TSF dam (m)	NA	NA	2 - 5	15 - 20	15 - 20	> 50
6	Height of the emergency water pond dam (clean water) (m)	NA	NA	2 - 5	6 - 12	6 - 12	NA
6	Position of the downstream draining device (m)	NA	NA	NA	15	21	NA
6	Position of the upstream impermeability device (m)	NA	NA	NA	19	27	NA
6	Final crest width (m)	NA	NA	(2,5)	3 - 6	3 - 6	17
6	Final base width (m)	NA	NA	NA	30 - 40 (50)	48	> 300
6	Total Freeboard height (difference between the water level and the dam's crest) (m)	NA	NA	(< 2)	1 - 1,5	1 - 2	(~3)
6	Downstream security factor of the embankment	NA	NA	-	1,31	1,31	1,33 to 1,68
6	Upstream security factor of the embankment	NA	NA	-	1,44	1,44	1,33 to 1,68
6	Nature of the materials of the embankment	NA	NA	Saprolites	Saprolites	Saprolites	Saprolites and crushed rocks
6	Texture of the materials of the embankment	NA	NA	clay-sandy to clay	clay-sandy to clay	clay-sandy to clay	clay-sandy to clay
6	Tailings settlement method (dry/wet)	NA	NA	-	-	NA	50% solid after thickening
6	TSF dam raising method	NA	NA	-	Upstream	Upstream	Downstream
6	Emergency pond dam raising method	NA	NA	Upstream	Upstream	Upstream	NA
7	Prevention measures in case of dam failure	NA	NA	revegetation, overflow device, diversion channels, bottom drains, spillway channels, observational monitoring, (geotextiles)	revegetation, overflow device, diversion channels, bottom drains, spillway channels, monitoring, geotextiles, piezometric	revegetation, overflow device, diversion channels, bottom drains, spillway channels, geotextiles, piezometric studies, pit stability, risk flood analysis etc.	revegetation, overflow device, diversion channels, downchutes, bottom drains, spillway channels, monitoring, geotextiles, piezometric studies, pit stability, risk flood analysis etc.

7	Mitigation measures in case of dam failure	NA	NA	Downstream emergency pond	studies, pit stability Downstream emergency pond	Downstream emergency pond	
5	Additional infrastructures						
7	Life-camp surface(ha)	NA	NA	< 1	~ 1	> 2	> 10
7	Transport infrastructures	quad, 4x4, canoe	quad, 4x4, canoe	quad, 4x4	quad, 4x4, canoe	quad, 4x4, canoe, helicopter	quad, 4x4, helicopter
7	Mechanization	yes	yes	yes	yes	yes	yes
8	Total equipment units for the exploitation (shovel, monitor water guns)	NA	NA	< 10	10 - 50	> 50	> 100
9	Electric supply system	NA	NA	on site + solar panels	on site	on site	on site + 80% solar panel
0	Number of electrical transformers and power generating units	NA	NA	1 - 2	> 2	(> 5)	> 2
8	Total electric power (kW)	NA	NA	~ 40 KVA	> 250 KVA	1178.4	~ 20 000
2	Water supply system	NA	NA	NA	NA	NA	Pit water
8	Total surface of mining routes (ha)	NA	NA	~ 1,5	NA	NA	10
4	Fuel storing capacity (l)	NA	NA	5 000 - 10 000	15 000 - 30 000	15 000 - 30 000	> 100 000
5	Total production						
8	Annual extracted gold/mine soil footprint ratio (kg/ha)*	NA	NA	~ 1,5	~ 1,5	~ 3	5 - 10
6	Annual average revenues (k€/years)	NA	NA	< 1 000	> 1 000	> 1 000	> 200 000
8	Maximum annual gold production (kg/year)	NA	NA	(< 150)	150 - 300	> 400	> 5 000
8	Annual duration of activity suspension (months/year)	NA	NA	2	2	2	0
9	Average project life-cycle (year)	NA	NA	< 2	NA	NA	> 10
1	Employment during exploitation and processing						
9	Number of direct jobs	NA	NA	10-15	>50	50 - 350	> 350
2	Number of indirect jobs (sub-contracting chain)	NA	NA	NA	NA	NA	> 2 000
9	Local population among mining workers (%)	NA	NA	NA	NA	NA	90 (goal)
3	French population (out of French Guiana) among mining workers(%)	NA	NA	NA	NA	NA	10 (goal)
9	Foreign population among mining workers (%)	NA	NA	> 80 (Surinam, Brazil)	> 80 (Surinam, Brazil)	> 80 (Surinam, Brazil)	10 (goal)
5	Function performed by local workers	NA	NA	NA	NA	NA	workforce, technician (driller, drivers, ...) ...
9	Function performed by French workers (out of FG)	NA	NA	NA	NA	NA	Qualified workers
9	Function and main task performed by foreign workers	NA	NA	workforce, technician	workforce, technician	workforce, technician	Management (directors, engineers, geologists) ...
0	Total CAPEX (k€)						
1	Feasibility and engineering studies (k€)	none	none	< 10	> 50 -300	> 50-300	> 2 000
0	Environmental/Social Impact assessment studies (k€)	none	none	< 10	> 50 -300	> 50-300	> 1 000
1	Duration of the EIES (year)	none	none	2	12	12	(~ 6)
3	Preparatory works for mine site development (pre-production) (k€)	NA	NA	NA	NA	NA	(~ 50 000)
0	Exploitation equipment cost (k€)	NA	NA	400	NA	NA	NA
6	Total CAPEX in pre-production (k€)	NA	NA	NA	NA	NA	> 150 000
1	Processing plant cost (k€)	NA	NA	NA	NA	NA	> 300 000
0	Infrastructures for tailings/waste management (k€)	NA	NA	NA	NA	NA	> 150 000
1	Total CAPEX for exploitation and mineral processing (k€)	NA	NA	NA	NA	NA	> 600 000
2	Total CAPEX for waste, tailings and water management(k€)	NA	NA	NA	NA	NA	> 15 000
1	Revegetalization and reclamation system	NA	NA	NA	Directly or sub-contracting	Directly or sub-contracting	NA
4	Total CAPEX for mine closing(k€)	NA	NA	NA	NA	NA	> 50 000
5	TOTAL CAPEX (k€)	NA	NA	NA	NA	NA	~ 800 000
1	Total OPEX(k€)						
6							

1	0	Total private investments during exploitation (k€)	NA	NA	NA	NA	NA	> 500 000
1	7	General administrative costs (G&A) (k€)	NA	NA	NA	NA	NA	> 200 000
1	8	Environmental and social management (k€)	NA	NA	NA	NA	NA	> 2 000
1	9	Workforce cost during excavation (k€)	NA	NA	1 800 - 3 000 per month	1 800 - 3 000 per month	1 800 - 3 000 per month	> 250 000
1	0	Fuel cost (k€)	NA	NA	< 100 000	> 1 000 000	> 1 000 000	> 200 000
1	1	Fuel consumption (l/h)	NA	NA	< 10	16 - 25	16 - 25	> 40
1	2	Explosive cost (k€)	NA	NA	-	-	-	~ 100 000
1	3	Other equipment for excavation (k€)	NA	NA	NA	NA	NA	~150 000
1	4	Total OPEX during excavation (k€)	NA	NA	NA	NA	NA	> 500 000
1	5	Workforce cost during processing (k€)	NA	NA	NA	NA	NA	> 50 000
1	6	Cost of the consumed products and inputs for processing (k€)	NA	NA	NA	NA	NA	> 250 000
1	7	Consumption of input products (NaCN) for one processed ton (kg/t)	NA	NA	-	-	0,1	> 0,4
1	8	Electric supply cost (k€)	NA	NA	NA	NA	NA	(> 250 000)
1	9	Energy requirements (kWh/year)	NA	NA	NA	(15 000 - 30 000)	(15 000 - 40 000)	(> 100 000 000)
1	0	Total OPEX for tailings, waste and process water management (k€)	NA	NA	NA	NA	NA	(> 5 000)
1	1	Water requirements (m3/j)	NA	NA	NA	NA	> 300	> 5 000
1	2	Residues and waste rocks management infrastructures cost (k€)	NA	NA	-	-	NA	> 500
1	3	Tailings and wastewater management infrastructures cost (k€)	NA	NA	NA	NA	NA	> 5 000
1	4	Maintenance costs (k€)	NA	NA	NA	NA	NA	(~50 000)
1	5	Financing costs (except if self-financed) (k€)	NA	NA	NA	NA	NA	company funds
1	6	TOTAL OPEX (k€)	NA	NA	> 100	> 1 000	> 3 000	> 1 000 000
Taxation (€)								
1	3	Total economic outcomes during mining life-cycle (k€)	NA	NA	NA	NA	NA	> 1 000 000
1	4	Royalties (€/kg) to Department	none	none	NA	NA	NA	> 25
1	5	Royalties (€/kg) to French Guiana (Region)	none	none	NA	NA	NA	> 500 (not always)
1	6	Special consumer tax (TSC)	none	none	NA	NA	NA	(~ 90 000)
1	7	Tax on company profits	none	none	NA	NA	NA	~ 150 000)

Appendix 8 – Structure of the database listing the worldwide historical accidents in the mining sector. The database is currently under development and it has been improved by two students of the Ecole des Mines of Nancy (France).



Appendix 9 – Extract of the risk database developed for the identification of risk events in French Guiana during the three years of PhD.

Code	Risk event	Scale	Type	Source	Actor
EV_336	Development of new vectors for diseases	S3	CT	INT14	ADMIN
EV_337	Diseases vector clusters	S3	CT	INT14	ADMIN
EV_338	Malaria	S3		INT14	ADMIN
EV_339	Water physical deviation			INT14	ADMIN
EV_340	Degraded miner life-style			INT14	ADMIN
EV_341	Regulatory system failure			INT14	ADMIN
EV_342	Chagas disease	S3	CT	INT14	ADMIN
EV_343	Hantavirus disease	S3	CT	INT14	ADMIN
EV_344	Political instabilities			INT2	MINOP
EV_345	Local employment	S1		INT3, A30	MINOP
EV_346	Industrial risks	S1		INT3	MINOP
EV_347	Energy supply			INT3	MINOP
EV_348	Illegal miners hijacking			INT3	MINOP
EV_349	Associative life participation	S3	other	INT3	MINOP
EV_350	Lack of local suppliers for materials			INT4, A30, A32	MINOP
EV_351	Security costs at mining sites			INT4	MINOP
EV_352	Accidents against illegal miners			INT4	MINOP
EV_353	Project localization (far)				MINOP
EV_354	Communication constraints			INT4	MINOP
EV_355	Demographic changes	S3		INT5, A32	ADMIN
EV_356	Regulatory sanctions			INT6, J31	ADMIN
EV_357	Soil erosion			INT6, A25, A26	ADMIN
EV_358	Natural erosion of soil			INT9, A26	ADMIN
EV_359	Dust particle diffusion	S3		A6_37, INT00, A32	ADMIN
EV_360	Lack of communication	S1	FM	INT2, A6_38, A30	MINOP
EV_361	Proximity to sensitive zone (natural, social)			INT2, A30	MINOP

EV_362	History and social conflicts of the territory			INT2, A30	MINOP
EV_363	Lack of local knowledge in mining (and mining culture)			INT2, A30	MINOP
EV_364	Lack of information			INT3, A6_38	MINOP
EV_365	Extreme weather conditions in tropic climates	S3	CM	INT3, A28, J31	MINOP
EV_366	Proximity to populated areas			INT3	MINOP
EV_367	Transport of products for mining activity			INT3, A6_38	MINOP
EV_368	Proximity to water streams			INT3, A6_39, A30	MINOP
EV_369	Lack of transparency from the company	S1	FM	INT3	MINOP
EV_370	Lack of vulgarization	S1	FM	INT3, A30	MINOP
EV_371	Strikes of fuel workers			INT4	MINOP
EV_372	Presence of illegal placer miners on the site			INT4	MINOP
EV_373	Interruption of communication			INT4	MINOP
EV_374	Lack of skills for responsible mining			INT4, A30	MINOP
EV_375	Lack of institutional support			INT4	MINOP
EV_376	Inadequate mine reclamation and revegetalization	S1	FM	INT4	MINOP
EV_377	Lack of competent mining staff			INT4	MINOP

I. What are mining dams?

Mining dams are retaining and protection embankment that are used for mine sites and/or metallurgical plants (Bourbon and Mathon, 2012). They have two main functions:

- to create sedimentation impoundments for the storage and settlement of fine waste materials coming from mining operations or mineral processing (called “tailings”). In this latter case, they are referred to as tailings store facility (TSF) (Lottermoser, 2010; Kossoff *et al.*, 2014; Ponce-Zambrano *et al.*, 2014).
- to create decantation ponds to hold and clarify water that may be returned for the mine to operate in a closed-circuit, after settlement in dam via penstocks and piping (Babbitt and Graham, 1996).

Despite several common features (e.g. water storing function, hydraulic parameters, geotechnical monitoring), tailings dams differ significantly from conventional water retention dams (UNEP, 1996; Rico *et al.*, 2008b; Martin and Davies, 2000; Schoenberger, 2016). TSF retain potential hazardous materials and not only water. Moreover, they represent a necessary cost for the owner – even after mine closure – and not an asset for common use (UNEP, 2017). Indeed, TSF are designed to “secure storage of tailings in perpetuity” (UNEP, 2017), requiring high costs and surveillance even after mine closure. They are constructed in stages, simultaneously with their operation, hence, their conditions and safety parameters are continually changing. Furthermore, TSF are often earth-fill dam types (Smith and Connell, 1979; Ozer and Bromwell, 2012), built of mine wastes (rather than boulders or concrete) or of locally collected materials (soils, coarse waste, overburden from mining etc.).

In order to fulfill the mentioned functions of storage and decantation of mine tailings and operation waters, three main *performances* are defined for a TSF (Bourbon and Mathon, 2012; Li *et al.*, 2018; USSD, 2018):

- iv) Physical stability, which is the capacity to support the applied stress for a long time without suffering any significant deformation or movement;
- v) Impermeability, which is the capacity of the mining dam not to allow the transfer of fluids under specific pressure conditions, except when needed;
- vi) Sufficient storage capacity which represents the aptitude of the embankment to contain the required volume of materials and fluids, without reducing stability and impermeability.

These performances – among which it is important to include the legal constraints and requirements for environmental, occupational, health, safety and geotechnical performances – rely on a great range of structural and functional components, which depend on the type of the mining project. Three major components are here considered (Fig. 48): i) the embankment, main structural element of the dam; ii) the foundation soil where the embankment is built on; iii) the effluent contained within the embankment and composed by the supernatant (tailings

liquid or tailings water) and, beneath it, the mine tailings (the solid fraction remaining after the extraction of the valuable ore minerals) (Zandarin *et al.*, 2009; Lottermoser, 2010; Kossoff *et al.*, 2014). Along with these components, a great range of specificities influences the functioning of a mining dam and the application of specific safety measures, such as the respect of the freeboard, the presence of spillway channels, bottom draining and overflow devices, to ensure water collecting and balancing, especially during emergencies (Bourbon and Mathon, 2012). A geomembrane or other geosynthetics may be used to protect the dam walls to reduce erosion, scouring and spills (Zornberg and Christopher, 2007). Sometimes a system of diversion channels dug in the natural terrain can be used to assure a closed-circuit functioning. Finally, sequential structures over the dam through particular elevation methods of the dam can increase the storing capacity of the embankment: the elevation can be done upstream towards the tailings (more than 50% of TSF today), downstream away from the tailings or in centerline (Lottermoser, 2010; INERIS, 2014) (Fig. 48).

II. Overview of dams used in gold mining sector in French Guiana

Several technical reports give an insight about the specificities and the utilization of TSF in FG gold mining sector (Laperche *et al.*, 2008; Barras, 2010; Bourbon and Mathon, 2012; Cottard and Laperche, 2012; INERIS, 2014; SRK, 2017; GéoplusEnvironnement, 2017; Aesteergts, 2018; Urien, 2018). These TSF differ considerably depending on whether the exploitation concerns primary or secondary deposits. In both cases, they are usually built from local soils and materials, because of the difficulties of access and transport of heavy materials.

However, building materials might be too much heterogeneous and permeable. Every block with a size bigger than 20 cm is considered not suitable (Barras, 2010). Forbidden materials for the construction of tailing dams are plastic clays, sandy and coarse materials and every oil organic matter-enriched material. The banks of the dam are built up by a series of thin compacted layers, after the selection, preparation and compacting of the foundation soil. The organization of external and internal drainage systems aims to reduce pore pressures, ensure a sufficient permeability to control water balance and reduce erosion risks. At the moment, no chemical additives are used for gold processing in FG primary and secondary legal exploitations and, thus, tailing's dams only retain water and geomaterials (Barras, 2010).

In **primary gold exploitations**, the arrangement of mining dams consists in one or several ponds designed to stock mine tailings in a slurry (10 to 30% of solid fractions), having a sandy to clayey texture (Bourbon and Mathon, 2012) (Fig. 49-50). These ponds are embanked by two or more dams, usually built with the anciently or recently excavated materials available on site (Cottard and Laperche, 2012). In FG, the most common elevation technique is the upstream method because it is easier to preform and economically more viable. Nevertheless, this method implies that the raised-up dams partly rely on non-compacted materials. Moreover, the increasing height enhances the risk of landslide and reduces the security factor, leaving the saturation level and runoff flows less monitored (Bourbon and Mathon, 2012). In FG, the initial

dam is usually not permeable, to reduce the water level because of closed-circuit functioning requirements and because of logistical and energetic needs (Fig. 49-50). Hence, waste desaturation takes much more time. Other ponds are used to decant and settle wastewater; they are located disparately on the site according to the topography, logistical needs or risk mitigation measures. They usually concern one or several secondary settling ponds. The longer the water is stored, the better colloids are deposited at the bottom, improving water clarification. More precisely, the downstream pond usually stocks the largest part of clarified water to be recycled for the closed-circuit functioning of the mine (Bourbon and Mathon, 2012). Finally, emergency ponds are located within the mine site, downstream the tailings pond, in order to receive the potential release of water and tailings in case of overflows (Fig 49-50).

We visited the dam system of a potential MSM-c that would stock de-cyanated tailings. The system used consists in the adaptation of the old dam system, through a sequence of ponds with particular draining systems and overflow devices. Each pond receives the potential overflow of the upstream-ones and finally is pumped back to assure the closed-circuit operation. No information has been found related to i-ASMp dams.

In secondary gold exploitations, the arrangement of mining dams consists in a sequence of ponds used both for tailings storage and water settlement as long as the exploitation progresses (Fig. 51). As it was explained in Chapter 4, these structures embank the *barranques* and, as the exploitation progresses along the riverbed, the previous extracting ponds are used to stock turbid water and the tailings of the “active” upstream *barranque* (Barras, 2010; Bourbon and Mathon, 2012). Once extracted, the minerals are processed by grain-size, a first time through gravimetry directly in the current exploitation pond, and then sent into the downstream ponds to settle (Fig. 51). No chemical additives are used. Secondary gold mining dam systems are found as well in primary gold mining projects that exploit secondary gold as complementary activity.

Around the *barranques*, waste soils are embanked for a height of 3-4 meters in order to separate each nearby pond and to protect them against flood and overtopping for the preservation of natural surface waters. These structures can be assimilated to dykes rather than actual dams. The life cycle of each *barranque* is quite short (one to several weeks) but they have an evolving nature. (Bourbon and Mathon, 2012). Indeed, exploited areas move constantly and *barranques* are continuously built up and then wiped out. According to the report by Bourbon and Mathon (2012), it is important to distinguish between internal dams – that create the *barranques* or water supply channels and have an evolving short-term life cycle. – and external dams – which are used to protect the surrounding environment from wastewater and potential emergencies. The same authors underline the priority of monitoring the stability of external dams for environmental protection. External dams are built at the beginning of the exploitation works and they are kept during the whole lifecycle of the

exploitation. The same system is set for i-ASMs, using dykes protected by wooden devices, but few information has been found.

Therefore, the main differences between the dams in primary and secondary gold mining are:

- 5) A greater storage capacity and height of primary gold mining dams, due to the difference of surface exploited, the financial and technical equipment available and the production rate.
- 6) The systematic distinction, for primary gold mining projects, between tailings dams and water settling ponds.
- 7) The localization of the ponds which depends on a progressive downstream-to-upstream sequencing for secondary gold mining and are essentially topography-driven for primary gold exploitations.
- 8) The potential storage of decyanated tailings outcoming from processing plants and the utilization of dry storage for some primary gold exploitations.

III. Mining dam failures: mechanisms, causes, consequences

In 1556 Agricola wrote that when the ores are washed the water used poisons the brooks and streams, destroys the fish or drives them away. Almost five hundred years later, approximately 23 000 tons of oil products spilled into the environment in a nickel mine in Russia in May 2020 due to the possible collapse of a fuel reservoir (Kim, 2020 for NPR News). In March 2020, in Heilongjiang Province (China), more than 2.5 million cube meters of tailings contaminated the environment, threatening drinking water provisioning of almost 70 000 people. In 2019, more than 12 million cubic meters were released after the collapse of a tailings dam in an iron mine near Brumadinho (Brazil), killing more than 250 people. These were only the major among the 21 big tailings dam failures that have been reported by WISE, 2020 after the 2015 Samarco failure. Indeed, the greatest challenge for mining is the treatment and storage of mine waste, estimated to 5 – 14 000 Mt/year (Kossoff *et al.*, 2014; Schoenberger, 2016). Tailings ponds represent the most significant environmental liability associated with mining operations (Martin and Davies, 2000), being more vulnerable than conventional dams (Rico *et al.*, 2008a).

Several definitions of failures are given by Smith and Connell (1979); FEMA (2004); Caldwell *et al.*, (2015), but none applies to all the contexts. In this study, a **mining dam failure** is referred to as the effect of the potential occurrence of single or multiple events which reduce one or more performances of a mining dam (e.g. stability, impermeability, storage capacity), leading to the alteration of its functions (i.e. tailings and water storage and settling).

Despite large dam failures low probability (Fu *et al.*, 2018), consequences may be catastrophic. Hence, mining operators are under constant scrutiny by governments (Martin and Davies, 2000). Moreover, if some authors emphasize that the interest in this type of event has been,

at occasions, the “result of a series of well-publicized failures subjected to largely biased, sometimes disproportionate, and sensationalized reporting in the media” (Vick, 1996; Martin and Davies, 2000), the high number of failures occurred in the last 150 years is undeniable. Besides Table 15, other authors report several tailings dam failures (Castro-Larragoitia *et al.*, 1997; Martin and Davies, 2000; Rico *et al.*, 2008a; Lottermoser, 2010; Franks *et al.*, 2011; Kossoff *et al.*, 2014; Caldwell *et al.*, 2015; Concha Larrauri and Lall, 2018; Glotov *et al.*, 2018; Venancio Aires *et al.*, 2018). In the Guiana Shield region, the main recent event concerns the Omai gold mine dam failure in 1995, detailed by Vick (1996).

According to authors, the rate of major tailings dam failures – thus, excluding “minor” accidents – is of 2 to 5 accidents per year (ICOLD, 2001; Davies, 2002), which means an annual probability between 1 in 700 to 1 in 1750, while it is only 1 in 10,000 for conventional dams (Davies, 2002). And this rate is estimated to increase each third of a century (Robertson, 2011), especially for earth-dams (Shahraki *et al.*, 2012; Fu *et al.*, 2018).

Multiple failure mechanisms are described by authors (Kossoff *et al.*, 2014; INERIS, 2014; Ponce-Zambrano *et al.*, 2014; Strachan and Goodwin, 2015). According to UNEP, (2017) eight main failure mechanisms are considered: mine subsidence, slope instability, foundation failure, structural failure, seismic instability due to earthquakes, overtopping, seepage or internal erosion and finally external erosion (Fig. 51).

Currently, overtopping is estimated to be the leading mechanism of mining dam failures (Strachan and Goodwin, 2015; Bowker and Chambers, 2017; UNEP, 2017) (Fig. 51). Moreover, it seems that overtopping events are increasing, which may show deficiencies in design and water management (Concha Larrauri, 2017). For this reason, overtopping was chosen as failure mechanism for the development of the RSa presented hereafter.

Overtopping is defined as the event during which water flows over the top of the dam, sometimes causing the erosion of the embankment (UNEP, 2017). The probability of occurrence of such events is influenced by a very wide range of interacting causes related both to the internal management of the mining project and its infrastructures, and the external environment of the mining project it-self. **Internal causes** can be related to:

- a) Deficiencies in controlling water balance (e.g. inadequate spillway channels, and improper maintenance, technical failures) (Strachan and Goodwin 2015; Lynas, 2018) and inadequate geotechnical studies (e.g. errors concerning the mechanical behavior of the materials, in-situ water loads, capillary water and pore pressures, landslide occurrence) (Smith and Connell, 1979; Zandarin *et al.*, 2009; Caldwell *et al.*, 2015);
- b) Inadequate construction methods (Le Poudre, 2015; Zhang *et al.*, 2016) and upstream elevation methods affecting dam stability (Rico *et al.*, 2008a; Kossoff *et al.*, 2014; Caldwell *et al.*, 2015). More than 66% of the worldwide reported dam

failures concern embankments constructed using the upstream method (do Carmo *et al.*, (2017).

- c) Other factors related to: dam height (do Carmo *et al.*, 2017), inadequate dam's location (Rico *et al.*, 2008b), age (Smith and Connell, 1979; Caldwell *et al.*, 2015), design, monitoring and peer reviews, limited engineer involvement and overconfidence of the mining operator (Caldwell *et al.*, 2015) but also its activity or inactivity (Rico *et al.*, 2008a; Kossoff *et al.*, 2014; Strachan and Goodwin, 2015).

The first **external cause** responsible for overtopping is represented by the meteorological conditions at mine site (Rico *et al.*, 2008a; Bourbon and Mathon, 2012; Ozer and Bromwell 2012; Kossoff *et al.*, 2014; Ozer and Bromwell, 2012), especially in areas prone to heavy rains, where physical stability of mining ponds and the control of water level on the long term can be a challenge (Franks *et al.*, 2011). Other causes are very variable and depend on the geological conditions, the topography of the site and the nature of the terrain (Stead, 1990; Emiroglu, 2008; Forzieri *et al.*, 2008; Schoenberger, 2016), the occurrence of earthquakes (Kossoff *et al.*, 2014). Climate change must be accounted for, because of a significant influence on water management at mine site (Odell *et al.*, 2018), particularly in FG (Lecomte *et al.*, 2011).

Finally, external causes can be also socio-political, related to the existence and application of preventive regulatory frameworks and of how exigent and comprehensive they are enforced (Schoenberger, 2016). In other cases, they might be economic, related to market dynamics the increasing of metal prices correlate with high rates of tailings dam failures (Kossoff *et al.*, 2014).

The **consequences** of the overtopping of a mining dam are extremely diverse and, if the probability of occurrence of this event is relatively low, its consequences can be catastrophic. The immediate consequence of an overtopping is for the water to overflow the embankment, eroding and damaging the structure of the mining dam it-self. Therefore, a first series of events concern the consequences directly at the scale of the mining project. Overtopping might cause physical impacts on the workforce at mine site and destruction of mining infrastructures and, hence, the halt of mining activity and a considerable cost for the mining operator which may be increased by additional judicial proceedings, compensation costs etc. However, in case of insufficient reactive safety measures, the overtopping might create a vast flood area which exceed the mine perimeter and affect the surrounding socio-ecological system. Because of their catastrophic nature, these territorial consequences are the most reported by media and scientific literature.

Once outside the mine site, the flood generated by the overtopping may trigger direct and indirect consequences on livelihoods, health, well-being of human populations extending to a much wider area of the basin, reducing the offer of ecosystem services and jeopardizing well-being of local population (, *et al.*, 2016). Direct environmental and societal consequences are multiple and very heterogeneous. Indeed, these triggered floods may affect local population and their safety and destroy public and private infrastructures (Fernandes *et al.*,

2016; Venancio Aires *et al.*, 2018), enhance silting and erosion, the release of total suspended solids, toxic and acid wastes or heavy metals contaminating soils, groundwater and surface water resources, destroying natural habitats, biodiversity and ecosystems (Castro-Larragoitia *et al.*, 1996; Kossoff *et al.*, 2014; Neves *et al.*, 2016; Glotov *et al.*, 2018; Venancio Aires *et al.*, 2018). These direct consequences may affect the surrounding human activities as well (e.g. arable crops, tourism) or drinking water catchment points, threatening human health and generating great socio-economic losses (e.g. loss of jobs and revenues, reduction of freshwater supply, social struggle due to the loss of revenues directly from the mine site).

These disastrous consequences for nearby communities and the environment have always a negative effect that rebounds on mining companies, who may consequently face high financial and reputational costs (Franks *et al.*, 2011; Concha-Larrauri and Lall, 2018). Moreover, they may generate a widespread controversy and projects' opposition (Caldwell *et al.*, 2015), leading to clean-up, compensation and litigation costs, the non-willingness of governments and communities to support new mining operations and, thus, lost future opportunities for mining operators (Franks *et al.*, 2011).



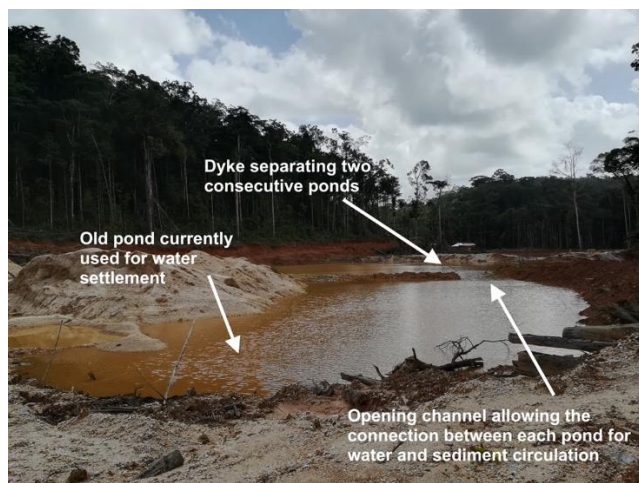
A mining dam system in a ASM project type. The pond currently exploited and the sluice-boxes used for gravitary exploitation



In some cases, primary gold mines exploit as well secondary gold as complementary activity. In this case, both the mining dam systems are present within the same mine site



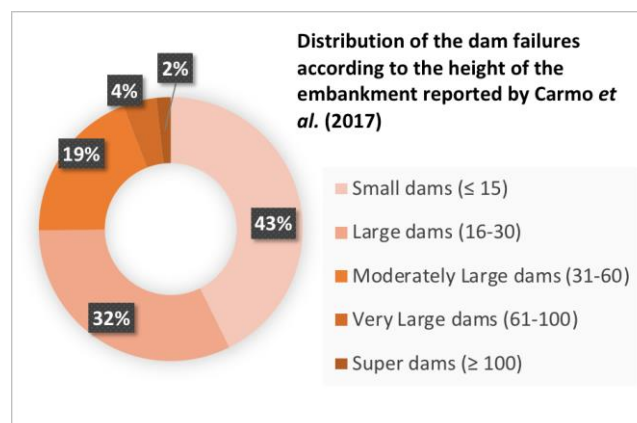
A mining dam system in a ASM project type. The ponds (barranques) are separated from the diversion channels by lateral dykes of few meters



A mining dam system in a ASM project type. Each barranque is connected with the others through spillway channels that allow the progressive settlement of sediments and the clarification of water



Mining dam system in a primary gold exploitation in FG (MSMg-type) showing a closed-circuit functioning. D2 is the most downstream dam (Barras, 2010)



Distribution of mining dam failures according to the height of the dam (adapted from Do Carmo et al., 2017). It can be discussed that furthermore that worldwide small dams are accounted more than large dams worldwide. The level of consequences of large dams is often much higher than in the case of small dams failures. However, small dams have, in theory, less technical and financial resources to assess and monitor the characteristics of the dams to reduce the probability of occurrence of the failure.

Appendix 11 – Synthetic review of the main numerical models commonly used for the estimation of the flooded areas

Model	Description	References
ANSYS FLUENT	Fluid dynamics and rheological analysis	Liu, 2018
NWS BREACH	Physically based mathematical model for predicting the outflow hydrograph from breaching of an embankment dam.	Mohamed <i>et al.</i> , 2001 Wahl, 1998
CASTOR	Tool to simulate dam breaches and estimate the hydraulic parameters for the assessment of public safety risks. The tool considers the riverbed between the dams with specific dam-related parameters (storage, breach geometry), the influence of water flow on the breach, the type of failure, the downstream nearby areas through simplified 2D flow models, the propagation of the breach wave, including the influence of the dam.	Aureli <i>et al.</i> , 2013 Renzoni <i>et al.</i> , 2005 GeoPlus Environnement, 2014
Columbia Water Center - Tailings dams empirical equations	Tool to estimate the volume of tailings released in the event of a tailings dam failure and the corresponding distance traveled by the tailings (run-out distance). The analysis is based on the empirical relationships developed by Rico <i>et al.</i> , 2008b using historical tailings dam failures. The original data was reviewed and expanded to include recent failures using data from Chambers and Bowker. These equations have great uncertainty around the mean estimation from the regression so the conditional distribution is displayed for risk analysis purposes., https://columbiawater.shinyapps.io/ShinyappRicoRedo/	Concha Larrauri and Lall 2018 Concha Larrauri, 2017
DMBRK	The model consists of two conceptual parts, namely: (1) description of the dam failure mode, i.e., the temporal and geometrical description of the breach; and (2) a hydraulic computational algorithm for determining the time history (hydrograph) of the outflow through the breach as affected by the breach description, reservoir inflow, reservoir storage characteristics, spillway outflows, and downstream tailwater elevations; and for routing of the outflow hydrograph through the downstream valley in order to account for the changes in the hydrograph due to valley storage, frictional resistance, downstream bridges or dams. The model also determines the resulting water surface elevations (stages) and flood-wave travel times.	Zhou, 2005 Bozcus and Kasop, 1998 Wahl, 1998
FLDWAV	Model used for unsteady flow analysis using the full equations of motion. It is a combination of two popular NWS programs: the Dynamic Wave Operation Network Model (DWOPER) and the Dam-Break Forecasting Model (DAMBRK) (break parameters, width, formation time, length, geometry, slope factor)	Zhou, 2005 Wahl, 1998
FLO-2D	Physical process model that routes flood hydrographs over unconfined flow surfaces or in channels. It is a simple volume conservation model and has a number of components to simulate street flow, buildings and obstructions, sediment transport, spatially variable rainfall and infiltration, floodways and many other flooding details. The unsteady flow equations in two dimensions also solved by the FLO-2D model can be expressed as follows	Lynker, 2019 Haltas <i>et al.</i> , 2016 Pilotti <i>et al.</i> , 2014

FloodGIS		<p>Cost-effective GIS tool that is able to provide: the evaluation of the instantaneous breach outflow discharge for masonry dams, the analysis of downstream flood propagation, and the creation of downstream flood-prone area maps, for dam-break analysis. The tool consists of a model for evaluating the dam-break outflow hydrograph, downstream flood propagation, a Digital Elevation Model (DEM)-based method for the delineation of dam-break hazard-prone areas. The GIS tool is capable of simulating one-dimensional unsteady flow using the St. Venant equations with the kinematic wave approximation, combined with wave front propagation as a monoclinical rising wave in a channel. As a final result, the tool provides the peak discharge, the peak elevation, and the peak time at different distances below the dam. The use of this tool is based on commonly available information concerning dam geometry (i.e., reservoir capacity, dam height and crest length), and a freely available online DEM.</p> <p>based on the commonly available data for masonry dams, i.e., dam geometry (e.g., reservoir capacity, dam height, and crest length), and a Digital Elevation Model. The model allows for rapid and cost-effective dam-break hazard mapping by evaluating three components: (i) the dam-failure discharge hydrograph, (ii) the propagation of the flood, and (iii) the delineation of flood-prone areas.</p>	<p>Albano <i>et al.</i>, 2014</p> <p>Albano <i>et al.</i>, 2019</p>
FloodRisk		<p>Prototype software tool able to calculate and view the number of people affected and direct damages to properties caused by any flood scenario in any chosen area. The tool performs a simple risk assessment in which it considers fixed event scenarios where the probability of each scenario is estimated separately and it calculates the consequences deterministically. The key data required concern: hazard (maximum depth values, maximum velocity values, warning time), receptors (the polygon boundary of the study area, census map of population, buildings and/or land use map, infrastructures lines maps (e.g. roads, railways etc.)) and vulnerability ("fatality rate" as the percentage of population at risk who die based on flood severity, warning time, and warning quality). Fatality rate assessment is based on empirical methodologies of literature calibrated on historical cases.</p>	<p>Mancusi <i>et al.</i>, 2015</p>
Flow Lenght module	Path GIS	<p>GIS module used to calculate the maximum upstream or downstream distance or weighted distance along the flow path for each cell based on 'Deterministic 8 (D8)' (O'Callaghan and Mark 1984) flow directions.</p>	<p>Lindsay and Seibert, 2013</p> <p>Lindsay, 2014</p> <p>Lindsay, 2016</p> <p>Lindsay, 2019</p>
Geomorphic Flood Tool	Area	<p>Open-source QGIS plug-in to realize a fast and cost-effective delineation of the floodplains in the contexts where the available data is scarce to carry out hydrological/hydraulic analyses. It is based on two main sets of inputs: a Digital Elevation Model (DEM) to calculate the Geomorphic Flood Index (GFI); and a detailed flood hazard map usually derived from hydraulic models, representing the reference standard data used to train the linear binary classifier based on the GFI (e.g. maps provided by river basin authorities or emergency management agencies). This calibration map, in the form of a raster grid, is necessary for limited portions of the basin of interest.</p>	<p>Samela, 2017</p> <p>Samela, 2018</p>
HEC-RAS, HEC-GeoRAS		<p>One-dimensional river hydraulics model used for steady flow and unsteady-flow water surface profile computations though a network of open channels In dam break study HEC-RAS is used to rout the inflow hydrograph throughout the reservoir and the outflow hydrograph of the breach throughout the downstream of the river. HEC-RAC can be used to route an inflowing flood</p>	<p>Duressa and Jubir, 2018</p> <p>Khalfallah and Saidi, 2018</p>

	hydrograph through the reservoir with any of the following three methods based on Saint Venant equations. HEC-RAS can be used to model the reservoir using fully dynamic wave routing. If it is not possible, or reasonable to perform full dynamic wave routing through the reservoir, or if the presumed difference between level pool routing and dynamic routing is small, then level pool routing can be performed with HEC-RAS. HEC-GeoRAS is a geographic river analysis system developed using ArcGIS Desktop and ArcGIS Spatial Analyst and 3D Analyst extensions	Zhou, 2005 Haltas <i>et al.</i> , 2016 Xiong, 2011 Demir and Kisi, 2016 Leoul, 2015
ISIS Flood	Hydrodynamic simulator for modeling flows and levels in open channels. It is able to model complex looped and branched networks, and is designed for simulating flood plain flows. It incorporates both unsteady and steady flow solvers, with options that include simple backwaters, flow routing and full unsteady simulation.	Almassri, 2011
MIKE Flood	Commercially available integrated tool for detailed floodplain studies. It is an integration of two numerical hydrodynamic models MIKE 11 (1-D) and MIKE 21 (2-D) with a unified user interface and gives you the best of both steady and unsteady flow computations , but the disadvantage is that the detailed spatial modeling where needed, plus the speed of 1-D calculations where appropriate. MIKE FLOOD is ideal for many types of analyses such as flooding, storm surge, dam break, embankment failure, and more.	Dat <i>et al.</i> , 2018 Kumar <i>et al.</i> , 2013 Shah <i>et al.</i> , 2017 Yu <i>et al.</i> , 2016
<i>r.damflood</i> module (GRASS GIS)	The new <i>r.damflood</i> command developed within the Free and Open Source GRASS GIS software is integrated within the RiskBox project and provides the users with new capabilities of dam break risk assessment: in fact starting from commonly available base maps (DTM, land use map, etc), it is possible to derive intensity maps that can be directly used within the GIS for exposure assessment and damage estimation. Moreover, the simulated temporal evolution of the flooding can be used to define protection and evacuation measures. It is based on elevation raster map (accounting for reservoir's bathymetry and dam elevation), lake water depth raster map (easily obtained with <i>r.lake</i> GRASS GIS module), dam breach width raster map (decreased dam height due to failure), Manning's roughness coefficient raster map, simulation time duration.	Cannata and Marzocchi, 2012 ; Marzocchi <i>et al.</i> , 2013
SCS TR-55 Model	Method which uses the CN method to estimate direct runoff from storm rainfall. This method determines CN values based on watershed's soil and cover conditions which represent the hydrological soil group, cover type, land-use treatment strategies and hydrological condition, and the direct runoff is determined based on the CN values (USDA 1986). Technique Release 55 (TR-55) is a commonly used hydrological model. This model uses runoff depth data obtained from SCS-CN as an input to determine the peak discharge of watersheds and enables the model to simulate runoff and peak discharge to identify flood phenomenon in urban areas.	Dang and Kumar, 2017
SMPDBK	Simplified prediction model of flood caused by dam breaks provides the required data to determine areas exposed to the flood. Applying the mentioned model reduces the amount of required time, data, computer facilities and experts in comparison with application of other complicated unsteady flow routing models. It is to say that, the user of the SMPDBK model is able to predict the maximum out flow of dam break, maximum elevation and maximum transfer time in specified points of downstream with the	Gee and Brunner, 2005 Motevalli and Zadbar, 2012 Shahraki <i>et al.</i> , 2012

minimum facilities, i.e. a microcomputer in a very short time. The input required for a SMPDBK model are a stream centerline, cross sections, and information regarding the storage and failure of the dam being modeled.

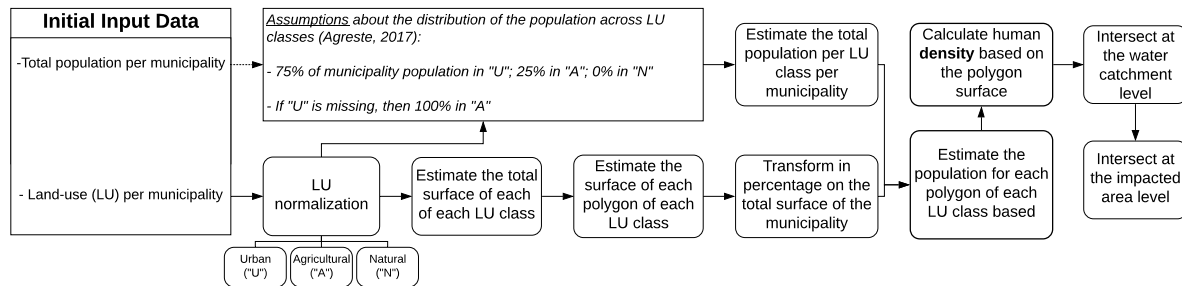
Day, 2016
Bozcus and Kasop,
1998

SWAT

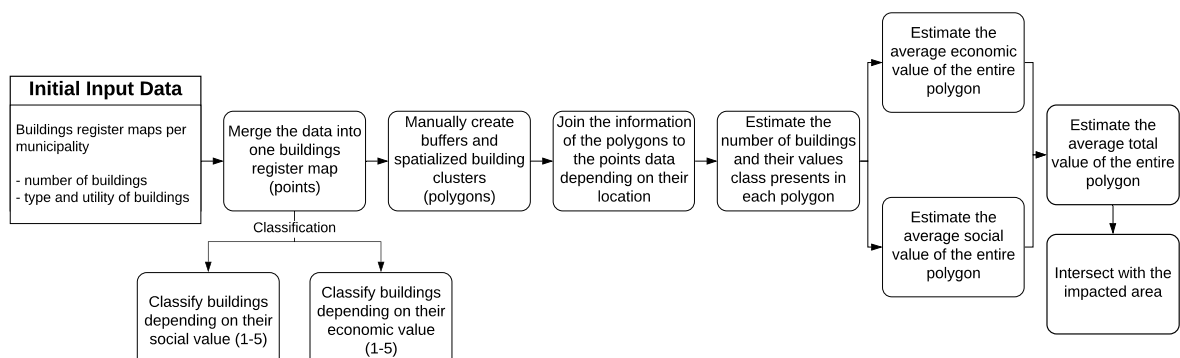
Soil and Water Assessment Tool, developed by the U.S. Department of Agriculture (USDA), is a quasi-distributed model used for simulating runoff at the watershed scale. It is a continuous simulation model that, besides its variegate functions, can also be used to predict the stream flow time series, both with and without dams, then analyzed to produce flood frequency curves.

Lee *et al.*, 2017

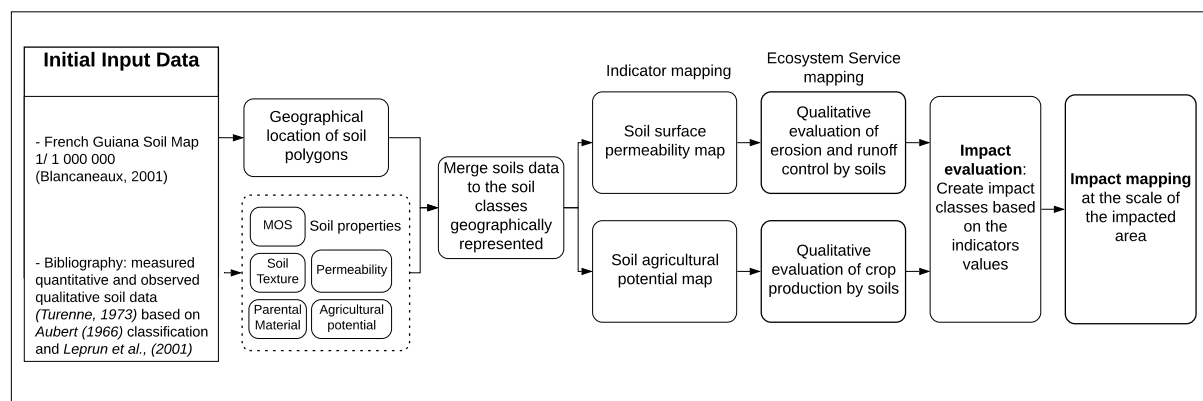
Appendix 12 – Simplified flowsheets of the methodologies developed for the assessment of socio-ecological vulnerability at the Mana river basin scale, based on the available data.



Flowsheet of the methodology developed for the assessment of population vulnerability based on land-use and demographic data.



Flowsheet of the methodology developed for the assessment of building vulnerability based on buildings-related data concerning their concentration per polygon and their destination of use (e.g. residential, monuments, public offices).



Indicator	Ecosystem Service	Reference
Soil permeability	Runoff control	
Crop production	Soil agronomic potential	

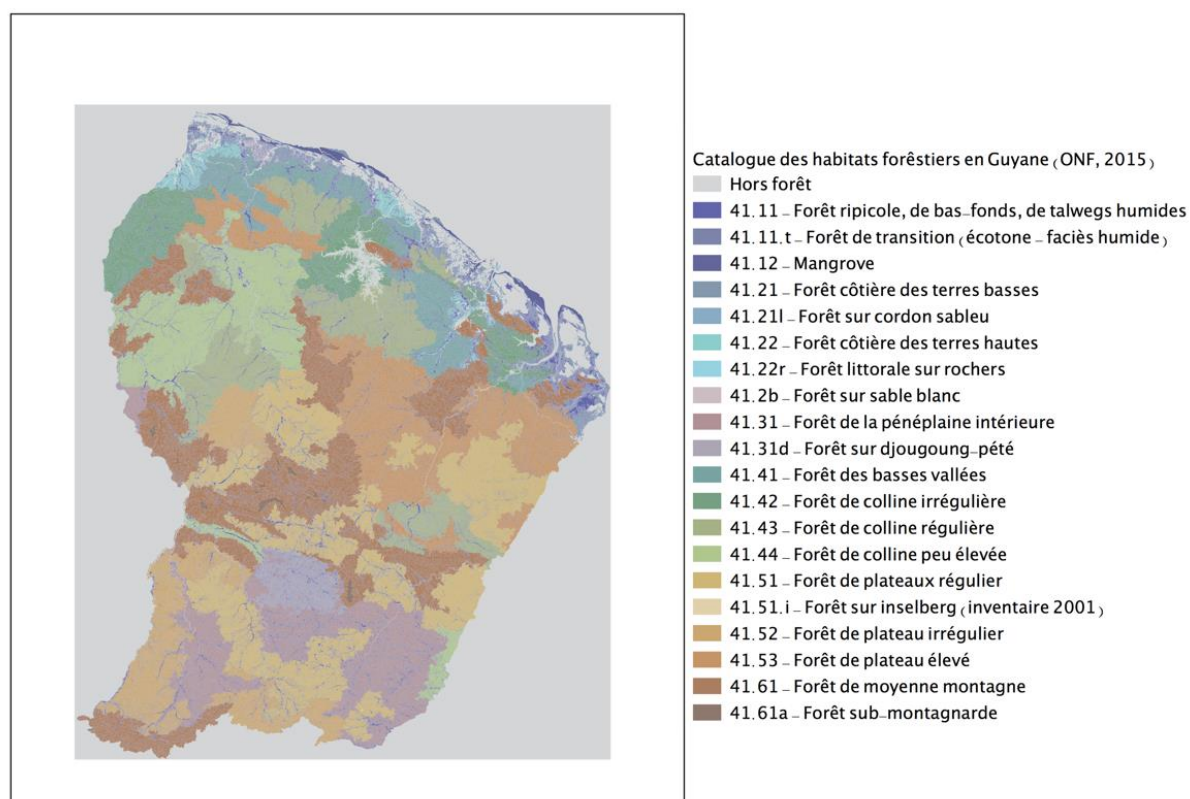
Flowsheet of the methodology developed for the assessment of soil ecosystem services vulnerability based on semantic and spatialized data. The association between these two types of data is given in the Table below.

Association table for the expert-based estimation of the soil permeability and soil agronomic potential indicators. For each given to each soil spatial unit in Blancaneux, (2001) a specific dominant soil has been associated and their characteristics have been described and associated.

Association sols Blancaneux 2001 - Turenne 1973

`Code Blancaneux, 2001	Code Turenne, 1973	Code Marius, 1966	Critères associatifs	Perméabilité	Potentiel agricole
PJ1	I.2		sols minéraux bruts, d'apports, matériaux alluvionnaire marin recent	Very low	Very low
PJ2	II.1, II.2		sol peu évolués d'apport, salés, pyrites, hydromorphie, sur matériaux alluvionnaires marins argileux	Moderately low	Moderately low
PJ3	II.3, V.3.1, V.3.2, V.4		hydromorphie, humus et matière organiques, gley, anmoor acide, salés, pyrites sur matériaux alluvionnaire	Moderately low	Moderately low
PA1	III.4.1, III.4.2		podzolisation, alios, matériaux alluvionnaires marins et fluvio-marins, ferrallitisols avec lessivages, appauvrissements, cuirasse, sols hydromorphes sur anciennes alluvions marines et fluvio-marines	Moderate	Very low
PA2	III (sauf III.4.1, III.4.2), IV.1.1, IV.3.3		ferrallitisols avec lessivage et appauvris avec podzols sur matériaux sableux, argileux continentaux	Very high	Moderate
S1	cuirasse lateritique, sol inexistant		pas de sol	Very low	Very low
S2	IV.2.1, IV.3.4, IV.4.1		ferrallitisols avec rajeunissement, appauvrissement et cuirasse sur schistes de Bonidoro	Moderate	Moderately low
S3	IV.1.3, IV.1.4	MO 19, MO 12, MO 1, MO 17	ferrallitisols avec remaniement, rajeunissement, appauvrissement sur schistes argileux d'Orapu	Very high	Moderate
S4	IV.3.1, IV.1.4		ferrallitisols avec remaniement, rajeunissement, appauvrissement sur granites Guyanais	Moderately high	Very low
S5	IV.1.2, IV.1.4, IV. 4.5		ferrallitisol avec remaniement, rajeunissement, appauvrissement et lessivage sur matériaux granitiques Caraïbe/Galibi	Moderately high	Moderate
S6	IV.1.2, IV.2.2		ferrallitisol remaniés et rajeunis, sur complexe volcano-sédimentaire Paramaca	Moderately high	Moderate
S7	IV.1.2, IV.2.2		ferrallitisol remaniés et rajeunis, sur complexe volcano-sédimentaire Paramaca	Moderately high	Moderate
S8	IV. 4.2, V.5.1, V.6		minéraux, sur matériaux sablo-argileux	Moderately low	Moderately low
S9	IV. 4.4., V.4.3, V.5.1		depôts fluviatiles, hydromorphes, fonds de vallée	Moderately low	Moderately low

Appendix 13 – Data used for the assessment of the vulnerability related to soil resources. The database has been published by the ONF (ONF, 2015) in French Guiana and it the spatialized data has been provided to us by local ONF experts.



Example of data used for the assessment of socio-ecological vulnerability indicators. In this case, the catalog of forest habitats developed by ONF, (2015) was used, interpreted and adapted to assess the consequences related to biodiversity, wood production and landscape degradation

grid_code	Description	POURC_FRE	SOIL	BIODIV	WOOD	BIOMAS	tMS_ha	PAYSAG	PB
0	Hors forêt								
41110	Forêt ripicole, bas fonds, talwegs humides	9	Gleysol	Moderate	Low	Moderate		High	Riverbank erosion
41111	Forêt de transition (écotone - faciès humide)	9	Gleysol	Moderate	Low	Moderate		High	Riverbank erosion
41120	Mangrove	0,6		High	Low	Moderate	450	High	Coastal erosion
41210	Forêt côtière terres basses	2		Very high	Low	Low		High	Tourism
41211	Forêt sur cordon sableux	< 0,1	Arenosols	High	Low	Low		High	Tourism
41220	Forêt côtière terres hautes	1		High	Low	Moderate		High	Tourism
41221	Forêt littorale sur rochers	< 0,1		High	Low	Low		High	
41230	Forêt sur sable blanc	0,1	Podzol	High	Low	Moderate		High	Tourism
41310	Forêt de la pénéplaine intérieure	8	Arenosols	High	Low	Moderate		Moderate	-
41311	Forêt sur djougoung pété	1		High	Low	Low		Moderate	-
41410	Forêt des basses vallées	4	Acrisols	High	Moderate	High		High	Soil erosion
41420	Forêt de colline irrégulière	5	Acrisols	High	Moderate	Moderate		High	Soil erosion
41430	Forêt de colline régulière	7	Acrisols	Low	Moderate	Moderate		Moderate to low	-
41440	Forêt de colline peu élevée	6	Acrisols	Moderate to low	High	High		Moderate to low	-
41510	Forêt de plateau régulier	12	Ferralsols	Moderate	Very high	High		Low	-
41511	Forêt sur inselberg (inventaire 2001)	< 0,5	Leptosols	High	Low	Low		High	Tourism
41520	Forêt de plateau irrégulier	6	Ferralsols	Moderate to low	High	High		Low	-
41530	Forêt de plateau élevé	9	Ferralsols	Low	High	High		Low	-
41610	Forêt de moyenne montagne	14	Plinthosols	Very high	Moderate	Moderate		High	Slope erosion
41611	Forêt sub-montagnarde	0,3	Histosols	High	Low	Moderate		High	Slope erosion

Example of information extrapolated by the ONF catalog (ONF, 2015)

Appendix 14 – Presentation of the conference paper illustrating the methodology to estimate the susceptibility of mining dam failure by overtopping developed with two students at the Ecole des Mines de Nancy. The paper has been presented at the ESREL Conference in 2019.

Development of a method to assess the susceptibility of tailings dams' failure due to overtopping

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ABSTRACT. In the last 20 years, more than 40 major tailing dam accidents occurred posing major economic, social and environmental threats like for instance, the dam failures of Baia Mare in Romania (2000), Mariana in Brazil (2015) and again in Brazil with the recent Brumadinho dam failure (2019). There are several existing methods to monitor the safety and efficiency of tailing dams, such as field measures, numerical and physical models, monitoring and expert judgment from referred professionals. However, these methods are very time, labour and money consuming. The purpose of this article is to propose a method to assess the susceptibility of failure of a tailings dam due to overtopping which: i) depends on qualitative and quantitative input variables ii) is adapted to the available amount of information and iii) gives a relevant confidence level. This methodology will be practical for preliminary evaluation of the state of a tailings dam and to point out the necessity of future study for the structure's safety.

Key Words: Tailings dam failure; Probability; Susceptibility; Overtopping; Mining; Vulnerability; Bow-tie Diagram

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Appendix 15 – Copy of the questionnaire that has been distributed among local stakeholders for the development of weighting coefficients. The on-line version of the questionnaire is available [here](https://docs.google.com/forms/d/e/1FAIpQLSevfQOV7vGggRmCsKGuRS9G66h6dL2Qa11yJb1i_99fPHCv0w/viewform)

https://docs.google.com/forms/d/e/1FAIpQLSevfQOV7vGggRmCsKGuRS9G66h6dL2Qa11yJb1i_99fPHCv0w/viewform

Questionnaire sur les impacts des projets miniers en Guyane française

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Ce questionnaire a été développé dans le cadre de ma thèse de doctorat en géosciences portant sur l'analyse des impacts des projets miniers à l'échelle territoriale. L'objectif du questionnaire est de connaître l'importance relative – selon vous et selon vos principaux usages, besoins et bénéfices (matériels, culturels, esthétiques, etc.) – des différents éléments, naturels et humains, qui pourraient être modifiés par un ou plusieurs projets miniers d'or en Guyane.

S'il vous plaît, cochez uniquement la case représentant le niveau d'importance que vous donnez selon qu'il soit : insignifiant (note 0), peu important (note 1), modéré (note 2), important (note 3), très important (note 4).

Les réponses sont entièrement anonymes. Je vous remercie par avance de votre participation.

Pour accéder à la version en ligne de ce questionnaire veuillez [cliquer ici](#) ou scanner le QR code ci-contre.

Merci d'envoyer le questionnaire complété à : ottone.scammacca@univ-lorraine.fr



Informations générales

Age : ☐ 0 – 14 ☐ 15 – 29 ☐ 30 – 44 ☐ 45 – 59 ☐ 60 – 74 ☐ 75 ou plus

Commune de Naissance :

Commune de Résidence :

Êtes-vous en activité professionnelle ? ☐ Oui ☐ Non ☐ Autre (retraité, etc.)

Si « Oui », dans quel secteur ?

- ☐ Administration, fonction publique
- ☐ Agriculture, pêche, artisanat
- ☐ Étudiant
- ☐ Entreprises privées

- ☐ Professions libérales
- ☐ Secteur minier artisanal
- ☐ Associations, ONGs, etc.
- ☐ Services de secours

- ☐ Secteur minier industriel
- ☐ Recherche, enseignement, formation
- ☐ Autre(s)

Importance relative des impacts des projets miniers en Guyane française, selon vous

1. Quels sont vos usages prioritaires des ressources en eau ? (vous pouvez cocher plusieurs cases dans)
- | | |
|--|--|
| <input type="checkbox"/> Domestiques (dont l'eau potable) | <input type="checkbox"/> Agricoles (irrigation, aquaculture etc.) |
| <input type="checkbox"/> Industriels (lavage, évacuation déchets, refroidissement des installations) | <input type="checkbox"/> Énergétiques (barrages, hydroélectricité) |
| <input type="checkbox"/> Loisirs (baignade, kayak et autres) | <input type="checkbox"/> Sanitaires (cures thermales etc.) |

En fonction de ces usages :

1.1. Quel niveau d'importance donnez-vous aux ressources en eau (non potable) en bon état?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4

1.2. Quel niveau d'importance donnez-vous à l'approvisionnement d'eau potable ?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4

1.3. Quel niveau d'importance donnez-vous à la préservation de l'état physique des cours d'eau contre l'érosion des berges, la déviation de crues ?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4

2. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous aux infrastructures d'un site minier ?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4

3. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous aux infrastructures de transport et au réseau routier ?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4

4. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous aux infrastructures publiques, bâtiments et structures résidentielles ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
5. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous à la présence de biodiversité (régulation des écosystèmes naturels, approvisionnement de nutriments, écotourisme)
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
6. L'érosion des sols peut contribuer à la dispersion de particules fines, métaux lourds et sédiments dans les cours d'eau. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous à la stabilité des sols et à leur résistance à l'érosion ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
7. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous à la fertilité et de certains sols guyanais ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
8. En fonction de l'usage que vous en faites, quel niveau d'importance donnez-vous à la bonne qualité de l'air ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
9. Quel niveau d'importance donnez-vous à l'offre d'emplois directs et indirects provenant d'une activité industrielle ou artisanale ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
10. Quel niveau d'importance donnez-vous à la santé et la sécurité de la population locale ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
11. Quel niveau d'importance donnez-vous à santé et la sécurité des mineurs travaillant sur le site ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
12. En fonction de l'usage que vous en feriez, quel niveau d'importance donnez-vous à la préservation de paysages naturels et forestiers guyanais ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
13. Quel niveau d'importance donnez-vous au développement économique guyanais lié à l'activité minière ?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4
14. Voyez-vous d'autres aspects qui pourraient être positivement ou négativement modifiés par la présence de projets miniers d'or en Guyane qui n'ont pas été mentionnés dans ce questionnaire ?
.....
.....
.....
15. Souhaitez-vous avoir un retour sur l'analyse statistique et anonyme des résultats de ce questionnaire dans le cadre de ma thèse ? Si oui, voulez bien laisser vos coordonnées de contact mail, téléphonique ou autre s'il vous plaît :
.....
16. Comment avez-vous reçu ce questionnaire ?
☐ Directement par le questionneur ☐ Indirectement par une autre personne ☐ Autre
☐ Réseaux sociaux ☐ Internet – email

Pour toute suggestion, commentaire ou remarque :

.....
.....
.....
.....
.....

Appendix 16 – Map of Classified Installation for Environmental Protection (ICPE) in French Guiana in 2019. The fist diagram shows how many of them are functioning, under construction or have been stopped. The second diagram shows the distribution of ICPE according to their codes, based on French legislation (source: <http://www.guyane.developpement-durable.gouv.fr>)

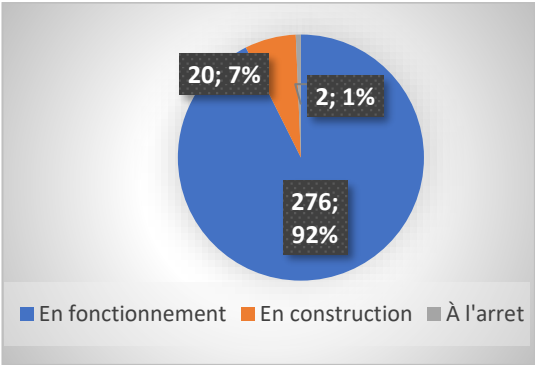
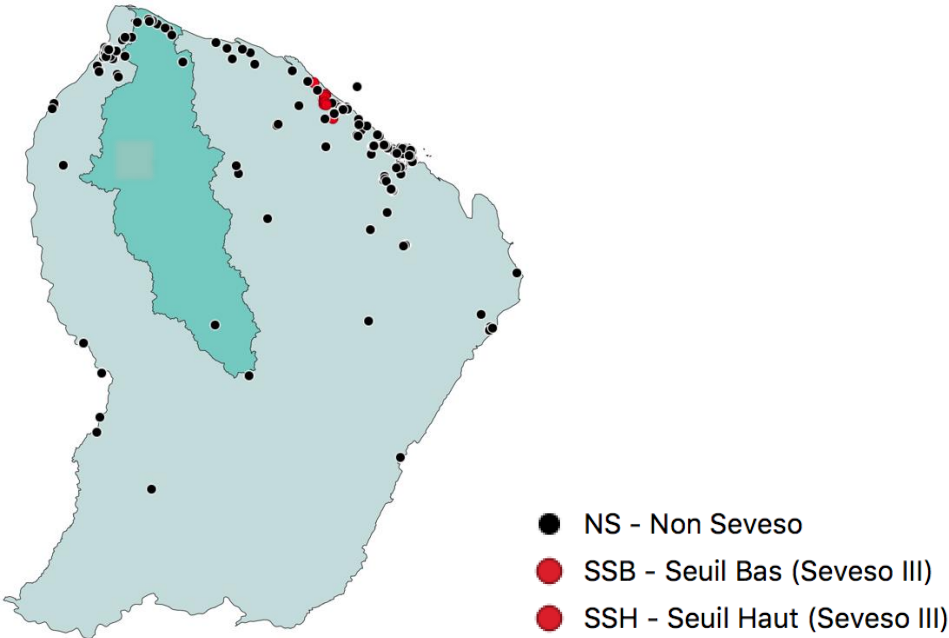


Diagram 1

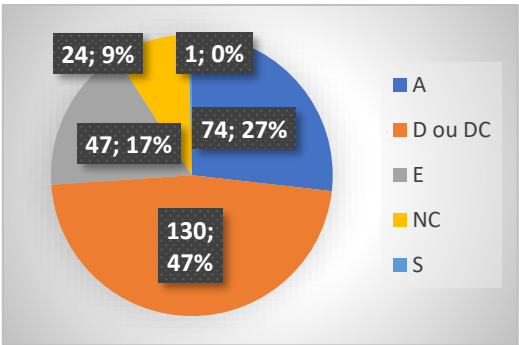


Diagram 2

Appendix 17 – Example of SWOT analysis per gold mine-type in French Guiana, according to the hypothetical point of view of mining operators

SWOT analysis per gold mining project type in FG based according to mining operators

	Strenghts What unique resources ? What more than the others ?	Weaknesses What could be improved ? What less than the others ?	Opportunity What trends can be taken advantage of ?	Threats What can be source of harm ? Which exposure, and to what ?
i-ASMp	<ul style="list-style-type: none"> - Low surfaces exploited - Higher gold recovery rate - Reduced mined surfaces - Cheap labour force - Free exchanges and mobility 	<ul style="list-style-type: none"> - Heavy duties and weak communication in closed environment - Socio-environmental performances - No public economic outcomes - No OHS standards - Local opposition 	<ul style="list-style-type: none"> - Formalization (economic outcomes, entrepreneurship, safety) - Informal savoir-faire and workforce experience 	<ul style="list-style-type: none"> - Criminal behaviours and episodes - Military and police enforcement - Informal networks and criminality - Self-destructive violence of illegal mining sites - Underground mining-related technical risks - Mercury-related risks
i-ASMs	<ul style="list-style-type: none"> - Accessibility of the exploitation - Higher gold recovery rate - Cheap labour force - Free exchanges and mobility 	<ul style="list-style-type: none"> - Great surfaces consumed - Socio-environmental performances - No public economic outcomes - No OHS standards - Local opposition 	<ul style="list-style-type: none"> - Formalization (economic outcomes, entrepreneurship, safety) - Informal savoir-faire and workforce experience 	<ul style="list-style-type: none"> - Criminal behaviours and episodes - Military and police enforcement - Informal networks and criminality - Self-destructive violence of illegal mining sites - High visibility - Mercury-related risks
ASM	<ul style="list-style-type: none"> - Juridical advantages (AEX) - Reduced regulatory costs - Local-scaled exploitation - Territorial integration - Reduced environmental impacts 	<ul style="list-style-type: none"> - Very low gold recovery rate - Low security and protection - Non-trained and self-formed technical and entrepreneurial skills 	<ul style="list-style-type: none"> - Cooperatives (incrementing gold recovery rate) - Improvement of technical and entrepreneurial skills - Technical support 	<ul style="list-style-type: none"> - Non viability of the project - Water management and TTS releases - Difficult logistics, acces, mobility to the mine site- Mine site preparation - Insecurity and hold-ups - Global gold market trends
MSMg	<ul style="list-style-type: none"> - Deposits with higher rates - Trained and skilled workforce - Technical liability - Monitoring and controls - Financial insurances 	<ul style="list-style-type: none"> - High costs for primary exploitation - Low recovery rate - Moderate to low security and protection - High monitoring form public authorities 	<ul style="list-style-type: none"> - Cooperatives (incrementing gold recovery rate) 	<ul style="list-style-type: none"> - Insecurity and hold-ups - Water management, floods and TTS releases - Difficult logistics, acces, mobility to the mine site - Dam failures - Global gold market trends
MSMc	<ul style="list-style-type: none"> - Deposits with higher rates - Trained and skilled workforce - Technical liability - Monitoring and controls - Financial insurances - Higher gold recovery rate 	<ul style="list-style-type: none"> - Constraints related to the utilization of hazardous chemicals - Very high costs - Moderate security and protection - High monitoring form public authorities 	<ul style="list-style-type: none"> - Cooperatives (shared costs) - Improvement of technical and entrepreneurial skills 	<ul style="list-style-type: none"> - Insecurity and hold-ups - Difficult logistics, acces, mobility to the mine site - Cyanide-related risks - Governmental and policy risks - Local contestation (cyanidation) - Global gold market trends
LSM	<ul style="list-style-type: none"> - Deposits with higher rates - Trained and skilled workforce - Technical liability - Monitoring and controls - Financial insurances - Higher gold recovery rate 	<ul style="list-style-type: none"> - Constraints related to the utilization of hazardous chemicals - Very high operational costs - High monitoring form public authorities 	<ul style="list-style-type: none"> - Financial investments - Rasant public image of the well-trained industrials - Communication and transparence 	<ul style="list-style-type: none"> - Difficult logistics, acces, mobility to the mine site - Geopolitical trends - Cyanide-related risks - Governmental and policy risks - Local contestation (cyanidation and size of the exploitation) - Global gold market trends

Abstract

Mining can be the source and target of opportunities and threats of different natures exceeding the mine-site perimeter, affecting the socio-ecological system where mining is performed and leading to social tensions and entrepreneurial risks for mining companies. Hence, a mining project is a matter of land-planning rather than a simple industrial object. Nevertheless, current mandatory risk and impact assessment methods are often performed on one project at a time, sometimes neglecting the cumulative dimension of risks, the great variability of coexistent mining activities, and the socio-ecological vulnerability in which mining is performed.

This thesis proposes an approach to develop and compare, based on the assessment of their risk, different potential scenarios for land-planning strategies in mining territories. This approach is operationalized through the development of a framework via its application on French Guiana gold mining sector. Here, gold mining involves a great variety of forms and techniques in a very sensitive socio-ecological context.

Five territorial mining scenarios (TMS) involving different mine-types (e.g. legal artisanal, medium, large scale mining, illegal mining) are developed for the same amount of gold production. For each TMS, two types of risk scenarios are distinguished whether they concern the normal or accidental (e.g. dam failure) functioning of the mining project(s). Risks are assessed through a GIS-based approach that consider the socio-ecological vulnerability of the territory where the mines are located. The TMS are finally weighted, discussed and compared based on a global risk score.

Despite the reliability of its results, this thesis provides an original and adaptable approach for the rapid comparison of mining strategies at the territory level, based on risk assessment. Further developments need to be achieved in order to optimize and improve the proposed approach and its application to the selected case-study (e.g. integration of the uncertainty analysis, better probabilistic models, data availability, GIS-automated tools).

Résumé

L'extraction minière peut être la source et la cible d'opportunités et pertes de différentes natures, qui généralement excèdent le périmètre du site minier et affectent le système socio-écologique dans lequel les projets miniers sont installés. Ces pertes peuvent aussi entraîner des oppositions et donc un véritable risque entrepreneurial pour les compagnies minières. Pour cette raison, un projet minier doit être considéré comme un enjeu d'aménagement territorial plutôt qu'un simple objet industriel isolé. Néanmoins, les méthodes d'étude d'impact ou d'analyse de risques appliquées au secteur minier sont souvent réalisées sur un projet à la fois, sans intégrer la dimension cumulative des risques liés à plusieurs projets coexistant sur le même territoire et en négligeant la vulnérabilité socio-écologique de ce dernier.

Cette thèse propose une approche originale qui vise à développer différentes stratégies de développement minier dans une perspective d'aménagement territorial et à les comparer sur la base de leur niveau de risque. L'approche est rendue opérationnelle à travers un cadre méthodologique développé via une application à titre démonstratif sur le cas de l'exploitation aurifère en Guyane française.

Cinq scénarios miniers territoriaux (SMT) sont développés en incluant des projets miniers de différentes types (e.g. mine artisanale, de taille moyenne, de grande taille, orpaillage illégal) pour la même quantité d'or produit. Pour chaque SMT, deux scénarios de risques sont considérés selon qu'ils concernent le fonctionnement normal ou accidentel (e.g. rupture de digue) des projets miniers. Ces risques sont évalués par une approche SIG en considérant l'estimation de la vulnérabilité socio-écologique du territoire. Les SMT sont enfin pondérés à partir des acteurs concernés (e.g. société civile, autorités locales, opérateurs miniers) et comparés sur la base d'un score représentant le niveau global de risque.

En dehors de la structuration d'importantes quantités de données concernant la Guyane, cette thèse démontre la faisabilité et la rapide application de notre approche en permettant une première comparaison – basée sur l'analyse de risque – de stratégies minières dans une perspective d'aménagement territorial. S'agissant d'un premier développement, des améliorations devront cibler l'approche proposée ainsi que son application (e.g. analyse d'incertitude, meilleurs calculs probabilistes, amélioration des données, automatisation).