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Ottone Scammacca, Yann Gunzburger, Rasool Mehdizadeh. Gold mining in French Guiana: A multi-criteria classification of mining projects for risk assessment at the territorial scale. *The Extractive Industries and Society*, In press, 8 (1), pp.32-43. 10.1016/j.exis.2020.06.020 . hal-02946557

HAL Id: hal-02946557

<https://hal.science/hal-02946557>

Submitted on 9 Mar 2023

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Gold mining in French Guiana: a multi-criteria classification of mining projects for risk assessment at the territory scale

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1. Introduction

Mining can be both a driver of economic development and damaging to ecosystems and human wellbeing (Badri *et al.* 2012; Lechner *et al.* 2017; Bansah *et al.* 2018; Mancini and Sala, 2018). Planning for the latter, however, can be challenging for large-scale mine operators, who are under pressure from governments, financial institutions and civil society to perform at a high level on all fronts (Hodge, 2014; Kemp *et al.* 2016). When their socio-ecological performance is considered unsatisfactory, therefore, mining projects run the risk of being suspended and/or fined (Pokorny *et al.* 2019) leading to delays, investment losses or even a cessation of activity (Bergeron *et al.* 2015).

Since the positive and negative risks – both triggered and suffered – mostly extend beyond the perimeter of mine sites themselves, any project must be factored into territorial land planning rather than being treated as a standalone local industrial object. Risk assessment, therefore, is crucial, and must be performed at different spatial scales, properly taking into account the vulnerability of the socio-ecological spheres in which one or multiple mining projects are located and, possibly, interact.

Risks associated with mining vary considerably depending on the intrinsic features of the mining project 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 acknowledge during the risk assessment phase. This is particularly true for specific commodities such as gold, diamonds, copper, which are exploited by both artisanal miners and large companies. Indeed, current mining risk assessment methods are usually focused on one project alone (Castilla-Gomez and Herrera-Herbert, 2015). They rarely take into consideration the interactions between coexisting mining projects or the cumulative risks they generate up to the territorial level (Franks *et al.* 2013). Moreover, risk assessment is mainly performed on large-scale capital-intensive projects and generally neglects smaller or artisanal activities.

The purpose of this paper is to propose an operational classification of mining project types for risk assessment purposes at the territory level. Gold mining in French Guiana has been selected as a case study to explore different scenarios because here, very different mining projects coexist in a small area, each of which has significant and controversial social and ecological impacts on vulnerable territory. Despite specific issues related to its localization in South America and in its bordering countries (e.g. illegal immigration and informal gold mining), French Guiana, as a French Overseas Territory, falls under the regulatory umbrella of France and the wider European Union. The gold-mineralized terrain of French Guiana is currently largely under-exploited, and decisions have yet to be made about the potential future development strategies for its mining sector.

There is also a shortage of information about different mining projects in French Guiana. Apart from a collection of technical reports, no structured and systematic description of gold mining projects, their functioning and induced risks, can be found in the scientific literature. This information gap may undermine future risk assessment studies; a finer classification is thus needed. The authors are cognizant of the political dimensions of gold mining, often driven by non-technical considerations, in French Guiana. The technological applications for gold as a commodity are much lower than its uses in jewelry and finance; however, the objective of the paper is not to question the utility of gold mining but to develop typologies for its extraction for territory-based risk assessment purposes.

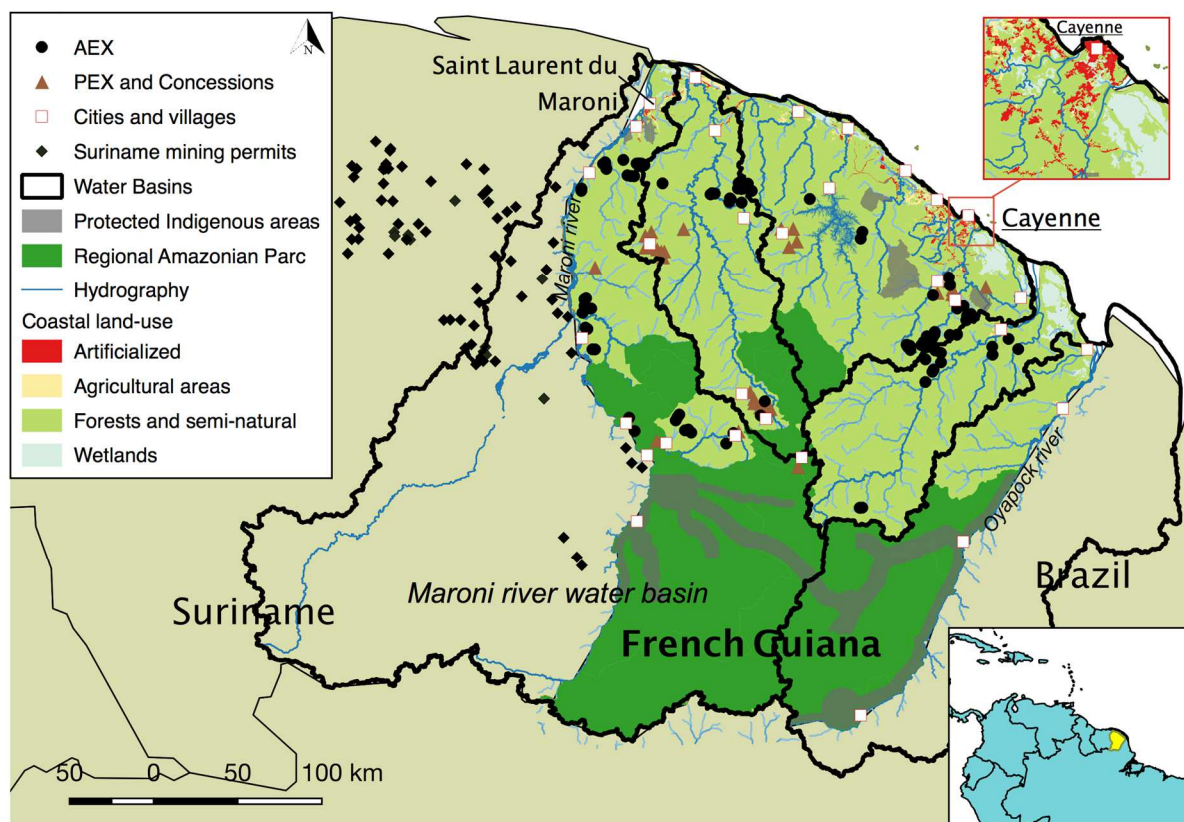
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Figure 1. Localization map of the studied area (French Guiana). The different types of mining permits delivered (AEX, PEX) are shown. Human settlements concern mainly the littoral area and along the two boundary rivers. More than 92% of the territory is covered by rainforest. Mining activities in Suriname – who shares a water catchment with French Guiana are shown as well.

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2. A call for a classification of mining project types for territorial risk assessment

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2.1 The most-cited impacts of gold mining in French Guiana and their causes

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The potential impacts of mining projects on the human and natural environmental spheres are widely discussed in the scientific literature (Hentschel *et al.* 2002; Amirshenava and Osanloo, 2019). Table 1 provides a list of the most widely-known effects of mining. However, the nature and the intensity of these impacts, as well as the probability of their occurrence, vary considerably depending on the technical features of the mining project, and the territory where activities are found. A classification for impact assessment purposes at the territorial level should, therefore, be based on these intrinsic factors. Hereafter, some of the most classic risk-related factors are briefly reviewed in the case of gold mining in French Guiana. They are identified as follows: gold deposit type, mining regulatory framework, mining footprint, and exploitation and recovery methods.

Table 1 Positive and negative impacts of gold mining

Impact Category	Potential Impacts	Nature	Reference(s)
Economic	Crimes and insecurity for local communities (e.g. corruption, drug and arm dealing, prostitution, child labor)	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 or 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; Deloitte, 2018
	Price increase of local primary goods	Positive or 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
Support to ethnic minorities	Positive	MDO, 2018	
Technical and Operational	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 programs	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 <i>et al.</i> 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

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83 *2.1.1 The local regulatory framework*

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85 Because of the impacts it potentially generates and its strategic importance, the mining sector
86 is highly-regulated. This influences the functioning of a project, the amount of surface area
87 required and the techniques featured during each phase of operation. Several mineral
88 commodities, however, are exploited informally (IGF, 2018; Kemp and Owen, 2019; Hilson
89 *et al.* 2020; Smits *et al.*, 2020), and associated with activities that can be a route out of poverty
90 for entire communities. Gold is the most important mineral extracted worldwide by informal
91 miners (World Bank, 2008): it has a considerable value-to-volume ratio, which means that
92 even small deposits can generate important profits and be easily sold (Hinton *et al.* 2003;
93 Verbrugge and Geenen, 2018).

94

95 In the case of French Guiana, mining permits are administered under two complementary
96 frameworks: the Mining Code, which establishes the size and the duration of the mining
97 permit depending on the mining phase (Table 2), and the Departmental Mining Plan, which
98 states where mining can and cannot take place. Moreover, and as indicated, a number of
99 European dispositions apply in French Guiana. At least 10,000 illegal miners – or
100 *garimpeiros*, as they mostly come from Brazil – operate outside such frameworks across 500
101 to 900 mine sites in the country (Moulet *et al.* 2006; Tudesque *et al.* 2012). Despite
102 significant military intervention, however, illegal mining still persists here. It produces 10
103 times more gold than legal mines; total production from illegal operations over the last decade
104 is estimated to be about 10 tons of gold per year, compared to 1–2 tons from legal operations
105 (WWF, 2018).

106

107

Table 2 Mining permits and regulations according to the French Mining Code

Type of permit	ARM	AEX	PER	PEX	Concession
<i>Description</i>	<i>Authorization for mining exploration</i>	<i>Authorization for mining exploitation</i>	<i>Permit for mining exploration</i>	<i>Permit for mining exploitation</i>	-
Nature of the activity	Exploration	Exploitation	Exploration	Exploitation	Exploration
Max. surface (km ²)	3	1	Free	Free	Free
Max. initial duration	4 months	4 years	5 years	5 years	50 years
Max. renewal times	1x4 months	1x4 years	2x5 years	2x5 years	∞ x25 years
Spatial scale of the delivering authority	Regional	Regional	National	National	National

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Source: DEAL, 2015

109

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2.1.2 Gold deposits

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112 The type of geological deposit dictates what techniques are selected for mining, and therefore
113 in large part determines associated impacts. There are generally two main categories of gold
114 deposits (Thomassin *et al.* 2017 and Figure 1). The first is primary gold, which is mainly

115 found in quartz veins (type 1) or in oxidized (type 2) and residual (type 3) deposits, depending
116 on the extent of weathering. Secondary deposits are comprised of gold particles that have
117 been subjected to significant displacement from the primary source along the lateritic profiles
118 (type 4) or by gravimetric concentration in streams (type 5) (Dardenne and Schobbenhaus,
119 2003). Acid mine drainage (AMD) is generally associated with primary gold deposits rich in
120 sulfides and occurs under specific operational and environmental conditions (e.g. oxidizing
121 conditions, absence of carbonates, high temperature, acid pH, microbial activity) (Miramond
122 *et al.*, 2006; Simate and Ndlovu, 2014; Skousen *et al.*, 2019).

123

124

125 2.1.3 Mining surface footprint

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127 Since the most widespread gold mining techniques in French Guiana are linked to surface
128 mining, the soil footprint of the mine site is an important indicator of the land use-related
129 impacts of a project. This is especially important in French Guiana because more than 90% of
130 its territory is covered by tropical rainforest (De Santi *et al.* 2016). According to the Mining
131 Code, the maximum authorized surface of mining projects depends on the individual permit
132 and, thus, on the nature of the mining activity and the aspects of the project phase (Table 2)
133 (DEAL, 2015).

134

135 2.1.4 Gold mining extraction techniques

136

137 Depending on the geological deposit, gold extraction can take a wide range of forms and sizes
138 (Verbrugge and Geenen, 2018). For instance, the evolution of legal and illegal artisanal and
139 small-scale mining communities is mainly due to the geological accessibility of some gold
140 deposits, especially where they are too small, scattered or remote for large-scale mining
141 (Hentschel *et al.* 2002; Verbrugge and Geenen, 2018). For this reason, since access within the
142 rainforest is limited, current gold extraction in French Guiana centres on predominantly
143 secondary deposits (types 4 and 5), featuring artisanal and small-scale techniques (Moulet *et*
144 *al.* 2006; Cassard *et al.* 2008).

145

146 In French Guiana, secondary gold mining is usually oriented around surface (mining)
147 techniques (“placer mining”), which have been documented in detail in technical reports
148 produced by the French Geological Survey (Laperche *et al.* 2008; Barras, 2010; Bourbon and
149 Mathon, 2012; Cottard and Laperche, 2012; Aertgeerts *et al.* 2018). A mine site consists of a
150 sequence of ponds (called “*barranques*”) interconnected through spillways which support the
151 gradual decantation of water from the newer ponds, where sediments settle, to the oldest,
152 where water is decanted and re-pumped to the hydraulic monitors. Once the gold particles are
153 separated from the other materials by grain-size through settling tables, concentrates of gold-
154 enriched “sands” are transported to the laboratory for recovery.

155

156 Only a small group of mining projects are engaged in the extraction of primary deposits
157 (types 2 and 3), although the country’s type 1 primary gold is still mostly untouched
158 (Massoud, 2008). Primary gold exploitation in French Guiana is most visibly carried out via
159 open-cast means, which entails the excavation of a pit 20–25 m deep and the transfer of waste
160 materials on to waste rock piles. The ore is crushed, grinded and then pulped through sluices
161 to separate gold particles by grain-size. Secondary grinding and centrifugal activities are
162 performed to trap fine gold particles (Thomassin *et al.* 2017; Matheus, 2018).

163

164 More recently, illegal miners have begun exploiting primary deposits underground (Bourbon,
 165 2014; Bourbon, 2015). Miners reach the gold through excavating pits and vertical tunnels, the
 166 depth of which vary between 10 and 40 m. The equipment used is rudimentary, and tunnels
 167 are stabilized using wooden planks affixed to pit walls. Illegal gold mining is now recognized
 168 to be one of the main causes of environmental degradation in the Amazon.

169 2.1.5 Gold processing and recovery methods

170
 171
 172 In French Guiana, gold is recovered mainly using three techniques: gravimetric methods,
 173 cyanidation, and gold-mercury (Au-Hg) amalgamation. Legal primary and secondary mining
 174 projects use gravimetric methods: mechanically separating gold particles from the matrix,
 175 initially during the exploitation phase, to reduce the grain-size of recoverable ore, and
 176 subsequently during the recovery phase to concentrate the gold particles. Moderately
 177 sophisticated equipment (e.g. concentrators and laboratory sluice boxes) are used in addition
 178 to traditional panning (Aertgeerts *et al.* 2018). When the wastes are badly managed, stream
 179 water turbidity become a major risk.

180
 181 The cyanide-based methods developed for gold recovery in French Guiana are described in
 182 several reports (Moisan and Blanchard, 2012; GeoPlus Environnement, 2017; Menard, 2018;
 183 Urien, 2018). Although cyanidation is not presently used in French Guiana, one semi-
 184 industrial operator has constructed a cyanidation plant and accompanying apparatuses
 185 (Thomassin *et al.* 2017). Cyanidation is associated with specific risks, which are linked
 186 mainly to its transportation (INERIS, 2018) and storage before gold recovery (e.g.
 187 explosions), as well as after processing (e.g. dam failures). Any mishandling or mishaps could
 188 have catastrophic consequences (WISE Uranium, 2019); the dispersion of free cyanide ions
 189 could cause severe eco-toxicological impacts (Donato *et al.* 2017).

190
 191 Since the gold recovery rate by gravimetry is low, informal miners use mercury, as did legal
 192 small-scale miners before Hg was banned by the French Government in 2006. This is despite
 193 it yielding up to 90% gold recovery in some cases (Hinton *et al.* 2003). Gold particles are
 194 concentrated, and amalgamated with Hg in a simple napkin to obtain a soft nugget. Since the
 195 Hg melting point is lower than gold's, the amalgam is roasted using a retort or a simple
 196 spoon. The Hg-related risks in French Guiana's gold-mining sector have been widely
 197 discussed (Grimaldi *et al.* 2015), and are linked to specific concerns about the health of
 198 miners and welfare of local communities. Soil, air and water are all affected: 20% of Hg is
 199 lost during amalgamation, while 70% evaporates during the roasting phase (Moulet *et al.*
 200 2006). With an annual gold production of 10 tons, approximately 13 tons of Hg are also
 201 released into streams in French Guiana (WWF, 2018). Contaminated hotspots have emerged
 202 in areas located some distance from mine sites (Marchand *et al.* 2006), where the impacts on
 203 biodiversity are well documented (Fréry *et al.* 2001; Godard *et al.* 2006; Sebastiano *et al.*
 204 2016; Gentès *et al.* 2019). The most significant problems result when Hg is transformed in
 205 methylmercury (MeHg) (Guedron *et al.* 2011a). Illegal and ancient legal gold mines are
 206 locations of high concentrations and seasonal cross-watershed transfers of MeHg (Guedron *et al.*
 207 2011b). Contamination might affect the food chain and lead to severe endocrine disorders
 208 among local populations (Fréry *et al.* 2001). Human exposure to MeHg depends also on the
 209 receptors and their socio-cultural habits (Grandjean *et al.* 1999; Boudan *et al.* 2004; ARS,
 210 2013).

211 212 213 2.2. Existing classifications of gold mining project types

214
215 Gold mining project types are often considered individually, and their detailed specificities
216 neglected. The environmental and social impacts of artisanal and small-scale gold mining has
217 been widely discussed (Hilson, 2002a; Seccatore *et al.* 2014. Moreover, the definition of
218 these activities varies from country to country (e.g. Brazil, Ethiopia, Ghana, Mexico,
219 Suriname) (Hilson, 2002b and Table 3). Informal gold mining has been widely examined in
220 the literature, especially in the context of its social, environmental and governance-related
221 impacts. However, no explicit distinction between illegal (informal) primary and secondary
222 gold mining is usually made (Table 3), although the type of deposit demands the application
223 of different methods. Illegal gold mining is mostly contextualized as a social phenomenon
224 rather than a simple individual project, specifically framed as activities undertaken outside of
225 regulatory frameworks and without trained formal skills (Bansah *et al.* 2018; Zvarivadza,
226 2018). The success of these activities is contingent upon gold price variations in the global
227 market, the availability of an abundant and mobile workforce, the free circulation of products
228 for gold recovery, and finally the money laundering networks which bind the informal and
229 formal sectors of gold production (Heemskerk, 2010). Both legal and illegal artisanal and
230 small-scale mining “must be fast, easy and cheap” to assure simplicity and a low investment
231 (Hinton *et al.* 2003). Conversely, large-scale gold mining activities are typically capital-
232 intensive projects financed by multinational corporations. Medium-scale mining is rarely
233 discussed (Ribeiro-Duthie and Castilhos, 2016). Such “semi-industrial” activities are specific
234 to some territories, such as French Guiana; here, medium-scale operators target primary
235 deposits, with a view toward industrializing further.

236
237 The existing classifications do not comprehensively cover these different types of projects,
238 especially in the context of gold mining; the operations found in this sector vary in size, and
239 feature different techniques. Moreover, existing differentiations are based on a few
240 distinguishing factors (e.g. gold production, degree of mechanization, size of the company).
241 In French Guiana, the different types of mining projects and their attributes are only
242 addressed in various “grey” literature, mostly technical reports produced by public institutes
243 or private consultants hired by mining operators. The only exhaustive classification found in
244 the literature is presented in a report produced by the Brazilian Geological Survey, an analysis
245 which covers artisanal and small, medium and large-scale gold mining projects (Ribeiro-
246 Duthie and Castilhos, 2016). However, such categories are not structured specifically for
247 impact assessment purposes at the territorial level. Gold productivity is used as the only
248 distinguishing criterion but only stands for a project-centered approach: indeed, in some
249 cases, including, and as noted, French Guiana, illegal mining produces more gold than the
250 entire legal sector. Therefore, it is essential to switch from a project-centered to a “sector-
251 centered” approach. This underscores the need for a territorial-based approach to impact
252 assessment which takes into account a range of various coexisting mining projects of different
253 types. Such an approach must begin with a classification that distinguishes mining project
254 types according to multiple criteria.
255

256 *Table 3 General definitions of gold mining projects proposed by scientific 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 10,000–100,000 t/yr of ore	Vale, 2000
	Mining operations both labor 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 river banks to produce 0.1–0.5 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/yr	Ribeiro-Duthie and Castilhos, 2016
LSM	LSM usually involves a company “with many employees which exploit 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/yr	Ribeiro-Duthie and Castilhos, 2016
LSM	LSM projects 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	LSM are complex and highly demanding endeavors carried by multinationals which require large investments, systematic management structures, in-depth geological and economic analyses	Vergara, 2009

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

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2.3. Objectives and methodology for the development of a mining project classification for risk assessment

The spatial multiscalarly of mining projects might be viewed in two ways: on one hand, from the vantagepoint of the spatial variability of outcomes (positive and negative) of mining which extend beyond the site itself, and on the other hand, from the perspective of the formal variability of the methodologies currently employed for impact assessment studies in the sector. Such methods focus on one project only or, in other cases, on the vulnerability of the territory in which a mine is located, where the mining project is viewed as a black-box (Durucan *et al.* 2006).

The classification of mine projects for impact assessment purposes allows for the adoption of a methodology that does not neglect their technical and operational spheres while considering their potential interaction with other activities at a much larger spatial scale. The objective of the proposed classification is to offer a standardized representative typology of gold mine projects with details of the specific features of each, with a view toward providing a basis to analyze and compare risk-based scenarios for future land use planning. For instance, if a specific type A project is developed within an area, how many type B projects would be necessary to cover the productivity or produce fewer impacts?

As shown in Figure 2, as a first step, the foreground data were collected, drawn from a thorough bibliographic review (scientific literature, technical reports), interviews conducted with local experts between December 2017 and November 2018, and observations made during field visits. Further data were gathered during the public debate on the “Montagne d’Or” project or MDO (CNDP, 2018) and the information contained in several technical reports produced on industrial projects within the Guiana Shield (Allain *et al.* 2008; Théveniaut *et al.* 2011; SRK, 2016, 2017). The main categories of gold mine operators in French Guiana were classified according to different criteria. For each, standard flowsheets of the mining system were developed. In line with new socio-ecological objectives (e.g. ecosystem services support, contribution to local employment, stakeholders’ integration) linked to mining projects (e.g. financial viability and technical-operational requirements) (Azapagic, 2004; Hodge, 2014; Monteiro *et al.* 2019), the simplified models are based on the following questions:

- What is the function of a (gold) mining project?
- What are the objectives and performances leading to the achievement of this function?
- What are the components of a mining project that support such objectives?
- What happens if the objectives are not achieved and its performance is unsatisfactory, thereby leading to negative outcomes?

These models and their detailed features have been discussed with local experts for validation (Appendices A and B). For each project type, a series of standard qualitative and quantitative features (e.g. number of workers, tailings dam height, pit depth, etc.) have been specified based on mine site visits, interviews and analysis of literature focused on French Guiana (Table 4 and Appendix B). In a fourth and final step, both the potential positive and negative impacts of each project type were identified based on the same data sources presented above.

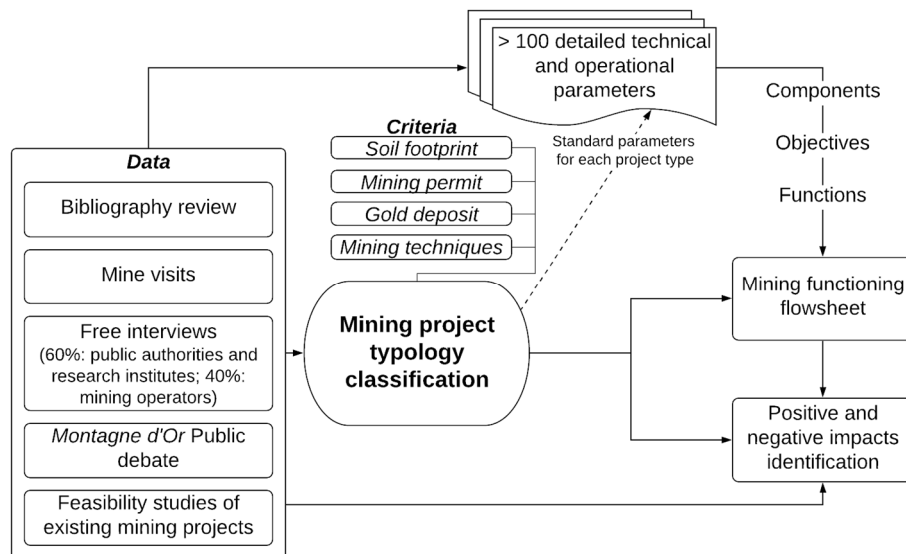


Figure 2 Conceptual flowchart of the methodology used for the classification of gold mining project types in French Guiana and their correspondent impacts

3. Proposed classification of gold mining projects in French Guiana and their associated impacts

3.1. Proposed classification of gold mining projects

From the information gathered, four main types of gold mines are identified. Each is based on several specific criteria intrinsic to the mining project itself: the type of geological deposit predominantly being exploited, the permitting status of the project, the techniques used for ore exploitation and processing, and the surface occupied by the mine site (Figure 3).

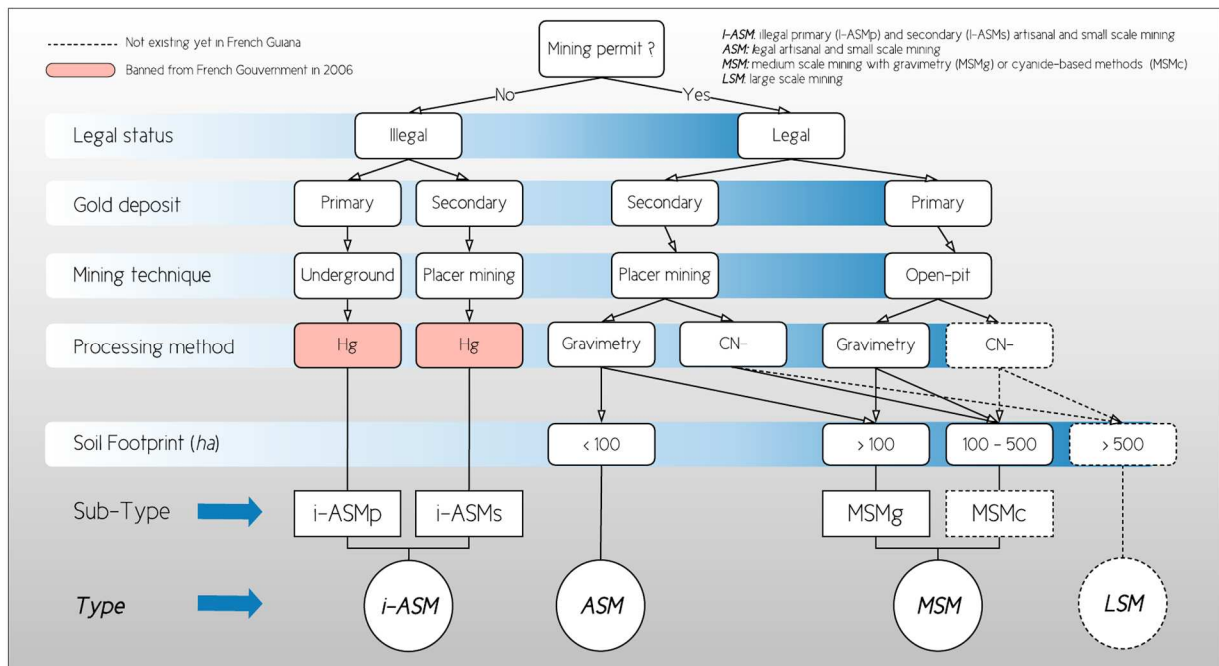
As indicated, in French Guiana, illegal artisanal and small-scale gold mining (“i-ASM”) can centre on underground or surface (placer) mining for the exploitation of primary (subtype i-ASMp) or secondary (subtype i-ASMs) gold deposits, respectively. The distinguishing feature of i-ASM is the use of Au-Hg amalgam for gold recovery.

Legal mining is divided into three main categories: legal small-scale mining (“ASM”) involves placer mining activities with gravity-based recovery methods, whereas medium-scale mining (“MSM”) and large-scale mining (“LSM”) exploit predominantly primary deposits. However, MSM and LSM operations also exploit secondary deposits depending on the morphology of the deposits and the confines of the mining permit.

Finally, MSM here is divided into two subgroups, depending on whether the project involves gravimetric (MSMg) or cyanide-based methods (MSMc) for gold recovery. Thus, the main distinction here between MSMg and LSM concerns the surface footprint. Although other criteria may be used for such purposes (e.g. average annual revenues, capital or operating expenditure, number of workers), for impact assessment, focusing on the surface occupied by a mine site allows for a first level of potential impacts to be conceptualized, which is particularly significant in vulnerable regions of the Amazon basin.

The proposed classification, therefore, aims to fill these gaps. Moreover, the distinguishing criteria are selected based on their influence over the intensity and nature of the positive and

339 negative impacts generated by a mining project. At present, no such structured and synthetic
 340 comprehensive view of French Guiana’s gold mining projects, adapted for the purpose of
 341 impact assessment, exists.
 342



343
 344 *Figure 3 Main types and sub-types of gold mining projects in French Guiana’s gold mining sector*

345
 346 **3.2. Characteristics and impacts of typical gold mine types in French Guiana**
 347

348 The specific features of each type of gold mining project in French Guiana are presented in
 349 Table 4. The specificities are detailed in Appendix B: the targeted geological deposit, the
 350 main regulatory constraints, the type of company, technical aspects concerning infrastructure
 351 (from excavation to mineral processing and waste management) with a specific focus on
 352 tailings dams, production and employment information, as well as fiscal and financial data.
 353 Unfortunately, a shortage of data means that some gaps remain. However, the presented
 354 characteristics confirm that the horizontal variability between each typology (“inter-class”
 355 variability) is higher than the vertical variability between the characteristics of each project
 356 type (“intra-class” variability), confirming the clear-cut classification. The presented data
 357 represent the inputs for the conceptual modeling of each project type and allow the
 358 development of standardized project types for risk and impact assessment purposes.
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368 Table 4 The main specificities of each legal gold mining project type in French Guiana

Main characteristics of each project type	ASM	MSM		LSM
		MSMg	MSMc	
Predominantly exploited gold deposit¹	Secondary (types 4, 5)	Primary (types 2, 3)		Primary (types 1–3)
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)	-	-	<1	>10
Processed materials by cyanidation (t/d)	-	-	100	>5,000
Gold recovery rate (%)	20–30	20–40	>90	>90
Decantation and storage system (wastewater and tailings)	<i>Barranque</i> (TSF and waterpond)	Gravitary TSF, water pond	Gravitary TSF, Cyanide TSF, Decantation ponds	Cyanide TSF
Total surface of gravitry tailings pond (ha)	0.5–2	10–20	>20	n/a
Total surface of cyanide tailings storage facility (TSF) pond (ha)	-	-	5–15	>150
Total capacity of gravitry TSF (m ³)	< 500, 000	500,000–3 000,000	500,000–3 000,000	-
Cyanide tailings per year (m ³ /yr)	-	-	>60,000	>10,000,000
Total capacity of cyanide TSF (m ³)	-	-	500,000–3 000,000	>100,000,000
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 (kW)	~40 kVA	>250 kVA	1,178.4	~20,000
Fuel stockage capacity (L)	5,000–10,000	15,000–30,000	15,000–30,000	>100,000

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370 The multi-criteria classification proposed in this article has been realized to categorize gold
371 mining project types according to specific characteristics (Table 4). Based on this
372 information, it is possible to identify and characterize a range of impacts, the occurrence,
373 nature and intensity of which depend on the defined gold mining project types. Table 5
374 highlights the typical impacts of gold mining projects in French Guiana based on the six mine
375 types of the proposed classification. The classification allows for an understanding of how
376 risks might vary from one project type to another, and which type of information is available
377 for their identification. Although some impacts are typical to all mining projects, others seem
378 to be specific to certain typologies and confirm the proposed classification. For instance,
379 AMD is a typical impact, mainly linked to mining projects working primary gold deposits.
380 Moreover, pit instability affects projects where excavation works are significant. However, in
381 some cases, a white-box might underline the absence of available information rather than the
382 absence of the impact itself.

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Table 5 Typical potential impacts of the gold mining sector in French Guiana, according to the proposed project typology.

Main potential impacts		i-ASM _p	i-ASM _s	ASM	MSM _g	MSM _c	LSM	Source
Negative	Destruction of ecological habitats and biodiversity	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Laperche et al. 2007 Galochet and Morel, 2015
	Deforestation	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	ONF, 2017 ; Rahm et al. 2017 WWF, 2018
	Surface water turbidity	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Tudesque et al. 2012 Gallay et al. 2018
	Heavy metals contamination in water and soils	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Laperche et al. 2008 Marchand et al. 2006
	Direct Hg pollution and contamination (e.g. gold recovery techniques)	○ ●	○ ●	○			○	Guedron et al. 2011b Kahhat et al. 2019
	Indirect Hg contamination due to the remobilization of ancient Hg	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Guedron et al. 2011a Gentès et al., 2019
	Dam failure related flood, contamination and turbidity	○	○	○	○ ●	○ ●	○ ●	Bourbon and Mathon, 2012 Ineris, 2018
	Cyanide spills	○	○	○	○	○ ●	○ ●	Moisan and Blanchard, 2012 Urien, 2018
	Soil erosion	○	○ ●	○ ●	○ ●	○ ●	○ ●	Laperche et al. 2008 Labriere et al. 2015
	Physical alteration of riverbeds (hydromorphological impacts)	○	○ ●	○ ●	○ ●	○ ●	○ ●	Laperche et al. 2008 Bourbon and Mathon, 2012
	Acid mine drainage (AMD)	○			○ ●	○ ●	○ ●	Miramond et al. 2006 Simate and Ndlovu, 2014
	Atmospheric pollution	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Melières et al. 2003 Laperche et al. 2007
	Landscape degradation	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Laperche et al. 2008 WWF, 2018
	Mine subsidence	○ ●						Bourbon, 2014 Bourbon, 2015
	Pit instability	○ ●			○ ●	○ ●	○ ●	Bourbon and Mathon, 2012 Bourbon, 2015
	Landslides	○ ●	○	○ ●	○	○	○ ●	Laperche et al. 2008 Bourbon and Mathon, 2012
	Health problems and serious epidemiological diseases (e.g. malaria, HIV)	○ ●	○ ●	○ ●	○			de Santi et al. 2016 Douine et al. 2018
	Migration of legal and illegal miners from bordering countries (“gold rushes”)	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Mouillet et al., 2006 Deloitte, 2018
	Work injuries	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Hentschel et al. 2002 Amirshenava and Osanloo, 2018
	Crimes and insecurity for local communities (e.g. drug, arm dealing, prostitution, child labor)	○ ●	○ ●	○	○	○	○	Hentschel et al. 2002 WWF, 2018
Social disruption (e.g. opposition, conflicts)	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Hentschel et al. 2002 Moisan and Blanchard, 2012	
Resource dispossession (e.g. land, water, crops)	○ ●	○ ●	○	○	○	○	Keovikignavong, 2019 Pokorny et al. 2019	
Positive	Direct economic outcomes (e.g. taxes, royalties)			○ ●	○ ●	○ ●	○ ●	Amirshenava and Osanloo, 2019
	Direct jobs opportunities	○ ●	○ ●	○ ●	○ ●	○ ●	○ ●	Amirshenava and Osanloo, 2019 Pokorny et al. 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

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

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389 **4. Discussion**

390

391 **4.1 The normalization of a clear-cut categorization of mining project types**

392

393 The intensity and nature of a mining project’s impacts vary according to the type, size and
 394 nature of the project itself. However, the variability among project types should first be
 395 examined through differences in their technical and operational features rather than their
 396 potential impacts. Thus, it is not sufficient to compare the impacts of each project type
 397 without “normalizing” them based on specific features that influence the nature and intensity
 398 of their impacts. Such normalization allows for relative values to be assigned to each project
 399 type and generates information fundamental to impact assessments.

400

401 Table 6 lists some examples of information that can be derived from Table 4. For instance, the
 402 ratio between the annual mass of gold extracted and the surface footprint of each project type
 403 might be a first overall socio-environmental indicator comparing positive economic
 404 production outcomes and negative environmental impacts prior to any further detailed
 405 assessment. The use of cyanidation for gold recovery by MSMc and LSM seems to ensure a
 406 better ratio for those project types, but only because this normalization does not consider the
 407 potential impacts related to this process. The inclusion of water consumption might therefore
 408 add considerable information about the overall environmental performance of a project.

409

410 The ratio between direct employment and soil footprint compares social compensation, in
 411 terms of employment, to the loss of surface area due to mining infrastructures. For instance,
 412 the progressive difference between MSMg and MSMc is mainly due to the fact that the
 413 construction and operation of cyanidation plants involves greater numbers of specialized
 414 workers and technicians. The ratio between the maximal dam height and annual gold
 415 extraction compares the potential impact of a dam failure, as indicated by the height of the
 416 dam, to annual gold production. However, the use of dam height as a simple overall indicator
 417 might not be pertinent: although the failures of higher and larger dams generate more
 418 considerable impacts than those of smaller dams, larger dams are also less likely to fail
 419 because of specific monitoring programs. Furthermore, the content of the tailings pond and
 420 possible chemical additives (e.g. cyanide, thiosulfates) should also be considered. Finally,
 421 legal underground exploitation might be theorized and potentially included within the
 422 classification to reduce both the soil footprint of the mine site and the potential volume of
 423 mine waste compared to illegal projects.

424

425

426 Table 6 : Examples of indirect information derived from data in Table 4 and Appendix B.

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

440

441 **4.2 Risk, vulnerability and safety measures**

442
443 Risk is calculated as the product of the probability of an event occurring and its consequences.
444 The risk of a particular mining project type therefore not only depends on the nature and
445 intensity of potential impacts, but also on their probability of occurrence and the vulnerability
446 of the potentially affected area. These latter aspects are not explored by the proposed
447 classification scheme, which focuses solely on the impacts (consequences) of a mining project
448 on socio-ecological spheres. Nevertheless, the probability of occurrence of an event depends
449 both on the vulnerability of the mined territory (e.g. climate conditions, soil type and political
450 stability) and the technical/operational and financial characteristics of the project.

451
452 On the one hand, the vulnerability of a socio-ecological system is related to the degree to
453 which the system is exposed to threats and its sensitivity and adaptive capacity (Berrouet *et*
454 *al.* 2018). Vulnerability assessments thus indicate how the positive and negative outcomes of
455 a mining activity might affect the socio-ecological sphere in which the project exists. On the
456 other hand, understanding the specificities of each project type allows comprehension of both
457 the technical/operational aspects and financial tools/circumstances that might affect the
458 likelihood of an event's occurrence. For instance, although the failure of the exploitation pit
459 of a LSM-type industrial operator might cause considerable damage, their greater financial
460 resources and technical skills allow for better pit monitoring, potentially preventing and thus
461 lowering the risk of pit failure.

462 Such project characteristics are key to risk assessment studies and are embodied by safety
463 “measures” or “barriers”, which can be proactive (e.g. monitoring systems and spillway
464 systems) or reactive (e.g. evacuation programs and alarm systems), depending on whether
465 their purpose is risk prevention or mitigation, respectively (Ehlers *et al.*, 2017). The concept
466 of safety measures – which can take different forms – is essential for the enhancement of the
467 socio-environmental performance of mining projects and might be useful in the integration of
468 new and “green mining” techniques into both mining operations and public policy.

471 **4.3 Limitations and adaptability of the proposed classification**

472
473 The proposed classification methodology – here for the gold mining sector in French Guiana
474 – can only partly be adapted to other cases, limited on a case-by-case basis by the criteria used

475 to classify mining project types. Indeed, the impacts of mining project types depend on the
476 targeted commodity: the exploitation of bauxite does not require the same infrastructure and
477 techniques used for gold mining. Annual productivity is also significantly dependent on the
478 mineral commodity and its market. Furthermore, the i-ASM sector is a social phenomenon
479 peculiar to gold and a few other commodities (Hentschel *et al.* 2002) that mainly concerns
480 “developing” countries because it is driven by property rights. The difficulty in defining such
481 projects lies in the fact that they are extremely heterogeneous and relevant data are usually not
482 available. Annual production rates thus greatly differ from one country to another (Seccatore
483 *et al.* 2014), and from site to site.

484
485 The main sectors of demand for gold are jewelry, investment and banking, with few industrial
486 application (World Gold Council, 2020). Therefore, gold can be considered a strategic
487 product rather than a simple natural resource in ways that differ from other commodities.
488 Moreover, the need for gold mining might be discussed in relation to its environmental costs,
489 whereas the recycling rate of gold is quite satisfactory at approximately 87% of reported
490 consumption (USGS, 2020).

491
492 Nonetheless, for a given mineral commodity, the classification of mining projects can be
493 greatly affected by the regulatory framework of the state considered. For instance, the gold
494 mining sector in Suriname is very similar to that in French Guiana: as both are located within
495 the Guiana Shield, the geological deposits are the same. However, Surinamese laws do not
496 forbid the use of Au-Hg amalgam for gold recovery. Thus, the use of Hg-based recovery
497 methods cannot be used to distinguish between legal and illegal mining projects in Suriname.

498
499 The MSM projects (i.e. projects of intermediate size between ASM and LSM) are specific to
500 French Guiana and a few other countries (e.g. Brazil). In the Guiana Shield and nearby areas
501 (e.g. Bolivia, Peru), similarly sized projects tend to be “mining cooperatives” that rather
502 represent the entrepreneurial and institutional choice of a structured sector for small- and
503 medium-scale miners to reduce negative socio-environmental costs and maximize economic
504 performances (Alves *et al.* 2019).

505
506 Finally, political and regulatory challenges might affect the pertinence and effectiveness of
507 such a classification for impact assessment purposes in two ways. The first concerns the
508 critical permeability and porosity that exists between legal and illegal gold mining projects,
509 especially in specific areas of the world. Moreover, in some cases, political decisions might
510 overtake the technical aspects of a mining project, becoming the main determinant of its
511 feasibility. The second is related to the transboundary nature of mining impacts: in some
512 ecological or strategic areas, multiple project types operating within contrasting regulatory
513 frameworks might coexist. One of the clearest examples is that of the Maroni river catchment,
514 which is the largest watershed in French Guiana, but straddles the border with Suriname
515 (Figure 1). There, two legal frameworks for gold mining coexist: one allowing and one
516 forbidding Hg-based recovery methods. These circumstances, when not properly addressed,
517 might hinder impact assessments – and more generally land-planning strategies – that require
518 cross-border efforts for mining governance and policymaking. Moreover, French Guiana is
519 the most frequent migrant destination in the Guiana Shield. However, this phenomenon does
520 not depend specifically on one or more types of gold mining projects (Table 5), since it is
521 strictly correlated to global gold trends and local political and judicial frameworks at a wider
522 scale (Taubira Delannon, 2000).

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4.4 Perspectives and example applications

Although the proposed classification leaves several open questions, it meets our objectives for risk and impact assessment purposes at the territory level. If the classification of mining projects represents a preliminary stage, the next step involves the detailed utilization of these standard project types within the risk assessment process.

The classification scheme proposed herein aims to support the elaboration of risk scenarios to compare future development strategies for mining territories. For instance, a fictional location might be selected for one or several standardized project types based on geological, regulatory, environmental and social criteria (Figure 3). Then, based on a chosen spatialized risk scenario, the area of influence of the mining project(s) and the consequences of one or more specific risk events can be estimated using GIS tools. This allows the analysis and comparison of impacts depending on the considered project type and the vulnerability of the mining territory to be developed.

Therefore, several strategies could be investigated to determine the most appropriate project type and location. For instance, if a government delivers a mining permit for a LSM project within an area, based on the characteristics presented in Table 4, how many MSM projects would be necessary to cover the same annual gold productivity? If, then, the impacts of the MSM projects are perceived or judged to be too important by local stakeholders and public authorities, how many ASM projects might be necessary to maintain the expected incomes?

These further steps are the subject of a future publication in which we report a concrete application of this preliminary risk assessment stage at the territory level.

5. Conclusion

Mining risks are strictly related to the intrinsic features of mining projects, and the impacts of mining exceed the mine site and impact the socio-ecological sphere in which mining activities are performed. For this reason, mining projects must be considered as a matter of land planning and their impacts must be assessed at the territory level. Here, we proposed a multi-criteria mining project classification for the gold mining sector in French Guiana. The distinguishing criteria were chosen based on their contribution to the impacts of gold mining projects. For each standardized project type, a range of technical and operational characteristics is presented to emphasize the differences between project types and their typical impacts.

The methodology used herein to create a multi-criteria classification of gold mining projects in FG might prove useful in creating risk scenarios to compare development strategies for a given mining territory. Indeed, such scenarios can be operationalized using standardized project types with representative features, which can then be sited in fictional locations to analyze their potential negative and positive impacts. Depending on data availability, our methodology should be at least partly adaptable to other case studies and/or commodities.

572 **Acknowledgments**

573 This work was supported by the French National Research Agency (ANR) through the
574 national program “Investissements d’avenir” (ANR-10-LABX-21-01/LABEX
575 RESSOURCES21).

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831 **Appendix A – Conceptual flowsheets of gold mining project types in French Guiana**
832 **(designed by Charlotte Travaillé ©)**
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835 **Appendix B - Classification criteria and specific features of standard gold mining**
836 **project typologies in French Guiana**
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