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LIPTAKOR, a participatory approach for increasing risk awareness and facilitating operational changes at artisanal gold mines

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A B S T R A C T

The literature highlights the importance of engaging local communities when attempting to raise awareness of environmental and human health-related risks at artisanal gold mines. There are, however, few reliable and tested methodologies available to achieve this or which can be adapted for use in a number of contexts. To help bridge this gap, we developed a tangible tool that takes the form of a game, which provides a space for participatory exploration of risk perceptions associated with artisanal gold mining. We present the results of this study, which was conducted in 2021 in the Nigerien Liptako–Gourma Region, and compare them to findings shared in the literature on risk perceptions related to artisanal gold mining.

Keywords:

Artisanal and small-scale mining (ASM)

Africa

Risk awareness

Environment

1. Introduction

1.1. The gold rush in Nigerien Liptako–Gourma

The Liptako–Gourma Region is located on the shared borders of Burkina Faso, Mali and Niger (see Fig. 1). It has a semi-arid, subtropical steppe climate, savannah-type vegetation, and a vast lateritic plateau. These three countries are collectively organized under the Liptako–Gourma Authority (ALG), established on the 3rd December 1970 in Ouagadougou. Covering an area of 370,000 km², the authority was conceived to facilitate economic development as well as combat poverty in the Liptako–Gourma Region (RAF/7/011). Geologically, Liptako–Gourma is situated at the northeastern edge of the West African craton, and is endowed with substantial metal deposits. Here approximately 30 minerals are found, distributed across 247 deposits and mining indexes in different metallogenic provinces (EITI, 2015).

Gold mining in particular plays an important role in the socio-economic development of these countries. In 2020, Mali and Burkina Faso ranked, respectively, as the fourth- and fifth-largest gold producers in Africa, following Ghana, South Africa and Sudan. Since the 1980s, artisanal and small-scale mining (ASM) has experienced significant growth in the Liptako–Gourma Region (Abdoul Razak, 2002; Hilson,

2009). This growth is attributed to a combination of factors, including an increase in the price of gold and a drought that fueled the movement of impoverished farm-dependent populations into ASM (gold) mining activities.

In addition to industrial-scale mineral exploration and extraction, ASM is critically important to Niger's economy. Estimating the exact number of active artisanal gold miners and their production in Niger's Liptako–Gourma region is challenging due to the temporary nature of some sites, seasonality and the unpredictable discovery of new mineralized areas. Combined, gold production from ASM in Mali, Burkina Faso and Niger is estimated to range between 15 and 85 tons annually, with the exact figure likely being around 50 tons (per year). This represents more than 50 % of the region's official gold production (OECD, 2018).

1.2. Sociodemographic impacts of Niger's ASM sector

As of 2018, Niger had approximately 200 documented gold mining sites, engaging, collectively, over 800,000 people (Ministry of Mines, Niger, 2022). It is very difficult to know the exact composition of this population of gold miners. Similar to other regions in Africa (Doucouré, 2014), in Niger, the development of gold mining activities brings about

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profound social, demographic, political, economic and environmental changes in host villages and areas.

Agriculture is the primary activity in the Liptako–Gourma region and is practiced by over 80 % of Niger’s population. However, despite local agricultural assets and potential, there has been a sharp decline in crop production due to gold mining. As a result, otherwise-productive agricultural land has been left idle, farm facilities have failed to materialize, and soil – when left exposed – has been rendered unproductive. Gold mining activities, especially the multiplication of mine sites and large-scale exploitation, have had major impacts, environmentally, on subsistence farming in Niger’s Liptako–Gourma Region; activities have degraded cropland and have been responsible for significant loss of vegetative cover. The effects of climate change have further impacted agricultural profitability. As a result, some farmers are frequently faced with seasonal unemployment and therefore elect to join gold mine sites for their survival (Hilson and Potter, 2005). While the situation in Niger suggests that ASM impedes farming, Hilson (2016) provides a more optimistic outlook on the activities in sub-Saharan Africa. Hilson argues that in light of the growing symbiosis between the two, they should no longer be seen as competing activities (or in opposition) in rural areas. Brugger and Zanetti (2020) also analyzed the multiple interactions between agriculture and artisanal gold mining at the household level in Burkina Faso. They identified four distinct patterns in how informal gold miners combine agriculture and mining.

As in other Sahelian countries, in Niger, foreign gold miners are present at sites; in the Liptako–Gourma region, they coexist with indigenous operators. They hail mainly from Burkina Faso, Mali, Benin, Togo, Nigeria and even Sudan. Their presence at sites is not only due to the porous nature of borders between neighboring countries but also because of the similarities of adjacent geological landscapes, which enables them to adapt fairly straightforwardly and engage in extraction. These “foreigners” are found at all stages of artisanal gold mining in Liptako–Gourma. However, their presence onsite and forced cohabitation with local populations often leads to friction with indigenous populations, typically over local values.

At most ASM sites in sub-Saharan Africa, there are typically a large number of women present. In Niger itself, as society views ASM as predominantly a sector for male employment, due to the physical strength and endurance required with a large share of the work, their presence is often condemned. Prostitution at sites has, unfortunately, objectified women. In some regions of the country, women are kept away from mining due to the belief that they “scare away” the gold. In neighboring Burkina Faso, where there are reportedly similar views,

Werthmann (2007) reported that in spite of this, economic pressures often lead to an increasing number of women pursuing work at ASM sites, where they engage mostly in petty trading, crushing and sorting. They often organize themselves into associations, which facilitates better execution of their tasks, and positions them to assume greater responsibilities: initially, as alluvial and eluvial gold panners, and subsequently, engagement in vein mining, which leads to the construction of sheds to process gold ore. Many of these sheds are now owned by women, although there is growing interest from men, which has often led to various forms of sex-based transactions (Ouedraogo, 2020).

1.3. Sociotechnological trajectories of ASM in Niger

The extraction techniques employed in gold panning in the Liptako–Gourma region are similar to those employed throughout West Africa. River panning, surface excavations in eluvium and alluvium, and vertical shaft sinking coexist. The mining process involves four stages: extraction, pre-treatment, processing and gold recovery (see Fig. 2).

Gold is extracted from shafts using traditional tools such as picks, crowbars and shovels. The ore is brought to the surface for processing. If a vein deposit is discovered, shafts are dug in the direction of it, often with little regard for the regulatory requirement to maintain an average distance of 5 m between shafts. During this phase, the gold miners support shaft walls using tightly wound wood coils, while ventilation is provided by locally manufactured plastic tubes. Some wells may reach the underground water table; dewatering is carried out using motor-driven pumps. The extracted water is often sold to the local population. Pre-treatment is applied to vein deposits and deep eluvium. This entails crushing the ore and grinding it to a grain size of 15/20 mm. This is performed in mortars that require a great deal of physical effort to operate and generate a lot of dust. The ore is then sieved through a light, tightly woven cloth. The discarded material from the sieve is further crushed using grain mills. This activity is more commonly undertaken by women and children, who typically belong to the most disadvantaged social strata at gold mining sites.

The final stage involves processing and recovering the gold using techniques such as gravimetry, followed by amalgamation and cyanidation. The gravimetric method is used to recover liberated gold. Amalgamation recovers gold from crushed ore, producing a mercury-gold alloy or amalgam. Cyanidation is carried out to recover gold. The ore is poured into several tanks, many of which are cemented, several meters in size, which are sprayed with cyanide and zinc shavings.

Afane and Gagnol (2020) describe in depth the sociotechnical

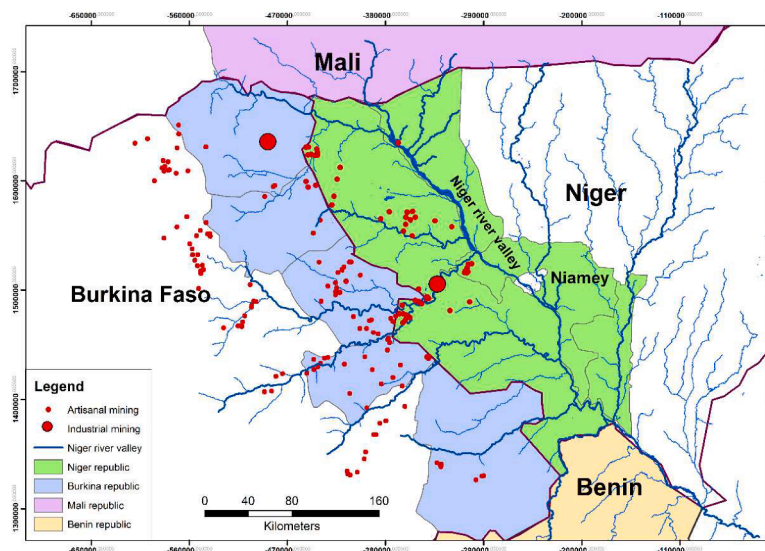


Fig. 1. An overview of gold mining in the Liptako–Gourma region (Maman Illatou, 2021).



Fig. 2. ASM technical processes observed in the Liptako–Gourma region: From left to right: panning and extraction from wells, pre-treatment by crushing and sluice, amalgamation, and cyanidation (photo credits: Oumar Maman-Illatou).

trajectories of informal mining in Niger since the unexpected discovery of gold nuggets and subsequent rush. Although the mining techniques employed at sites become increasingly mechanized over time, most sites remain semi-legal or clandestine in nature, characterized by low capital investment, low degree of mechanization, basic equipment usage, and high exposure to risks (UN, 1972; ECA, 2003; Hilson, 2009). As in other gold-producing regions, technological choices are heavily influenced by social, economic and political factors. The informality and illegality of the sector have spawned management systems focused on short-term, dangerous and polluting solutions (Seccatore and de Theije, 2017). Innovations in gold processing are deeply rooted in the configuration and organizational patterns of ASM sites. For example, Lanzano and di Balme (2021) analyzed the transition from mercury-based to cyanide-based techniques in the artisanal mining sector in Burkina Faso, which revealed a relationship between sociotechnical trajectories and ongoing power struggles. Gold mining sites are mainly ephemeral (they often disappear within a few months) and are poorly coordinated. A typical site is managed by the village chief in collaboration with administrative authorities and local elected representatives. Taxes are generally paid to village chiefs, commonly, in the form of one bag. Another is given to the corresponding landowner for every 10 bags mined. The government is only present through its directives at the departmental, regional and national levels.

The involvement of administrative authorities in the gold mining sector remains discreet and often ineffective, due to the security context of sites. Hilson et al. (2017) have argued that governments across sub-Saharan Africa are complicit in perpetuating informal artisanal gold mining. This observation holds true for Niger, where a lack of capacity on the part of the authorities to manage artisanal gold mining activities, coupled with inappropriate policies, is contributing to the informality of the sector (BNIC/SCP, 2013). Gagnol et al. (2022) have shown that governmental intervention in Niger has led to territorial reorganization, a convergence of political and economic interests between the elites of gold-producing peripheries and the central government, and ethical conflicts over access to deposits and profit distribution. These dynamics sometimes contribute to the illegalization, precariousness, and even criminalization of gold mining.

1.4. Environmental and health risks related to gold mining: the perception of risk

The Government of Niger has implemented technical interventions, supported by bilateral and multilateral organizations aimed at addressing practices that present health and environmental risks at sites. However, water and soil analyses routinely reveal that artisanal gold mines in Niger are severally polluted. This has been confirmed by several studies conducted over the years. They reveal that a number of ASM sites in Niger are contaminated, as a result of the use of toxic chemicals such as mercury, cyanide, and sulfuric and nitric acids, which feature during gold processing and extraction (Tankari et al., 2014; Sangaré et al., 2014). Studies highlight how the water used for human consumption is polluted; that soils and plants close to sites have elevated

concentrations of arsenic, mercury and cyanide; and that mine operations have contributed to the turbidity of rivers (COWI, 2004; Banchirigah, 2008; Armah, 2013; Adama et al., 2017; Lovasoa et al., 2018; Tankari et al., 2019; Zakaria et al., 2019; Maman-Illatou, 2021). Gold mining contributes to the release in high concentrations of these substances into groundwater through infiltration, and into surface water through runoff. The extraction of alluvial ore on the surface transforms a large area of land into terrain with a succession of holes and waste rock. The digging of pits promotes deforestation (Jaques et al., 2008; Maradan et al., 2011; UNEP, 2013; Bintou et al., 2020). Epidemiological studies in Burkina Faso and Mali have inventoried cases of affected populations, the result of pathologies associated with the consumption of water rich in arsenic and other metals, and respiratory diseases (COWI, 2005; Smedley et al., 2007; Barro-Traoré et al., 2008; Somé et al., 2012; Ousséni et al., 2013; Nzihou et al., 2013; Bretzler et al., 2017). Mercury inhalation leads to renal, neurological and pulmonary problems (WHO, 1991; Jaques et al., 2008; Bose-O'Reilly et al., 2010; Tomacic et al., 2011; Ouedraogo and Amyot, 2013; ATSDR, 2014; Herman and Keri, 2014; Adama et al., 2017; Black et al., 2017), and exposure to cyanide also has adverse health-related impacts (Adama et al., 2017; Razanamahandry et al., 2018; Astrid et al., 2020). It is interesting to note that these studies often highlight the heightened vulnerability of women gold miners to exposure to these pollutants. Ouedraogo (2021) studied in particular women's health issues at gold mining sites in Burkina Faso because they experience pregnancies, undergo childbirth and raise children in a very specific social, health and environmental context.

Environmental and health-related risks are closely intertwined with the sociotechnical pathways in ASM. Commenting broadly on the situation in the sector, Ajith et al. (2021) report that the recurrence of severe injuries at operations is influenced by a variety of factors, including alcohol and drug usage, inadequate safety and protectionary equipment, a lack of hazard identification, and poor communication. In parallel with characterizations and assessments of health issues related to gold mining, research has been undertaken that assesses perceptions of environmental and health-related risks among gold mining communities (Fadlallah et al., 2020). One of the few studies undertaken on this front in Burkina Faso was Sana et al. (2017), who assessed miners' knowledge of ASM impacts.

These perceptual approaches to risk are based on the underlying assumption that risk manifests itself through a complex process, in which individuals organize and process sensory data captured in the environment to represent external objects. These sensory data are then juxtaposed with the individual's experiences and own evaluation system, as well as with the risk classification systems historically structured within their community, which are inherited. The objective of this paper is to facilitate the implementation of risk management strategies designed using analysis of gold miners' awareness of hazards. It responds to the need to put gold miners and local residents at the heart of efforts aimed at raising awareness of environmental and health-related risks in the sector.

1.5. Involving local communities to develop risk awareness policies and strategies in ASM

In the Liptako–Gourma region, attempts made by governments and international organizations to coordinate and regulate ASM have been challenged by the persistence of informal activities, many of which are characterized by hazardous practices (Wireko-Gyebi et al., 2022). Stylo et al. (2020) highlight how tensions between those involved in informal mining and a government unwilling to engage with those whom it sees as operating illegally make it near-impossible to foster a dialogue between these parties on gold mining practices and risks. Andriamasinoro et al. (2020) compiled an inventory of situations in African territories, where the lack of dialogue between the different stakeholders linked to gold mining (gold miners, institutions, local residents, companies, etc.) has led to mistrust, misunderstanding and even conflict. For Fadlallah et al. (2020), gold miners and local residents should be involved in interventions to build capacity and promote safe and sustainable gold mining practices. Friendship and Furgal (2012) emphasize that the effectiveness of a risk management policy is measured by its ability to engage local communities through the building of strong partnerships. By involving communities in the production of knowledge about risks, they will be better equipped to identify and address them. As Stylo et al. (2020) explain, the approach should be inclusive and participatory when it comes to implementing strategies that foster local economic development, empowerment of communities, and protection of human health and the environment.

Once these observations are made, the remaining question is: *how* to involve gold mining communities and local residents in the effective management of the environmental and health risks posed by their practices? Risk perception studies generate information and data needed to facilitate improved decision-making. In the context of ASM, the information they generate promises to yield strategies that are capable of improving governmental dialogue with local communities based on a better understanding of the individual and collective mechanisms of their risk perceptions. But beyond these studies, very few concrete methodologies have been developed that respond to these needs. It is therefore crucial to develop methods and tools that involve all affected stakeholders. Such methods should collate the perceptions of gold miners and scientific and institutional knowledge in order to provide a broader, deeper and more intertwined understanding of environmental and health risks. Additionally, they should foster a cooperative decision-making dynamic to improve gold mining practices, in relation to environmental and health risks.

This article presents the results of an experiment conducted in 2021 in the Nigerien Liptako–Gourma region, which aimed to implement a participatory approach known as companion modeling (ComMod, 2005). The objective was to co-construct a serious game with institutional stakeholders and gold miners, with a view to creating a space for participatory demonstration of risk perceptions associated with artisanal gold mining. Through this participatory demonstration, a co-construction of practices capable of improving and sharing collective awareness was achieved. The study contributes to the literature on risk perceptions related to ASM while proposing a tangible tool to involve local communities in generating knowledge and contributing to solutions in this area. As participatory approaches are embedded in local contexts where power relations pre-exist, we carried out this work with the intention of opening pathways for further research with regard to the roles women play at gold-mining sites and helping to create a space suitable for them to express their points of view and have the capacity to take action, where necessary.

2. Methods

As explained by Andriamasinoro et al. (2020), participatory research in the mining sector has predominantly focused on socioeconomic simulation and multi-agent modeling but at the same time, has ignored

environmental and health issues and risks. Research on risk perception relies on qualitative research methods such as interviews (Issah and Umejesi, 2018; Friendship and Furgal, 2012) and questionnaires (Charles et al., 2013; Sana et al., 2017; Fadlallah et al., 2020), and to a lesser extent, focus groups. However, these are always conducted with a view toward collecting data for scientific and institutional research, with no consequences for local communities. Andriamasinoro et al. (2020) developed a participatory multi-agent simulation approach to test and discuss different scenarios to formalize the ASM sector in Africa. However, while the model produced has a solid theoretical and methodological foundation, it did not actively involve local communities and therefore cannot provide a comprehensive account of the tangible impact of individuals' changing perceptions of practices in gold mining over time.

Companion modeling aims to generate knowledge at the interface between researchers and local communities in order to facilitate collective decision-making through partnerships for the sustainable management of territories (Etienne, 2012). The design, implementation and use of spatialized models are at the heart of a co-construction process, which involves several iterations of the model between theoretical models and practical simulations. The involvement of local stakeholders occurs at each iteration (Le Page et al., 2014) based on the principle that all stakeholders, regardless of their role, are entitled to participate in the process (ComMod, 2003). Here, and in the following section of the paper, we provide a detailed account of three steps of participatory iterations involving local communities affected by artisanal gold mining in the Nigerien Liptako–Gourma region (see Fig. 3).

2.1. From conceptual model to serious game

The companion modeling is based primarily on field observations of artisanal gold extraction and recovery practices and techniques, measurement of pollutants (arsenic, mercury, cyanide and other trace elements) in the environment, local water-supply strategies, and the manifestation of health ailments (respiratory and dermatological diseases) among the mining populations. It is also based on several months of discussions with ASM stakeholders in the Nigerien Liptako–Gourma region. An initial conceptual model was thus developed using the ARDI approach (Etienne et al., 2011). This approach consists of describing and explaining the functioning of a territorial system by identifying, clearly, Actors, Resources, Dynamics and Interactions. Table 1 presents a synthesis of the main results of the implementation of the ARDI approach on the territorial system related to artisanal gold mining in Nigerien Liptako–Gourma.

Based on this ARDI analysis, a first conceptual model of the “Dynamics and Interactions” at work between “Actors and Resources” in a territory marked by growing artisanal gold exploitation activity was designed. Fig. 4 presents both a schematic representation of the conceptual model resulting from the ARDI analysis and the first elements of gamification. Considering the possible degradation of human health, following the consumption of water with high levels of trace metals, this gamified conceptual model focuses on the impacts of artisanal gold mining on surface and groundwater in relation to the use of chemicals such as mercury, cyanide, nitric and sulfuric acids during recovery.

It is not possible for the proposed model to integrate all of the socio-environmental impacts associated with artisanal gold mining, such as child labor, armed conflict, dust pollution, landscape degradation and the complexity of the sector. By modeling, we assume to lose particularity, materiality and multiplicity, to the point that, of all this real complexity, we only retain a few spreadsheets. But Latour (1993) describes that through this dynamic of complexity reduction, this modeling work allows us to obtain much more visibility, compatibility, and generality by amplifying certain phenomena that may not appear in the complex clamor of field reality. The modeling employed in this study focuses on enhancing the dynamics of interactions between gold extraction techniques and their impacts on the environment.

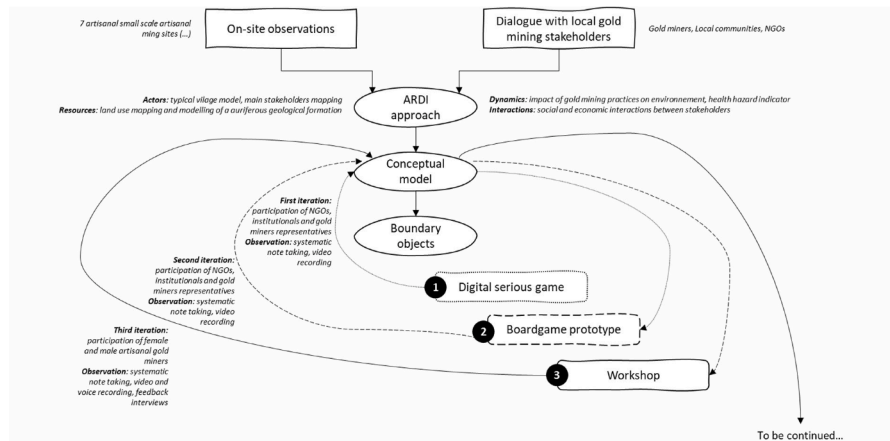


Fig. 3. Companion modeling applied to the perception of health and environmental risks in ASM using a participatory and iterative approach.

Table 1
Main results of the ARDI approach implemented for the conceptual modeling of the territorial system related to gold mining in the Liptako–Gourma region.

Actors	Resources	Dynamics	Interactions
Modeling a typical village using statistical data on Niger’s demographics and socioeconomic characteristics.	Modeling of a gold-bearing geological base according to a probability law modeling the variability of the deposit and the uncertainty inherent in the search for gold.	Modeling of arsenic, mercury and cyanide, and other trace element pollutions in soil, water resources and air as a function of artisanal gold exploitation phases and practices (extraction, pre-treatment, treatment, recovery)	Mapping of conflictual, collaborative, regulatory, etc. links between local stakeholders in artisanal gold exploitation.
Mapping of the main stakeholders: public authorities, mayors and customary chiefs, legal and illegal gold miners, farmers, local communities, especially youth and women, and NGOs.	Modeling of a territory whose land use (village, river, borehole, forest, agricultural areas and gold mining sites) is representative of a gold mining village in Niger.	Modeling of the risk of exposure of populations to pollutants related to artisanal gold exploitation according to the type of person, their vulnerability and the modes of exposure: calculation of the risk based on the estimation of the hazard (appearance of symptoms related to chronic exposure) and the issue (human presence and vulnerability).	Modeling of cash flows related to the purchase and sale of gold, but also of tools, products, compensation of employees and intermediaries, etc.

Specifically, the study examines the perception of water quality and its implications for human health.

The objective of the modeling is to encourage local communities to share their perceptions of the environmental and health risks associated with artisanal gold exploitation and to consider possible actions related to practices in their territory. It thus participates in a dynamic of

dialogue around this common problem. In other words, in the absence of complete and perfect mutual knowledge of the risks associated with gold exploitation among the stakeholders, this modeling invites them to cooperate in the pursuit of a supposedly common goal, which requires mediation. This mediation involves the use of a “boundary object”, revealing collaborations and exchanges between heterogeneous representations of risks. This “boundary object” is sufficiently common to several social worlds that it ensures a minimum of identity at the intersection level while being flexible enough to adapt to the specific needs and constraints of each of these worlds (Trompette and Vinck, 2009). It aims to foster the creation of a common meaning.

This “boundary object” takes the form of a serious game. Today, there is no consensus on the definition of a serious game. We defend the idea of the game as an “intermediate area of experience” (Winnicott, 1975) that offers actors a privileged space to experiment, without risk, by protecting themselves from the dramatic consequences they observe and experience on the ground. The game space represents the territory of the village with resources and activities. In our case, it includes land plots in the Nigerien Liptako–Gourma basement with scattered gold occurrences, plots along the *Sirba River* for mining, and agricultural areas representing the main activity of the population and its cohabitation with artisanal gold exploitation activities. The dynamics of the game focus on the processes contaminating rivers and groundwater, and their consequences on human health. The game space considers the presence of water supply points for the population, homes and schools, as well as the presence of wooded areas to conceptualize issues related to deforestation. The physical elements of the territory, presented as a game space, interact with each other, a simulation that yields an improved understanding of the dynamics of the release of pollutants and the contamination of surface and groundwater, as well as what consequences these developments have for human health. In addition to aspects of resource contamination, this game space considers all of the interactions between local actors, in particular the conflicts of land use between farmers and gold miners and the issues of deforestation. The virtual currency in the game, known as “ako”, is utilized for facilitating material transactions such as purchasing mining equipment, paying workers and taxes, and buying personal goods and food for families. Players take on the role of an asexual gold miner (*i.e.* in defining the role, the question of gender has thus been put aside). Besides developing one’s business and maximizing income, the collective goal of the game is to control the impacts of artisanal gold exploitation activities on the quality of water resources by identifying and adopting practices that are less polluting to the environment and less impactful on human health. Players who participate in the game accept its rules: for Brougère (2005), doing so means accepting its fictional and frivolous nature (players enter a world where actions have no dramatic consequences). It also means accepting that decision-making must take place within the

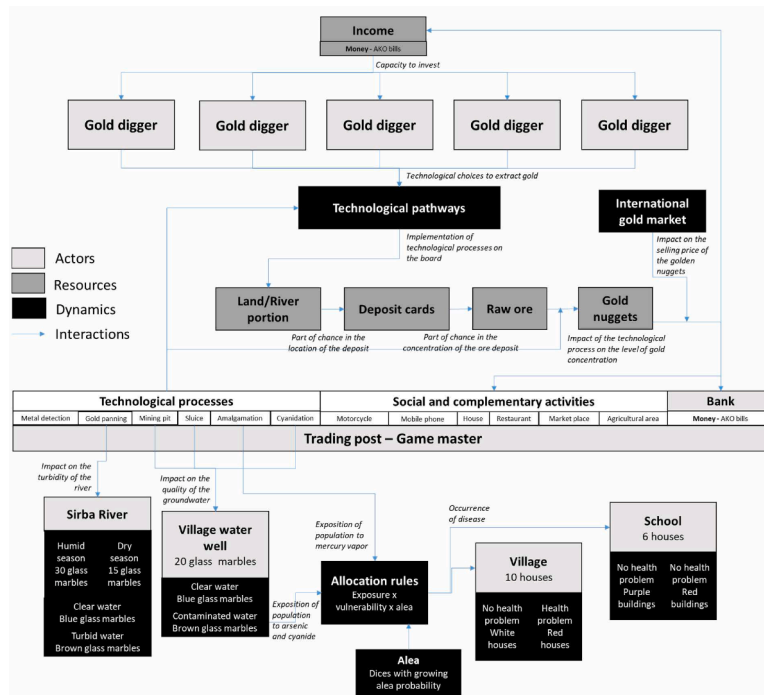


Fig. 4. Gamified conceptual model of the functioning of a territory marked by artisanal gold exploitation activity in the Liptako-Gourma region.

constrained framework of the game's rules and the presence of the almighty facilitator. Here, all gold miners' roles have the same status and are a part of the same decision-making space governing technological and investment choices, which contribute to leveling out the power relationships existing in mining contexts in order to highlight environmental and health issues. However, we recognize that power is not absent from serious games: the player has power over the evolution of the game through technological choices. Power is also expressed through the player's capacity for action, knowledge, and value system, and therefore his agency in decision-making. We will expose in Section 2.5 how we composed with pre-existing and ongoing power asymmetries associated with the co-construction process of the serious game.

2.2. First iteration: from a digital game to a board game

A first digital game (Fig. 5) was designed to take into account the constraints brought about by COVID-19 that limited movement. It spatially represents the territory organized around the Sirba River which is close to a gold mining site. It includes plots identifiable by a column and a row, including a space occupied by a village with a well, two

agricultural spaces and four legal gold mining sites. Players take on the role of legal and illegal gold miners who wish to develop their gold exploitation activity by developing a mining site, or digging extraction pits, using gravimetry, amalgamation and cyanidation techniques. Indicators are used to monitor the impacts of their technological choices on environmental risks, particularly on the quality of surface and groundwater.

The involvement of gold mining stakeholders in the creation of the scheme was initially carried out with actors from the public administration, NGOs and a representative of the gold miners' unions. As stakeholders, they are directly affected by artisanal gold mining in the Nigerien Liptako-Gourma region. Two game sessions were thus organized in an office, over video conferences, and under the constraints of COVID-19 (Fig. 6). An observation system (based on systematic note-taking) was set up to collect a maximum amount of verbal and non-verbal information to evaluate progress toward achieving these objectives.

At the end of the session, participants weighed in on the effectiveness of the tool as a mechanism for transferring knowledge to gold miners and the possibility of reaching them directly to caution and involve

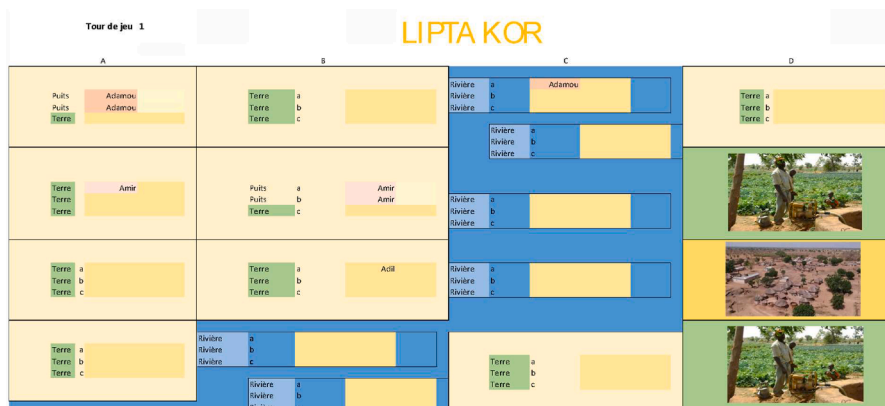


Fig. 5. Digital game interface designed on Excel®.



Fig. 6. Involvement of gold mining stakeholders in the first iteration of the conceptual model and serious game.

them:

"My feeling is: who is the game for? Who do we want to warn? If it's gold miners, is it possible? Will they understand?" (Interview with participants, September 2021)¹

Some elements of the game require the ability to read, which does not facilitate its appropriation by the target population, which consists mainly of gold miners with a high illiteracy rate. The participants therefore agreed on the importance of returning to a physical board game to allow for better appropriation by local communities. This iteration also highlighted the irrelevance and even counter-productivity of distinguishing between illegal and legal gold miners:

"Curiously, I got into the mindset of the illegal immigrant. Illegal immigrants are fatalistic. [...] So I stayed in the illegality" (Interview with participants, September 2021).

Regarding perceptions of environmental and health risks, this distinction does not make sense for local communities: using the same techniques, they all play a role in facilitating the diffusion of pollutants into the environment increasing peoples' health exposure.

2.3. Second iteration: finalization of the first serious game prototype

Based on this first iteration, a board game was developed (Fig. 7). The principle remained the same: to develop artisanal gold mining activity to provide for one's family while ensuring that communities are not exposed to environmental and health risks linked to surface and groundwater pollution. One round of the game represents five years of artisanal gold mining. The gold miners in place draw "Deposit" cards that determine the quantity of ore extracted. Having invested progressively in mining technologies, the ore is worked to extract a certain quantity of gold nuggets. The gold is negotiated at the village counter, depending on the evolution of its gold. With the money obtained, the gold miners can choose to invest in new pits, new technologies or other consumer goods. A spreadsheet calculates the impact of gold extraction on the game turn. These impacts are reflected in the turbidity in the river and/or the arsenic in the well. A die is rolled at the end of the game to determine the number of houses that are more exposed to health risks related to arsenic in drinking water.

For this second iteration, institutional actors, NGO officers and a representative of a support structure for Nigerien gold miners were involved. We could see that, as they gradually came to grips with the game system and asked a number of questions, the players refined their strategies to take better account of environmental and health issues. This observation was made after the game session:



Fig. 7. LIPTAKOR, a serious game to raise awareness of the health and environmental risks of artisanal gold mining: the board includes areas with natural vegetation, a village represented by white and red houses according to their level of exposure to health risks, a school (purple house) with a high vulnerability index, a river represented by blue marbles and a water well represented by a cup filled with blue marbles. A counter is positioned next to the board: it is the place of negotiation where brown stones representing the extracted ore and yellow stones representing the gold nuggets circulate, the AKO currency, cards with pictures representing the different technological choices (grinding, gravimetry, amalgamation and cyanidation).

"You realize at the beginning that there were things you didn't understand. You understand the rules as you go along. The better you know the rules, the better you can play." (Interviewed with participants, January 2021).

2.4. Third iteration: facilitation of a workshop with gold miners from Nigerien Liptako–Gourma

A workshop with gold miners from the Nigerien Liptako–Gourma region was organized in July 2021 with the objective of involving local communities in the production of knowledge about the risks and their perceptions, as well as in the co-construction of solutions to be implemented (Fig. 8). This workshop was organized thanks to a close partnership with gold sites' consultation frameworks set up by local stakeholders and a few NGOs to act as intermediaries with the gold miners, mainly in conflict management and in the identification of training needs. The representatives of these consultation frameworks chose to involve in the workshop 21 local professional and occasional gold miners who are fully invested within villages around the gold mining sites: 15 men and seven women, from seven artisanal gold mining sites. This third iteration provided an opportunity to develop an observation system to evaluate how the serious game influenced perceptions related to the environmental and health risks of artisanal gold exploitation. This observation system featured three stages: 1) the phase before the workshop, when perceptions of the main risks related to artisanal gold mining, through exchanges around photos taken in the field, were solicited; 2/ the time during the workshop, when audio and video recordings, and systematic notetaking took place; 3/ and a few weeks after the workshop, when interviews were conducted to ascertain potential changes in perceptions of the risks.

2.5. Toward a "critical companion position"

Our working hypothesis is in line with the companion modeling approach. We assume that participatory approaches encourage the exchange of knowledge, increase awareness, and stimulate searches for new solutions to socio-ecological problems. However, we are well aware that these participatory approaches are not without their biases. As identified by Daré and Venot (2017), and Barnaud and Van Paassen (2013), critics rightly point to the fact that these participatory approaches take place in varied social contexts, in which pre-existing power dynamics and conflicts of interest are present. Participatory approaches tend to fall short of fully addressing power imbalances and can

¹ All conversations were translated, verbatim, from Nigerien local languages into French, and then into English for the purposes of the publication.



Fig. 8. Workshop with gold miners from Nigerien Liptako–Gourma.

fail to take into account all behavioral traits, values and knowledge. As a result, this approach may hinder the development of emancipatory capacities and, even more so, potentially entrench further elite domination and control. In line with [Barnaud and Van Paassen \(2013\)](#), we assume that, though participatory research cannot be entirely neutral and distant, it is critical to take into account the inevitable power asymmetries and make transparent the underlying nonneutral assumptions and methodological choices made to avoid the risk to increase these initial asymmetries. We addressed this as follows:

- Taking over the larger context of North-South relationships by choosing the facilitator and observer: our participatory approach can be understood as a form of external intervention. However, facilitation and observation were led by a Nigerien PhD student and a Nigerien masters-degree student, both of whom were well-connected with local communities in the Nigerien Liptako–Gourma region.
- Addressing power imbalances among gold miners began with a deliberate selection of participants in the co-construction process. The initial focus was on influential stakeholders such as the public administration, NGOs, and a representative from the gold miners' unions. Convincing these key players of the importance and necessity of engaging in dialogues regarding sanitary and environmental risks in gold mining sites was crucial. As the co-construction process progressed, local representatives took the initiative to invite carefully selected local gold miners, ensuring a diverse and representative perspective. Notably, these local representatives chose to include women gold miners in the discussions. As described earlier, women working as gold miners are frequently marginalized and disregarded, and face heightened exposure and vulnerability to the environmental and health risks associated with the sector. The group of women selected for this study included gold miners, merchants, and a primary school teacher based at the sites. These women were chosen by local representatives based on their perceived legitimacy and importance within the community. They play a crucial role in conflict resolution among women at the sites and sometimes advocate for the interests of other women involved in gold mining activities.
- Shedding light on the hidden aspects of pollution from gold mining: the lack of visibility regarding water contamination from heavy metals such as arsenic or mercury also creates a power imbalance between those who are aware and those who are not, and those who have the resources to measure it and those who don't ([Jouzel and Dedieu 2013](#); [Gramaglia, 2022](#)). Our approach aimed to render the invisible *visible*, providing a path for the expression and consideration of local knowledge, and paving the way for renewed collective mobilization.

3. Main results and discussion

The results presented in this section of the paper are based on

observations made during the three participatory iterations involving stakeholders in artisanal gold mining in the Nigerien Liptako–Gourma region. These findings highlight that in the "intermediate experience area" introduced by the serious game, the mechanisms of risk perception become evident, promoting individual and collective awareness that is conducive to the co-construction of new practices for artisanal gold mining.

3.1. A laboratory for the manifestation of risk perceptions and collective awareness

3.1.1. Expression and manifestation of risk perceptions

Prior to the various iterations around the serious game prototypes, we asked participants to identify the greatest dangers of artisanal practices. On gold mining sites, deaths are regularly recorded due to rock falls and collapsed shafts. The old, abandoned sites also constitute "traps" for people and animals. The perception of risk is expressed here in the physical vulnerability of gold miners and local residents:

"The risk is that there are wells that can collapse and animals and people passing by can fall." (Interviewed at workshop, July 2021).

For some of them, perceptions of risks related to social tensions and conflicts between stakeholders in gold mining are also predominant, and can also result in personal injury:

"The dangers are multiple. [...] The problem of the lack of rehabilitation of these sites causes social risks, risks of conflict between industrial and artisanal mining, tensions between ethnic groups, between operators and landowners, violence against people, among others." (Interview with participants, January 2021).

For other participants, the environmental and health risks linked to water pollution are clearly part of the socially shared perceptions and representations around gold exploitation practices. During the workshop conducted with gold panners in July 2021, risks related to the use of mercury, exposure to cyanide, and the consumption of polluted water by humans and animals were identified as the most important. This perception of environmental and health risks is based on a combination of knowledge, observation, and experience of the gold miners. Since arsenic, mercury and cyanide pollution in the water are invisible, this perception is based on visible signs, notably the death of animals:

"We have been *informed* that even fish are contaminated with mercury and if people consume it, it causes illnesses, illnesses that start to develop little by little and then get worse" (Interview at the workshop, July 2021).

The use of chemicals in gold extraction around water points has disastrous consequences on livestock:

"Water contaminated by chemicals can kill the animals that drink it. I saw a similar case 8 km from Oubanga, where the herders' animals

had died after drinking the contaminated water, and this created conflicts between the herders and the gold miners. Afterwards, the gold miners were fined more than a million F CFA" (Interview at the workshop, July 2021).

These visible signs are also manifested in human beings, through dramatic accounts of people contracting serious diseases, relayed from site to site, participating in a collective story and awareness of this invisible risk:

"I saw similar examples when I was in Mali last year, and it was even reported to us that a woman died from a disease contracted at a gold mining site in that country. They are also in the water where the mining is practiced and this causes them discomfort on their bodies" (Remarks collected during the workshop, July 2021).

Thus, despite being derived from indirect perceptions, the level of awareness regarding the environmental and health risks associated with artisanal gold mining practices is relatively high within the communities involved in this co-construction effort.

3.1.2. Visibility of invisible pollutants and awareness of a common vulnerability

Before the actual game phase, initial exchanges revolved around the perception of risks associated with artisanal gold mining, with participants sharing their experiences and stories. In terms of environmental and health risks related to water pollution, these discussions emphasized the importance of making the invisible *visible*. This notion is supported by findings reported by [Nkuba et al. \(2019\)](#), who conducted a study on the Kamituga gold mine in the Democratic Republic of Congo. Their research revealed that the lack of awareness of the potential risks linked to the use of mercury by gold miners can be explained by the fact that these effects are not immediately visible. This invisibility of the harmful effects of pollutants on living organisms and, on the environment as a whole, contributes to the inaction and lack of accountability of the stakeholders involved in gold mining. When something is not perceived or recognized, it does not prompt action or legitimize responsibility, neither among the gold miners themselves, nor among the relevant authorities ([Gramaglia, 2020](#)).

The mechanics of the serious game render this invisible *visible*. The visual observations, through the presence of brown marbles in surface waters and dark blue marbles in underground waters, shed light on the turbidity and the pollution of rivers as well as the contamination of underground waters dedicated to human consumption:

"The game is a kind of guide because it gave us knowledge about the artisanal gold exploitation activity because there are fields, houses, schools, water next to the gold mining sites that have started to change color. This has attracted our attention" (Workshop, July 2021).

After several rounds, the game board changed color with the appearance of colored balls in the ground and surface waters, signs of water and environmental degradation, as well as the appearance of red houses showing increased exposure of populations to health risks:

"The game made us understand that there are advantages and disadvantages to gold exploitation. At first we thought we were winning, but in the end we saw what we were doing to the environment, the water turned red, the classrooms and so on" (Interview during the workshop, July 2021).

This game experience appears to contribute to individual and collective awareness of interdependencies and shared vulnerability surrounding the environmental and health issues associated with gold mining:

"We see the relationship between those who are not concerned with artisanal gold mining (village residents) and the gold panners and that the damage is shared.", "We see the relationship between gold

mining activities and the environmental pollution generated." (Remarks collected from participants, January 2021).

3.1.3. A very partial representation of feminine risk perceptions

As indicated, both women and men gold miners were invited to the workshop. It was seen as an opportunity to critically examine the conditions under which those with disregarded and marginalized perspectives could express their views. During the workshop organized in July 2021, the facilitation was not designed to give a specific place to women. It is very difficult for a woman to speak in front of men, given how, again, males dominate this sector. The women participated in pairs with the men and were completely dominated in the first exchanges of the game. They rarely spoke up at the beginning and followed the men's lead. But during the game session, they progressively took part in the debates, exchanges and negotiations. Their new participation in the game was accepted by men who also agreed to continue to play. Importantly, women were the first to detect and understand the emergence of sanitary and environmental impacts on the playboard, and quickly reacted by reorienting their activities toward agriculture. It quietly reflected the position of women, little heard in the collective of gold miners, that could be characterized by caution and care.

Although the relationship between men and women temporarily experienced some level of equality during the serious game, it was not explicitly discussed as an issue by the participants. The overall consensus reached regarding risk awareness at the conclusion of the serious game failed to adequately address the specific health issues faced by women, as extensively documented by [Ouedraogo \(2021\)](#). In addition to the increased vulnerability of women to environmental and health risks, important issues such as sexually transmitted diseases, pregnancies, and childbirth at gold mining sites, did not surface during the discussions among participants. Furthermore, the inclusion of women in the process failed to effectively challenge or alter the risk perceptions held by gold miners.

3.2. From awareness to action

Awareness is one thing; taking action is another. As demonstrated by [Jonsson et al. \(2012\)](#), having increased knowledge and awareness of the health risks associated with mercury use does not necessarily lead to the adoption of new practices. For [Charles et al. \(2013\)](#), there is no clear relationship between the perception of risks related to artisanal gold mining and the adoption of practices to avoid, control, or protect against their exposure. For other authors, risk perception and awareness still remain a prerequisite for changes in practices ([Sana et al., 2017](#)). While taking these debates into account, we first focus on the declarations of the stakeholders in gold mining who participated in the co-construction of this system.

3.2.1. Willingness to spread this awareness

Some gold miners feel that they are now able to pass on knowledge about the health and environmental issues of artisanal gold mining to their peers who are at their sites:

"With the knowledge I have gained through this game, I can train and educate people at my site about the health and environmental issues related to artisanal gold mining" (Interview during the workshop, July 2021).

Other gold miners suggest that the game be repeated in order to make it their own. According to them, the training must be ongoing to allow the representatives of the gold miners from the different sites to grasp the content and to be able to transmit this knowledge to the

mining communities at their respective sites. With this in mind, one gold miner put forward the following:

"Zari fo djawandi yan assi nan alberi kan lakalo go nango fo ma faham!² We have understood a little but we propose that the training be continuous so that we can appropriate this knowledge" (Remarks collected during the workshop, July 2021).

The gold miners, therefore, expressed their desire to continue learning new ways of doing things at sites through playing this serious game – to identify ways to carry out their activity without compromising human health and without causing massive environmental degradation.

3.2.2. Discussion about potential solutions

A participant in the July 2021 workshop recalled that in the Zarma language, there is a proverb that says: "Who knows how to destroy must know how to repair". The discussions gave rise to concrete actions to be taken to mitigate the environmental and health risks of artisanal gold mining activities. Among the actions identified, awareness-raising actions predominate:

"In my opinion, in order to protect the environment, gold miners *must be made aware* of the use of chemicals such as cyanide and mercury. They *must know how* to deal with them to avoid water and environmental contamination. They *need to know...*" (Remarks collected at the workshop, July 2021).

This awareness must be raised by local intermediaries, the representatives of the gold miners:

"In my opinion, it is the representatives of the gold miners from the different sites that must raise awareness on the environmental and health issues, and in turn they will inform and discuss with the gold miners from their respective sites" (Comments collected during the workshop, July 2021).

Ideas for action were also discussed, including the backfilling of old wells, soil remediation, and the revegetation and restoration of vegetation cover. However, several obstacles were identified, such as water supply for the plantations, the stability of the old wells, and the long-term diffusion of pollutants.

In terms of cyanide and mercury pollution, the participants emphasized that these actions must be carried out collectively:

"For health as well, we need to *unite as a block* to fight against the use of cyanide in homes" "[we need] to *find a consensus* with the gold miners" (Workshop, July 2021).

Indeed, the delicate social and economic balance lies in the challenge of reducing pollution while maintaining activity and peace on the gold exploitation sites:

"If the partners go with us to the sites to sensitize the gold miners, they will say that we, the representatives, have called you to come and forbid them to use cyanide. They are already spreading rumors that we are working with the partners to prevent their cyanide work." (Remarks collected at the workshop, July 2021).

This opens up interesting perspectives for gold miners to experiment with new governance models for these informal gold mining sites based on the preservation of water resources and health.

Thus, beyond this awareness, the exchanges show determination to find solutions to remedy the situation, with two complementary positions. The first position emphasizes the responsibility of government authorities:

"When the village turns red, action must be taken. A public authority must act." (Remarks collected from participants, January 2021)

A second approach favors empowering local populations:

"How can we make sure that the gold digger and the inhabitant himself can appreciate that his activity has an impact on his environment? How can he be an actor in the monitoring and control of pollution? The change in the color of the water, the gold digger sees the change in color." (Remarks collected from participants, January 2021)

3.2.3. The gap between intentions and actions

As we announced at the beginning of this section, awareness is one thing; taking action is another. Recent studies have shown that it is difficult to move from declarations of intent to commitments to action. In particular, the study by [Obuobi et al. \(2022\)](#) focused on the willingness to adopt mercury-free gold mining in Ghana, highlighting the importance of considering psychological factors in expressing this willingness to commit to new gold panning techniques. In another context, [Cuya et al. \(2021\)](#) demonstrated that while gold miners are aware of the environmental degradation at work on gold-mining sites, and while most of them are willing to get involved in the ecological conservation of their environment, political, bureaucratic and economic barriers hinder real commitment and the adoption of new practices. However, [Saldarrigga-Isaza et al. \(2015\)](#) identified the creation of local associations among small-scale gold miners as a leverage point for sustainable transformation in gold mining practices, allowing access to and acquisition of more environmentally friendly technologies.

4. Conclusion: the serious game – an area for demonstration?

We started by highlighting the widely recognized need to engage local communities involved in artisanal gold mining as key stakeholders in the generation of knowledge, perceptions, and practices related to the environmental and health risks associated with these mining activities. The aim was to improve the impact of awareness and support policies implemented by institutions. Beyond this observation, we showed that very few methods allow for the tangible involvement of these stakeholders in a participatory co-construction on changes in practices. In this article, we have proposed a methodological approach and a practical tool, based on companion modeling, which, through a series of iterations between research and field, fosters the emergence of a space for the expression of perceptions related to the risks of artisanal gold mining, for sharing an awareness of common vulnerability, and for engaging in dialogue around possible solutions that lead to the renewing of a collective.

Companion modeling and its outcome, namely this 'boundary object' that is the serious game, thus functions as a "demonstration" in line with [Rosental \(2021\)](#). The serious game's primary purpose is to showcase, provide evidence, and prompt participants to express themselves. Additionally, it serves to facilitate communication among participants by engaging them in a shared context. First, the serious game stands for an *observatory*. [Daré et al. \(2020\)](#) have highlighted the importance of observational practice in the development of serious games, in order to understand the evolution of relationships between players, to evaluate the effect of game participation on changing perceptions, and to perform comparative analyses between sessions. Serious games thus allow researchers to collect and carefully study verbal exchanges, non-verbal attitudes, and the positions of players. We detailed in the previous sections of this paper how it reveals the evolution of perceptions of the risks associated with gold exploitation. Second, the serious game spawns spaces of participation where different kinds of actors have opportunities to influence and shape the definition of issues worth addressing, as well as the decision-making process. For [Daré and Venot \(2017\)](#), participatory research can build a "room for maneuver": a space for the

² This expression means that the teaching of a single day cannot allow a head of the family who has the spirit elsewhere to assimilate everything.

expression of actors' agency in order to enhance knowledge, change behavior and redress power balances.

Before the co-construction process, gold miners already had some level of risk awareness. However, the serious game allows for a *demonstration* that makes the invisible *visible*, which says the unspeakable. As argued and detailed in earlier sections of the paper, the serious game participated, to a certain extent, in the "politicization" of the environmental and health risks of gold mining. By rendering previously imperceptible arsenic, mercury, and cyanide pollution visible, the game contributes to defining environmental and health risks as problems, bringing them into the political sphere, and potentially legitimizing mechanisms for empowering and mobilizing stakeholders. We also acknowledged that there is still a gap between awareness and willingness to change, and actual engagement and transformation of practices. There remains much to do still. However, the formation of a collective in the Nigerien Liptako-Gourma Region may be a first step towards bridging that gap.

To borrow the words of Rosental (2021), the serious game has also served as a *transactional medium*, facilitating exchanges and social connections between scientific and local knowledge. Its purpose – in this case – has been to raise awareness among gold miners, institutions and researchers about environmental and health risks and their perceptions, with the aim of encouraging collaborative modifications in practices in response. Furthermore, as a "room for maneuver", the serious game also seeks to amplify the voices of those who are often unheard. In addition to addressing environmental and health risks and the evolution of practices, the co-construction process involved local representatives who actively invited women to participate in the workshop. This initiative is significant as it reflects a nascent recognition of women's presence on gold-mining sites. It provided an opportunity to lay the foundations for addressing power dynamics between genders and feminine health issues within the ongoing co-construction process. During this first workshop, women only partially found a place to express feminine health issues, but further in-depth and long-term research is necessary. It would be valuable to conduct a study with women artisanal gold miners who participated in this project, to explore whether the initiative can contribute to the establishment of a dedicated space for their participation. These conclusions open up interesting directions for the future development of this serious game by explicitly integrating women, and through them, children.

Declaration of Conflicting Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abdoul Razack, A., 2002. Propositions pour l'optimisation de la mine artisanale Juin 2002. CESAM 02/RAP/2002-01.

Adama, S., Christophe, D.B., Hervé, H., 2017. Knowledge and perceptions of health and environmental risks related to artisanal gold mining by the artisanal miners in Burkina Faso: a cross-sectional survey. *Pan Afr. Med. J.* 27, 280, 2017.

Afane, A., Gagnol, L., 2020. Une Ruée Vers L'or Contemporaine Au Sahara: L'extractivisme Aurifère Informel Au Nord Du Niger, 20. *Vertigo*.

Ajith, M., Ghosh, A., Jansz, J., 2021. A mixed-method investigations of work, government and social factors associated with severe injuries in artisanal and small-scale mining operations. *Saf. Sci.* 138, 105244.

Andriamasonoro, F., Hohmann, A., Douguet, J.-M., Angel, J.-M., 2020. Serious games as a social learning tool in formalizing the artisanal and small-scale mining sector in African territories. *Extr. Ind. Soc.* 7 (2020), 1108–1120.

Armah, F.A., 2013. Artisanal Gold Mining and Mercure Contamination of Surface Water As a Wicked Socio-Environmental Problem: A Sustainability Challenge? 3rd Sustainability Forum, 1-30 November 2013.

Astrid, M.K., Andrea, F., Joël, O., Jessica, Z., Stefanie, M., Vreni, J.R., Jürg, U., Bernhard, W., Fritz, B., Serge, D., Mirko, S.W., 2020. Potential health effects of cyanide use in artisanal and small-scale gold mining in Burkina Faso. *J. Clean. Prod.* 252 (2020), 119689.

ATSDR, 2014. Agence Pour L'enregistrement Des Substances Toxiques Et Des Maladies Associées (2014). Medical Management Guideline for Mercury. <http://www.atsdr.cdc.gov/mmg/mmg.asp?id=106&tid=24>. consulté le 27 août 2014.

Banchirigah, S., 2008. Challenges with eradicating illegal mining in Ghana: a perspective from the grassroots. *Resour. Policy* 33 (1), 29–38. Volume March 2008, Pages.

Barnaud, C., Van Paassen, A., 2013. Equity, power games and legitimacy: dilemmas of participatory natural resource management. *Ecol. Soc.* 18 (2), 21.

Barro-Traoré, F., Tiendrébéogo, S.R.M., Lallogo, S., Tiendrébéogo, S., Dabal, M., Ouédraogo, H., 2008. Manifestations Cutanées De L'arcénisme Au Burkina Faso: Aspects Épidémiologiques Et Cliniques. *Mali Medical, Tome. XXIII*.

Bintou, A.M., Konan, E.K., Oumar, S., 2020. Évaluation de la dynamique de l'occupation du sol engendrée par l'orpaillage dans le bassin de Banankoro, Région de Koulikoro, Sud-Ouest du Mali. *Afr. Sci.* 17 (3), 28–39, 2020ISSN 1813-548X. <http://www.africainscience.net>.

Black, P., Richardk, M., Rossink, R., Telmer, K.k., 2017. Assessing occupational mercury exposures and behaviours of artisanal and small-scale gold miners in Burkina Faso using passive mercury vapour badges. *Environ. Res.* 152 (2017), 462–469.

BNIC/SCP, 2013. Etude Sur Les Impacts Socio-Environnementaux De L'exploitation Artisanale De L'or Au Niger, Rapport provisoire du Projet Exploitation artisanale de l'or: maîtrise des enjeux et sensibilisation des populations. EXOR, Niamey.

Bose-O'Reilly, S., McCarty, K.M., Steckling, N., Lettmeier, B., 2010. Mercury Exposure and Children's Health. *World's Worst Pollution Problems Report 2010: Top Six Toxic Threats*. Blacksmith Institute/Green Cross, Switzerland. Blacksmith Institute: New York, USA; pp. 33–38, 188-189.

Bretzler, A., Lalanne, F., Nikiema, J., Podgorski, J., Pfenninger, N., Berg, M., Schirmer, M., 2017. Groundwater arsenic contamination in Burkina Faso, West Africa: predicting and verifying region at risk. *Sci. Total Environ.* 584–585 (2017), 958–970.

Brogère, G., 2005. Jouer/Apprendre. *Economica*, Paris, pp. 173–p.

Brugger, F., Zanetti, J., 2020. In my village, everyone uses the tractor": gold mining, agriculture and social transformation in rural Burkina Faso. *Extr. Ind. Soc.* 7 (2), 940–953.

Charles, E., Thomas, D., Dewey, D., Davey, M., Ngallaba, S.E., Konje, E., 2013. A cross-sectional survey on knowledge and perceptions of health risks associated with arsenic and mercury contamination from artisanal gold mining in Tanzania. *BMC Public Health* 13, 74.

ComMod, 2005. La modélisation comme outil d'accompagnement. *Natures Sciences Sociétés* 13, 165–168.

COWI, 2004. Etude sur l'arsenic dans l'eau souterraine de la zone de PEEN (Ed.). COWI Engineering, Programme Eau Et Environnement – Région du Nord (PEEN): Ministère de L'agriculture. de l'hydraulique et des Ressources Halieutiques – Burkina Faso, Copenhagen.

COWI, 2005. Etude Approfondue Dans 8 Villages De La Région Nord Ayant Des Forages à Taux D'arsenic élevés. COWI Engineering A/S, Copenhagen.

Cuya, A., Gilkman, J., Groenendijk, J., Macdonald, D., Swaisgood, R., Barocas, A., 2021. Socio-environmental perceptions and barriers to conservation engagement among artisanal small-scale gold mining communities in Southeastern Peru. *Glob. Ecol. Conserv.* 31, e01816.

Daré, W., Hassenforder, E., Dray, A., 2020. Observation Manual for Collective Serious Games. CIRAD, Montpellier, p. 68.

Daré, W., Venot, J-P., 2017. Room for manoeuvre: user participation in water resources management in Burkina Faso. *Development Policy Review* 1–15.

Doucouré, B., 2014. Développement de l'orpaillage et mutations dans les villages aurifères du sud-est du Sénégal. *Africa Development* 39 (2).

ECA, 2003. In: Reports on Selected Themes in Natural Resources Development in Africa: Artisanal and Small-Scale Mining and Technology Challenges in Africa. Paper Prepared for the Meeting of the Committee on Sustainable Development. Addis Ababa, 7–10th October.

Etienne, M., 2012. Companion modelling: variant of geoprospective approach. *L'espace Géogr.* 41 (2), 128–137.

Etienne, M., Du Toit, D.R., Pollard, S., 2011. ARDI: a co-construction method for participatory modeling in natural resources management. *Ecol. Soc.* 16 (1), 44.

Fadlallah, M.A., Pal, I., Hoe, V.C., 2020. Determinants of Perceived Risks Among Artisanal Gold Miners: A Case Study of Beber Locality, 7. Sudan. *The Extractive Industries and Society*, pp. 748–757.

Friendship, K.A., Furgal, C.M., 2012. The role of Indigenous knowledge in environmental health risk management in Yukon, Canada. *Int. J. Circumpolar Health* 71, 19003.

Gagnol, L., Tchilouta, R.A., Afane, A., 2022. Enjeux territoriaux et éthiques de la régulation de la ruée vers l'or au nord du Niger. *Rev. Int. Des Études Du Dév.* 249, 173–196.

Gramaglia, C., 2020. Les sols, nouvelle frontière pour les savoirs et les politiques de l'environnement. *Rev. Anthropol. Connaiss.* 14-4.

Herman, G., Keri, G.O'L., 2014. Mercury exposure and health impacts among individuals in the Artisanal and Small-Scale Gold Mining (ASGM) Community. *Environ. Health Perspect.* 122 (7), 667–672, 2014.

- Hilson, G., 2016. Artisanal and small-scale mining and agriculture. Exploring their links in rural sub-Saharan Africa. IIED, London.
- Hilson, G., Hilson, A., Maconachie, R., McQuilken, J., Goumandakoye, H., 2017. Artisanal and small-scale mining (ASM) in sub-Saharan Africa: re-conceptualizing formalization and 'illegal' activity. *Geoforum* 83, 80–90.
- Hilson, G., 2009. Small-scale mining, poverty and economic development in sub-Saharan Africa: an overview. *Resour. Policy* 34 (1–2), 1–5.
- Hilson, G., Potter, C., 2005. Structural adjustment and Subsistence Industry: Artisanal Gold Mining in Ghana. *Development and Change* 36 (1), 103–131.
- Issah, M., Umejesi, I., 2018. Risks and vulnerability in uranium mining: a synthesis of local perspectives in the Great Karoo region of South Africa. *Extr. Ind. Soc.* 5 (3), 284–293.
- ITIE, 2015. Rapport De Mission De Collecte Et De Réconciliation Des Revenus Miniers Et Pétrolier. Exercice fiscal 2013, p. P163, 6^e rapport. Décembre 2015.
- Jaques, E., Zida, B., Billa, M., Greffé, C., Thomassin, J.F., 2008. Artisanal and small-scale gold mines in Burkina Faso: today and tomorrow. *Small-Scale Mining, Rural Subsistence and Poverty and West Africa*, Hilson, G.M. Practical Action Publishing, Rugby, UK, p. 354, 2008p.
- Jonsson, J.B., Charles, E., Kalvig, P., 2012. Toxic mercury versus appropriate technology: artisanal gold miners' retort aversion. *Resour. Policy* 38 (1), 60–67.
- Jouzel, J.-N., Dedieu, F., 2013. *Rendre visible et laisser dans l'ombre : savoir et ignorance dans les politiques de santé au travail*. *Rev. Fr. Sci. Polit.* 63 (1), 29.
- Labour, B., 1993. *We Have Never Been Modern*. Harvard University Press, Cambridge, MA.
- Lanzano, C., Arnaldi di Balme, L., 2021. Who owns the mud? Valuable leftovers, sociotechnical innovation and changing relations of production in artisanal gold mining. *J. Agrar. Change* 21 (3), 433–458.
- Le Page, C., Abrami, G., Barreteau, O., Becu, N., Bommel, P., Botta, A., Dray, A., Monteil, C., Souchère, V., 2014. *Models for sharing representations*. Companion Modelling: A Participatory Approach to Support Sustainable Development, Édité Par Michel Étienne. Springer Netherlands, p. 69101.
- Lovaso, C.R., Harinaivo, A.A., Hela, K., Joel, P., Hamma, Y., 2018. Modèle de prédiction de la pollution des sols par le cyanure dans la zone minière artisanale d'or en utilisant la régression logistique. *Catena* 162, 40–50 volumemars 2018, pages.
- Maman Illatou, O., 2021. *Impacts De L'orpaillage Et De L'agriculture Sur La Qualité Des Eaux Du Liptako Nigérien: Identification Des Hots Spots Des Pollutions Métalliques Et Organiques, Transferts De Connaissances Entre Recherche Et Terrain*. PhD Thesis.
- Maradan, D., Ouedraogo, B., Thiombiano, N., Thiombiano T., Zein K., (2011). *Analyse économique du secteur des mines liens pauvreté et environnement*. sba-Ecosys-CEDRES. Rapport MECV Burkina Faso, (2011) 69 p.
- Ministry of mining, 2022. *Plus De 800000 Orpailleurs Sur Plus De 200 Sites Que Compte Le Pays*. Niger express, 24 mai 2022. Site web. <http://nigerexpress.info/2022/05/24>.
- Nkuba, B., Bervoets, L., Geenen, S., 2019. Invisible and ignored? Local perspectives on mercury in Congolese gold mining. *J. Clean. Prod.* 221 (1), 795–804.
- Nzihou, J.F., Bouda, M., Hamidou, S., Diarra, J., 2013. Arsenic in drinking water toxicological risk assessment in the north region of Burkina Faso. *J. Water Resour. Prot.* 5, 46–52.
- Obuobi, B., Tang, D., Cai, X., Nketiah, E., Adu-Gyamfi, G., 2022. Sustainable mining practices: willingness to adopt mercury-free gold mining in Ghana. *J. Clean. Prod.* 230 (2), 135085.
- OECD, 2018. *Evaluation des chaînes d'approvisionnement en or produit au Burkina Faso, Mali et Niger*. Report.
- Ouedraogo, A., 2020. « Les détentrices de hangars de traitement de l'or face à la technique de cyanuration (sud-ouest du Burkina Faso) ». *J. des africanistes* 90-1, 168–187.
- Ouedraogo, A. 2021. *Tāngpōgsé : De l'anthropologie de l'orpaillage au féminin à la santé maternelle et infantile dans le Sud-Ouest du Burkina Faso*. PhD thesis.
- Ouedraogo, O., Amyot, M., 2013. Mercury, arsenic and selenium concentrations in water and fish from sub-Saharan semi-arid freshwater reservoirs (Burkina Faso). *Science of the Total Environment* 444 (1), 243–254.
- Ousséni, O., Marc, A., 2013. Mercury, arsenic and selenium concentrations in water and fish from sub-Saharan semi-arid freshwater reservoirs (Burkina Faso). *Sci. Total Environ.* 444, 243–254. Volume1 February 2013, Pages.
- Razanamahandry, L.C., Andrianisa, H.A., Karoui, H., Podgorski, J., Yacouba, H., 2018. Prediction model for cyanide soil pollution in artisanal gold mining area by using logistic regression. *Catena* 162 (2018), 40–50.
- Rosental, C., 2021. *The demonstration society*. MIT Press, Cambridge.
- Saldarriga-Isaza, A., Villegas-Palacio, C., Arango, S., 2015. Phasing out mercury through collective action in artisanal gold mining: evidence from a framed field experiment. *Ecological Economics* 120, 406–415.
- Sana, A., De Brouwer, C., Hien, H., 2017. Knowledge and perceptions of health and environmental risks related to artisanal gold mining by the artisanal miners in Burkina Faso: a cross-sectional survey. *Pan Afr. Med. J.* 27, 280.
- Sangaré, A., Driouch, Y., Salvi, S., Féménias, O., Siebenaller, L., Belkasm, M., Béziat, D., Dahire, M., Ntarmouchant, A., Adil, S., Debat, P., 2014. *Géologie Des Minéralisations Aurifères Du Gisément Tardi-Éburnéen De Kalana (Birimine, 36. Sud-Ouest du Mali)*. Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, pp. 85–108, 2014n.
- Seccatore, J., de Theije, M., 2017. Sociotechnical study of small scale gold mining in Suriname. *J. Clean. Prod.* 144, 107–119.
- Smedley, P.L., Knudsen, J., Maiga, D., 2007. Arsenic in groundwater from mineralized proterozoic basement rocks of Burkina Faso. *Appl. Geochem.* 22, 1074–1092.
- Somé, I.T., Sakira, A.K., Ouédraogo, M., Ouédraogo, T.Z., Traoré, A., Raore, Sonde B., Guissou, P.I., 2012. Arsenic levels in tube-wells water, food, residents' urine and the prevalence of skin lesions in Yatenga province, Burkina Faso. *Interdiscip. Toxicol.* 5 (1), 38–41.
- Stylo, M., De Haan, J., Davis, K., 2020. Collecting, managing and translating data into national action plans for artisanal and small scale gold mining. *Extr. Ind. Soc.* 7 (1), 237–248.
- Tankari, D.A., Tidjani, D.A., Idder, G.T., Yadjji, Dan, Lamso, N., Matsallabi, A., Ambouta, J.M.K., Feidt, C., Sterckeman, T., Echevarria, G., 2014. Diagnostic de la contamination des eaux par les éléments traces métalliques dans la zone aurifère de Komabangou – Tillabéri, Niger. *Int. J. Biol. Chem. Sci.* 8 (6), 2849–2857.
- Tankari, A.D., Ibrahim, O.Z., Guéro, Y., Morel, J.L., Feidt, C., Echevarria, G., 2019. Impacts of artisanal gold mining on soil, water and plant contamination by trace elements at Komabangou, Western Niger. *J. Geochem. Explor.* 205 (2019), 106328.
- Tomicic, C., Vernez, D., Belem, T., Berode, M., 2011. Human mercury exposure associated with small-scale gold mining in Burkina Faso. *Int. Arch. Occup. Environ. Health* 84 (5), 539–546, 2011.
- Trompette, P., Vinck, D., 2009. Retour sur la notion d'objet-frontière. *Rev. d'Anthropologie des Connaiss.* 3 (1).
- UNEP., 2013. *Convention de Minamata sur la pollution par le mercure, octobre 2013 à Kumamoto*.
- United Nations (UN), 1972. *Small-scale Mining in the Developing Countries*. Department of Economic and Social Affairs. United Nations, New York.
- Werthmann, k., 2007. Dans un monde masculin: le travail de femmes dans un camp de chercheurs d'or au Burkina Faso. Boesen, E., Marfaing, L. *Les nouveaux Urbains Dans L'espace Sahara Sahel. un cosmopolitisme par le bas*. Karthala.
- WHO, 1991. *Inorganic mercury*. In: *Environmental Health Criteria*, 118. Geneva: World Health Organization, p. 1991.
- Winnicott, D.W., 1975. *Jeu Et Réalité: L'espace Potentiel*. Gallimard.
- Wireko-Gyebi, R.S.Osei A., Baah-Ennumh, M., 2022. Planning for the effective and sustainable management of Ghana's artisanal small-scale gold mining industry. *Resour. Policy* 76, 102576.
- et Zakaria, O.I., Tankari, A.D-B., Guero, Y., Maissoro, F.M.-I., Feidt, Cyril., Sterckeman, T., Echevarria, G., 2019. Distribution spatiale des éléments traces métalliques dans les sols de la zone aurifère de Komabangou au Niger. *Int. J. Biol. Chem. Sci.* 13 (1), 557–573.