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New Guidelines for Post mining risks management in France

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Abstract

After having intensively exploited for several centuries the mineral resources present in its subsoil, France gradually saw its extraction sites cease their activity. The ending of mining activity did not, however, lead to the disappearance of phenomena likely to affect the surface areas located above or in the vicinity of mine workings. Thus, during a period following exploitation, traditionally called "post-mining", many disorders may develop, sometimes as soon as workings are stopped but also much later.

In addition to ground movements phenomena, surface above old mining sites may be affected by rising gases with dangerous compositions. Moreover, the irreversible disturbances caused by extraction work on ground-water flows can be the cause of possible disorders, both in terms of water flow movements (low-level flooding, disturbance of the watercourse regime) and water quality.

In order to manage risks associated with these phenomena and thanks to the experience gained in post mining management, the French State has a number of technical and regulatory tools. The purpose of these tools is to gather knowledge of the residual mining risks due to former mining operations in a given area, to locate the surfaces exposed to them and to define the conditions for the construction, occupation and use of lands as well as measures relating to the development, use or exploitation of existing property. In France, in the absence of a valid mining title, or in the event of the disappearance or failure of the operator, the French mine legislation makes the State responsible for compensation for damages caused by former mining operations which it has authorized in the past. This has a significant impact on land use opportunities above mining works.

At the request of the French Ministry of Ecology in charge of post-mining risks management, INERIS led the elaboration of two National handbooks with the support of GEODERIS and Cerema:

1 - a generic handbook for the management of post-mining risks,

2 - a handbook for the evaluation of hazards relative to specific post-mining phenomena.

These handbooks are intended for all stakeholders involved in the management of mining risks (government departments, local authorities, consulting firms, etc). They are designed as operational handbooks which allow the reader to identify the tools adapted to the local problems.

After briefly describing the context of post-mining in France, this paper introduces these two handbooks with a particular highlight on the evaluation of hazards and their impact in terms of land planning.

Keywords: *post-mining management, geotechnical and environmental mining risks and hazards, post-mining regulation, ground instabilities, land planning and use*

1 Introduction

Like many other European countries, France has a long mining tradition. Extraction and recovery of the raw materials present in its subsoil have contributed to the development of French industrial power.

In France, first indices of underground exploitation of mineral resources (former flint mines, salt springs) date back to Neolithic (5th to 3rd millennium BC). During the Gallo-Roman period the mining activity took a real boom as silver, lead, copper and iron were sought after and exploited. The mining activity then took the form of a multitude of small local exploitation sites spread over the whole of the territory (1st and 2nd centuries).

After the fall of the Roman Empire, exploration and mining were continued at a slow rate for nearly a millennium. Under the influence of Central Europe and to meet the economic needs growth as a result of population growth and political stabilization, prospecting and mining operations have once again proliferated (XI^{th}-$XIII^{th}$ centuries). This is the time when coal began to be exploited in the basins of Herault, Provence and Saarland.

However, it was the industrial revolution (17th - 18th centuries) that constituted the decisive impetus in the rise of French mining activity. Progress technology helped to transform an artisanal activity into an industrial production activity. In addition to the birth of the major mining basins (coal, iron, salt, etc.) that participated greatly to the wealth of the national economy, the beginning of the nineteenth century also characterized by an important diversification of prospected and exploited resources (oil, manganese, fluorite, zinc ...).

Mining activity continued to flourish in France during the first half of Twentieth century, mainly because of the two world wars. In the aftermath of the Second World War, the national effort undertaken for the reconstruction of the country and the reduction of French energy dependence facilitated the revival of mining activity. The production of coal and lignite increased rapidly to 60 million tonnes in 1958, a record year.

Different economic factors, the development of use of hydrocarbons in energy production, competition from other countries and the depletion of certain deposits have gradually generated the decline of French mining activity. Initiated in the early 1960s for coal and iron and in the early 1980s for the exploitation of other substances, this decline has accelerated since the early 1990s.

The closure of the last iron mine dates from 1995 and the exploitation of uranium ceased in 2001. Potash production in Alsace ceased in 2003 and coal exploitation stopped in 2004. Currently active mining activities in metropolitan France result from salt extraction, bauxite and hydrocarbon exploitation. In France, mining activities do not include “quarrying” industry activities (limestone, chalk…).

At the end of the 90s, the occurrence of various phenomena or nuisances in areas of former mining in particular land surface movements causing damages on houses (Lorraine mine subsidence in 1996, 1997 and 1998, with a total of more than a hundred houses), led French State to put in place tools for managing the consequences of the cessation of the mining activities in a phase called "post-mining".

In addition, old mining and industrial basins that have changed since progressive closure of mining and associated industries, have strong land planning issues that may be confronted with potential risks of mining origin.

It is therefore necessary to identify and locate as precisely as possible the risks and nuisances likely to persist after the end of the extraction to identify potential development opportunities and operational measures adapted to each context.

2 Phenomena and risks in the post-mining phase

Phenomena induced by an old mining, can be among the following:

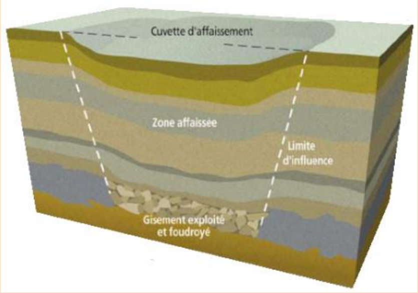
- The constitution of large residual voids in the underground, large scale rock slopes or mining waste installations may cause land movements, which may jeopardize the safety of persons or induce damage to buildings and infrastructures (cracks, collapses, etc.);
- The alteration of the circulation of groundwater or surface water and, concomitantly or not, may with the subsidence of land surface. The cessation of mining could have ceased the pumping of groundwater which allowed the underground mining operations. Since then, the stop of the mining works is followed by a rise of the underground water table that gradually returns to its natural level,

thus filling, fully or partially, underground mining reservoir, and reaching, on the surface, the hydrographic network or the low topographical areas that could have been generated by mining. These hydrological and hydrogeological disturbances can be harmful for the occupation of the soil or subsoil;

- Underground ore extraction contributed to create a reservoir that can be filled with gas, from the exploited material or from more distant origin. Under the effect of different mechanisms, mine gas can be routed to the surface through natural drains (faults, fractures, cracks ...) or artificial drains (shafts, galleries ...). Mining operations may also have generated drains (cracks...) linking the surface with subterranean formations that emit gas. These emitted gases are potentially dangerous;
- Extraction or storage operations of large quantities of solid waste generate physical and chemical instabilities that can disrupt the natural environment. One of the causes of pollution and nuisances, after mining, is the interaction between mining works and hydraulic flows, with consequent contamination of soil as well as surface and ground water. Surface conditions (air, rainfalls) can affect the release into the environment of potentially harmful or dangerous substances for people and / or ecosystems.

Table 1 lists and describes all potentially dangerous phenomena that may occur in post-mining phase. Moreover, the presence of opened shafts and galleries/adits, insufficiently closed can present hazards and generate physical risks through their accessibility (falling / drowning in a shaft, falling rock blocks in a gallery, Intoxication / asphyxiation ...).

Table 1 List and description of potentially harmful phenomena in the "post-mining" phase

Potentially harmful phenomenon	**Description**	
Sinkhole	Sinkholes are surface collapses generated by various mechanisms -underground galleries collapse, shaft collapse, isolated underground mining pillar rupture). In general, they are characterized by the brutal appearance on the surface of a crater whose horizontal extension varies usually from a few meters to a dozen of meters in diameter. The dimensions of sinkholes depend on the cavities volume and nature of lands that separate it from the surface. These phenomena can cause damage to people and buildings.	 **Figure 1 An example of sinkhole**
Gradual subsidence	Gradual subsidence results from the collapse of underground mining works of large extensions. On the surface, they result in the formation of a depression with a diameter of a few dozen to a few hundred metres, without significant breakage. In the center of the depression, lands go down vertically. On the edges, landsurface slopes. These phenomena occur gradually in a matter of days or months, according to a dynamics specific to the mining context and its geology. They usually result in damage to buildings on the surface.	 **Figure 2 Gradual subsidence: schematic diagram**

Global collapse	Global collapses result from the collapse of an underground mine section. They occur in very specific geological conditions with the rupture, often dynamic and nearly instantaneous, of all or part of a mining exploitation (between bottom of mine and the surface), thus affecting the stability of surface lands on areas up to several hectares. A seismic shock can be felt. The collapse height can reach several meters or even several tens of meters in the case of collapses of salt cavities. These phenomena can cause severe damages and "irreversible" destruction of surface installations and houses.	 **Figure 3 An example of global collapse**
Crevasse	Mining can be accompanied, in particular cases and concomitantly with the formation of subsidence depression, by creation crevasses in the cover. Some crevasses appear at the surface during mining exploitation, but some of them are found out several years after the end of mining exploitation. Crevasses come in the form of multi-decimetric opening cracks in the soil and have a multi-metric extension. The visible depth of these crevasses is pluri-metric but the actual depth is not known.	 **Figure 4 A crevasse that appeared in a garden, coal exploitation.**
Settlement	Settlements are observed within mine wastes deposition installations and sometimes in areas affected by mining. They consist of residual movements of low amplitude, affecting surface lands, both in terms of land lowering (of the order of few decimetres) and of extension of the affected area. Except for specific configurations, effects are generally limited and are only affect vulnerable buildings.	 **Figure 5 Cracks on a house, as a result of settlement, coal site.**
Landslide	Landslides are observed on the sides of mining deposits or the slopes of open pit mines constituted in soft ground. Landslides may be: • superficial or pellicular (involving volumes of about a few tens of m^3); • deep movements (an important volume of material is involved sliding along a surface, often circular).	 **Figure 6 Superficial landslide on a tailing**

Rockfall and rockslide	A rockslide is a brutal ground movement of a rock mass that detaches from a generally very steep rock wall to reach its foot. This phenomenon therefore essentially concerns open-pit mine fronts dug into massive hard rocks, with high slopes.	 **Figure 7 Rockfalls, bauxite mine**
Hydrological and hydro-geological disturbances, floods from mining origin	Old mining works and the drainage of mine water (during the exploitation phase) and mine rewatering (after exploitation), can disturb the underground and superficial circulation of water: • increase or decrease in the flow of springs or streams; • rising of water tables with the appearance of swamps; • flooding of low points with mine water; • brutal floods. Flood from water table rising may be due to the cessation of dewatering and a downward variation in local water consumption. Mine flooding can also result from the rupture of a settling pond in a mine, the modification of an outlet following the collapse or the poor maintenance of a gallery…	 **Figure 8 Wet area, iron mine**
Pollution	Several sources of pollution may be present, associated with the old mining and mining operations. These sources, which may contain metals (lead, nickel, mercury, etc.) and metalloids (arsenic, antimony), are likely to induce a risk for human health and the environment. Natural environment may be contaminated by overflow from flooded mining structures, leachate from ore deposits, waste rock, or from percolation water in old work. The environmental impact of former mining activities may reach areas far from original mining sites.	 **Figure 9 Arsenic pollution of a stream**

Gas emissions related to mining	After the mining has stopped, the unwatered underground voids may constitute a more or less confined reservoir, in which gases (which are diluted or evacuated during the operation) can accumulate at high concentrations. Rising to the surface through underground galleries or natural faults or fractures in the rock, gases may be dangerous: intoxication, asphyxiation, ignition, explosion. Mine gas is generally a mixture of gases of various origins, at varying levels. Some gases are contained in the deposit before exploitation (methane (CH4), carbon dioxide (CO2), etc.), others are produced from a chemical transformation of the deposit or certain elements of the mine, during or after operation (carbon monoxide (CO), hydrogen sulfide (H2S), ...). In addition, mining can link geological horizons that can emit gas under certain conditions with the surface.	 **Figure 10 Mine gas emission to the surface, iron basin**
Ionizing radiation emissions	Former uranium mining sites may cause specific exposures to ionizing radiation, due to the uranium content of the materials and wastes therein, as well as the presence of radionuclides descending from uranium. These substances were already present in the ores and rocks prior to their extraction from the subsoil and no new radioactive products were added by the mining activity. On the other hand, it has modified the distribution and the physical state of uranium and radioactive substances initially present in the subsoil, leading at the same time to an increased risk of dissemination in the environment and therefore of human exposure, even after the cessation of mining.	
Combustions, mining waste rock heating	Some mine deposits contain combustible materials and other oxidizable materials such as iron sulphides (pyrite). Some deposits may enter in combustion (in contact with an external heat source or after modifications to the deposit initiating self-heating phenomena). The combustion of a heap can spread slowly from the surface to the depth. The burning time can in this case reach several decades. The main risks associated are the risk of burning, falling in cavities generated by combustion, fire, related to toxic or flammable gases.	 **Figure 11 Heap Combustion, Mining basin of the Cevennes, Ales**

3 Tools for the management of post-mining risks in France

Tools for the management of post-mining risks in France are presented in a first guidebook, edited by Ineris in partnership with Cerema and GEODERIS, and available in French and English at http://ineris.fr (Ineris et al, 2017).

This guidebook draws a picture of the post-mining context in France and identifies potentially dangerous phenomena. It provides a panorama of the tools available for decentralized State services, Local Authorities as well as collectivities in charge of post-mining risks management.

Phenomena presented previously are managed with the help of different tools in France. The vast majority of phenomena are evaluated through a "hazards study".

The evaluation and the mapping of the hazards are carried out for the following phenomena: ground movements, gas emissions related to the mining exploitation, mining, combustion / heating of waste deposits, hydrological / hydrogeological disturbances and flooding.

On the other hand, for pollution issues resulting from the exploitation of mines, mapping is very complex, if not impossible. Indeed, the evaluation of the environmental impact of possible pollution requires:

- a satisfactory characterization of the sources of pollution, and in particular, distinguished from the local geochemical background;
- taking into account pollution transfer vectors, especially weather conditions, which could lead to a dispersion of the pollution in time and space and thus involve territories remote from sources of pollution;
- taking into account targets and their exposure, which are highly dependent on local uses by population.

These characteristics led to the conclusion that the evaluation process of the “hazards study” and risk induced is inappropriate for pollution issues. The prevention of the risks associated with these phenomena is not achieved by means of a mapping of the "pollution" hazards but through an environmental study.

With regard to hazards related to ionizing radiation emissions, they are taken into account and studied by a dedicated Institute of Radioprotection and Nuclear Safety (IRSN) and a specific Service within the Ministry in charge of Environment.

3.1 How are managed existing risks

Risk is the combination of hazards and stakes. Risk is assessed for existing constructions, according to the hazard and its level, and the state of the surface (geological nature and mechanical characteristics of the land). The State services determine the most appropriate measures to implement:

- **monitoring**;
- **treatment** of the area (for example, filling voids, treatment with depollution, etc.). The choice of treatment techniques depends first of all on:
  - technical aspects;
  - economic aspects;
  - environmental aspects, particularly in the event of closure of adits.

  However, the choice also depends on: objectives to be achieved in terms of risk managment and destination of the site, planned use for the site, the level of security eligible according to surface stakes;
- **expropriation** (by French mining code enforcement): the expropriation decision only intervenes when there is a serious threat to people when the means for safeguarding and protecting populations are more costly than expropriation.

3.2 How are managed future risks

Three codes govern future risks management in France:

- the Environnemental Code,
- the Urban Planning Code,
- the Mining Code.

These codes indicate the conditions of population information in terms of post-mining risks as well as the different urban planning tools which differ in terms of scale of action (municipal, departmental, regional).

4 Tools for post-mining hazard evaluation and mapping in France

A second guidebook (Ineris, 2018), deals with the evaluation of post-mining hazards. It describes the approach and provides recommendations to carry out a hazard study. For each potentially dangerous phenomenon, it describes initiating scenarios, damaging effects, the evaluation criteria for the intensity and the predisposition of the hazards. It benefits from more than a decade of experience of French post-mining operators by providing information on the frequency of events.

4.1 Concepts and principles relating to hazard assessment

Hazard is a commonly used term for risk prevention. It corresponds to the probability that a phenomenon (of mining origin in this case) will occur on a site, during a reference period, by reaching a qualifiable or quantifiable intensity. The characterization of a hazard is classically based on the combination of the predictable intensity of the phenomenon with its probability of occurrence.

In terms of risk prevention, reference period refers to a period of several tens, or even hundreds of years, to set an order of magnitude. It is therefore necessary to include in the analysis the ineluctable degradation over time of the old mines and the evolution of the materials and effluents (gases, water) that come from them.

The **intensity** of the phenomenon corresponds to the extent of the disorders, sequels or nuisances likely to result from the dreaded phenomenon. This incorporates a notion of magnitude of the events feared (size and depth of a crater, height of water slice, nature and content of a gas emission ...), but also their potential effects on people and property.

The notion of probability of occurrence reflects the sensitivity of a site to be affected by a given phenomenon. Whatever the nature of the events of mining origin feared, the complexity of the mechanisms, the heterogeneous nature of the natural environment, the partial nature of the information available and the fact that many disorders, sequels or nuisances are not repetitive, explain why it is generally impossible to analyse with a quantitative probabilistic approach. A qualitative classification that characterizes a **predisposition** of the site to be affected by this or that type of phenomenon is used. It is therefore this notion which is retained in the rest of the article.

4.2 Example of sinkhole hazard evaluation

4.2.1 Sinkhole hazard: intensity

Sinkholes are likely to affect the safety of people and houses on the surface.

It is mainly the diameter of the collapse that influences the foreseeable consequences for the safety of the people and goods present in the area of influence of the disorder. It is therefore this parameter which is retained as the representative quantity.

The depth of the crater can also affect the dangerousness of the phenomenon but it is often difficult to predict.

Among the main factors that may influence the value of the diameter of the collapse are: the size of the residual voids in the underground works (volume of the adits) as well as the thickness and the nature of the lands constituting the overlap. In this connection, it should be noted that the thickness and nature of the sub-surface lands play a predominant role, since their rupture (in the case of deconsolidated land) can contribute a lot to the dimensions of the sinkhole.

A recent study analysed more than 1800 sinkholes generated in the post-mining phase, in different French mining configurations (Ineris, 2015). Figure 12 shows the repartition of sinkholes according to their diameter.

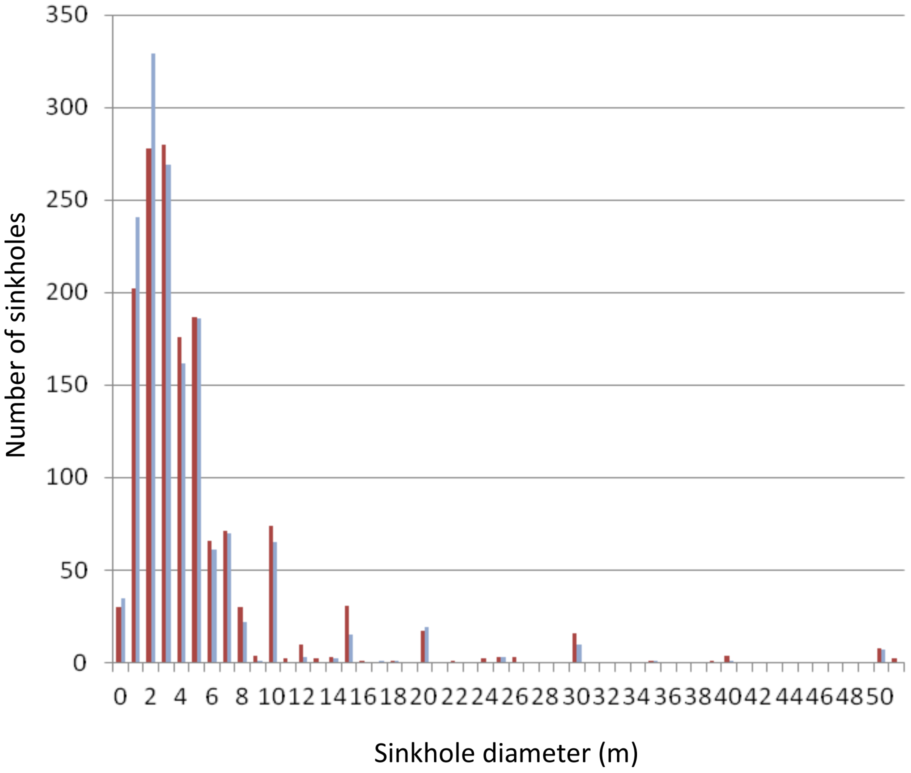


Figure 12 Repartition of the 1800 studied sinkholes in terms of diameter. In red: sinkhole longitudinal diameter, in blue: sinkhole lateral diameter

It shows that:

- 90% of the sinkholes have a diameter less than 10 m;
- More than 1/3 of them have a diameter less than 3 m;
- Around 2/3 of them have a diameter less than 5 m.

According to the French Scientific and Technical Center of the Building (CSTB, 2011), surface areas where sinkholes may occur are constructible when predicted sinkholes diameter is less than 5 m and according to specific recommendations.

As a consequence, sinkhole hazard intensity is defined according to Table 2.

Table 2 Definition of sinkhole hazard intensity according to predicted sinkhole diameter

Sinkhole hazard intensity	**Sinkhole Diameter (Ø)**
low	Ø < 5 m
medium	5 m < Ø < 10 m
high	Ø > 10 m

4.2.2 Sinkhole hazard: predisposition

The evaluation of the predisposition of a site to the occurrence of a sinkhole depends on three classes of parameters:

- presence of similar phenomena on the site or in identical or similar configurations (geology, operating conditions, etc.);

- parameters related to the predisposition to the rupture of the underground structure: it is mainly the width of the gallery or the room and the nature of the first beds of the roof (thickness, resistance, fracturing);
- parameters related to the predisposition to the recovery of instability to the surface: the nature and the thickness of the banks of the cover which will determine the coefficient of expansion or the formation of a stable vault.

4.2.3 Sinkhole hazard: mapping

The studied mining perimeter is divided into homogeneous areas in terms of intensity and predisposition. Then, combination of intensity and predisposition allows to evaluate a sinkhole hazard level as shown in Figure 13.

Intensity	**Predisposition**		
	Low sensitivity	**Medium sensitivity**	**High sensitivity**
Low	Low	Low	Medium
Medium	Low	Medium	High
High	Medium	High	High

Figure 13 Combination of intensity and predisposition to evaluate hazard level

The final hazard mapping includes (Figure 14):

- a margin of influence corresponding to the potential influence of the cone of collapse;
- a cartographic uncertainty (depending on the quality of data location).

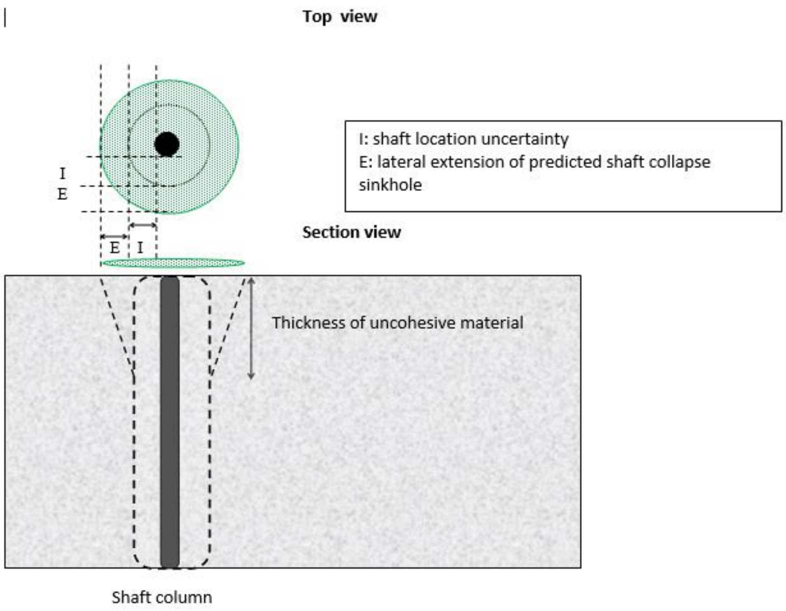


Figure 14 Principles for mapping sinkhole hazard in relation with a shaft collapse

Next to “hazards study”, a transcription in terms of regulations to define constructible or not constructible surface land areas may be carried out.

5 Conclusion

In order to manage risks associated with post-mining potentially harmful phenomena and thanks to French experience gained in post mining management for more than 10 years, the French State has a number of technical and regulatory tools. The purpose of these tools is to gather knowledge of the residual mining risks due to former mining operations in a given area, to locate the surfaces exposed to them and to define the conditions for the construction, occupation and use of lands as well as measures relating to the development, use or exploitation of existing property. In France, in the absence of a valid mining title, or in the event of the disappearance or failure of the operator, the French mine legislation makes the State responsible for compensation for damages caused by former mining operations which it has authorized in the past. This has a significant impact on land use opportunities above mining works.

Two guidebooks edited by Ineris deal with **post-mining risks management tools** and **the evaluation of post-mining hazards** respectively.

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