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Multi-hazard risk pathway scenarios associated with unconventional gas development: Identification and challenges for their assessment

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Abstract

In this paper we summarize a number of risk pathway scenarios that are often claimed in literature as of priority for risk analyses in unconventional gas development. The resulting scenarios are structured in diagrams representing causal relationships between events. We argue that science is called to fill gaps regarding the main processes characterizing the involved events and defining the conditions under which their occurrence may be enhanced or inhibited. In this way, these scenarios can be more objectively parameterized, making their quantitative assessment a more feasible task and opening the way for the formulation of appropriate risk mitigation strategies.

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Keywords: Multi-hazard risk; risk pathway scenarios; unconventional gas development.

1. Introduction

Without exception, the exploitation of any energy resource produces impacts on the surrounding environment and intrinsically bears risks. Therefore, to make sound decisions about future energy policies, it is important to understand the potential environmental impacts and risks in the full life-cycle of a project, distinguishing between the specific impacts intrinsically related to exploiting a given energy resource and those shared with the exploitation of other energy resources [1]. Technological advances as directional drilling and hydraulic fracturing have led to a rapid expansion of the development of unconventional natural gas (UNG) resources and, as a consequence, it is feasible that UNG development projects can get closer to inhabited areas raising both public health and environmental concerns (see e.g., [2, 3]).

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Hydraulic fracturing is a method used to improve fluid flow from rocks in the subsurface by creating new fractures after the high-pressure injection of fracking fluids. Conventional reservoirs have hydrocarbons (oil and gas) located in well-connected pores in the rock, whose permeability is often sufficient to allow extraction. In unconventional reservoirs (as e.g., shales), hydrocarbons are found in small and poorly connected pores and cracks and, for this reason, it is necessary to increase permeability by artificial means to extract this resource (e.g., [4]). However, it has been suggested that the development of UNG might have links to a variety of potential local environmental problems as, for example, the pollution of surface water bodies and groundwater, the emission of volatile components, and even the enhancement of slip on nearby faults (e.g., [4, 5, 6, 7]). For these reasons, the use of hydraulic fracturing techniques has been the focus of strong controversy. The fact that different actors with different perspectives and expertise play a role around the UNG development, it makes this debate an interesting topic in which science is called to support the risk management process, providing objective inputs to shed light on a number of critical issues.

As with any other energy resource exploitation, a wide range of possible environmental impacts can be associated with the development of UNG. Arbitrarily, we can divide these environmental impacts in two general groups: (a) impacts caused by ordinary routine operations, and (b) impacts caused by incidents due to system failures or extreme events. A close examination of these two impact groups can provide insights into the potential environmental impacts associated with exploiting unconventional gas resources. However, from the perspective of major risk assessment, which is the main scope of the multi-hazard risk approach considered here, the impacts caused by incidents, being low probability/high consequence events, are usually those of paramount importance because such events have often the potential of causing the most disastrous and unexpected damages. Conversely, the impacts associated with routine operations are usually better constrained and managed during operations.

The development of multi-hazard risk (MHR) assessment tools have provided a theoretical framework for facing complex problems such as those related to assessing risks linked to UNG development. In short, the MHR approach aims at harmonizing both the methodologies employed and the results obtained from assessments considering different risk sources and taking into account possible risk interactions (e.g., [8, 9]). A quantitative MHR assessment requires as input a set of risk pathway scenarios whose identification constitutes the first task to be performed. In this context, the main objective of this paper is to discuss a number of potential scenarios emerging from the review of specialized literature where possible risk pathways are proposed as possible mechanisms for impacts on the environment. Identifying risk pathway scenarios associated to UNG operations is a complex task that implies taking into account a number of issues. For example, a number of external hazards might be considered as potential triggering mechanisms; such hazards can be either of natural origin, occurring underground (as e.g., natural earthquakes), in the atmosphere (as e.g., extreme meteorological events) or at the air/ground interface, or anthropogenic events caused by the same industrial activities (as e.g., subsidence, triggered seismicity). On the other hand, failures might propagate through the industrial elements, leading to complex scenarios according to the layout of the industrial site. Finally, it is worth noting that there are different potential risk receptors ranging from environmental elements (as the air, soil, surface water, or groundwater) to communities (e.g., people, infrastructure) and ecosystems.

The paper is organized as follows: first, an overview of the main concepts related with the MHR assessment problem is presented. Second, we present and discuss the main risk pathway scenarios that have been identified in a selected set of publications. Finally, in the last part of the paper we perform a general discussion about the main challenges for an objective assessment of the occurrence likelihood of most of these scenarios.

2. Multi-hazard risk assessment applied to UNG operations

The main objective of a MHR assessment applied to UNG operations is to identify and to assess the rate (or the likelihood) of occurrence of incidents, and their potential impacts on the surrounding environment, considering different hazards and their interactions [10]. According to this general objective, the implementation of a MHR assessment applied to UNG operations needs to consider different issues as the following: (a) the possibility of multiple (natural and anthropogenic) hazards as possible triggering mechanisms; (b) it has to explore all the plausible scenarios of cascading events, identifying the logical relationships among the different events leading to an unwanted consequence; and (c) it has to assess the possibility of impacting different typologies of environmental and man-made exposed elements. Considering the typology of problems faced in the case of industrial activities such as UNG operations, a quantitative risk analysis can be structured in the following main steps (see, e.g., [11]):

- **The identification and description of potential incidental events in the system**. An incidental event is usually defined as a significant deviation from normal operating conditions that may lead to unwanted consequences. In the oil/gas industry, for example, a gas leak may be defined as an accidental event.
- **The potential causes of each incidental event are identified by causal analysis**. The causes are usually identified in a hierarchical structure that may be described using a fault tree. If probability estimates (of the basic events) are available, these may be put into the fault tree and the probability/frequency of the accidental event may be calculated.
- **The possible consequences of incidents on the surrounding environment can be analyzed using an event tree structure**. Likewise, most industrial systems include various barriers and safety functions that have been installed to stop the development of accidental events or to reduce their consequences; these elements should be considered in the consequence analysis.

The MHR approach for this problem is set by considering multiple hazards as possible sources of system's perturbations that might lead to the development of an incidental event. The first part of the analysis is the identification and structuring of scenarios of interest. Given the complexity of the problem, when performing this task we adopt a multi-level approach [8], in which we first perform a qualitative analysis oriented to the identification of a wide range of possible scenarios. This process is based on a literature review of potential impacts in different risk receptors of interest and is condensed in a number of causal diagrams (as shown, e.g., in Fig. 1a). From all the screened scenarios, those considered more relevant for quantitative analyses are structured following a 'bow-tie' (BT) approach (Fig. 1b). This selection is based on the identification of major risks, i.e., those related with the occurrence of low probability/high impact extreme events.

The BT approach is a graphical tool that facilitates structuring accident scenarios, starting from the accident causes and ending with the consequences. It is targeted to assess the causes and effects of specific critical events (also called 'top events', TE). It is composed of a 'fault tree' (FT) on the left hand side of the graphic plot, identifying the possible events causing the critical TE, and an 'event tree' (ET) on the right-hand side showing the possible consequences of the critical event.

Considering the development of UNG projects, multiple categories of risk receptors ranging from environmental to man-made elements can be considered. For convenience in the modeling process, we arbitrarily divide the possible risk receptors in two groups: 'Primary risk receptors' and 'Final risk receptors'. In this work, primary risk receptors are defined as the environmental elements that might be affected by the industrial activity associated with UNG development, which fundamentally corresponds to the groundwater, the surface water, the soil, and the air. Final risk receptors are those that potentially can be impacted either indirectly by the impacts in a primary risk receptor, or directly by the effects of the industrial activity. There are two main categories of final risk receptors: (a) the community related elements (that in general includes the people and the building environment) and (b) the ecosystems localized in the surroundings of a UNG development project. In general terms, it can be said that impacts to primary risk receptors may be defined as possible TEs of a fault tree, whereas impacts to final risk receptors may drive the construction of the ET.

It is worth noting that the main scope of this paper is to perform a critical discussion regarding the main risk pathway scenarios generally associated with UNG development. For this reason, hereinafter we will focus the attention on describing and discussing the most relevant identified scenarios.

3. Identification and structuring risk pathway scenarios in UNG development

As a first step for the scenario identification process, we have analyzed relevant literature in order to put in evidence those scenarios more recurrently claimed as of priority for risk analyses for UNG development. This process has been performed analyzing a number of research publications in peer-reviewed literature (74% journals and 8% other reports) and grey literature (18%, including open reports from academic, government and industry sectors). A list of the references used for this literature analysis is presented in Table A.1 (Appendix A). The identified scenarios (considering impacts caused by both ordinary routine operations and incidents due to system failures or extreme events) were classified by development stage of an UNG project, which for the sake of simplicity have been divided in: (a) Site development and drilling preparation; (b) Drilling; (c) Hydraulic fracturing; (d) Production; and (e) Abandonment.

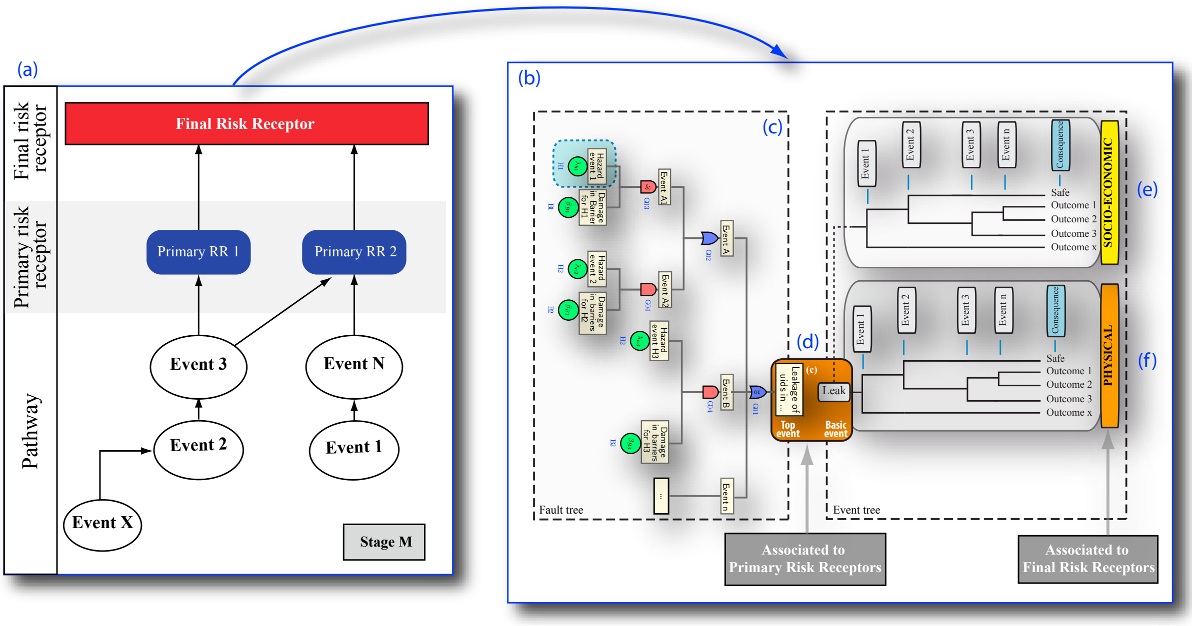

Fig. 1. Example of the passage from a causal diagram to the structuring of a set of scenarios following a bow-tie structure. (a) causal diagram of the identified scenarios; (b) bow-tie structure implemented for a given critical top event of interest (for details see the text).

Once a set of risk pathways have been identified, the next step is to construct ‘causal diagrams’, which are graphical tools that qualitatively represent causal relationships between events or variables in a causal model. For each one of the project development stages defined, a causal diagram has been created. In the following paragraphs we discuss the causal diagrams created for the site development and preparation, drilling, and hydraulic fracturing. The discussion is focused on these three stages since they enclose most of the activities that are specific to UNG development.

3.1. Stage 1: Site development and drilling preparation

Figure 2 shows the causal diagram representing the main risk pathway scenarios identified for the site development and drilling preparation phase. Most of the identified pathways correspond with environmental impacts associated with routine activities. The primary risk receptors mostly involved in this phase are the soil, air, surface water, and also shallow ground water. Air is mostly affected by routine activities as emissions from vehicles and site construction equipment operating for road construction and well-pad site preparation. Shallow groundwater and surface water bodies can be affected by different ways, but the most common causes being the runoff and erosion (associated with road and well-pad construction) and potential vehicle accidents. A number of phenomena directly impacting final risk receptors have been also identified. In particular, noise caused by equipment and vehicles and ground vibrations may cause disruptions to communities and ecosystems. On the other hand, the construction of roads may produce habitat loss and/or fragmentation. The scenarios related with the pollution of soil, surface- and shallow ground-water caused by accidents of vehicles transporting chemical materials are in general the pathways of main interest in a MHR assessment.

3.2. Stage 2: Drilling activities

Figure 3 shows the causal diagram representing the main risk pathway scenarios identified for the drilling phase. Different pathways impacting primary risk receptors (air, surface- and ground-water) have been identified. Considering the scenarios leading to incidents, the main possible pathways are related to surface or underground blowout events caused by uncontrolled kick events or by potential lost circulation caused by finding high permeability zones. Another source of incidental scenarios are associated with damages in fluid storage facilities.

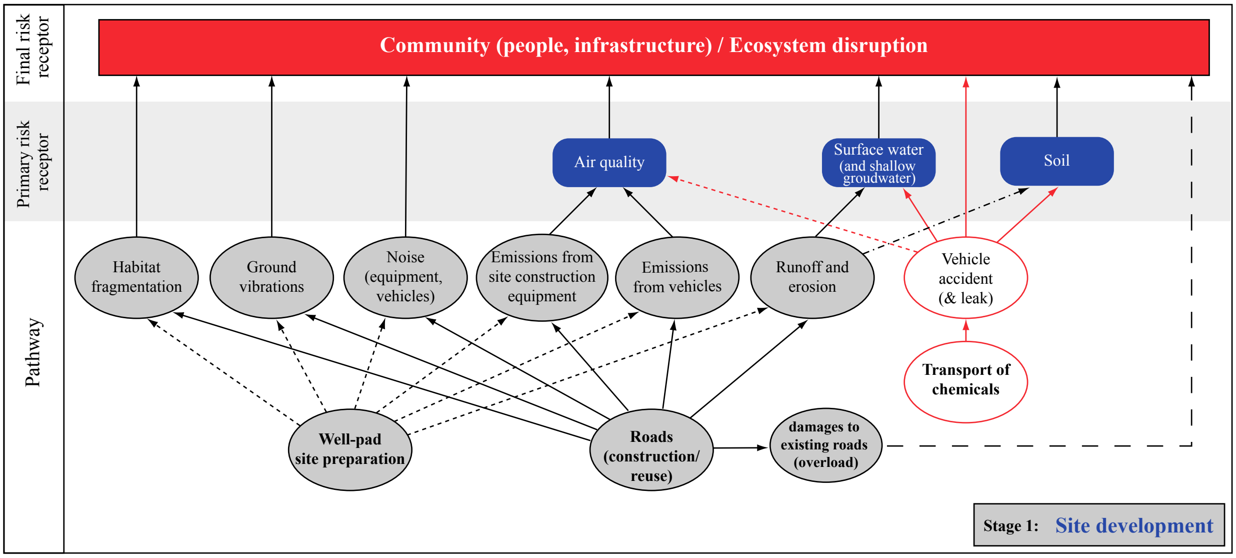

Fig. 2. Risk pathways identified for the site development and drilling preparation phase (gray circles identify events associated with ordinary routine operations, and white circles identify events associated with incidents)

3.3. Stage 3: Hydraulic fracturing

This set of scenarios is probably the one of paramount importance, since it encloses the main possible pathways specifically associated with the hydraulic fracturing activities. Therefore, in this group we may find the phenomena that are more relevant and specific for UNG development activities. Figure 4 shows the pathways identified for the hydraulic fracturing phase. Effects in final risk receptors can be associated with direct impacts caused by events derived from hydraulic fracturing operations (as induced seismicity) or through impacts to primary risk receptors (in particular impacts to surface water, groundwater and air).

Regarding the scenarios associated with incidents or extreme events (relevant for MHR assessment), a number of pathways can be outlined. For example, surface water and ground water can be both affected either by on-site spills caused by loss of containment, fluid transport, or by flowback/waste water disposal. It has been also hypothesized that groundwater pollution can be associated with fluid migration from the fracturing target formation, from leaks following well integrity failures, or, in the case of underground injection of flowback and waste water, by fluid migration from injection formation. Finally, in this phase induced seismicity can be associated with both hydraulic fracturing (e.g., [1]) and waste water injection (e.g., [12, 13]).

4. Discussion: Challenges for quantitative assessment of risk pathway scenarios

Unconventional oil and natural gas extraction enabled by horizontal drilling and hydraulic fracturing has driven an economic boom with consequences that, according to the perspective adopted, are described from revolutionary to disastrous; reality probably lies somewhere in between [14]. What seems to be out of discussion is that the development of UNG is destined to be the focus of controversy: on the one hand, it can be considered that UNG development generates income and, done responsibly, it can lead to reduced air pollution and water use, as compared with other fossil fuels. On the other hand, it could slow the adoption of renewables and, if done poorly, toxic chemicals could be released into the environment [14].

Beyond the controversial aspects of UNG development, a MHR approach offers the tools for a comprehensive quantitative evaluation of risks. As a fundamental step in the MHR framework, the identification of risk pathway scenarios associated with UNG activities is an important preliminary task that is required throughout the exploration of the possible chains of events potentially leading to unwanted consequences. As it emerges from the review presented

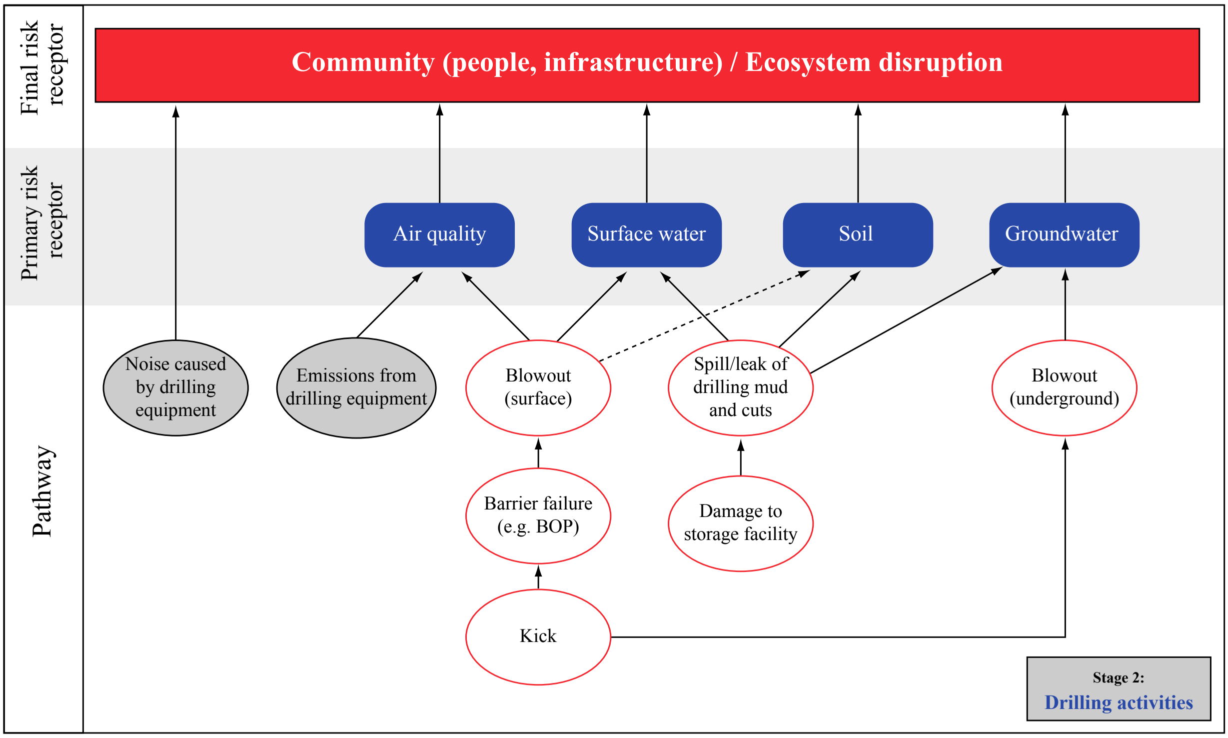

Fig. 3. Risk pathways identified for the drilling phase (gray circles identify events associated with ordinary routine operations, and white circles identify events associated with incidents).

in this paper, a number of possible scenarios have been widely discussed and proposed in literature. An important point of discussion that we want to highlight is that the scientific support confirming or rejecting the possibility that a given scenario may occur is not always evident. In fact, many publications are limited to perform a qualitative description of scenarios that plausibly may occur, without providing evidence of quantitative analyses defining the conditions under which the proposed scenario may or may not effectively happen.

As briefly presented throughout this paper, currently there exist a broad number of possible risk pathway scenarios that describe (at least qualitatively) an important number of possible mechanisms by which the activities associated with UNG development could have an unwanted impact in the environment. Therefore, the first scientific challenge for objectively assessing these risk pathway scenarios is to answer the questions: under which conditions may it happen? and how likely is it? Science is called to analyze these scenarios, identify the physical, chemical, and/or biological phenomena and processes involved, and to define the conditions under which such phenomena may be enhanced or inhibited. In this way, these scenarios can be more objectively parameterized, making more feasible their quantitative assessment. As a consequence, the potential impacts can be realistically understood, opening the way for the formulation of appropriate risk mitigation strategies.

For example, one of the most diverging points of controversy around UNG development is the possibility of groundwater pollution from fluids migrating upward from the target formation to reach shallower groundwater reservoirs. While the possibility of such a scenario is considered as a matter of fact in many publications, other authors (see e.g., [15]) argue that on the base of real fracture-growth data mapped during thousands of fracturing treatments in some of the most active shale plays in North America (Barnett shale in Texas, the Woodford shale of Oklahoma, the Marcellus shale in the northeast US, and the Eagle Ford shale in south Texas), there is no evidence that fracture treatments grow into the aquifers present in the vicinity of the fractured wells. We argue that analyzing such a scenario implies taking into account different parameters as the geomechanical conditions in situ, the depth of both the target formation and the aquifers, the duration of the high pressure stimulation, and so on. Therefore, in such a case there is no space

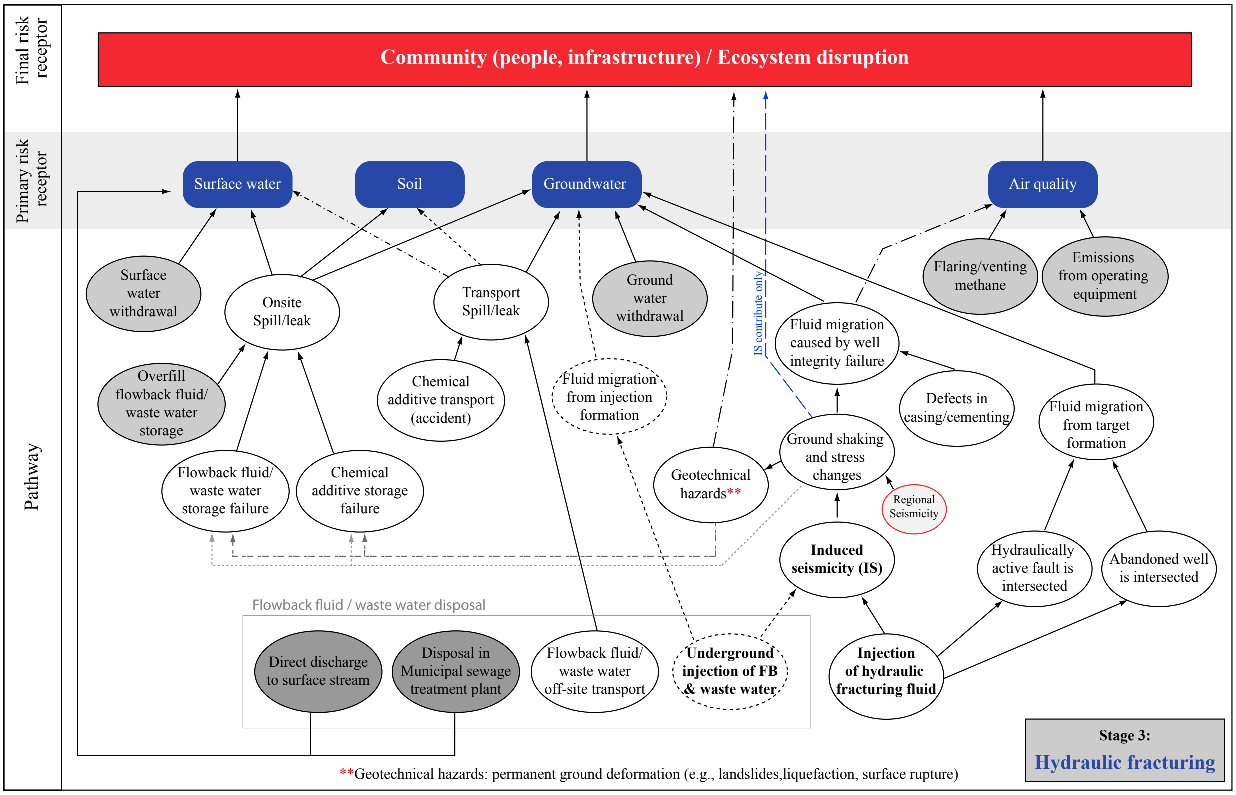

Fig. 4. Risk pathways identified for the hydraulic fracturing phase (gray circles identify events associated with ordinary routine operations, and white circles identify events associated with incidents)

for general considerations; rather, when considering the specific conditions under which a given site is found (e.g., geomechanics, spatial distribution, stimulation operations, etc.), it is possible to figure out how likely (or unlikely) it is that a fracture effectively can reach a shallower aquifer, or which conditions would be required for this scenario to occur.

A second important challenge for objectively assessing risk pathway scenarios associated with UNG development is to avoid possible biases driven by the risk perception. As discussed in the previous example, the focus on scenarios receiving particular attention mainly due to the public concern (as the groundwater pollution caused by fluid migration from the target formation) will move other relevant scenarios into the background. For example, most of the UNG project development stages raise concerns related to pollution of surface water bodies and groundwater caused by accidental events during the transport and storage of chemicals. As a consequence, it may result that the picture emerging for the possibility of groundwater pollution as a consequence of UNG development is basically constrained to the case of fluid migration from the target formation during hydraulic stimulations, inducing in this way to neglect other relevant pathways.

A third challenge for holistically evaluating the effects of UNG development is the assessment of socio-economic impacts. In general, socio-economic effects associated with UNG operations might be framed in terms of opportunities and risks. The development of UNG may generate substantial short-term economic benefits, which may transform in depressed local economies in the long run (see e.g., the boom-and-bust cycle described by [16]). However, socio-economic data related to the development of UNG are still poor as the shale boom started just few years ago, causing the assessment of possible busts to be difficult to evaluate. A reliable assessment of the short- and the long-term, socio-economic effects of UNG development constitutes therefore an important field of research for implementing objective cost-benefit assessments supporting the risk analysis process.

5. Conclusions

In this paper we present in a compact way a number of risk pathway scenarios derived from the analysis of an important number of available documents (mainly peer-reviewed publications, but also relevant grey literature). It is worth noting that while our effort has been focused in selecting the most relevant literature available, shortcomings are in any case inevitable because it is very likely that important documents have been overlooked, some scenarios might be incomplete or not included at all. Considering the identified scenarios, events are outlined using causal diagrams and can be considered as a basic set of scenarios useful for guiding the process of structuring the fault trees and event trees required for quantitative MHR assessments. Although all these scenarios are in general well known, the arguments supporting many of them, as found in literature, are often based on qualitative assessments. Therefore, it is important to stress the importance that the development of evidence-based research will have in the near future for widening the base of relevant studies, as well as to better constrain the conditions under which the involved events might eventually happen.

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Appendix A. List of publications used for the identification of relevant risk pathway scenarios

Table A.1. Summary of the specialized literature used for the screening of risk pathway scenarios associated with UNG development.

Typology of publication	Percentage	References
Peer reviewed papers	74%	[1, 5, 6, 7, 12, 13, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28] [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45]
Peer reviewed reports	8%	[4, 46, 47, 48]
Other reports	18%	[2, 49, 50, 51, 52, 53, 54, 55, 56]

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