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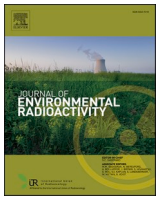

Societal aspects of NORM: An overlooked research field

Catrinel Turcanu [a,*], Tanja Perko [a], Melisa Muric [a,b], Jelena Mrdakovic Popic [c], Robbe Geysmans [a], Nadja Železnik [d]

[a] Belgian Nuclear Research Centre SCK CEN, Boeretang 200, 2400, Mol, Belgium
[b] Department of Political Science, University of Antwerp, Lange Nieuwstraat 55, 2000, Antwerpen, Belgium
[c] Norwegian Radiation and Nuclear Safety Authority (DSA), Grini næringspark 13, 1361, Østerås, Norway
[d] Milan Vidmar Electric Power Research Institute, Hajdrihova ulica 2, 1000, Ljubljana, Slovenia

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ABSTRACT

While technical aspects of exposures to the naturally occurring radioactive material (NORM) are well explored, social science research on NORM is scarce, poorly indexed and dispersed across peer-reviewed literature, as well as various academic disciplines. Through an exploratory review of grey literature and a systematic review of scientific peer-reviewed articles published until December 2020, this paper addresses the following questions: (a) What are the societal challenges related to NORM? (b) What type of scientific research is being conducted on the societal aspects of NORM and (c) To what extent do the findings answer the identified challenges? Unfortunately, results of this study demonstrate a research gap related to the social, economic and cultural aspects of NORM management. Although the few existing studies offer some insights, for instance in relation to risk perception and risk communication, most of the societal challenges identified have not been addressed yet. This demonstrates the strong need for evidence based social science studies in order to improve the management of NORM.

1. Introduction

Naturally occurring radioactive material (NORM) is material that contains none other than primordial radionuclides that occur in nature (e.g. uranium, thorium, potassium), and their radioactive decay products (e.g. radium and radon), in which the concentrations of these radionuclides have been changed by some process and may give rise to an elevated radiation exposure to humans and the environment (ICRP, 2019). Many industries worldwide that process raw materials containing NORM, produce a variety of products, by-products, discharges, residues, and wastes. After industrial extraction, processing and technical manipulation, the concentrations of radionuclides can be increased or unevenly distributed between the various materials arising from the different processes. The main activities giving rise to NORM are mining and milling of ores, production of coal, oil and gas industry, extraction and purification of water, use of geothermal energy, production of industrial minerals, including phosphate, clay and building materials. Furthermore, NORM can also be present in commodities, food, feed, drinking water, agricultural fertilizers, soil amendments and construction materials (IAEA, 2014b).

A significant number of active NORM involving industries and NORM affected legacy sites can be found around the globe (IAEA, 2003; IAEA, 2013b; IAEA, 2018; ICRP, 2019). The presence of NORM might pose potential health risks for workers, the public and the environment due to increased exposure to ionizing radiation.

Over the last two decades, research interest for the different aspects of NORM has grown internationally, being intensified in parallel with the introduction of regulatory requirements in the international standards for protection against ionizing radiation, the IAEA Basic Safety Standards (IAEA BSS) and the EU Basic Safety Standards Directive (EU BSSD). The main features of NORM, leading to this global attention increase, are:

- Presence of long lived, radiotoxic radionuclides,
- Occurrence in geological formations worldwide,
- Occurrence in different industrial processes and environmental media, depending on a variety of ambient and environmental conditions,
- Commonly large quantities of NORM waste/residues being deposited, and/or discharged, in the environment, in a way unaccepted for waste containing artificial radionuclides, remediation measure choice,

* Corresponding author.
E-mail address: cturcanu@sckcen.be (C. Turcanu).

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- Simultaneous presence of radionuclides with other hazards (such as heavy metals or acids),
- Historical neglect of the problems related to NORM as the focus has been only on artificially produced radionuclides,
- Due to NORM abundance, higher probability for workers, the general public and biota to be exposed in comparison to other radiation types,
- Difficulties in communication of risks related to naturally occurring radiation,

Information about the actual and potential extent of NORM and related issues (global abundance, different NORM sources, radionuclide activity concentrations, mobilization and concentration processes, exposure scenarios, impact assessment, dose modelling, etc.) is of high importance for getting an accurate perspective of problems that may be encountered (IAEA, 2021; IAEA. MODARIA II Programme, 2019; IAEA, 2018; IAEA. MODARIA I Programme, 2015; IAEA, 2003; Vandenhove et al., 1999).

Additional to these technical issues, the analysis of the social, economic and cultural environment is a prerequisite for the effective management of NORM sites and exposures (Briquet et al., 2005; Jacomino, 2015). First, such analysis may uncover and explain the perceptions of risk, as well as the interests, concerns and expectations or demands of different stakeholders, cultural sensitivities and the complexity of radiological protection behaviors. Neglect of these factors may severely hamper or even prohibit effective NORM management. Second, it informs and contributes to improved risk communication and stakeholder engagement and encourages historical perspectives and long-term thinking (Renn, 2017; Sjöberg, 2000; Slovic, 1996; Slovic et al., 1982; Slovic and Peters, 2006). Third, the inclusion of societal considerations in decision-making and the engagement of stakeholders, notably the local population is being called for as this is deemed to increase trust, cooperation and understanding between implementers and other stakeholders and support the development of sustainable solutions (JRC, 2016; OECD, 2019; Worrall et al., 2009; Fernandes et al., 2006; Briquet et al., 2005). Finally, the social dimension is recognized as a key component of sustainable environmental remediation of NORM sites; this has gained increasing importance reflecting an evolution from technical solutions towards "green and sustainable remediation" (Mobbs et al., 2019; OECD 2016). Sustainability assessment methodologies for environmental remediation or the management of legacy mines, highlight several aspects pertaining to the social dimension, such as human health and safety; ethics and equality; neighborhoods and locality; communities and community involvement; and uncertainty and evidence for sustainable environmental remediation; ownership; responsibility; cultural issues; local participation; and local acceptance (CLAIRE, 2020; Worrall et al., 2009; Rosén et al., 2015). However, there are very few social scientific studies dedicated to the assessment of social sustainability indicators for environmental management and there is a limited inclusion of these indicators in decision support tools for sustainable environmental remediation (Cappuyns, 2016).

This paper answers the following questions: What are the main societal challenges associated with NORM? What type of social scientific research is being conducted on the societal aspects of NORM and to what extent does this answer the identified challenges? What can we learn from this research? and What is still needed?

To this end, we first conducted an exploratory review of grey literature to obtain a preliminary overview of main societal challenges associated to NORM management and decision-making. This allowed taking stock of practical experiences and expert advice captured in case studies, international guidance and legal prescriptions, Next, we conducted a systematic review of social-scientific research addressing NORM in order to identify and examine key social science concepts, methods, research practices, main findings and routes for further research. The systematic review allowed to further detail the societal challenges and reflect on the extent to which these are addressed by existing studies. Our review focused on NORM from industrial processes, thus excluding a large number of studies addressing indoor radon exposure in private or public spaces, as the latter has been the object of other recent studies (Tomkiv et al., 2021).

The review methodology employed in this study is presented in Section 2, while the results are summarized in Sections 3 and 4 and further discussed and synthesized in Section 5. The findings from this study serve to inform researchers, policy makers and broader stakeholders on key aspects of NORM management, highlighting remaining gaps in research.

2. Method

The study proceeded in two steps. First, an exploratory, non-systematic review of grey literature was made, aimed at highlighting societal challenges related to NORM.

In a second step, a systematic review was made of social scientific studies related to NORM. The aim of this in-depth review study was twofold. First, it identified and examined key social science concepts, methods, and research practices in the field of NORM. Second, it summarized main findings, as well as current knowledge gaps and routes for future research.

2.1. Review of grey literature

A document analysis was conducted of international and European legislation, directives and standards, as well as regional and national legal and technical documents, guidelines and proceedings. In addition, documents (e.g. presentations, local information leaflets) related to case studies in Belgium (historical pollution by phosphate industry, remediation in progress), Norway (historical pollution from former niobium mining, remediation is pending) and Spain (historical pollution by phosphate industry, remediation is pending) were collected and analyzed (Guillevic et al., 2018).

2.2. Review of scientific literature

It is noteworthy that research investigating the societal challenges of NORM is generally poorly indexed and dispersed across peer-reviewed literature as well as various academic disciplines, in both natural and social sciences and humanities areas. A requirement for a thorough investigation was maintaining a broad review scope, which was realized through the application of expansive inclusion criteria. In this systematic review, the focus lies on published peer-reviewed literature, highlighting both the study designs and methods, as well as the main research findings.

2.2.1. Literature search

As a first step, database searches were conducted in Web of ScienceTM, Scopus®, Medline and Sociological abstracts, covering all publication years. The search was performed from the 23rd of November till the December 1, 2020. The initial search covered both indoor radon as well as NORM, and was conducted as part of a larger state-of-the art investigation within the European RadoNorm Project (Tomkiv et al., 2021). This paper focuses on NORM-related articles.

The search strings were developed in cooperation with an experienced university librarian and consisted of NORM -related keywords combined with the keyword "radioactive" and keywords on methods used in social sciences. The NORM keywords included relate to industries known to experience contamination with naturally occurring radionuclides, for instance *"mining" or "geothermal"*. A separate search was conducted for combinations with the methods *"survey" and "experiment"* whereby additional keywords related to the subject (humans) were introduced (see Table 1). The reason for this separate search was that surveys and experiments are commonly used in natural sciences, yet not necessarily with reference to social considerations.

Table 1
Search String in Web of Science format.

NORM	(radioactiv*) AND ((natural NEAR/1 (radiation OR "radioactive material")) OR tenorm OR residue OR remainder OR leftover OR waste OR oil OR gas OR water OR phosphate* OR fuel* OR geothermal OR building* OR "flying ash" OR mining OR mine OR "NORM industries" OR "building material*" OR "alum shale" OR (environment* NEAR/0 remediation))
Social science research method	(((field OR case OR comparative OR cohort OR archival) NEAR/2 stud*) OR ((network OR content OR sentiment OR meta OR framework OR media OR discourse OR morphological OR text* OR conversation OR narrative) NEAR/2 analysis) OR ((systematic OR meta) NEAR/0 review) OR ((mixed OR mental OR mixed OR delphi OR q OR economic) NEAR/2 method*) OR "delphi techniq*" OR "focus group*" OR "repertory grid" OR "analytic induction" OR "life history*" OR historiography OR "socio mapping" OR "feeling thermometer" OR "cybermethod*" OR "participatory action" OR bibliograph* OR questionnaire* OR "secondary data" OR "e-research" OR "memory work" OR interview* OR observation* OR ethnography OR phenomenolog* OR RCT OR "randomized controlled trial*" OR workshop OR "public opinion" OR panel* OR omnibus OR poll OR triangulation OR hermeneutic) (survey* or experiment*) AND (public* OR citizen* OR participant* OR respondent* OR resident* OR person* OR stakeholder*)

All records identified were uploaded into the literature review tool Rayyan (Ouzzani et al., 2016). Through an automated process, duplicates were removed, following which 16.590 unique records remained on the topics of radon and NORM.

2.2.2. Literature selection

Records were screened on eligibility by three reviewers, based on title, abstract and meta-data. To ensure the reliability of the selection procedure, a sample of 22% of the articles was screened by at least two coders. Whenever there was conflict (only 26 cases), an additional independent reviewer screened the record, after which a discussion followed to agree on the final decision to accept or reject the record.

After the initial screening, a full text examination of the articles followed and 14 relevant articles on NORM were retained. Relevant in this context means that the articles focused on societal aspects (e.g. risk perception, stakeholder engagement, governance), and discussed issues related to technically enhanced levels of NORM, hence excluding e.g. a bulk of literature on indoor radon exposure.

The reader can find an extensive review on societal aspects related to exposures to indoor radon elsewhere (Tomkiv et al., 2021). Studies addressing indoor radon due to industrial activities, e.g. from uranium residues (e.g. König et al., 2014), or radon in water were however included in this review. From a regulatory standpoint a distinction is made between uranium mining or uranium ore processing activities related to the nuclear fuel cycle. However, in our review we retained the case studies on legacy sites due to uranium mining or processing (e.g. Brugge and Goble, 2002) since from a social science perspective such distinctions between uranium and other ores are less relevant.

Furthermore, papers that addressed aspects related to natural radioactivity in general, e.g. perception of natural radioactivity as an environmental health risk (e.g. Kara et al., 2011; Pugliese et al., 2019; Alsop, 2001), but made no reference to the source of radioactivity or mentioned only "radon" were excluded as they do not provide NORM-specific insights. Articles that addressed known NORM industries, but made no reference to radiation or radioactivity either in the description of the case study or in the specific issues included in, or arising from, the inquiry (e.g. McKenzie et al., 2016) were also excluded in this review. However, studies centered on social aspects of NORM industries that did mention the presence of radioactivity in the problem formulation (e.g. Zierold and Sears, 2015a) were included, even when the topic of radioactivity did not come up spontaneously in their research (e.g. in interviews with people living near coal ash storage sites).

Through snowballing from the lists of references of these articles, 6 additional articles were identified which had not been initially retrieved from the four databases searched. Table 2 summarizes the eligibility criteria.

2.2.3. Data analysis

A data extraction form was created in Qualtrics based on the template of the Cochrane research institute (Higgins et al., 2020) with the following items: author(s), publication year, publication title, study aim, study location, study design, population and sample characteristics, methods, dependent and independent variables, quality assessments (e.g. reliability, validity), type of analysis, conclusions, and information regarding ethical considerations (conflicts of interest, funding and privacy).

Data was extracted by trained coders and reviewed by two independent master coders. A data extraction form was used to summarize the studies, in terms of their topic, objective and geographical setting, key concepts serving as dependent and/or independent variables, measurement objectives, employed techniques and main findings.

The summarized data served as a directory to summarize the state-of-the art knowledge, identify research gaps and methodological deficiencies. It does not intend to serve a prescriptive purpose.

3. Key societal challenges for the management of exposure situations due to NORM industries and legacy sites identified from case studies and grey literature

3.1. Challenges associated to evaluating the impact on humans and the environment

Naturally occurring radioactive materials contain long-lived, radiotoxic radionuclides, and when processed, disposed or discharged in large quantities, NORM may potentially affect human health and the environment. The average annual effective dose worldwide due to natural sources is estimated to be 1.14 mSv, with exposure to radon contributing an additional 1.26 mSv (UNSCEAR, 2000). Depending on many factors, such as type of NORM site, radionuclides mobilization, transfer pathways and exposure scenarios, additional radiation exposure doses from NORM can be significantly different, for both occupational and public exposure (Kunze et al., 2019; Mrdakovic Popic et al., 2020; RP 122, 2001; RP 135, 2003; Skipperud et al., 2013; Sneve et al., 2020). In order to consider potential radiation exposure, the main NORM exposure routes, inhalation (dust containing NORM and radon), ingestion and

Table 2
Inclusion and exclusion criteria.

Inclusion
• Publication time frame: no date limit • Publication type: peer-reviewed articles • Publication language: English • Topic of research: societal aspects (i.e. related to the attitudes, perceptions and behaviors of humans) in relation to (technically enhanced) NORM exposure, or exposure to radon in water, or exposure to indoor radon due to industrial residues, or uranium mining or processing • Publication design: quantitative, qualitative and mixed methods
Exclusion
• Publication type: no full text, dissertations, letters, reviews, editorials, books, essays • Publication language: not English • Topic of research: studies merely mentioning, not investigating societal consequences, studies addressing only indoor radon exposure unrelated to any industries, studies inquiring risk perception of natural radioactivity in general (no reference to the source of radiation or only "radon" mentioned) • Publication design: no methodological information provided

external exposure need to be evaluated in NORM exposure situations. An investigation of exposure doses from different types of NORM industry, showed that external exposure and the inhalation of radon and dust can contribute significantly to the total occupational exposure, while the dose via direct ingestion of particles and skin contamination is avoidable by common radiation protection and hygiene measures (Weiss, 2005).

However, while planned activities in NORM involving industries are generally well regulated and exposure doses are commonly of no radiological concern, existence of non-remediated NORM affected legacy sites pose, in many countries, a significant radiation risk for both workers and public health (Stegnar et al., 2013; HERCA, 2016). Moreover, legacy sites may contain other hazards that might be of even greater concern than radiological ones (Haanes et al., 2019; Mrdakovic Popic et al., 2011; Stegnar et al., 2013; Sneve et al., 2020; Vandenhove et al., 1999). Therefore, NORM affected legacy sites may pose serious problems in many countries. This is, for instance, the case when related pollution issues are well known, but legacy sites are still outside the regulatory control (mostly due to responsibility assignment issues). Another example refers to cases where a started remediation process produces a significant amount of NORM waste.

At the present time, information about the extent and various issues related to NORM exposure sites is commonly available at national levels, mostly for European countries (Vandenhove et al., 1999; HERCA, 2021). However, in many cases, data are rather old or partially missing (e.g., for less developed countries or for legacy sites which still are outside the regulatory control). Hence, making an updated, systematic European overview of NORM exposure sites has been considered as beneficial and is currently being conducted in the European RadoNorm project (RadoNorm Project, 2020). Focus will be put on gathering the nationally available information on NORM exposure sites, but also on identifying the activities that may be of concern, but which currently are not included in the industry list in the EU BSSD (Euratom Directive 2013/59, Annex VI). Additionally, a broad range of NORM associated issues, including industrial and environmental conditions leading to radionuclide disequilibrium, transfer pathways and workers and public exposure scenarios and dose evaluation, as well as related industrial, regulatory and societal challenges will be investigated in the course of this project.

Furthermore, one of the well-known challenges related to NORM is the simultaneous presence of NORM and non-radioactive chemical hazards, which is often seen in NORM involving industries and NORM legacies (ICRP, 2019). This subject is still little investigated with respect to possible environmental impacts, effects and doses, and there is a need to investigate also how multiple-hazards exposure situations should be considered within the holistic decision making processes and with respect to public perception of risks (Mrdakovic Popic et al., 2020; Haanes et al., 2019; RadoNorm Project, 2020).

Finally, until recently, relatively little attention has been paid to the potential, direct environmental and non-human biota impact associated with NORM residues originating from industries and/or legacy sites. In recent decades (ICRP 2007, 2008, 2014; Bréchignac 2011; Bradshaw et al., 2014), radiation protection has undergone a substantial change in emphasis from anthropocentrism towards ecocentrism, by subsuming anthropocentrism and ecocentrism, due to new drivers: (a) increased public awareness and interest in environmental issues, (b) scientific data showing prominent ecological effects in endangered and vulnerable ecosystems, (c) changes in regulatory approaches requesting explicit demonstration rather than assumption of environmental protection, and (d) need for assurance of the overall social and environmental benefits in impacted areas.

3.2. Challenges associated with the social, economic, legal, political, cultural and historical context

Aside of the technical and scientific challenges highlighted above, management of radiological exposure situations due to NORM may be challenged by several other social, economic, legal, political, ethical, cultural and decision-making factors (Perko et al., 2019; Briquet et al., 2005; Hayumbu et al., 2005).

Social challenges of managing long-term exposures from contaminated NORM sites may arise for instance from the plurality of values and interests of the different stakeholders, the lack of mutual trust, poor stakeholder involvement, limited understanding of remediation among the members of the affected communities, and the lack of holistic approaches to decision-making (Perko et al., 2019; IAEA, 2014a, 2016b; Joint Research Centre, 2016).

Differing perceptions of risks from sites contaminated with, or remediated from, NORM, particularly between technical experts and affected communities, have also been pointed out in international and national documents and reports (Gonzales, 2013; IAEA, 2014a, pp. 9; Guillevic et al., 2018). For instance, experts and other stakeholders may have different views on the risks from radiological contaminants in comparison to chemical contaminants, making it difficult to adopt an optimal solution in terms of risk and socio-economic cost (HERCA, 2016). This may lead to differences in stakeholders' expectations regarding the end state of a remediated site, or their appreciation of the remediation impact on the socio-economic development of the region.

In-depth analysis of media reporting shows that affected population, remediation experts and mass media are concerned about different issues and, therefore, express or are confronted with different uncertainties. The ways in which they frame the problem are also different: mass media frames it as "radiological contamination", experts frame it as "mixed contamination" (chemical and radiological) and people living in an affected region as "pollution" (Perko and Sala, 2019).

Not only experts, but also societal stakeholders are confronted with challenges related to lack of, or incomplete, knowledge or awareness about NORM sites and related risks (Pepin et al., 2016; IAEA, 2014a; IAEA, 2016a; NRPA, 2016; Mrdakovic Popic and Holmstrand, 2017; Fernandes et al., 2006). These may be due to unknown or poorly defined sources of contamination and radiation, or people's lack of awareness of being exposed to dangerous amounts of radioactivity or mixed contaminations, among others.

In this context, communication is a key factor contributing to effective management of NORM, as recognized by international organizations (IAEA, 1994, 2007; ICRP, 1991; IEA, 2006; IAEA 2014a), and broader scholarly literature (Barry, 2012; Feldman and Hanahan, 1996; Oughton, 2013; Slovic, 1996; Slovic et al., 1980; Perko, 2014). Communicating about radiological risk is particularly complex given the scientific and technical uncertainties, for instance in relation to health effects of low radiation doses. Unsuitable communication styles (e.g. one-way communication as opposed to societal dialogue) and lack of transparency have been pointed out as barriers to effective communication (Perko et al., 2019).

Further challenges arise from gaps in legal frameworks, e.g. related to national policies for remediation of NORM sites. The lack of appropriate environmental standards and guidelines is reported in different international and national reports (e.g. IAEA, 2013a; IAEA, 2015; IAEA, 2016b; Pepin et al., 2016; FANC, 2015; Holmstrand, 2015; Nielsen, 2015; NRPA, 2016; Michalik, 2009; Fernandes et al., 2006; Jacomino, 2015). The legal framework should also demonstrate inclusion of good practices, requiring public consultation and stakeholder engagement in environmental decision making, and ensuring that requirements are implementable and provide for adequate control.

Furthermore, economic aspects have an important impact on NORM management, as highlighted in national and international documents (e.g. NGI-UMB, 2010; IAEA, 2014a; IAEA, 2016a; NRPA, 2016; Mrdakovic Popic and Holmstrand, 2017; Pepin et al., 2016, pp.132). Unexpected contaminations or large waste volumes can, for instance, lead to major differences between the estimated and the real cost of NORM remediation. In many cases, there are uncertainties about who will be responsible for remediation, who will pay the costs, what will be the cost of remediation including waste management, how to ensure long-term

stewardship, or whether there has been transparent use of financial resources (Guillevic et al., 2018).

All these aspects may be directly, or indirectly related to societal concerns regarding NORM management, and thus warrant attention from social sciences and humanities researchers. However, as shown in the next section, very few studies are available in scholarly literature addressing these aspects.

4. Results from the review of social scientific studies on NORM

4.1. Methodological aspects

As a first finding, this study revealed a dearth of social scientific studies on NORM. Only 20 articles were identified that addressed ethical, cultural, political, and/or social dimensions of specific NORM case studies and were supported by empirical data (see Appendix). While our review may have missed some studies (e.g. Perko et al., 2019), given the complexity of indexing social studies on NORM, it nevertheless shows that existing peer-reviewed research on this topic is very limited.

Furthermore, one in four studies was published more than 20 years ago, and may thus not account for social, cultural, regulatory and other changes that may have occurred in the past decades. Moreover, some papers refer to the same set of empirical data, leaving the number of distinguishable studies even lower than the total number of papers.

The majority of studies (16 out of 20) were conducted in the United States and only four in other countries in the world (UK, Australia, Germany Romania). No social studies on NORM have been found in other geographical areas using our database search query. The particular situations addressed included:

- uranium mining & milling (N = 4) e.g. media reporting of incidents, workers' information and exposure, exposures due to waste;
- legacy sites from nuclear weapons production (N = 2), e.g. citizens' actual and desired level of involvement, preference toward remediation options;
- coal ash storage site (N = 3), e.g. parents' perception of risks;
- oil and gas exploration (N = 4), e.g. policy analysis of societal aspects of hydraulic fracturing or workers' perceptions of radiological risks on off-shore oil and gas platforms;
- other industries (N = 4), e.g. how people link health problems with environmental contaminants from sand-mining legacies; or communication related to a legacy site from the chemical industry;
- drinking water (N = 3), e.g. testing for radon, experts' or citizens' preferences towards policy options.

In some articles (e.g. Zierold et al., 2015a, 2015b), radioactivity did not emerge spontaneously from the analysis, while in others (e.g. Flin et al., 1996; Torres et al., 2017a, b) risk perception or other variables related to radiological risks were part of the study setup.

Data collection and analysis methods included quantitative (e.g. surveys with residents or experts), qualitative (e.g. focus groups, historical analysis, interviews) and mixed methods approaches (e.g. focus groups combined with surveys). In one study (Petrescu et al., 2019) the analysis reported was largely quantitative despite the *a priori* known small sample volume (N = 15); aside of methodological concerns, this also indicates a missed opportunity to achieve the depth insight that a qualitative analysis would have offered.

Main target populations addressed in the studies were residents, parents, workers and experts, living in areas affected by, or working with NORM. In relation to what is considered as the "affected area", Whittaker (1998) offers a holistic perspective in that the study area is defined not only geographically, but also as a social space. This leaves it up to the community, rather than experts, to define what is affected and in which ways.

Samples used in quantitative studies were in general not representative for the target population. For instance, in the study of Malecki et al. (2017), researchers recognized the under-representation of certain socio-demographic categories and vulnerable groups. Only one quantitative study (Flin et al., 1996) reported a representative sample with respect to the socio-demographics of the studied population, and another study (Mancl et al., 1994) used weighting to correct for the biases. Furthermore, the sample used by Torres et al. (2017a) in the study on hydraulic fracking combined members of the general public, oil field operators, produced water hauling truck operators and experts, and reported several analysis results from all these groups together.

Concerning recruitment of respondents for quantitative analyses, only one study used a random sampling method (Mancl et al., 1994) and another used random stratified sampling (Feldman and Hanahan, 1996). Other quantitative or mixed quantitative-qualitative methods studies used purposive sample, with selection of participants depending on the research interest of the researcher, or convenience samples, with participants selected based on their willingness to participate or convenient presence.

In qualitative studies, the recruitment of respondents (if applicable) resulted from purposive sampling (e.g. Whittaker, 1998) or convenience sampling (e.g. Zierold et al., 2015a, 2015b). In some cases, the sampling strategy was not reported (e.g. König et al., 2014).

Some quantitative studies used scales validated in the literature and used in previous studies (e.g. Flin et al., 1996; Malecki et al., 2017) while others did not make references to the literature or did not provide full explanations of how the concepts were measured. Weaknesses in the formulation of items were noted in some studies, e.g. using only one item to measure a latent variable; or a knowledge questionnaire with "yes" being the correct answer for all items (Mancl et al., 1994). Some other methodological issues related to the study design that should be improved in future research are the absence of control groups in experimental setups (Arvai and Gregory, 2003) or possible desirability bias. For instance, Malecki et al. (2017) investigated self-reported actions, as opposed to real actions, which might have triggered respondents to provide an answer they saw as socially desirable.

Only one study (Flin et al., 1996) reported about the reliability of the measurements used. Furthermore, a number of studies (Flin et al., 1996; Arvai and Gregory, 2003) conducted pre-testing, e.g. a pilot study of a survey, or held discussions or interviews to assess the clarity and completeness of survey questions or communication materials used in experiments. A good example is also De Lemos et al. (2009) where a survey was developed with Navajo community member participation, field-tested by bilingual Navajo community environmental health workers, and approved through Navajo Nation and University Institutional review boards.

Three studies specifically mention that informed consent has been received from participants (Zierold et al., 2015a, 2015b; Zierold et al., 2016) and a larger number of studies reported having received approval from institutional advisory boards or ethics committees. One study paid specific attention to ethical considerations in recruiting participants: in order to preserve privacy breaches, König et al. (2014) used gateway processes to recruit participants for interviews among residents.

Direct financial incentives were offered e.g. in Arvai and Gregory (2003) to volunteers in the study or in Malecki et al. (2017) to all contacted households, whereas while Flin et al. (1996) chose to offer incentives in the form of a charity donation.

4.2. Insights from NORM studies

4.2.1. Knowledge and awareness about NORM exposures

Several studies highlight the low awareness of the presence of radiation from natural sources among the general public (e.g. Torres et al., 2017a; Mancl et al., 1994). In the study of Mancl et al. (1994) only 13% of their respondents (random sample of residents of Ohio) knew that bricks used for the construction of houses can be a source of natural radioactivity. This low awareness was present across all education levels, albeit higher education was associated with higher awareness. In

the same study, 29% indicated coal ash as a source of radiation and, as an exception compared to all other radiation sources investigated, correct answers were more frequent among those with lower education levels.

Some studies point towards lack of timely information and low awareness about long term health risks associated to NORM industries, especially among vulnerable groups (e.g. Brugge and Goble, 2002). Brugge and Goble (2002) show in their historical study a lack of awareness among native American miners and their families of the long-term health hazards associated with uranium mining.

In the case of the historical pollution reported by König et al. (2014), residents were confronted with the unexpected -for them-discovery of old radioactive contaminants in the soil due to a former chemical plant. Despite all respondents having university degrees, they expressed difficulties to understand "the scientific risk assessment, the different dose concepts, diverse data collections, and various thresholds or standard values, and needed time to create their own understanding of risk (pp. 583). Later on, however, they became virtual 'radiation experts' by autodidactic learning.

In a different context, Torres, Yadav and Khan (2017a) similarly encountered low levels of knowledge regarding the contents of wastewaters from hydraulic fracturing in oil and gas industry, how these waters are managed, and who to contact in case of a potential spill, even among those who know someone working in the oil industry.

Zierold and Sears (2015a) bring further evidence that awareness is low also among healthcare providers; in their study, more than half of patients living near a coal ash site were never asked whether they lived near an environmental hazard.

Furthermore, as the case of Whittaker (1998, pp.323) shows, distrust in the polluting industry and in authorities, contradicting theories and uncertainties may lead to "conflict and competition for legitimacy between lay ways of knowing and professional forms of knowledge".

4.2.2. *Perception and acceptability of risk*

Environmental hazards may raise concerns among communities with NORM legacy sites, whether directly linked to radioactivity, or to other types of pollution that can be more readily observed through human senses (Zierold and Sears, 2015b; Feldman and Hanahan, 1996) and be perceived as a direct threat to their own health and that of their children.

The study by Torres et al. (2017a) on NORM and water produced in the context of hydraulic fracturing found, for instance, that a majority (59%) of their respondents, originating from a convenience sample including also 8% experts, had a moderately to very negative image of fracking wastewater. Natural radioactive material was associated with affective imagery including "dangerous" (about one in five respondents) and health hazard (about one in 10 respondents), but with "natural and/or safe" as the second most frequent category (also about one in 10 respondents). The authors explain this latter finding by reference to the lower risk perceptions people have when it comes to natural versus man-made situations, which has been found also in other studies (Perko, 2014). The same study of Torres and colleagues also found that negative images and thoughts associated with produced water, lower familiarity with produced water handling and content, and lower knowing how to proceed in case of a spill of produced water were associated to higher risk perception, measured as the level of concern about health risks in three scenarios.

Radiological risks from NORM may be associated with high-risk perception also among those professionally exposed. Flin et al. (1996) measured different work-related risks on offshore oil and gas platforms on the UK Continental Shelf among workers on 6 different platforms. Among others, they investigated the extent to which respondents felt safe when working with radioactive substances, as an item among a number of other risks. Their results revealed that less than half of the respondents (46%) felt safe when working with radioactive substances.

Contrary to evidence from other studies on radiological risks (e.g. Perko, 2014), in Torres et al. (2017a) previous experience (working or having worked in the oil field) and being an expert were not associated to higher or lower risk perception. A second study by the same authors (2017b) points out discrepancies between technical experts' risk assessments and other stakeholders' risk perceptions, including members of the public (Torres et al., 2017b).

König et al. (2014) identified four aspects relevant to risk perception: residents' own health, their children's health, the cost of remediation and injustice. They describe how residents had difficulties to reconcile the fact that they lived in the area for many years without knowing anything about radioactive pollution in their environment with the fact that local authorities discovered residues of uranium, thorium and their decay products in the soil more than 100 years after the demolition of the chemical plant generating the legacy site. The fact that residents were responsible to cover partly the remediation costs amplified their concerns about health risks.

Pidgeon and Fischhoff (2011), Renn (2017) and others pointed out that how people evaluate risks depends on values attributed to the outcomes at stake, and that includes not only health consequences, but also consideration of who is most exposed, who bears the costs, who bears the risks, and what the impact is on community culture and way of living. Whittaker (1998) illustrates that residents' concerns surrounding legacy sites go indeed beyond the physical state of health of people and their environment: they are connected to concerns about preserving community values and the social space it occupies.

Feldman and Hanahan (1996) suggested however that concerns about personal health and wellbeing were ranked as more important for NORM remediation decision making than community image or property values.

4.2.3. *Health perceptions and behaviors*

NORM sites are generally characterized by a mix of radioactive and chemical pollution. While concerns about radioactivity are not always spontaneously surfacing, several studies describe a feeling of helplessness that people living near legacy sites may be confronted with. The studies of Zierold and Sears (2015a, b, pp. 381) and Zierold et al. (2016) among residents living in the neighborhood of coal ash storage sites revealed residents' concerns regarding the protection of their and their children's state of health, and their feeling of being *"trapped by pollution*". Participants in the latter study also expressed their belief that everyone living in the neighborhood was exposed and that most community members were concerned about the issue.

Studies where residents were aware about the radioactivity highlighted similar concerns for their own health, as well as their children's health, as well as uncertainties about the potential correlations between theirs or their neighbors' illness history and the radioactive pollution (e.g. König et al., 2014; Whittaker, 1998).

The study of Whittaker (1998) shows differences in health perceptions among residents of a community having been faced with two legacy sites, one of which due to sand-mining activities, depending on the duration of residence. Contrary to newer residents, longer term residents spontaneously identified sand-mining activities as a possible cause of cancer, expressing concerns that the radioactive thorium from tailings had contaminated the water table in private water bores used as primary water source or for gardening.

Some studies suggest a link between the level of concern about environmental pollution and health behaviors. Residents who were concerned "a lot" about coal ash (not linked to radioactivity) were more likely to describe their health condition as "poor" and more likely to apply protective behaviors (Zierold et al., 2016).

Malecki et al. (2017) investigated different aspects related to monitoring of private well water. Their study showed that the majority of owners who use well water for daily drinking, cooking and bathing do not test the water regularly, and that among those who had tested their wells only 7% tested for radon. This was the least frequent test with the exception of gasoline; for comparison, 54% tested for bacteria and 48% for nitrates. Living in a particular geographic region and income were

found in the study to be the most significant predictors of testing and treatment. Main barriers for testing well water were related to lack of knowledge about water testing, low risk perception, convenience and social norms, while main motivators for testing were concerns about water safety and real estate transactions.

4.2.4. Trust in, and perceived competence of, risk management actors

Trust in risk governance actors is a key issue, since "*if trust is lacking no form or process of communication will be satisfactory*" (Slovic, 1999, pp. 88). Several studies point towards distrust from residents towards authorities and polluting industries, which may lead to opposition to remediation plans (Feldman and Hanahan, 1996).

As shown by Whittaker (1998), residents living near a former sand-mining legacy site remained mistrustful of local government authorities, industries and development even after remediation works, they questioned their interest in the issue and their legitimacy for environmental decision-making. In another NORM field, Torres et al. (2017a) also found a low level of trust in the different organizations involved, directly or indirectly, with management of waste water from hydraulic fracturing.

The study of Arvai and Gregory (2003) suggests that allowing for considerations that go broader than technical risk estimates as input to decision making may increase stakeholders' trust in decision-makers and facilitate their involvement.

Some studies bring insights into factors affecting trust in the context of NORM. With regard to one such factors -perceived social justice- König et al. (2014) describe a case in which residents felt they were treated unfairly as they had to pay for the remediation of a legacy site and they had not been informed about the possibility of a contamination when they bought their properties. This resulted in a lack of confidence in the responsible authorities.

Perry (2012) further points out conflicting scientific reports from different agencies as a factor creating mistrust regarding risks from hydraulic fracking.

4.2.5. Stakeholder involvement

The importance of public involvement in policy decisions on remediation processes and the establishment of two-way communication between citizens and regulators and remediation implementers is pointed out by several studies (e.g. Feldman and Hanahan, 1996; Arvai and Gregory, 2003). Several key stakeholders are highlighted in the studies reviewed, including citizens (different ethical groups, vulnerable populations, different generations), workers professionally exposed to environmental health risks from NORM, parents, school personnel, authorities, community leaders, local environmental groups and other non-governmental actors, health practitioners, risk communication specialists, and others.

Perry (2012) reinforces the need for authorities to engage also non-governmental actors and public health practitioners from various disciplines in scoping, planning, analyzing, and managing environmental risks related to NORM. As seen also in other nuclear fields (e.g. radioactive waste management, Elam and Sundqvist, 2007), local stakeholder groups created to address a specific problem become important stakeholders at regional or national levels. Whittaker (1998) shows how a local environmental group, created as a reaction to the failure of the local authorities to close down a waste dump, became gradually recognized and gained greater legitimacy in local and regional government organizations by broadening its scope to include wider range of local issues, and by creating links with regional and national environmental groups.

Stakeholder involvement, or lack thereof, is inherently linked to the distribution of power in society (Whittaker, 1998; Arvai and Gregory, 2003). When perceived unequitable, this may heighten anxiety and risk perception. The study of Whittaker (1998) shows for instance that cancer fears among a community with a sand mining legacy site were linked to feelings about lack of access to power.

Community involvement is thus needed, as it empowers people to regain the feeling of control over their own lives. To this end, Arvai and Gregory (2003) showed how citizens expressed their belief that important public policy decisions that affect them should include input from both 'experts' and 'the public'.

Furthermore, Hamilton (2003) argues that productive stakeholder involvement requires an understanding of the different ways people use to learn about and assess the risks, and the technical and/or cultural risk arguments mobilized by different stakeholders.

4.2.6. Risk communication

Communicating about risks and benefits of environmental remediation options increases trust in risk regulators (Arvai and Gregory, 2003). However, communicating about NORM is not straightforward: there are scientific and societal uncertainties, as well as a plurality of values and interests at play. Perry (2012) pointed out in relation to hydrofracking the tensions between regulator and industry and their trade organizations, and the conflicting risk related information provided by different governmental actors, which creates public distrust.

König et al. (2014) identified four main reasons for problems in risk communication and risk management of historical TENORM sites: lack of understanding by authorities of residents' values, the complexity of risk communication in a crisis situation, the regulatory gap between radiation protection and soil protection with regards to TENORM/NORM legacies in Germany, and the challenge of communicating a highly complex scientific topic to non-scientists. The authors of the study also pointed out the added value of an external facilitator acting as mediator between scientists and residents, that would take the time to answer residents' questions and acknowledge their concerns.

The study of De Lemos et al. (2009) highlights that effective communication of health risks requires situated approaches that consider both the socio-cultural context and the state of the art in risk communication methods. Their study suggests that thematic maps, developed in collaboration with the affected communities, are easy and culturally-adapted forms of presenting health risk information, enabling community members to make their own decisions about daily activities and their exposure to the contaminant. The visual (rather than written) communication of these maps and the iterative way in which stakeholders are involved in its development are highlighted as particularly important.

4.2.7. Ethical considerations

Several studies direct their attention to vulnerable populations. Brugge et al. (2007) highlight, for instance, how incidents at uranium mining or milling facilities located in low income, rural, native American communities are not well studied and receive less attention from academia, regulators and policy makers than incidents affecting other communities, with higher socioeconomic status or white victims.

Brugge and Goble (2002) direct attention towards particular cultural and socio-economic factors that render specific populations more vulnerable due to lack of access to knowledge about risks associated with uranium mining. Their historical study revealed that the Navajo population did not have equal access to knowledge about radiation and its hazards due to their geographical location, language, and low literacy level.

Malecki et al. (2017) further points out in their study on radioactivity in water from private wells that most vulnerable populations include those that not only have potentially highest exposure from radio-contaminants in groundwater, but also those who are less inclined to test and apply mitigation measures: e.g. in their case younger individuals, or those with lower education and income.

Another dimension of vulnerability is time. The study of Feldman and Hanahan (1996) also highlighted concerns about future generations living close to contaminated sites.

Who bears the responsibility for remediation also raises ethical questions, especially in case of historical pollution. The study of König

et al. (2014) highlighted the perceived injustice resulting from having to pay for the remediation of historical contamination caused by a third party.

Equity was revealed as important also by Johnson (2014) in a study relating to management options for radon in water and indoors. This showed that health, costs, and equity were main values pointed out by participants, meaning, for instance, that effectiveness of policies should receive equal attention to fairness.

4.2.8. Risk management and decision-making considerations

The study of Feldman and Hanahan (1996) concerning environmental remediation of a site contaminated from uranium ore processing revealed that respondents were most concerned about those issues which had the highest potential of affecting their individual health and well-being. In terms of remediation strategies, they preferred those seen as most effective in addressing these issues: treatment and excavation with off-site disposal. The least preferred strategies were those involving on-site management of contaminated soils, with the exception of maintaining the site unchanged, subject to institutional controls.

When confronted with a case study of radium in drinking-water in Iowa (US), Rajagopal and Tobin (1990) found that a majority of 'expert' respondents perceived corrective action to be desirable but not needed immediately. In terms of which corrective actions to apply, the blending of contaminated supplies with other sources was the most preferred option, especially among those respondents with higher educational levels. In general, in a context of incomplete information, most experts preferred some form of action rather than postponing actions due to uncertainty. In terms of the decision-making process, both local and state governments and experts were deemed major players in managing the problem of radium in drinking water. A lower, but still important, role in the management and decision-making process was assigned to federal agencies, the general public, and civic organizations.

Social studies on risk perception and risk communication show that members of the public use a wider range of considerations compared to experts, when making judgments about specific risks (Slovic et al., 1982; Sjöberg, 2000; Renn, 2017). The decision analysis experiment by Arvai and Gregory (2003) provides empirical evidence that information reflecting a wider range of societal values, rather than simply techno-scientific facts, is more helpful for people to make choices about clean-up options in a way that reflects "*what really matters to them*" (pp. 1475). While both a science-based and a values-based approach are reported to have a positive effect on people's self-assessed knowledge, comfort with their choices, and feelings that their choices match their actual concerns, the values-based approach proved better suited to support 'non-expert' stakeholders in making decisions.

With respect to radon in water, an interesting finding of Johnson (2014) was that several participants in their study made a difference between responsibilities for the management of radon in water as compared to radon indoors. Radon in water was seen as an "utility issue", requiring responsible management by authorities, whereas in air it was considered as "an individual issue."

Several of the articles analyzed substantiate the need for social studies informing NORM risk –management policies. As Feldman and Hanahan (1996) point out, remediation strategies and concerns about the site are related. In her study on hydro-fracking, Perry (2012) further argues that minimizing or ignoring local or regional societal implications "*may lead to faulty decision making and make it more difficult to accurately identify local hazards and manage risks and uncertainties in the future*" (pp. 353).

Perry (2012) and Torres et al. (2017a, 2017b) also emphasize the need to engage researchers, non-governmental actors and public health practitioners from various disciplines in scoping, planning, analyzing, and managing environmental risks related to NORM.

5. Discussion

This systematic review of social scientific literature clearly illustrates that more research is needed on the societal aspects of NORM. This finding converges with priority list identified by the Strategic Research Agenda for Social Sciences and Humanities in the field of ionizing radiation (SHARE, 2020). As König et al. (2014, pp. 575) noted, "*despite several decades of studies on the risk assessment and risk perception of ionizing radiation, risk management of radioactive materials remains a challenging issue*." Perry (2012) also pointed to the lack of integration of social, community, and health science information with environmental data, by either the scientific community or the regulatory community.

Table 3 summarizes main societal challenges related to NORM, as derived from the present study (sections 3 and 4). This table also provides examples of studies that have investigated or – to a lesser extent- addressed various aspects related to these potentially overlapping and/or mutually shaping challenges. As evident from the review of scientific papers, these challenges are addressed to a limited extent by scholars in social sciences and humanities.

Based on existing studies, our review highlighted a number of aspects connected to risk perceptions, social concerns and preferences towards specific remediation or risk management options. This includes, among others, perceptions of residents' own health, their children's health, cost of remediation, equity and justice, participation and preservation of community values. However, there is a need for methodological improvements and a stronger empirical evidence, covering a broader spectrum of NORM exposure situations and cultural contexts. Better indexing of such studies is also necessary to allow for an easier retrieval in dedicated literature reviews.

In some studies (e.g. Whittaker, 1998), concerns about radioactivity were spontaneously brought forward by residents, while in other cases people's main concerns centered around the types of pollution that are readily discernible by human senses (e.g. Zierold and Sears, 2015b; Zierold et al., 2016). The question is then whether in the latter cases, people were unaware about the mixed pollution, or whether they perceived radiological risk as lower than those they could more easily assess using their senses. Studies from Flin et al. (1996) or Whittaker (1998), among others, point more to the direction of the former, rather than the latter hypothesis. Lack of timely information about the presence of radioactivity in the environment due to NORM industries may take a heavy toll on the effective management of risks from NORM and undermine people's trust in authorities, science and the industry (Hamilton, 2003). Indeed, several authors (e.g. Perry, 2012) argue for more complete disclosure of the risks associated with NORM industries and in relation to NORM sites.

The scientific articles analyzed also point towards topics of particular interest for social scientific studies, among others: incidents at uranium mining or milling facilities located in communities with low socio-economic status (Brugge et al., 2007), risk perception and the psychological and social stress in communities with oil and gas industries (Perry, 2012), or the protection of vulnerable populations who are exposed to NORM -now or in the future, or who are less likely to know about and/or test for radioactivity and apply mitigation measures (Malecki et al., 2017). Although some of the studies suggesting these research needs are more than ten years old, no follow-up studies addressing these have been found, which indicates that these research needs continue to be open issues.

Priority research areas for social science studies on NORM are also highlighted in the Strategic Research Agenda of the SHARE platform (Social Sciences and Humanities in Ionizing Radiation Research, SHARE, 2020), for instance multidisciplinary and participatory approaches to building radiological protection culture; the influence of framing on risk perception and (self)protective behaviors; communication of uncertainties; or holistic approaches to decision-making for NORM sites.

Further social studies should address these topics, as they can identify and help address societal concerns, inform policy makers,

Table 3
Social, economic, political, legal and cultural-historical challenges for NORM management.

Type of issue	Challenges for NORM management	Studies researching or addressing the challenges (cf. no. in Appendix)
Impact of contamination/ remediation	● Uncertainties about the links between illness history and the radioactive pollution ● Remediation impact on the socio-economic development of region ● Health impact of NORM and influencing factors (e.g. cultural, behavioral or social) ● Health impact of remediation works ● Long-term effectiveness of remedial actions ● Preservation of community values and the social space it occupies	1, 3, 9, 10, 16, 18
Knowledge and awareness	● Limited technical knowledge of general population and other stakeholders and low understanding of NORM remediation issues and processes ● Limited knowledge on the sources of contamination and radiation ● Unknown exposure to dangerous amounts of radioactivity ● Exposure to mixed contaminations ● Conflicting scientific reports ● Lack of timely information	1, 2, 7, 8, 9, 12, 14, 18
Trust between societal actors	● Lack of trust between the stakeholders involved in the NORM management process	3, 10
Risk perception and acceptability or risks	● Different risk perceptions on NORM contaminated or remediated sites, especially between experts and residents ● The meaning of end state of a remediated site ● The justification of using specific models for radiological assessments. ● Different problem framing/ vocabulary and understanding of radiological risks ● Potentially high risk perception of risks from the radioactive pollution	4, 6, 7, 8, 9, 11, 14, 15, 17, 18, 19, 20
Plurality of values and interests	● Differences in demands and concerns between stakeholders ● Opposition to the remediation programme from individuals or groups ● Opposition to waste disposal on-site	3, 10
Historical and cultural context	● Negative experience with remediation programmes, or lack thereof ● Negative experience with stakeholder involvement ● Remediation of cultural heritage sites ● Less attention (e.g. from media or politicians) to rural, low income areas	1, 2, 3, 4
Communication	● Unsuitable objectives of communication plans about remediation programs e.g. to educate instead of engage ● Lack of transparency or uncertainty about transparency of communication ● Scientific uncertainties related to low doses and lack of communication about knowledge limitations ● Unsuitable style of communication e.g. numerical communication instead of risk comparisons ● Understanding of constraints ● Uncertainty about the correctness of information ● Uncertainties about the effectiveness of communication ● Lack of understanding by authorities of residents' values ● Regulatory gap between radiation protection and soil protection with regards to NORM ● Communicating a highly complex scientific topic to non-scientists ● Potentially insufficient media attention in specific situations ● Lack of communication practices that reflect differences between technical and cultural understandings of risk	1, 2, 3, 6, 11, 13, 20
Political factors	● Lack of support by governmental authorities to implement remediation programmes ● Limited national interest for underprivileged areas, e.g. populated by indigenous people	1, 2, 10
Policy and legal	● Verifying fulfilment of international obligations as established in treaties or conventions ● Lack of a legal and regulatory framework ● Regulatory authority is not independent or is ineffective ● Lack or incompleteness of environmental remediation regulations and standards or guidelines. ● Assignment of responsibility for remediation ● Changes in administrative procedures and legal framework related to remediation ● Lack of social studies and lack of integration of multiple disciplines and sources of knowledge by scientists and regulators ● Regulatory and institutional barriers that make	11, 16, 19

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Table 3 (*continued*)

Type of issue	Challenges for NORM management	Studies researching or addressing the challenges (cf. no. in Appendix)
	incorporation of societal costs difficult	
Stakeholder involvement	● Absence of, or ineffective, national policy and legal framework for stakeholder engagement ● Groups and individuals opposing stakeholder involvement in remediation programmes ● Complex procedures for involvement ● Changing positions within one stakeholder group ● Limited capacity to express opinions in public ● Lack of funding sources to undertake involvement ● Limited access to information and communication ● Information overload ● Too little use of independent facilitation ● A lack of motivation to participate in the process ● Unrealistic expectations ● Absence of continuity in stakeholder involvement and communication ● Lack of balance between transparency and security ● Perceived unequal distribution of power, feeling of being trapped in pollution ● Inclusion of local population in communication tools' development	3, 5, 19
Evaluation and decision processes	● Little recognition of the links between environmental, economic, and social concerns of the stakeholders ● Lack of sufficient empirical evidence for social determinants relevant to NORM management ● Justifying the content of the decision framework in term of risk and cost–benefit analysis ● Demonstrating that the framework reflects good practice, enables stakeholder engagement in environmental decision making, and that requirements are implementable and provide for adequate control	13
Economic	● Real costs of NORM management (e.g. unexpected contamination found, large waste volumes) ● Who will bear the costs of remediation ● Shared ownership of pollution (e.g. chemical or radiological) ● Polluter doesn't exist anymore ● Availability of funds ● Transparent use of financial resources ● Costs related to extent to which remediation should be done ● Costs related to type and volume of waste to be deposited on site or removed and deposited externally ● Long-term stewardship ● Challenges related to limited budget to cover stakeholders' demands;	11, 19
Ethical	● Equity and social justice ● Balancing the principle of individual dose limitation with the principle of positive benefits for the greatest number of people in society ● Identification and protection of vulnerable groups ● Under-representation of vulnerable groups in social studies	1, 2, 4

researchers and implementers, and contribute to enhanced NORM management.

6. Limitations

Our literature review study selected only scientific papers published in the English language. It therefore did not account for any studies in national or regional journals published in another language.

7. Conclusions

NORM management is a complex issue that requires scientific input from a variety of disciplines, not least social sciences and humanities.

Existing social scientific studies suggest that factors potentially related to risk perceptions, social concerns and preferences towards remediation or risk management options include – among others, residents' perceptions of their own health, their children's health, the cost of remediation, equity and justice, community participation in decision making, and the preservation of community values. However, there are only few social science studies in the literature addressing NORM management and they provide limited coverage of planned and existing NORM exposure sites and of geographical areas.

Our review showed that there is a need for further social science research in order to strengthen and broaden the empirical evidence and to follow up older studies such as to account for social, cultural, regulatory and other changes. Future work should also be devoted to designing methodologies to identify and address social considerations of NORM, conducting situated social studies focusing on particular NORM situations as well as longitudinal studies.

Declaration of competing 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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Appendix. Social scientific studies addressing NORM identified through the systematic review

No	Reference	NORM situation addressed	Study objective	Method and target population	Country	Variables/dimensions in focus
1	Brugge et al. (2007)	Accidents at uranium mining and milling facilities	Raise awareness on the environmental and health impact of uranium mining. Explain the lack of attention to incidents at uranium mining and milling facilities occurring in low-income and rural native American communities.	Qualitative: narrative description based on document analysis and experiential knowledge. Population: low-income and rural native American communities	USA	Radiation exposure Health impacts Media and regulators' attention to incidents occurring in the first few stages of the nuclear cycle
2	Brugge and Goble (2002).	Exposure to radon of workers in uranium mining	History of the development of uranium mining in the US from the lens of the experience of Navajo People	Qualitative: historical research Population: native American communities	USA	Recognition of radon as a public health problem Implementation of protective measures Communication about radon with miners Health regulations Social actions from Navajo community members
3	De Lemos et al. (2009)	Exposures due to wastes from uranium mining	Utilize both environmental and water use data to define land and water resources that may act as routes for toxicant exposure; and integrate these data using GIS tools into thematic maps to inform Navajo people of (public and ecological) health risks from historical mismanagement of waste from uranium mining.	Mixed methods (quantitative and qualitative): public health surveys (N = 151 residents completed surveys out of 500 distributed), and feedback from 'working group' of Navajo stakeholders (N = 10). Participants recruited at water hauling locations, chapter meetings, public events, or by word of mouth.	USA	Self-reported activities and behaviors influencing exposure to historic uranium mine wastes: water and land use patterns, occupational histories, locations of residences and proximity to contaminated sites, socio-economic factors, cultural practices, health risk factors and medical status. Effectiveness of developed risk communication maps when displayed in homes (assessment by working group members).
4	Petrescu et al. (2019)	A legacy site of a former uranium mine	To capture and assess relevant aspects of sustainable development in a Romanian community characterized by the presence of a former uranium mine.	Mixed: Secondary data and a questionnaire (open and closed questions) administered through face-to-face interviews with N = 15 members of (all) households living in the selected community. Data coded and analyzed in a quantitative manner despite the limited sample.	Romania	Socio-demographic variables (members of household, years spent in the community, income, foreign languages spoken, family members abroad and in jail). Indicators of sustainable development (e.g. in terms of individual development, social system, infrastructure, economic system, resources and environment). Negotiation power of local community members (stakes, coercive power, expert power, etc.)
5	Feldman and Hanahan (1996)	Historic contamination with naturally occurring radionuclides (uranium-238, tho-rium-232, radium-226) and by-products of their decay (radon and thoron) from uranium ore processing (nuclear weapons program)	Identify actual and desired levels of public involvement in the remediation of a radioactively contaminated site. Gain insight into preferences of local citizens regarding the remediation strategy, and their concerns related to environment, health, the economy and future land-use.	Quantitative: a survey with residents living in the vicinity of the contaminated site (N = 199, completed response rate of 20%). Random stratified sample. Respondents contacted via mail, with follow-up by mail and telephone to non-respondents.	USA	Socio-demographic variables (gender, education, employment status, length of residence, distance of residence from considered sites, children in household). Type of activities related to site remediation that respondents had previously participated in, and frequency of participation. Type of activities they would be interested in participating in. Opinions about considered remediation strategies. Opinions on issues related to the site and its remediation (e.g. health, future land use, property values, environment, transportation of contaminated materials, public involvement)
6	Hamilton (2003)	Radium in wastes on historical site of a U processing plants for nuclear weapons production	Analyze how participants in a public debate regarding two options for management of radium waste (site cleanup vs. radium extraction for cancer treatment and delayed cleanup)	Qualitative: Rhetorical analysis of a public meeting transcript, highlighting rhetorical strategies and arguments used: technical (grounded on values of science e.g. quantification,	USA	Key terms used by an expert and members of the public to define the situation. *Rhetorical strategies* mobilized by participants, and how these related to *frames of acceptance*

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No	Reference	NORM situation addressed	Study objective	Method and target population	Country	Variables/dimensions in focus
			used technical and/or cultural rationales to formulate their views and persuade others.	objectification), and/or a cultural (grounded on values such as experience, analogy, historical precedent)		Use of technical and/or cultural rationales to create common understandings and persuade others.
7	Zierold and Sears (2015a)	Coal ash storage sites	Explore if healthcare providers ask patients whether they reside near a coal ash storage site. Evaluate if differences in demographics and perception of health are related to whether or not a healthcare provider asks about living near a coal ash storage site. Assess which health conditions prompt healthcare providers to ask if a patient lives near an environmental hazard.	Mixed methods (qualitative and quantitative): - focus groups (five groups with N = 26 adults living next to coal ash storage site based on semi structured protocols) - cross-sectional survey (N = 231 community members, questionnaire with 38 multiple choice questions and one open ended question). Participants recruited with help from community leaders, at two community-wide meetings. Radioactivity not emerging spontaneously as an issue	USA	For focus groups: (1) community strengths and weaknesses (six questions), (2) perceptions and beliefs about coal ash and coal ash exposure (four questions), and (3) perceptions about community health and personal/family health (five questions). Cross-Sectional Survey: (1) demographics, (2) concern about coal ash, (3) perceptions of health, (4) health conditions, (5) symptoms, and (6) exposure-reducing health behaviors. Demographics included gender, current age, length of time living near the coal ash storage site, and whether the respondent owned or rented their home.
8	Zierold and Sears (2015b)	Coal ash storage site	Explore parents' perceptions of the health and exposure of children living near the site	Zierold and Sears, 2015a	USA	Idem Zierold and Sears (2015a)
9	Zierold et al. (2016)	Coal ash storage sites.	Investigate attitudes, perceptions and protective behaviors of neighboring communities with regards to the hazard posed by coal ash storage sites, and links between the level of concern about coal ash and exposure-reducing behaviors.	Zierold and Sears, 2015a	USA	Idem Zierold and Sears (2015a)
10	Whittaker (1998)	Radioactive contamination from previous sand-mining activities	Investigate how people from the Oceanpoint community construct their discourses about environmental pollution and risks of cancer related to land contamination legacy due to a land-fill dump site and radioactivity from previous sand-mining activities.	Mixed methods (qualitative): in-depth interviews with N = 88 residents (from a total population of 2715 people) and seven focus groups. Purposive sample recruited via community groups.	Australia	Ethnographic study using the concept of 'popular epidemiology' to investigate how people make observations of health problems, form hypotheses linking health problems with environmental contaminants, seek information and undertake political activism.
11	König et al. (2014)	Legacy site from a former chemical plant, in which uranium was processed for coloring agents and thorium for mantles for gas lanterns, leading to soil contamination and indoor radon due to uranium residues.	Investigate underlying reasons for communication problems between experts and affected citizens in the risk assessment phase, for the case of a remediation site with residual radioactive contamination in a residential area.	Qualitative content analysis based on semi-structured interviews with open ended questions. Guided interviews with local residents of the contaminated area (N = 11), the contaminated community gardening area (N = 2). Expert interviews (N = 11) with experts from the Hanover remediation case (N = 5) and from the uranium mining remediation case in Saxony (N = 6). Interviews with journalists (N = 2). Experts contacted via professional and direct contacts; recruiting of residents via gatekeeper processes to preserve privacy.	Germany	The interview guidelines with residents included personal data (duration of living in the area), respondent's experience of the remediation case, perception risk from of TENORM residues, perception of risk management by authorities' and professionals, evaluation of risk communication (e.g. information received). Expert interviews included questions about professional data, description of the case, notably particular characteristics relating to TENORM remediation, assessment of risk, perception of residents' reactions, risk communication (e.g. personal experiences related to the case).
12	Mancl et al. (1994)	Sources of natural radiation, among which uranium ore, smoke detectors and bricks used to build brick homes	Determine people's awareness of sources of radiation in their environment. Effect of education on awareness.	Quantitative: Telephone survey with random selection of households (random digit dialing). N = 892 complete responses out of 1450 households contacted.	USA	Socio-demographics (e.g. education, gender). Agreement (yes/no) that a number of activities generate radiation exposure, among which bricks used to build brick homes. Agreement (yes/no) that a number of elements can be

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No	Reference	NORM situation addressed	Study objective	Method and target population	Country	Variables/dimensions in focus
						sources of radiation, among which uranium, radon and ash coal from coal plants.
13	Arvai and Gregory (2003)	Three hypothetical sites: i) former nuclear weapons facility, ii) irrigation - tunneling project with radon emissions, iii) storage depot for farm fertilizers containing trace amounts of radioactivity.	Compare two approaches of informing 'non-expert' stakeholders about contaminated sites, with respect to facilitating their involvement in decisions regarding remediation: - A 'science based' approach (providing detailed factual information) - A 'value-based' approach (connecting similar factual information with prioritized values).	Quantitative, experimental set-up. N = 50 respondents: 'paid volunteers' recruited through a data services laboratory.	USA	Relations between the information approaches and respondents' (self-reported) level of knowledge, degree of comfort with decisions, choices regarding remediation (in terms of intensity of the clean-up effort and size of funding allocation per site), and how well their stated choices reflected their concerns. Respondents' levels of trust in 'official' decision-makers (government) were also measured.
14	Torres et al. (2017a)	NORM in water produced from hydraulic fracturing in Oil and Gas exploration and production	Understanding stakeholders' risk perception and awareness regarding NORM and the management of produced water in the process of hydraulic fracturing in North Dakota (US). Determine most influential variables on risk perception as well as the inter relation between the variables.	Quantitative: online survey, with four stakeholder groups (N = 191 completed surveys): general public, oil field operators, produced water hauling truck operators, and experts (16 people working directly with oil production and produced water management or as part of the emergency management personnel). More than 60% of the participants between 18 and 34 years old. Sample not representative. All data presented together apart from cross-tabulation with 'expert'.	USA	Socio-demographic information, sources of information used by respondents, image perception, risk perception (three scenarios: produced water storage, failure of equipment for handling produced water, transport of produced water by truck), awareness and familiarity with contents and management of produced water, trust in organizations involved in management of produced water, for experts only: estimated levels of awareness and risk perception among different stakeholder groups
15	Torres et al. (2017b)	NORM in water produced from hydraulic fracturing in Oil and Gas exploration and production	A holistic assessment of risk regarding surface water contamination with lead from oil produced water.	Quantitative: A technical risk assessment combined with the results of a 'social' risk perception study. The latter is identical in terms of method and target population as Torres et al. (2017a.)	USA	The 'social' risk perception study builds on part of the data reported in Torres, Yadav and Kahn, 2017a, particularly the questions focused on risk perception and awareness of produced water, and experts' opinions on other stakeholders' awareness and perceptions.
16	Perry (2012)	Hydraulic fracturing in Oil and Gas exploration and production	Develop a framework for addressing societal costs associated with natural gas extraction and production from tight shale, tight sand, or coal-bed methane formations that use hydraulic fracturing processes	Qualitative: desktop case study of US EPA's 2011–14 Hydraulic Fracturing Study	USA	Societal costs (psychological, social, community and human health risks and uncertainties). Regulatory and institutional barriers to incorporation of societal costs. Stakeholder engagement.
17	Flin et al. (1996)	Off-shore oil and gas platforms	Investigate subjective risk perceptions of workers on offshore oil and gas installations and how these relate to more objective risk data (e.g. accident rates).	Quantitative (survey): Off-shore Risk Perception Questionnaire Workers on 6 UK offshore oil and gas installations. N = 622 respondents 40% response rate. Representative in terms of demographics (average 40 years, 98% male etc.)	UK Continental Shelf (UKCS)	Socio-demographics: current job situation, physical working environment, job satisfaction, occupational health, personal accidents and near-misses, personal support and help from others. Perception of risks from installation related hazards Probability of injury Perception of risk related to work tasks Safety facilities and others' concern for safety Safety attitudes (particularly safety vs. production) Platform safety case and accidents
18	Malecki et al. (2017)	Radon in private well-water	Survey private well users to quantify testing and treatment patterns and gather data on motivations and barriers to well stewardship.	Quantitative (survey) (+physical exam in baseline). Population: Private well users, N = 719 households. Convenience sample, selected from previous baseline health	USA	Socio-demographics: gender, age, marital status, education, income, BMI, smoking status, urbanicity, children, health region Private well user testing

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No	Reference	NORM situation addressed	Study objective	Method and target population	Country	Variables/dimensions in focus
				study. Response rate: 64%. Greater participation by older and more educated; sample does not fully represent private well owners in the state, particularly more vulnerable individuals.		patterns, amongst others for radon - parameters tested for - what organization conducted the test - risk perceptions and concerns driving testing behavior - types of treatment used - reason for treating not treating the well - knowledge and information - convenience or lack therefore
19	Rajagopal and Tobin (1990)	Radium in drinking water	Identifying preferences of experts with regard to economic and policy options in ground-water protection, focusing on the case of radium in drinking water in Iowa (USA).	Quantitative: mail survey with closed and open questions, distributed among a selected sample of 'experts' (people who are or have been actively involved in ground-water protection issues) in the US mid-West. Purposive sample of participants. Response rate: 80% out of 150 experts agreed to participate in the study; out of these, 81% (N = 97) returned the completed questionnaire.	USA	Socio-demographic variables: (level of education & subjects studied; professional experience & position; institutional affiliation; residential status in Iowa) Perceived seriousness of the problem Preferred corrective actions Who should pay Level of involvement of different stakeholders in decision-making.
20	Johnson (2014)	Radon in drinking water	Illustrate communication challenges and gain better understanding of how citizens think about policy trade-offs in management of radon risks in drinking water and indoor air. Identify citizens'-preferred options concerning management of radon in water and indoor air.	Qualitative: six focus groups, averaging 10 people each (N = 60 participants in total). Participants recruited from customers of utilities that would be affected by the policy choices.	USA	Trade-offs in management of radon risks in drinking water and in indoor air. Citizens' views on policy objectives Values underlying citizens' preferences for specific (real or fictive) policy options. Self-reported radon knowledge

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