Taking Nanotechnological Remediation Processes from Lab Scale to End User Applications for the Restoration of a Clean Environment

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WP9: Dissemination, Dialogue with Stakeholders and Exploitation

DL 9.1

Promoting Nanoremediation Using Nanoscale Zerovalent Iron (nZVI): Risk-Benefit and Markets Appraisal, Initial Exploitation Strategy and Consultation

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Executive Summary

NanoRem (Taking Nanotechnological Remediation Processes from Lab Scale to End User Applications for the Restoration of a Clean Environment) is a research project, funded through the European Commission's Seventh Framework Programme. NanoRem focuses on facilitating practical, safe, economic and exploitable nanotechnology for *in situ* remediation of polluted soil and groundwater.

This report provides an overview of NanoRem WP9 outputs from Months 1-24 (up to January 2015) of the project. The overall objective of WP9 is to facilitate dissemination, dialogue and exploitation, transmitting the results of NanoRem widely amongst user communities.

The work outlined in this report had the aim of developing an understanding of the "value proposition" (the overall promise of value to be delivered) for iron nanoparticles/ nanoscale zero valent iron (nZVI) in remediation in terms of a risk-benefit appraisal of its use given the current state of knowledge. A webpage has been developed for the NanoRem project, which includes the salient points from the risk-benefit analysis as "Information for Decision Makers". Workshops have been organised and carried out to elicit expert and stakeholder opinions on the sustainability of nanoremediation, factors affecting its potential market development and the risks associated with the deployment of NPs. The outcomes of stakeholder engagement and the risk-benefit appraisal work have been incorporated into scenario analysis. Scenario analysis has been used to explore possible market developments and the factors affecting this over the short and medium to longer term. An analysis of strengths, weaknesses, opportunities and threats (SWOT) and how these might change over time has been used to draw some conclusions about the broad actions that might support better exploitation of nanoremediation. This report focusses on nZVI, as the most frequently used nanoparticle type for remediation. Future NanoRem work will involve undertaking similar analyses for other nanoparticles being developed by NanoRem.

This report forms Deliverable 9.1 of the NanoRem project and has been developed using summarised information from NanoRem Internal Deliverables 9.1, 9.2, 9.3 & 9.4; alongside a risk-benefit appraisal report for nZVI.

This report is a preliminary out put of NanoRem and readers are invited to comment on its contents. This can be done online via www.nanorem.eu. All comments received will be considered in an updated risk benefit appraisal taking place over the second half of the NanoRem project. The consultation period will be open until July 31st 2015.

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1 Introduction

NanoRem (Taking Nanotechnological Remediation Processes from Lab Scale to End User Applications for the Restoration of a Clean Environment) is a research project, funded through the European Commission's Seventh Framework Programme. NanoRem focuses on facilitating practical, safe, economic and exploitable nanotechnology for *in situ* remediation. This is being undertaken in parallel with work developing a comprehensive understanding of the environmental risk-benefit for the use of nanoparticles (NPs), market demand, overall sustainability, and stakeholder perceptions. This work is being carried out by "Work Package 9" (WP9) of the NanoRem project.

In situ remediation techniques (exploiting biological, chemical, physical stabilisation and/or thermal processes within the subsurface) are being increasingly used to avoid excavation of materials or surface treatment of groundwater from "pump and treat" projects. The use of NPs potentially extends the range of available *in situ* remediation technologies, and it may offer particular benefits in some applications (Bardos *et al.* 2014, O'Carroll *et al*. 2013, Bardos *et al*. 2011).

This Deliverable focuses on nano-scale zero valent iron (nZVI) as the best known and most frequently encountered NP, although the information provided may also be indicative for other NP types used in remediation.An outline of risk-benefit appraisal activities is provided, as well as an overview of the NanoRem website and an initial outlook on the broad exploitation strategy for nZVI. This report forms NanoRem Deliverable 9.1, providing an overview of NanoRem WP9 work up to project Month 24 (January 2015 – two years into the project). The report is based on information in NanoRem Internal Deliverables 9.1, 9.2, 9.3 & 9.4; alongside a publically available risk-benefit appraisal report for nZVI[1].

This report is a preliminary output of NanoRem and readers are invited to comment on its contents. This can be done on line at www.nanorem.eu. All comments received will be considered in an updated risk benefit appraisal taking place over the second half of the NanoRem project. The consultation period will be open until July 31st 2015.

2 Overview of WP9 Outputs up to Month 24

Table 1 provides a list of NanoRem WP9 outputs up to project Month 24 (January 2015), including a brief description of the content of the output. These form the base material on which this report has been developed.

[1] http://www.nanorem.eu/Displaynews.aspx?ID=525

Table 1 - Summary of NanoRem outputs Months 1-24

Output	Overview
IDL 9.1 – NanoRem Project Website	A website for the NanoRem project was developed. The website encompasses an Intranet and an Extranet. Access to the Intranet is limited to members of the NanoRem consortium. The Extranet serves for communication with stakeholders and provides Information for Decision Makers (see Milestone 3, below). Annex 2 and Annex 3 provide further information on the project website and the Information for Decision Makers. www.nanorem.eu
Milestone 3 - Webpage operating as information / support tool for negotiations with owners / regulators	MS3 initially comprised a set of Frequently Asked Question (FAQ) pages to provide Information for Decision Makers on the NanoRem website. The focus of these pages is on nZVI. Subsequently this information was supplemented with a series of subject orientated Thematic Pages. This will be gradually expanded over time, for example to include other types of NP, leading towards MS8 (Month 36). http://www.nanorem.eu/Informationfordecisionmakers.aspx
IDL 9.2 – Workshop report on "risks" including the Interim Position Statement for field trials and research requirements	A pre-deployment "risks" workshop was held in Nottingham, UK in July 2013. This was developed into a report (IDL 9.2). The key outcomes of this work are discussed in Section 4 and Annex 1. The full IDL9.2 report is restricted to the NanoRem consortium. Summarised information is available at: http://www.nanorem.eu/displayfaq.aspx?id=15
IDL 9.3 - Workshop report on "sustainability and markets"	A second workshop was held in Oslo, Norway in December 2014. This workshop focussed on understanding factors affecting available markets and key sustainability concerns across a range of professional and expert stakeholder opinions. A workshop report will be made available by Summer 2015 from: (Tomkiv *et al.* 2015) http://www.nanorem.eu/displayfaq.aspx?id=12
IDL 9.4 - Broad exploitation strategy and risk-benefit analysis (Bardos *et al.* 2015) (initial versions)	This report looked to develop an understanding of "value proposition" (Defined as: the overall promise of value to be delivered) for nZVI use in remediation in terms of a risk-benefit appraisal of its use given the current state of knowledge. It provides an overview of the interim results of scenario analysis conducted to explore factors affecting the development of the market for nanoremediation in the EU by 2025. A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was used to draw some broad conclusions about actions that might support better exploitation of nanoremediation. http://nanorem.eu/news.aspx
Task 9.3.2 - Risk-benefit appraisal and developing a market consensus	Discussions are ongoing with Common Forum and NICOLE networks with the purpose of developing a link for potential future engagement work.
	A Risk-Benefit Appraisal for the Use of nZVI report was released in June 2014 (Bardos *et al.* 2014). Available at: http://www.nanorem.eu/Displaynews.aspx?ID=525. This was used to inform Milestone 3 and IDL 9.4.

3 nZVI: a Brief Technology Description and Market *Status Quo*

Micro-scale zero valent iron (granular ZVI) has been used as a treatment reagent for *in situ* groundwater remediation for many years, in particular within permeable reactive barriers (NATO, 1998). Nano-scale zero valent iron (nZVI) is a type of iron NP that has been injected *in situ* as a groundwater and aquifer treatment.

NPs are typically defined as particles with one or more dimension of less than 100nm (Rauscher *et al.* 2014). As a result of their size, NPs can have markedly different physical and chemical properties compared to their micro-sized counterparts, potentially enabling them to be utilised for novel purposes, including remediation. To date the most widely used NP in remediation has been nZVI. Whilst the possibility of unique characteristics gives nZVI promise for beneficial applications, it is simultaneously a cause of concern, as there is a degree of uncertainty with regards to particle behaviour, fate and toxicity. As produced, most nZVI tested falls into the 10-100 nm size range (O'Carroll *et al.* 2013, Müller & Nowack 2010, Karn *et al.* 2009, Nurmi *et al.* 2005), although it tends to agglomerate to form larger particles.

The first documented field trial of nZVI, in 2000, involved treatment of trichloroethylene in groundwater at a manufacturing site in Trenton, New Jersey, USA (Elliott and Zhang, 2001). Several commentators anticipated that nZVI technology would take off rapidly because of its perceived benefits such as rapid and complete contaminant degradation. However, subsequent uptake of the technology has been relatively slow compared to other contemporary process based technologies. Lee *et al.* (2014) have reviewed 60 field applications worldwide. Bardos *et al.* (2014) identified around 70 projects documented worldwide at pilot or full scale. Most such deployments of nZVI have focussed on the degradation of chlorinated solvents for plume (i.e. pathway interruption) management although pilot studies have also demonstrated successful treatment of BTEX, perchlorates, hexavalent chromium, diesel fuel, PCBs and pesticides. O'Carroll *et al*. (2013) detail the chemical processes involved in the treatment of chlorinated solvents and various metals by nZVI. Several approaches can be taken to NP deployment for contaminant remediation, including direct injection.

In 2007, a European report forecast that the 2010 world market for environmental nanotechnologies would be around $6 billion (Rickerby & Morrison 2007). In practice, this market has not been achieved. To date, the use of nZVI in remediation in practice is largely a niche application for chlorinated solvents in aquifers, competing with more established techniques such as *in situ* bioremediation, chemical reduction and granular ZVI (e.g. in permeable reactive barriers). Bardos *et al*. (2011) identified just 58 examples of field scale applications of nZVI, which was expanded to 70 examples by Bardos *et al.* (2014). Of the identified examples, only 17 were in Europe (Czech Republic, Germany and Italy). The limited adoption of nZVI is linked to uncertainty over the balance of benefits versus risks from NP use in remediation. An additional factor that is likely to have hindered the development of the nanoremediation market is that nanoremediation costs are thought to be high relative to other technologies (see Section 4.2.2).

Dread[2] describes a situation of significant uneasiness about a technology, for example, nuclear or genetic modification technologies. This is not necessarily related to specific concerns. Technologies that evoke dread can acquire a stigma, which is often perpetuated by the media and those who oppose the technology (Marchant *et al.,* 2008; Gilligan, 2006). This has been a particular impediment to the adoption of nZVI compared with other technologies as it appears to lead to a heightened perception of risk of nanotechnology's use amongst the public and other stakeholder groups, including landowners (Tomkiv *et al.* 2015). More specific regulatory concerns exist about nZVI use in remediation, including its potential human health implications and its possible ecotoxicological effects. As the potential risks of NP deployment for *in situ* remediation are considered to be poorly understood, precautionary and conservative regulatory positions have been taken in a number of countries. For example, there has been a voluntary moratorium on the release of engineered NPs in the UK, in response to a Royal Society/Royal Academy of Engineering report (Anon. 2012, RS/RAE 2004).

Process based remediation techniques seen as "new" within a particular jurisdiction have historically encountered significant market barriers and required verified field based performance data to gain widespread regulatory and market acceptance. It is not unusual for such evidence to be demanded by regulators and landowners for specific conditions encountered or perceived in their country. Given the heightened perception of potential risks from NPs in the environment, as well as the limited evidence base related to nZVI use in the field - particularly for modified forms - it is likely that a higher burden of proof will be required by regulators prior to permitting of nZVI based *in situ* remediation techniques, compared with other *in situ* remediation techniques.

Although the establishment of the nanoremediation market has been slow there are a number of initiatives and development opportunities to expand its uptake, including the NanoRem project. NanoRem aims to aid upscaling of nanoremediation technologies, which could potentially deliver cost reductions associated with economies of scale. Additionally, NanoRem will investigate the fate, transport and toxicity of NPs in the environment to address public and regulatory concerns related to the current uncertainties associated with nanoremediation.

This information has been summarised from Bardos *et al.* (2015) (which will be downloadable from: http://nanorem.eu/news.aspx) where more detailed information and supporting citations are available.

4 Risk-Benefit Appraisal Activities

4.1 Stakeholder Workshop on "Nanoremediation Deployment Risk Assessment"

This section provides an overview of a workshop held in July 2013 regarding the assessment of risks from renegade NPs[3] arising from the injection of NPs into polluted groundwater. More detailed information on the workshop outcomes can be found in Annex 1.

[2] To dread is to anticipate with great apprehension or fear.

[3] renegade particles are those particles that "are injected into groundwater but either do not reach the intended treatment area or pass through it" (LQM 2014).

4.1.1 Objectives

One of NanoRem's objectives is to provide field evidence of the safe and effective deployment of NPs to remediate polluted groundwater. The health and safety aspects of injecting NPs do not pose a particularly novel challenge. However it is necessary to consider the extent of potential risks posed by injecting NPs into groundwater.

4.1.2 Approach

The fate, transport and toxicity of renegade NPs (NPs that do not get consumed in the remediation process and escape from the source or plume footprint) was considered during an expert elicitation workshop organised by NanoRem partners, Land Quality Management Ltd (LQM), in July 2013, in Nottingham, UK. The workshop outcomes, supported with evidence from the literature, formed the basis for a simple and conservative protocol for use during NanoRem field trials to control the risk posed by NP deployment and to reassure regulators that trials would be safe. The work focused on the risks posed by the NPs being researched by NanoRem (See NanoRem 2014 News Letter).

4.1.3 Key Outcomes

The key outcomes of the workshop were as follows:

- The workshop participants agreed that there was a potential for the NanoRem NPs to be toxic, but that they would be substantially less potent than nano-silver.
- NPs are likely to interact with the aquifer matrix, groundwater and each other to rapidly lose mobility.
- NPs are unlikely to penetrate into the aquifer more than a few metres from the point of injection.
- A conceptual site model should be developed for sites deploying NPs, to address the possible risks arising from renegade NPs.

The risk assessment protocol will be updated once the results of the NanoRem field trials and other experiments are available.

4.2 Summary Risk-Benefit Appraisal

This risk-benefit appraisal is a summary based on information collated in Bardos *et al.* (2014), the full report of which can be downloaded from http://www.nanorem.eu/Displaynews.aspx?ID=525. Please see the full report for detailed discussion and further references. In addition, a summary of key risk-benefit information on nZVI has been added to the NanoRem website: "Information for Decision Makers", at www.nanorem.eu/Informationfordecisionmakers.aspx.

4.2.1 Potential Benefits of Using nZVI in Remediation

The principal potential benefits of nZVI use that have led to its development, particularly in comparison to the use of conventional zero-valent iron, are the extent and speed of contaminant degradation possible from nZVI. These result from the greater surface area (and therefore increased reactivity) of nZVI. Furthermore, there may be a potential extension of the range of treatable contaminants to include types traditionally seen as recalcitrant. This may include destruction of organic contaminants and the transformation and/or precipitation of inorganic contaminants (Huang *et al.* 2013, Liu *et al.* 2005, Song & Carraway 2005, Zhang 2003). Several studies have suggested that nZVI may have advantages over granular ZVI for *in situ* stabilisation (and reduction) for a range of potentially toxic elements (Li *et al.* 2006 a, b). However, there is some uncertainty regarding whether or not nZVI will extend the range of treatable contaminants in the field compared to granular ZVI, although it is projected that at least a comparable treatment capability will be achieved.

When compared to bioremediation, nZVI usage also offers a probable reduction in the formation of toxic intermediate products for the degradation of some chlorinated solvents (e.g. the chloroethenes). Bench scale studies of nZVI use indicate that in the presence of nZVI, perchloroethene is degraded fully to ethane, ethene, or other light non-chlorinated hydrocarbons, without the build-up of toxic intermediates that are part of the metabolic sequence followed in bioremediation (Taghavy *et al.* 2010, Wang *et al.* 2010, Henn & Waddill 2006, Gavaskar *et al.* 2005). Moreover, the overall evidence suggests that nZVI has little, if any, deleterious effect on (and may possibly even stimulate) dehalorespiration, a key process in bioremediation (Comba *et al.* 2011, Kirschling *et al.* 2010, Xiu *et al.* 2010). nZVI therefore has the potential for synergistic application with bioremediation techniques.

As the active lifespan of nZVI is likely to be limited (owing to passivation and agglomeration), the impacts on the receiving environment and its ecology are likely to be reduced compared to other *in situ* remediation options.

4.2.2 Implementation Issues for Using nZVI in Remediation

The high chemical reactivity of nZVI particles means that their specific activity and ability to move through the subsurface is limited by several processes within the sub-surface, namely:

- Agglomeration - where NPs adhere together in clusters,
- Passivation - where NP surfaces are chemically inactivated (although activity may remain within particles)
- Sorption onto or entrapment within aquifer materials.

To help overcome these problems, and thus increase the usefulness of nZVI in remediation, a number of modifications to the NPs have been developed, including: stabilisation, emulsification, and anchoring the particles to a supporting matrix. In addition, bimetallic NPs have been developed. These are also nZVI variants typically containing a small amount of a noble metal, such as palladium (typically less than 1%), which acts as a catalyst, increasing both reaction rates and the range of treatable contaminants. These are particularly useful in transforming more recalcitrant contaminant classes such as the aryl halides (Zhu *et al.* 2008, Zhu & Lim 2007).

The processes limiting activity and mobility, combined with their typically high reactivity, means that the handling of nZVI products requires quite a lot of care. Handling needs to prevent the oxidation (and indeed for some products combustion) of nZVI on exposure to air. The design of both injection processes and an overall injection grid needs to take account of the relatively low mobility of nZVI in the subsurface and the high density of nZVI suspensions which affects how they are handled and pumped.

Treatment costs are contentious. Overall, cost-effectiveness for nZVI, as is also the case for other *in situ* processes, is likely to be specific to site circumstances and characterisation (Cook 2009). The available evidence suggests that currently costs for nZVI are likely to be higher than granular ZVI on a weight for weight basis. At present, nZVI costs in the USA are typically in the order of \$30-40/lb while granular ZVI is around \$1-5/lb and millimetre-scale iron is generally in the range of \$0.25-0.75/lb (D.W. Elliott 2011 Pers. Comm.) However, as nZVI has the potential to be more reactive, nZVI may be comparable to granular ZVI in terms of cost-efficiency of actual remediation outcomes, as theoretically less would be required for the same treatment impact. It should also be noted that material cost of the reactive media (e.g. nZVI) may only be a small proportion of an overall site remediation budget; Lacinová *et al.* (2013) showed that the implementation costs associated with nZVI use (e.g. management, operational costs) were collectively higher than the cost of the nZVI material. In addition, over the medium to longer term, economies of scale could reduce nZVI production, transport, handling and application costs.

4.2.3 Potential Deployment Risks from nZVI Use in Remediation

For the purposes of clarity this report refers to risks from the use of introduced nZVI as "deployment risks" to distinguish these risks from the risks from contamination being managed as a remediation process. Perceived deployment risks from nZVI use, as a part of general concerns over the environmental release of NPs, have led to a precautionary regulatory approach in many countries, in some cases leading to a voluntary moratorium on the release of engineered NPs (e.g. in the UK, see Section 3). It is a matter of debate whether such a stringent regulatory position is supported by the available documented evidence.

As with many substances deployed by different *in situ* remediation techniques, the use of nZVI may pose risks to human health and the environment. The level of risk depends on the likely fate, transport and toxicity to receptors of the substance added and the likely exposure of those receptors to the substances.

In the case of nZVI research based on laboratory studies and the fate of naturally occurring iron NPs indicates that the long term fate of manufactured nZVI in an aquifer will be conversion into larger particles of iron (II) and (III) oxides/hydroxides, similar to naturally occurring minerals (Reinsch *et al.* 2010, Sohn *et al.* 2006, Johnson *et al*. 2013). Transport of nZVI will be limited by processes of agglomeration and sorption (Tratnyek & Johnson 2006; Phenrat *et al.* 2007), as well as its density. The transport of readily reactive nZVI will diminish rapidly as a result of processes of passivation. In broad terms there is an inverse relationship between reactivity and mobility; the most reactive particles agglomerate and sorb to surfaces more readily, reducing distance transported. If nZVI has been modified to increase mobility, it is likely to have lost a significant degree of reactivity to achieve this, meaning the particles which pose the greatest hazard in terms of reactivity are also the most easily contained.

The direct effects of nZVI on human health are poorly understood. Concerns regarding the toxicity of nZVI can be broadly split into those related to dose-response relationship of the iron and of the particles' nano-scale size. With regards to iron toxicity, it should be noted that iron is an essential element for growth in nearly all species, including humans. Although as for any element, Fe can be toxic at high enough concentrations. It has been suggested that for toxicity associated with NP size, unique behaviours are only observed in NPs smaller than 30nm and that larger particles can be considered analogous to bulk materials (Auffan *et al.* 2009). nZVI used in remediation is typically in the 10-100nm size range as produced, but tends to agglomerate to larger particles.

Laboratory studies have reported contradictory results with regards to the toxicity of nZVI. For example, nZVI has been found to cause toxic effects in bacterial cells *in vitro* over and above toxicity levels caused by granular ZVI (Lee *et al*. 2008). However, nZVI toxicity was attributed to the prevailing deoxygenated conditions. Other studies have reported no or mixed impacts of nZVI on soil and groundwater micro-organisms (Fajardo *et al.* 2013*,* Wang *et al.* 2012). For non-microbial soil and water organisms, such as *collembola, ostracods* and earthworms, some degree of toxic response to nZVI has been shown in laboratory experiments (El-Temsah & Joner 2013*,* El-Temsah & Joner 2012). However, toxicity was largely observed to reduce in magnitude over time, which was attributed to oxidation. Overall, the toxicity of nZVI appears largely attributable to changes in pH and deoxygenation of water.

The principal receptors of concern are likely to be groundwater and surface water, and their ecologies, away from the area impacted by the pollutants being remediated. Assuming that nZVI is deployed in the subsurface, where it remains, human health exposure pathways are likely to be limited to those possible from occupational exposure. Occupational exposure during nZVI deployment can occur through dermal contact, inhalation, and ingestion. Appropriate measures should be in place relating to the manufacture and transport of nZVI, for example as defined in Material Safety Data Sheets, so occupational exposure scenarios are regarded as routinely managed and therefore unlikely.

Deployment risks from the use of nZVI are likely to be manageable. The available evidence, which is typically based on laboratory based data and/or modelling, indicate that their environmental persistence is relatively short (<1 year (Phenrat *et al.* 2009, Liu & Lowry 2006), typically days or weeks) and its ability to travel is extremely limited (<1m to, exceptionally, 100 m for modified nZVI). Indeed, it has been speculated that even modified nZVI is not likely to travel much farther than 100 m from an injection location and much shorter distances when site conditions limit mobility. Most reports of field scale deployments of nZVI report that nZVI travels only a few metres from the injection point. However, it is generally felt that there are insufficient well validated field studies of nZVI to draw firm conclusions about its mobility under field conditions. This evidence gap is a major research priority for the NanoRem project over the next few years (to 2016).

4.2.4 General Risk–Benefit Appraisal for nZVI Deployment

nZVI is anticipated as having two major benefits for process based remediation: possible extension of the range of treatable contaminant types, and increasing the efficacy of treatment (speed and degree of completion), and several additional or consequential benefits. To date, the use of nZVI in remediation in practice has largely been for chlorinated solvents in aquifers, competing with more established techniques such as *in situ* bioremediation, chemical reduction and granular ZVI (e.g. permeable reactive barriers). The majority of nZVI applications have taken place in North America, with a small number of applications in the field in mainland Europe (e.g. in the Czech Republic, Germany and Italy).

At present nano-remediation may offer advantages in some applications, compared with other *in situ* remediation tools, but this will be highly dependent on site specific circumstances. In the medium to longer term nanoremediation could substantially expand the range of treatable land contamination problems.

The available evidence supports, but does not irrevocably confirm, a view that the risks of nZVI deployment should be considered in the same way as other potentially hazardous treatment reagents, such as persulphates (commonly used *in situ* remediation reagents (Nathanail *et al.* 2007, US EPA 2006) which are potentially harmful to the biological functioning of soil and can be transported over significant distances in groundwater plumes).

A substantial impediment to the use of nZVI in remediation is the uncertain basis for understanding the risks of its deployment to the wider environment, in particular to groundwater and surface water receptors. Although most laboratory studies and practitioner experience would suggest that adverse effects would be minor, localised and short-lived, there is a lack of effective particle monitoring technologies and peer reviewed and validated data from applications in the field that corroborates this view. This presents a significant challenge to regulatory acceptance which the NanoRem project seeks to address.

5 Stakeholder Workshop on "Sustainability and Markets"

5.1 Objectives

Sustainabilty considerations are increasing of importance as part of environmental remediation decision-making processes, requiring an evaluation of environmental, economic and societal aspects. In order to build a cross-sectorial view of key sustainability issues related to nanoremediation, the NanoRem project invited land managers, consultants, technology contractors, planners, regulators and other experts, with various background and interests, to attend a "Sustatinability and Markets" stakeholder workshop. The focus of the workshop was on developing an overview of the opinions of these stakeholders on: (1) the sustainability of nanoremediation and issues likely to influence perceptions of its sustainability, including socioethical concerns, (2) sustainability of nanoremediation compared to other remediation technologies, and (3) factors that push or pull the market development for the nanoremediation technology in the medium to longer term.

5.2 Approach

The workshop was held in Oslo in December 2014 and gathered 36 participants from nine different countries (Austria, Belgium, Czech Republic, France, Germany, The Netherlands, Norway, Poland and United Kingdom), with a split of 16 participants from the NanoRem project and 20 external participants. All stakeholders could be classified as "expert" or professional representatives.

The workshop was divided into three main sessions. Session 1 explored generic issues associated with the sustainability of nanoremediation. Session 2 discussed sustainability assessment in the context of a specific (hypothetical) site, and Session 3 was titled "market opportunities".

The workshop used interactive discussions in small groups, following the World Café ™ [4] style, to ensure every participant could contribute their views. Discussions were facilitated by representatives

[4] http://www.theworldcafe.com/method.html

of NanoRem. Several lectures were given at the start of Session 1, to provide a background on the subject. The participants were then divided into groups to proceed with discussions on the general sustainability of nanoremediation.

Session 2 built upon the discussions in Session 1 and considered sustainability assessment in the context of a specific site (presented at the start of the session as a case study) and nanoremediation in comparison to other risk management options. The aim was to identify criteria that are likely to be important in differentiating between the sustainability of competing management options within the site context. The hypothetical case study site presented was based on one of the NanoRem field test sites, and included groundwater contaminated with chlorinated ethenes. The four treatment options compared were:

- Baseline (prohibition of use of wells, periodic monitoring);
- Pump and treat (removal of contaminated groundwater for treatment above ground);
- *In situ* enhanced bioremediation (treatment of contaminants in the ground by creating optimal conditions for biodegradation);
- *In situ* nanoremediation (treatment of contaminants in the ground by adding NPs to promote abiotic treatment).

Session 3 is discussed in Section 6, below.

5.3 Key Outcomes

The key issues raised by participants and outcomes of the workshop were as follows[5]:

- Session 1 (generic nanoremediation sustainability issues):
  - Many of the sustainability issues named during the discussion were common to remediation in general and not specific to nanoremediation.
  - The three pillars, or elements, of sustainability – environmental, social and economic – were agreed, and the assessment of risks and benefits should be balanced across these three categories.
  - Sustainability should be considered beyond the immediate human impact, and should address long term global and intergenerational impacts.
  - How nanoremediation performs compared to alternative technologies would be an important part of its sustainability appraisal.
  - Environmental benefits include that nanoremediation may be less invasive and have a low impact compared to alternatives.

[5] It should be stressed that the information presented represented reflects the opinions of the workshop participants, and in some cases their views on what other stakeholders' perceptions might be, and how these might influence issues. As such, the statements should not be taken as evidence-based.

   - Environmental concerns were largely related to the potential intrinsic hazards of nanoparticles themselves, including the potential for air releases of the particles and migration of particles resulting in negative environmental effects outside the treatment zone.
   - Economically, nanoremediation has the potential to be faster and cheaper compared to some alternatives. However, there were concerns related to the currently high production and transport costs for NPs.
   - Social benefits include the potential for job creation and a greater number of contaminated sites to be remediated as a result of a new technology being developed that could treat currently untreatable substances.
   - Concerns related to social aspects included the public perception of nanoparticles and existing knowledge gaps and uncertainties related to the technology performance.
   - Overall, more research and fewer knowledge gaps were integral to sustainability assessment.
- Session 2 (hypothetical case study):
   - The relevance at this site of a set of possible categories of indicators of sustainable remediation produced by SURF-UK were discussed (CL:AIRE 2011). For the site in question the most important indicator categories (to help differentiate between nanoremediation and alternatives) were determined to be: Groundwater and surface water; Natural resources and waste; Direct economic costs and benefits; Project lifespan and flexibility; Human health and safety; Community and community involvement; Uncertainty and evidence.
   - The relative importance of each indicator category varied depending on the compared treatment, e.g. “Natural resources and waste” may strongly differentiate nanoremediation from pump and treat, but other categories may be more important for differentiating between nanoremediation and bioremediation.
   - It was generally agreed that there was little to differentiate between *in situ* bioremediation and nanoremediation apart from uncertainty and evidence. Numerous categories differentiated nanoremediation and pump and treat.

The findings of the workshop will be used to frame how retrospective sustainability assessments will be carried out for NanoRem field trial sites. Overall, whether or not nZVI represents a sustainable *in situ* remediation option is likely to be largely based on site context and the suitability of the technology to the site in question. The NanoRem project will continue to consider the sustainability of NP use in remediation by carrying out site specific sustainability assessments (WP 8.3).

6 Medium to Longer Term Market Development

In order to develop an exploitation strategy that considers the medium to longer term potential market development for nZVI, any analysis has to deal with an uncertain future. The factors (i.e. drivers and uncertainties related to driver development) that foster or inhibit the evolution of the market need to be better understood. It is unclear how the factors likely to influence the nanoremediation market development are linked, and how they are likely to develop in the future. It is challenging, therefore, to make any straightforward predictions regarding the emerging nanoremediation market. As a result, traditional supply and demand modelling is unsuitable. A scenario approach will therefore be used to help forecast potential market developments. The outcomes are utilisable for: "real-world" business development, deducing strategies for market activities; informing policy development, identifying governance options for market expansion; and/or informing regulatory authorities, highlighting the potential for nanoremediation.

6.1 The Scenario Approach

Scenarios can be defined as "internally consistent stories about ways that a specific system might evolve in the future" (March *et al.* 2012). In essence, a scenario-based approach to understanding possible market trends uses available evidence and stakeholder participation to develop a number of narratives describing the potential evolutionary outcomes of a specific market system. Hence, this approach has been applied in order to help determine:

(i) What the factors (drivers and uncertainties) are in the nanoremediation market-system.

(ii) What the extent of the factors' impacts is.

(iii) How the factors interdepend.

Scenario design and analysis differ, but usually a stepwise approach is taken. In NanoRem, the following procedure was selected:

1) Conducting a present situation analysis to establish the baseline for scenario development and a framework for factor identification.
2) Filtering and systematising factors that drive or inhibit market development. Establishing key determinants.
3) Projection of key factors' developments and producing consistent stories about ways the system might evolve in the future. Identification of multiple alternative development trajectories is possible.
4) Deciding on planning-oriented exploitation strategies, which may be responsive or proactive. Development of governance recommendations.

Figure 1 below, gives an overview of the the work conducted so far as part of a scenario approach, and ongoing work. The steps are discussed further in the following sections. The overall approach is discussed in more detail in IDL 9.4 (Bardos *et al.* 2015) and the workshops is reported in further detail in Tomkiv *et al.* 2015.

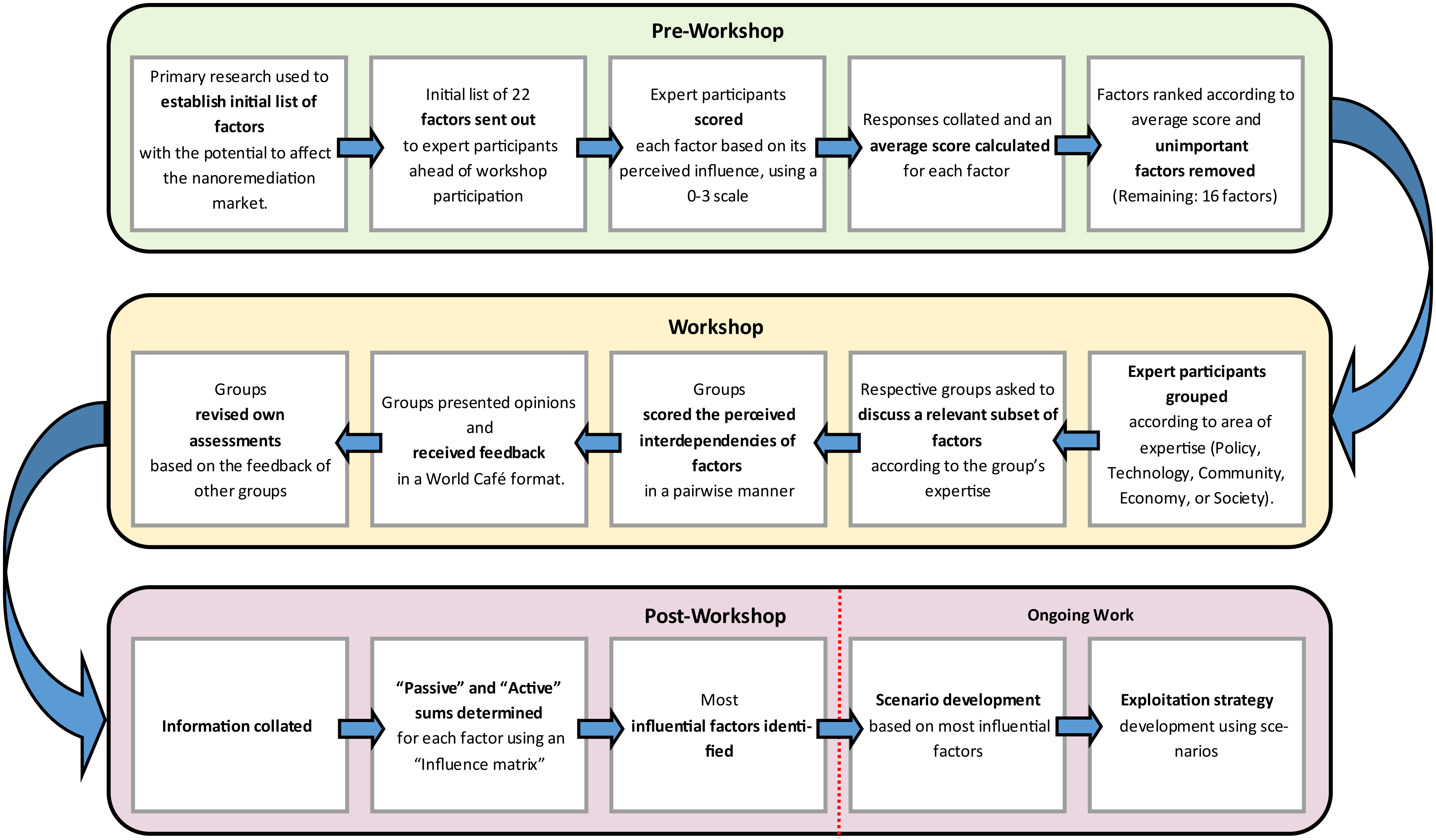

Figure 1 - Overview of the scenario approach process.

6.2 Establishing the Baseline for Scenario Development

To fulfil step one of the scenario development approach, a baseline understanding of the nanoremediation market and the set of factors with the potential to influence the future development of the nanoremediation market was established. This was achieved via key-informant interviews and literature analysis, taking into account the market *status quo* and risk-benefit appraisal (outlined in Sections 3 and 4, above). This preliminary research helped establish a variety of external determinants from economy, technology development, politics and society that may affect:

- The property market in general;
- The industry for contaminated land remediation broadly, and;
- The potential evolution of nanoremediation in particular.

Expert engagement (key informant interviews and expert discussion) was utilised to establish the most worthwhile timeframe for the scenario approach. A consensus was reached that evolution of the market up to 2025 was the most appropriate scope. It was felt that a very long-term assessment would be impossible due to the significance of unknown and uncertain factors. Nevertheless, any factors found to be potentially more time-sensitive will be reported and carefully considered when determining exploitation strategies. After several iterations with expert involvement, a condensed list of 22 potentially influencing factors was established.

6.3 Systematising Market Development Factors

To aid step two of the scenario design process, a “Market Opportunities” session was included in the Sustainability and Markets workshop (see Section 5).

The 22 factors determined in the preliminary research stage (see Section 6.2) were grouped into different categories (policy, economy, society, communication, technology and megatrends). The use of categories helped to align the factors with appropriate expertise for later discussions. In order to further condense the list of factors and remove less important factors, the list was sent to the workshop participants in advance of the workshop. Participants were asked to provide feedback on how important they perceived each factor to be for the development of the EU nanoremediation market from present to 2025. Participants scored each factor according to the following scale:

(0) = Negligible relevance – the factor is not an important driver or inhibitor;

(1) = Minor relevance – the factor might have a limited but not so important effect;

(2) = Considerable relevance – the factor is likely to have a notable (indirect) effect;

(3) = Key relevance – this factor is most certainly among those of utmost importance to push or pull the nanoremediation market development.

The responses (20 respondents) were collated and an average score (the arithmetic mean as the sum of the scores collected from all the respondents, divided by the number of the respondents) was calculated for each factor. The results are shown in **Table 2**, below, in descending order of obtained scores.

Table 2 – Preliminary factors and their perceived importance with regards to influencing nanoremediation market development in the EU up to 2025

Factor	***Score***	***Category***
Most important factors (≥2.00):		
Innovation on treatment of known contaminants with NPs	2.48	Technology
Regulation of nanoparticles	2.45	Policy
Validated information on NP application potential	2.40	Communication
Costs of competing technologies	2.35	Economy
Standardization for nanoparticles	2.20	Policy
Innovations along NPs production chain	2.18	Technology
Environment (especially soil) protection policies	2.10	Policy
Synergies with other technologies	2.05	Technology
Public stakeholder dialogue	2.00	Communication
Less important factors (>1.50 and <2.00)		
NP treatment of emerging contaminants	1.95	Technology
Public perception of NPs in general	1.93	Society
Science-Policy-Interface	1.93	Communication
Technology and research policies	1.75	Policy
Growing number of nanoparticles suppliers	1.73	Economy
Real estate market development	1.68	Economy
Innovation attitude	1.60	Society
Environmental awareness	1.55	Society
Minor relevant factors (≤1.50)		
EU economic development	1.50	Economy
Globalisation	1.20	Megatrend
Industrial and military land use	1.00	Society
Climate change	0.70	Megatrend
Demographic change	0.60	Megatrend

The scorings indicate that several factors influence the market's development. Some of the scorings, e.g. the ability to treat emerging contaminants with NPs, are surprising and may indicate either bias or epistemic issues in the mind of the responders. As no factor had a scoring > 2.50, it was concluded that no factor is likely to singlehandedly "push" or "pull" nanoremediation market development.

In order to create scenarios, the interdependencies of the factors determined to be important needed to be better understood. Stakeholders were provided with the factors in Table 2, including short descriptions of each factor. During the workshop, stakeholders were asked to provide opinions, comments and suggestions about the factors and were also asked to identify and discuss the interrelations of the factors. In order to do this, stakeholders were divided into smaller groups based on their field of expertise. The groups formed were Regulators / Policy makers, Technology, Communication, Economy and Society. Participants in the respective groups were asked to discuss the influence of three or four factors of their respective expert domain on the full list of factors identified to be of importance. Next, following a "World Café ™" format, the experts were invited to discuss the results of the other groups and finally to review and revise their own assessments based on the feedback of others. These discussions are reported in detail in Tomkiv *et al.* (2015)

After the workshop, the information collected from the group sessions was analysed and the factors that are more "active" in influencing other factors were identified, as well as those that are more driven by the active ones. These relationships are expressed by the "active sum" and "passive sum" in Table 3 below. Table 3 lists the factors recorded in Table 2 in order of their activity (i.e. how influential a factor is relative to other factors).

The third and fourth steps of the scenario approach will be carried out over Year 3 of the project and have the objectives of deducing recommendations for the exploitation strategy based on a deeper understanding of the key factors identified as market determinants. During the third step, key factors will be filtered in order to guide the design of consistent stories about ways the market system might evolve in the future – the following Section 6.4 outlines this step. In the fourth step, recommendations will be concluded from this exercise.

Table 3 - Interrelatedness of factors determining the development of the nanoremediation market

Factor	**Active sum***	**Passive sum***
Science-Policy-Interface	38	26
Validated information on NP application potential	36	21
Environment (especially soil) protection policies	25	17
Public stakeholder dialogue	25	20
Synergies with technologies	24	20
Innovations along NPs production chain	24	21
Costs of competitive technologies	24	24
Growing number of nanoparticles suppliers	24	28
Regulation of nanoparticles	23	19

Technology and research policies	23	27.5
Innovations in treatment of known contaminants with NP	22	29.5
Environmental awareness	21	19
NP treatment of emerging contaminants	19	26
Innovation attitude	16.5	24
Public perception of NPs in general	14	21
Real estate market development	11.5	8

*Active and Passive sums had a maximum potential value of 48. The closer the active sum for a factor is to 48, the more influential that factor is. Conversely if the passive sum for a factor is close to 48, it is likely to be highly influenced by changes in other factors.

6.4 Projection of Factor Development and Establishing Consistent Scenarios

As part of ongoing work, a series of expert engagement activities is underway. In March 2015, NanoRem conducted a first focus group meeting and expert workshop in Berlin, Germany, in order to discuss the establishment of consistent scenarios. The participants were provided with an overview of the interim results of the scenario analysis work. They were shown that the two most “active” of the key factors were identified as: “Science-Policy-Interface” and “Validated information on NP application potential” (see

Table **3**) and hence, these factors are likely to be crucial in determining the development of the nanoremediation market system. These two factors were suggested for the development of framing elements for a conceptual scheme for scenario states. The participants discussed the meaning of these factors and tentatively defined them as follows:

- Science-Policy-Interface is part of a broader ‘Dialogue’, which is the process by which stakeholder groups (in particular those from science, policy and regulation) have informal/formal discussions, consultations and other forms of engagement in order to ascertain the potential application of nanoremediation (in general or in specific cases).
- Validated information on NP application potential is an ‘Information’ dimension, which describes the quality of available information for decision-making. Information can range from a level of great uncertainty with regards to the potential developments of the market and the set of factors driving the market, to a situation where information about nanoremediation is readily available, well tested, and broadly accepted (i.e. “validated”). “Validated information” gives credence to a decision regarding its applicability.

These dimensions form the conceptual scheme for the scenario states of the nanoremediation market. These scenario states show four potential future states for the market, see Figure 2 below, (going clock-wise in each quadrant of the matrix):

I. Validated information is broadly available AND there is comprehensive dialogue between stakeholders, in particular those from science, policy and regulation.

II. Validated information is lacking and uncertainty is still significant BUT there is comprehensive dialogue between stakeholders, in particular those from science, policy and regulation.

III. Validated information is lacking and uncertainty is still significant AND there is no or only minimum dialogue between stakeholders, in particular those from science, policy and regulation.

IV. Validated information is broadly available BUT there is no or only minimum dialogue between stakeholders, in particular those from science, policy and regulation.

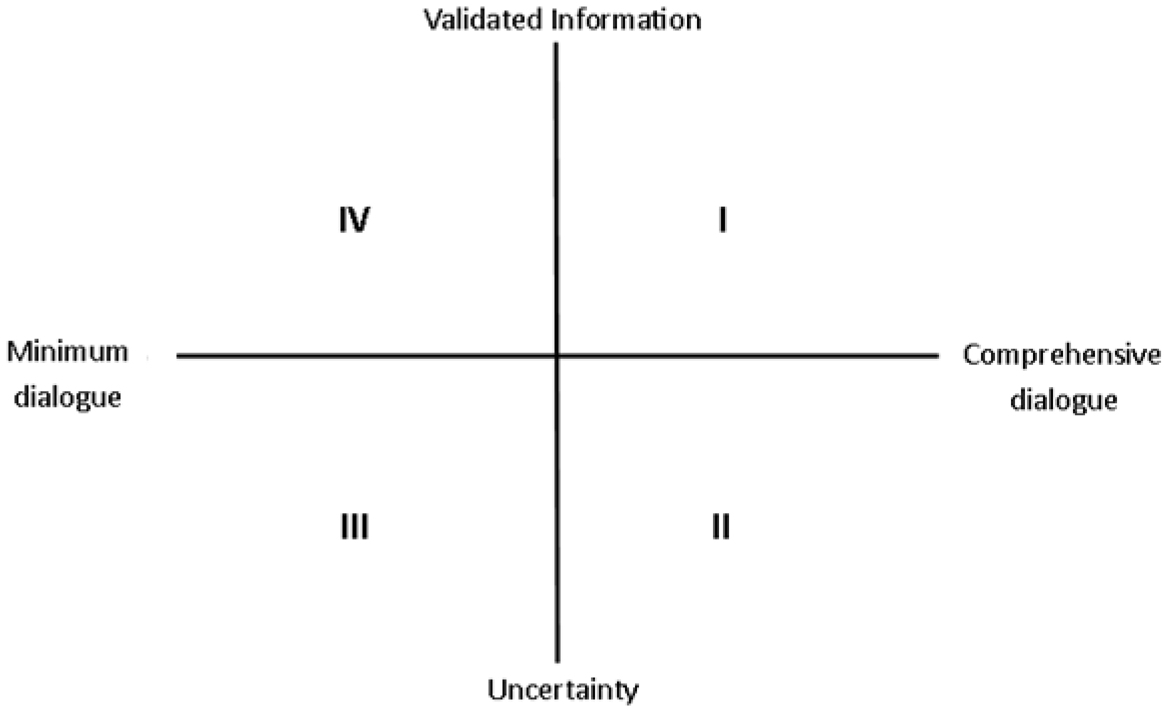

Figure 2 - Conceptual Scheme for Scenario States

The final steps of the scenario analysis will be the discussion of the key factors' developments within the different scenario states, and based on these, the deduction of scenario storylines. These discussions will finally inform the conclusion of recommendations for the exploitation strategy. The Berlin workshop was the first event in a series of further expert engagement activities foreseen in Year 3 of the NanoRem project (see below Section 8.3).

7 SWOT Analysis

A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of factors that may affect (positively or negatively) the value proposition[6] and exploitation of the nanoremediation market has been

[6] Defined as: the overall promise of value to be delivered

developed (Table 4). SWOT issues naturally fall into a series of broader categories. We have indicated these in Table 4 and used a colour scheme to make them more obvious. An ongoing task of Year 3 of the NanoRem project will be to link the categorisations used in the SWOT with the broader market factor categories used in Table 2 (exploitation).

Table 5 provides an initial, and tentative, view on how time sensitive the broader categories may be: if they will change over time; what we can say now about likely changes; and how certain we are about these changes.

Over the second half of the NanoRem project, this tentative and preliminary view will be integrated with the forthcoming focus group work. This assessment will also be expanded to encompass other NP types under investigation by NanoRem (potentially: air-stable powder nZVI, milled iron, biomagnetite, palladised biomagnetite, carbo-iron, Fe-zeolites, Fe-oxides, barium ferrate, nano-goethite, Al and Mg), being developed by the project over Years 3 and 4. Years 3 and 4 of the project will also see the risk-benefit appraisal broadened to these other NP types. See Section 8.1 for further details of ongoing NanoRem work.

Table 4 - nZVI Strength, Weakness, Opportunity and Threat (SWOT) for the use of nZVI in remediation

Strengths		Weaknesses	
Improving the speed of contaminant destruction	Relative effectiveness	Field scale deployments are limited in scope of remediation problem being addressed and tend to lack verified / validated performance information	Field scale experience
Improving the extent of contaminant destruction	Relative effectiveness	Knowledge gaps regarding fate, transport, toxicity in environment	Current knowledge
Extending the treatable range of contaminants	Relative effectiveness	Knowledge gaps relating to toxicity to humans	Current knowledge
70 known field scale deployments	Field scale experience	Handling risks may be greater than granular ZVI	Relative risks
Limited longevity of action may reduce environmental risks	Relative risks	Limited longevity due to rapid agglomeration & passivation. May require several applications	Relative effectiveness/ Ease of use
Compatibility with other treatments	Synergy	Poor mobility due to rapid agglomeration & passivation in the short term	Relative effectiveness/ Ease of use
Can utilise existing techniques for deployment	Ease of use	Potential groundwater contamination by NPs	Relative risks
As an *in situ* technique there may be reductions in site costs compared to *ex situ* remediation (e.g. reduced waste generation, reduced fuel usage)	Relative costs	Lack of comprehensive sustainability assessment	Current knowledge
As an *in situ* technique there may be reductions in some site risks compared to *ex situ* remediation (e.g. reduced exposure of workers to contaminants)	Relative risks	Cost of nZVI is currently high relative to granular ZVI	Relative costs

Opportunities		Threats	
Concentration of field scale experience in some countries, e.g. Czech Republic, creates an opportunity for cross comparison of field scale deployments in one jurisdiction	Field scale experience	Unwillingness to provide regulatory or problem holder permission to use nZVI	Field scale experience
Cost reductions associated with economies of scale	Relative costs	Potentially significant public concern about nanotechnology being inherently risky	Technology dread
Optimisation of field trials improving NP delivery methods	Relative effectiveness	Numerous coatings, modifiers, catalysts which could make establishing risks complicated	Relative risks
Treatment of contaminants in the vadose zone	Relative effectiveness	Costs remaining high relative to competing technologies	Relative costs
Potential for treatment of source terms	Relative effectiveness	Source term treatment effectiveness is in general constrained by the accessibility of the source	Relative effectiveness
Improved understanding could lead to reduced public and regulatory fears	Technology dread	Difficulties in tracking NP transport	Relative risks
Inclusion of nanoremediation in *in situ* integrated treatment approaches	Relative effectiveness		

Table 5 - Possible future trends affecting broader SWOT categories

Item	Time sensitive?	Possible development by 2025	Certainty of development
Relative costs	Yes	Economies of scale may lead to cost reductions related to: a) production of NPs b) application of NPs Increased costs of NP material could raise costs.	Dependent on level of market uptake and the overall demand for NPs.
Field scale experience	Yes	Additional field trials including a wider range of contaminants could strengthen the evidence base for nZVI effectiveness and reduce public concerns associated with deployment safety	Highly likely. This is a key task of the NanoRem project (WP10)
Relative effectiveness	Yes	a) Research funding to address difficult contaminants and develop novel NPs b) Vadose zone treatment, if developed, could have huge benefits for difficult / untreatable problems such as highly recalcitrant contaminant classes (e.g. PCBs, dioxins, etc.) c) Development of coatings to improve persistence and mobility	a) Likely – There are a number of research projects taking place across Europe b) Currently vadose zone treatment has not been well investigated, but exploiting NPs for this use may be possible c) Relatively certain, research being carried out, including by NanoRem
Relative risks	Yes	Development of coatings to improve persistence and mobility – introducing an additional element of risk	Relatively certain, research being carried out, including by NanoRem
Ease of use	Yes	Development of coatings to improve persistence and mobility	Relatively certain, research being carried out, including by NanoRem
Technology dread	Yes	Field trials and research into potential toxicological effects could help address “dread” associated with the technology	Improvement of the situation is possible. NanoRem is working towards consensus development for appropriate NP use. NICOLE and Common Forum will assist

Item	Time sensitive?	Possible development by 2025	Certainty of development
Current knowledge	Yes	Knowledge expansion leading to reduced dread, improved certainty of effectiveness, increased uptake of the technology.	Improvement of the situation is likely. NanoRem is working towards improved knowledge and dissemination. For example, NanoRem is developing better methods of monitoring field deployments of nZVI (Oughton *et al.* 2015).
Synergy	Yes	New synergies could be discovered, incorporating previously un-trialled technologies in combination with nZVI	Likely – experimental work exploring synergies of nZVI with e.g. bioremediation are already under way, including by NanoRem

8 Conclusions and Next Steps

8.1 Conclusions

Nanoremediation may offer notable advantages in some remediation applications. However, to date, uptake of the technology has been limited as a result of numerous factors, including: knowledge gaps (e.g. regarding the risks of NP usage), high production costs, difficulties regarding ease of use and lack of field trials demonstrating use of the technology. The NanoRem project seeks to address these and other uncertainties that currently form a barrier to market development for nanoremediation. This report has summarised the work of WP9 during the first two years (Months 1-24) of the NanoRem project.

A key element of WP9's work has been a risk-benefit appraisal for nZVI, the overall conclusion of which suggested that the risks of nZVI deployment could be considered in the same way as other potentially hazardous treatment reagents. However, more research is needed to establish evidence for both the suggested benefits and low risk level (relative to the high perception of risk) of nZVI deployment. A webpage has been developed for the NanoRem project, which includes the salient points from the risk-benefit analysis as "Information for Decision Makers".

Engagement workshops have been organised and carried out to elicit expert and stakeholder opinions on the sustainability of nanoremediation, factors affecting its potential market development and the risks associated with the deployment of NPs.

The outcomes of the stakeholder engagement and risk-benefit appraisal work are being incorporated into scenario analysis, which was initiated in an attempt to better understand the factors with the potential to shape the nanoremediation market. A conceptual scheme for scenario states based on two of the factors found to be dominant has been proposed regarding the nanoremediation market in Europe in 2025. However, these are interim results - the final steps of the scenario analysis are still under development, with further expert engagement activities foreseen in Year 3 of the NanoRem project (see below Section 8.3).

A SWOT analysis for nZVI use currently indicates a relatively well balanced perspective for the strengths, weaknesses, opportunities and threats for nanoremediation. This is consistent with its fairly low penetration into the market thus far. A number of these factors are time sensitive, therefore encouraging the exploitation of nanoremediation in a broad way depends on achieving improvements in these factors over time. While this is only a tentative analysis, it does indicate that improvements over time will happen and NanoRem's activities are a key component in achieving this improvement.

8.2 Next Steps

8.2.1 NanoRem Website

The NanoRem website will continue to be developed and updated throughout the project. Milestone 8 - "Full blown web-based info-tool available based upon outcome of laboratory and field studies" is due in Month 36 of the project. It is anticipated that additional NPs will be reviewed and incorporated into the Milestone 8 work, however this is dependent on both the availability of information from other work packages and project progress generally. An aim of NanoRem is to provide a full PDF archive available on the project website; it is estimated this will be achieved by Month 44 of the project.

8.2.2 Risk-Benefit Appraisal

Risk-benefit appraisal work will continue in Years 3 and 4 of the NanoRem project, with the objective of expanding appraisal work to include other NanoRem NP types in addition to nZVI. Stakeholder engagement work will continue, and discussions are ongoing with the key stakeholder networks Common Forum and NICOLE. Risk-benefit appraisal work will be used as a context for developing opportunities for market exploitation.

8.2.3 Market Development (Scenario) Work and SWOT Analysis

The Scenario approach will continue to be expanded, with scenario development continuing over Year 3 of the NanoRem project (see Section 6.4). Further expert engagement in focus groups and workshops has been planned in order to discuss the scenario scheme and future market states that reflect the interactions identified in the Oslo workshop and specify directions of factor development under the potential market states. The scenario storylines concluded from these activities will be used to derive conclusions on the medium to longer term exploitation opportunities and recommendations for entrepreneurs and policymakers.

SWOT analysis will be expanded, and ongoing work will endeavour to link SWOT categories with market factor categories (see Section 7). Discussions regarding the time sensitive aspects of the SWOT categories will be integrated into upcoming focus group work where possible.

Ongoing work in NanoRem will seek to determine a greater level of linkage and evidence for nZVI exploitation between scenario analysis and SWOT analysis. Future scenario development and SWOT work is anticipated to include other NP types.

8.2.4 Consultation

This report is a preliminary out put of NanoRem and readers are invited to comment on its contents. This can be done on line at www.nanorem.eu. All comments received will be considered in an updated risk benefit appraisal taking place over the second half of the NanoRem project. The consultation period will be open until July 31st 2015.

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Annex 1 – Deployment Risk Considerations for NanoRem Case Studies

This Annex provides information from NanoRem's Thematic Page 9: Summary of renegade nanoparticle risk assessment protocol for NanoRem field deployments[7].

Aim

The aim of this Annex is to summarise the way NanoRem is tackling the assessment of risks posed by any nanoparticles (NPs) injected into polluted groundwater that migrate beyond the intended treatment zone. A detailed technical review of the issues was carried out to inform a NanoRem specific protocol for use in field trials. This will form the basis of a widely available risk assessment protocol once the field trials and laboratory experimentation phases of NanoRem have been completed.

Introduction

The aim of NanoRem is to support and develop the appropriate use of nanotechnology for contaminated soil and groundwater remediation. NanoRem focuses on facilitating practical, economic and exploitable nanotechnology for in-situ remediation. This can only be achieved in parallel with a comprehensive understanding of the environmental risk-benefit balance for the use of NPs.

Risk Assessment Protocol Development for NP Deployment in Groundwater

One of NanoRem's objectives is to provide field evidence of the safe and effective deployment of NPs to remediate polluted groundwater. The health and safety aspects of injecting NPs do not pose a particularly novel challenge. However it is necessary to consider the extent of potential risks posed by injecting NPs into groundwater. Risk assessment specialists from Nottingham-based SME Land Quality Management Ltd (LQM) developed a protocol to allow the NanoRem field trials to evaluate the risks posed by NPs that do not get consumed in the remediation process. The fate, transport and toxicity of these so called renegade NPs was considered during an expert elicitation workshop organised by LQM at its University of Nottingham Innovation Park offices. The workshop outcomes, supported with evidence from the literature, formed the basis for a simple protocol for field trial sites to use to evaluate the risk posed by their NP deployment and demonstrate to regulators the trials would be safe.

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[7] http://www.nanorem.eu/displayfaq.aspx?id=15

Figure 1.1 - Summer 2013 Expert Elicitation Workshop Facilitated by NanoRem partner Land Quality Management (© Land Quality Management 2013)

LQM's work focused on the risks posed by the NPs being researched by NanoRem (See NanoRem 2014 News Letter). While these NPs could have a significant toxicity, the workshop participants agreed that it would be substantially less potent than highly ecotoxic nano-silver. Furthermore the NPs are likely to interact with the aquifer matrix, each other and groundwater to rapidly cease to be mobile NPs. They are therefore likely to be difficult to penetrate into the aquifer more than a few metres from the point of injection.

Conceptual Site Model Development

For an environmental risk to exist all of the following must be present: a source of contamination (S), a receptor (R) and a pathway(s) (P) linking the two - i.e. a contaminant linkage (S-P-R) and such linkages are shown on the conceptual site model (CSM) see Figure 1.2.

A CSM addressing the possible risk from renegade NPs needs to be created separately from, and is in addition to, the CSM which should already have been developed for the contamination problem at the site that is driving the need to remediate. For the pre-deployment risk assessment for NP injection, the NP themselves are considered as the source, with the CSM used as a tool to consider whether there are potential pathways for NPs to any relevant receptors.

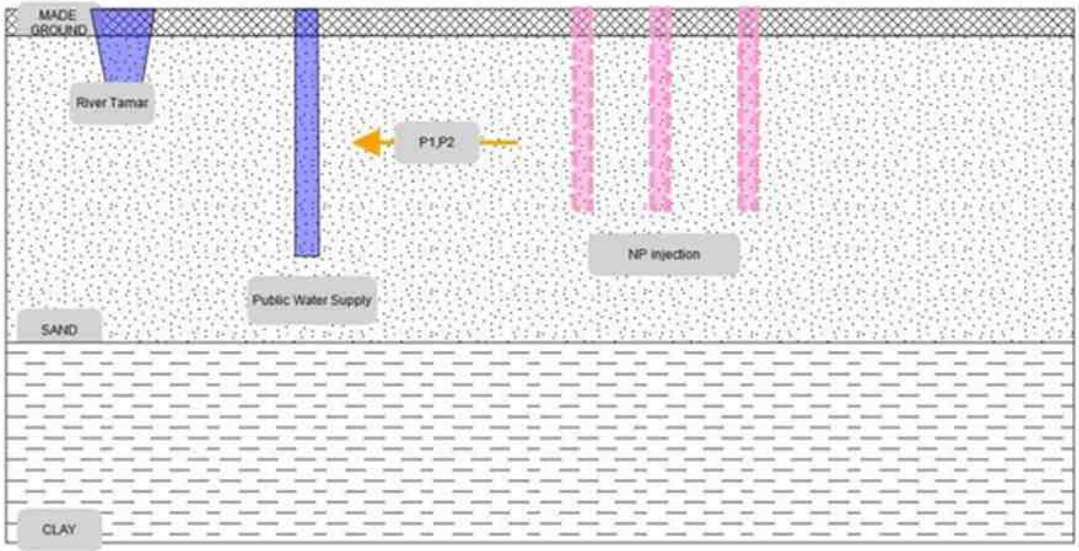

Figure 1.2 - Cross section from CSM (This site is an illustrative example only and does not represent any of the pilot sites) (© Land Quality Management 2014) (See NanoRem 2014 News Letter).

Receptors that could be affected by NPs include: human health, surface water, ecosystems and, though to a lesser extent, groundwater, although for some of these the potential exposure scenarios are unlikely. Despite the uncertainties identified in our current knowledge base and that NanoRem laboratory and field studies are addressing, LQM identified a range of circumstances that indicate NP can be safely deployed. These include an absence of receptors (other than the already contaminated groundwater), where a site has pathway interruption or limited NP transport means the receptor would not be reached by renegade NP.

Since developing the protocol, LQM staff have provided detailed online training and face to face mentoring to case study partners on the development of their conceptual site models to help them then apply the protocol to their sites. The site specific evaluation of the risks posed by injected NPs forms part of the evidence submitted to relevant regulators and other stakeholders in order to gain the necessary site specific permissions to carry out the field trials.

Overall while there are considerable uncertainties particularly with regard to NP transport, the ability of NPs to penetrate far into the formation is likely to be limited. At this stage such a protective situation is welcome. Once the results of the field trials are available, LQM will update the risk assessment protocol for eventual publication and consideration for wider take up.

Annex 2 – NanoRem Website

The website (www.nanorem.eu) presents the NanoRem project (including its aim and project description) and the project partners involved. Milestone 3 "Dissemination 1: Webpage operating as information/ support tool for negotiations with owners / regulators" was reached in month 12. The website includes both an Intranet (access limited to consortium members) and an Extranet. The Extranet serves for communication with stakeholders. It includes an "Information for Decision Makers" section (see Annex 3) to convey information to regulators and other stakeholders. Initial FAQs pages were supported by the later addition of Thematic Pages and substantive technical publications as PDFs (e.g. the deployment risks workshop report, and a risk-benefit appraisal for nZVI use in remediation). A screenshots of the welcome page for the official website is shown in Figure 2.1.

Figure 2.1 – NanoRem Website Homepage

Annex 3 – Information for Decision Makers

Information for Decision Makers is provided on the NanoRem website (www.nanorem.eu). The information focuses on nZVI as the best known and most frequently encountered NP, although the information may also be indicative for other NP types used in remediation. The introduction page of the Information for Decision Makers follows:

Nanoremediation: Information for Decision Makers from NanoRem

Introduction to Frequently Asked Questions (FAQs) **and** Thematic Pages

In situ remediation technologies are now in use for managing risks from a range of soil and water contamination problems in several countries. The small particle size and high reactivity of nanoparticles may offer particular remediation benefits compared with existing *in situ* techniques. The best known and most frequently encountered is nano scale zerovalent iron (nZVI). The information for decision makers provided here focuses on nZVI, although it may also often be indicative for other NP types used in remediation.

nZVI has been deployed in the field at a substantial number of sites in several countries, in particular for the remediation of chlorinated solvent plumes. Laboratory and theoretical studies indicate that nanoremediation also has promise for offering treatment of a wide range of persistent contaminants such as PAHs, PCPs, PCBs and trace elements such as Cr (VI). nZVI may also offer the potential for faster and more complete remediation treatments.

Since the inception of nanoremediation as a technology more than ten years ago, a number of questions have been raised about it that decision-makers may need to consider. In this NanoRem information area we provide a list of "frequently asked questions" (FAQs) to provide brief summary information, supported by pages of more detailed technical information organised in thematic topics. These pages are in constant review over the lifetime of the project, both to update their technical content and to extend their scope. Each page provides signposting to additional information, in particular the outputs of the NanoRem project as they become available in the NanoRem Publications Catalogue.

An important objective for NanoRem is to promote exchange between nanoremediation practitioners and decision makers and to allow them to provide feedback both on the project activities and nanoremediation more generally. These FAQs are intended to provide initial information to support nanoremediation project decision-makers, and also to begin this process of engagement. This information and exchange area will be further developed as the project progresses.

FAQ

Currently we have the following FAQ pages:

- FAQ: What are nZVI nano particles and how does nanoremediation work?
- FAQ: Are there any risks from nZVI nanoparticles associated with the use of nanoremediation at contaminated sites?
- FAQ: What are the potential benefits of nZVI nanoremediation and its likely advantages over alternative technologies?

- FAQ: Where have iron nano particles (nZVI) been used in remediation?
- FAQ: What affects regulatory acceptance for nanoremediation (nZVI)?

THEMATIC PAGES

The thematic pages are under development but will provide information on the following topics:

- Thematic Page 1: Application of nZVI in Remediation
- Thematic Page 2: Benefits of Using Nanoparticles in Remediation
- Thematic Page 3: Implementation Issues for Using Nanoparticles in Remediation
- Thematic Page 4: Factors Affecting Potential Deployment Risks from nZVI Release into the Environment
- Thematic Page 5 Risk Perception Issues
- Thematic Page 6: Sustainability Considerations
- Thematic Page 7: Risk Benefit Appraisal
- Thematic Page 8 Managing Deployment Risks
- Thematic Page 9: Summary of the renegade nanoparticle risk assessment protocol for NanoRem field deployments
- Thematic Page 10: Initial sustainability assessment protocol for nanoremediation deployments within the NanoRem project

FULL REPORT

This information is drawn from the NanoRem report: A Risk/Benefit Appraisal for the Application of Nano-Scale Zero Valent Iron (nZVI) for the Remediation of Contaminated Sites. The full report including additional information, detail and referencing can be downloaded from:
www.nanorem.eu/Displaynews.aspx?ID=525.