Nanoremediation - all you wanted to know (a practical guide to nanoremediation) –

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Introduction

This is the first of two free sessions intended to provide delegates with sufficient information to decide if nanoremediation and new techniques in nanoremediation is a viable activity for their organisation. It is particularly targeted at practitioners such as site owners/managers, service providers (consultants contractors), and regulators.

Nanotechnologies could offer a step-change in remediation capabilities: treating persistent contaminants which have limited remediation alternatives, avoiding degradation-related intermediates and increasing the speed at which degradation or stabilisation can take place (Müller and Nowack 2010), among other potential benefits. In 2007 in Europe it was forecast that the 2010 world market for environmental nanotechnologies would be around $6 billion (JRC Ispra 2007). In fact, adoption of nanoremediation has been slower, with fewer than 100 field scale applications, since the first field application in 2000. However, the recent emergence of nanoremediation as a commercially-deployed remediation technology in several EU countries, notably the Czech Republic and Germany indicates that it is timely for service providers and site owners or managers in Europe to reconsider its potential applications and the consequent implications for their business activities.

Since early 2014, the EU FP7 NanoRem project (www.nanorem.eu) has been carrying out an intensive development and optimisation programme for different nanoparticles (NPs), along with analysis and testing methods, investigations of fate and transport of the NPs and their environmental impact. NanoRem is a €14 million international collaborative project with 28 Partners from 12 EU countries, and an international Project Advisory Group (PAG) providing linkages to the USA and Asia. It is a major initiative, which will support the effective deployment of nanoremediation technologies in Europe. As part of its work it offers these two sessions to provide key information for organisations considering diversifying into nanoremediation, or already beginning that process.

- The **first** session focuses on providing a practical grounding in nanoremediation theory and practice with particular reference to applied examples in the field.
- The **second** session focuses on providing business and strategic intelligence for delegates with interests in using nanoremediation at their sites or developing nanoremediation activities at their organisations.

Miroslav Černík, Technical University Liberec, Czech Republic: What nanoremediation is and what it can and cannot do

This presentation provides a practical foundation into the application of nanotechnology to environmental remediation. It provides a survey of the major drivers underpinning the development of the nanoscale zero-valent iron (nZVI) technology, other related nanotechnologies under development, as well as the key identified applications of the technology and implications associated with its use. Perspectives on the last two decades of development will be covered including key upsides/downsides, technology advances, regulatory issues, and apparent limitations.

NPs are typically defined as particles with one or more dimension of less than 100nm. 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. As produced, most nZVI tested falls into the 10-100 nm size range (O'Carroll et al. 2013, Karn et al. 2009), although it tends to agglomerate to form larger particles.

nZVI is used in two broad contaminant risk management configurations: elimination of source terms and/or pathway (plume) management. A range of deployment techniques may be used, and the nZVI may be modified in different ways to improve its remediation effectiveness (in particular its ability to be transported through zones of contamination, its resistance to deactivation, and its ability to bring about contaminant degradation). All of these interventions have a bearing on the relative balance of deployment risks and benefits from the nZVI use. O'Carroll *et al.* (2013) detail the chemical processes involved in the treatment of chlorinated solvents and various metals by nZVI.

Wiesner *et al.* (2006) describe two general nZVI synthesis methods that are used commercially: bottom-up and top-down approaches. The bottom-up approach begins with dissolved iron in solution and uses a reductant to convert dissolved metal to nZVI. The top-down approach begins with micrometre to millimetre-sized iron filings, which are ball-milled to fine, nano-sized particles. Top-down methods may also include condensation and attrition processes. In addition, a number of modifications have been developed to improve the effectiveness of nZVI by reducing the scale of agglomeration and the immediacy of passivation. Other modifications include doping with other metals to improve reactivity and suspension in emulsions to better access free-phase non-aqueous phase liquid NAPL (reviewed in Bardos *et al.* 2014). An example application in the Czech Republic is described in Annex 1.

Dan Elliott, Geosyntec Consultants, USA: Practical experience in nanoremediation

This presentation will trace the field experience using nanotechnology in remedial applications starting with the pioneering initial nZVI field demonstration in 2000 and progressing into the present day. Key aspects including the evolving thought on the role of nZVI in remedial design, dosage and delivery systems, stabilisation methods, and utilisation with complementary technologies will be covered.

The first documented field trial of nZVI, in 2000, involved treatment of trichloroethylene in ground-water 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.

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, 17 were in Europe (Czech Republic, Germany and Italy).

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.

Elsa Limasset, BRGM, France Regulatory perspective on nanoremediation use

This short article draws on three publicly available NanoRem resources which are extensively referenced to external sources.

- Paul Bardos, Brian Bone, Padraig Daly, Dan Elliott, Sarah Jones, Gregory Lowry, Corinne Merly, Stephan Bartke, Jürgen Braun, Nicola Harries, Niels Hartog, Thilo Hofmann, Stephan Wagner, Paul Nathanail (2014) A Risk/Benefit Appraisal for the Application of Nano-Scale Zero Valent Iron (nZVI) for the Remediation of Contaminated Sites, NanoRem Taking Nanotechnological Remediation Processes from Lab Scale to End User Application for the Restoration of a Clean Environment Project Nr.: 309517, EU, 7th FP, NMP.2012.1.2. s www.nanorem.eu.
- Paul Bardos, Sarah Jones, Stephan Bartke, Elsa Limasset, and Brian Bone (2015) IDL 9.4 Broad exploitation strategy and risk benefit appraisal NanoRem Taking Nanotechnological Remediation Processes from Lab Scale to End User Application for the Restoration of a Clean Environment Project Nr.: 309517, EU, 7th FP, NMP.2012.1.2. NanoRem Project Internal Deliverable IDL9.4 www.nanorem.eu. DOI: 10.13140/RG.2.1.3773.0728
- Tomkiv, Y., Bardos, P, Bartke, S., Bone, B. And Oughton, D. (in publication). The NanoRem Sustainability and Markets Workshop, Oslo, Norway, December 2014. NanoRem Report. To be available (August 2015) from http://www.nanorem.eu/displayfaq.aspx?id=12

In general "nanotechnology" has been perceived with wide-ranging worries by some parts of society in the same way as genetic modification and nuclear energy. This general "dread" is potentially a major barrier to the use of nanotechnology in remediation as regulators reflect societies' demands for what are perceived as environmental threats. There are two broad components that underpin these fears, the first is a worry about a general threat, and the second is that benefits are uncertain or are restricted to particular groups (e.g. "big business"). Despite is first field scale deployment being in 2000, nanoremediation has been slow to come into use, with this far perhaps around 70 field scale deployments worldwide.

A key goal for NanoRem is to provide the necessary evidence for a proper understanding the balance between risks and benefits. This short article summarises (1) where fears about nanoremediation are impeding its deployment, (2) NanoRem's interim findings on the balance of risks and benefits for nanoremediation use, (3) suggests that nanoremediation is not a special case for regulation and (4) attempts a cautious prediction of the direction of future travel.

1. Concerns about nanoparticle release in several countries regarding the use of nanoparticles for remediation

Despite having first been implemented in the field some 15 years ago, nanoremediation is still seen as an emerging technology. In 2007 JRC made predictions of substantial markets for nanoremediation. However in practice these markets have not emerged. The majority of nZVI applications have taken place in North America. As of 2014 NanoRem has identified only 17 field scale deployments in Europe (Czech Republic Germany and Italy) from available publications (including grey literature sources). This lack of adoption of the technology has attributed to difficulties in securing permits for release. The situation is very varied:

- In some countries where there appears to be no specific regulatory impediments to nanoremediation deployment, and it has been widely deployed (Czech Republic).

- In several countries (e.g. Austria, Switzerland, UK, USA, Canada (Quebec) there has been questioning of the balance between the benefits of nanoremediation, compared with the *potential* risks of releasing nanoparticles (NPs) into the environment. A key concern has been a lack of knowledge of the environmental fate and behaviours of these particles.

- In two countries (the UK and Germany) these concern led to “voluntary” moratoria on the use of NPs in remediation, which has prevented the permitting for use for nanoremediation. “Voluntary” is a misleading word, as the effect is actually one of prevention of deployment, rather than service providers choosing not to deploy.
    - In the UK the moratorium has implemented via the regulatory process for permits for remediation technology use.
    - In Germany at least one published nanoremediation deployment has taken place despite the deployment, so there is clearly some variability in the regulatory implementation of its moratorium.
    - This cautious approach has also been adopted as a public statement by at least one major private sector corporation (Du Pont).

The NanoRem project specifically focuses on the perceived gaps in knowledge of both the technology and in the fate and transport of NPs in the environment identified by the various risk-benefit reviews that have been published.

2. NanoRem – Interim Risk-Benefit Perspective (for nZVI)

nZVI is anticipated as having two major benefits for process based remediation, at least in theory: possible extension of the range of treatable contaminant types, and increasing the efficacy of treatment (speed and degree of completion). However, the case for substantial benefits over available technologies is far from certain. To date, the use of nZVI in remediation in practice has been largely a niche application for chlorinated solvents in aquifers, competing with more established techniques such as *in situ* bioremediation and chemical reduction.

On the other hand, the available evidence reviewed by NanoRem supports, but does not irrevocably confirm, a view that the risks of nZVI deployment should be considered in the same way as any other potentially hazardous treatment reagents already widely used for better established *in situ* chemical reduction/oxidation technologies.

However there is some uncertainty in understanding the risks to the wider environment of nZVI deployment in particular to groundwater and surface water receptors. Although most laboratory studies and subjective practitioner experience would suggest that adverse effects would be minor, localised and short-lived, there is a lack of effective field based particle monitoring technologies and definitive (peer reviewed and validated data) from applications in the field that corroborates this view. This may present a challenge to regulatory acceptance which the NanoRem project seeks to address.

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.

3. What affects regulatory acceptance for nanoremediation- is it a special case?

One of the findings of a recent NanoRem Workshop on *Sustainability and Markets* which took place in Oslo in December 2014, was that the application of NPs in remediation processes was not foreseen as requiring specific regulatory inputs for permitting the technology, compared with other *in situ* technologies[1].

At EU level, regulators do not raise any fundamental concerns regarding nanoremediation, although they is still demand for more information to prove the applicability of NP at acceptable risks (as for any new technology).

Whether or not nanoremediation is seen as a special case is therefore related to *where* it is being considered (which country / which region). Anecdotally, NanoRem's own conversations imply that *fear* of regulatory constraints may be a barrier to interest in nanoremediation as a technology by site owners and service providers. This fear may affect deployment outside the countries / regions where nanoremediation actually is a special case.

4. Likely future direction of travel

NanoRem does not anticipate any specific European regulatory regime that considers nanoremediation in principle different to other forms of in situ remediation. The NanoRem risk-benefit work is now being extended to a wider range of nano-particles, and all of its risk-benefit findings will be updated as the findings of its scientific programme and field scale deployment tests become available. NanoRem hopes its findings will facilitate a European consensus on appropriate use of nanoremediation, supported by, the major European contaminated land stakeholder networks. This in turn may provide greater consistency in how nanoremediation permitting is considered in different countries.

Jürgen Braun, University of Stuttgart, Germany: The NanoRem experience: large scale and case study testing

A key part of NanoRem's research agenda is the use of large scale tank experiments and well monitored field based case studies to provide the kind of practical performance data that some regulators and users feel may be missing. This presentation provides an overview of NanoRem's work and findings to date from these activities.

A feature of the NanoRem project, unique in Europe, is the inclusion of the VEGAS containers which allow not only a closed mass balance but also indoor experiments at a field relevant scale with exactly controlled initial and boundary conditions. Moreover these containers allow maximum flexibility with contaminants and a highly disaggregated monitoring grid. Thus direct conclusions regarding the improvement of the real field sites may be drawn.

Three container experiments have been set up:

1. *The Large Scale Container*

In a large heterogeneous, unconfined aquifer (L x W x H = 9 x 6 x 4.5m) steady state groundwater flow was established. Then a BTEX plume was introduced. The goal of the experiment was to inject Goethite nanoparticles to enhance the microbial degradation of this plume.

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[1] In common with other chemical substances nanopartciles fall under the REACH regime

The container is equipped with 378 groundwater sampling ports, thus a highly defined spatial analysis of the plume was possible. A numerical model (MODFLOW) was set up to model flow and transport in the aquifer. This model was also used to optimize the location of an injection well for the nanoparticles. Requirement for the injection was that the particles are "homogeneously" distributed throughout the pathway of the contaminant. At the same time it had to be insured that the injection flowrate would allow for a maximum particle transport while daylighting was prevented.
Based on these calculations then 6 m³ of a slurry containing 20 kg/m³ goethite nanoparticles was injected at t a rate of Q=0.7 m³/h. Water samples were taken to delineate the spreading of the nanoparticles: It had to be shown that the particles reach the target zone and at the same time that they do not migrate beyond this zone. Subsequently the groundwater was sampled at regular time intervals to delineate the effect of the nanoparticle injection on the BTEX degradation.

2. *The large Scale Flume I*

The first large scale flume experiment was set up to chemically reduce a chlorinated hydrocarbon (PCE) source using nano zero valent iron (nZVI) produced by Nanoiron (CZ). The artificial aquifer in the flume has dimensions of L x W x H = 6 x 1 x 3m. The unconfined aquifer (WT = 1.7 m) is homogeneous and a steady state groundwater flow (q = 0.2 m/d) was established to simulate field conditions. In this aquifer 2 kg of PCE were injected in 20 mL increments to create a residual contaminant source of about 0.7 m³.
At 32 sampling ports water samples were taken at regular intervals to prove that the source was stable in space (no remobilization) and that a steady state plume was established. After establishment of the plume Nanofer 25s particles were injected using a direct push rod. The injected slurry was prepared online using the AQUATEST Vulcanus mixing unit which allows for a continuous addition of concentrated nZVI slurry into the injection stream. A total of 1 m³ suspension with a concentration of c_{nZVI} = 10 kg/m³ was injected at different locations throughout the contaminant source. The spreading of the nanoparticles was monitored using susceptibility probes as well as micro pumps. Again the injection pressure and flowrates were limited to prevent daylighting. First preliminary results indicate that the injection rate thus chosen (Q = 0.1 m³/h) was not sufficient to provide a flow field sufficient to transport the nanoparticles for an appreciable distance. Currently the particle suspension is being improved to obtain better migration results in the next injection.

3. *The Large Scale Flume II*

The aquifer in the second large scale flume is identical to the one in the first flume, but the monitoring equipment installed is slightly different. Where the first flume sports a series of susceptibility spools, these have been omitted in the second flume since here Carbo-Iron® is to be injected. Carbo-Iron® contains of approx. 60w% activated carbon (AC) and both 25w% nZVI 15wt% iron oxide inside the AC grain. To obtain an injectable suspension, 20kg Carbo-Iron® powder and a minimal amount of CMC (5 wt% compared to particle mass) are mixed in tab water. CMC is used to prevent agglomeration of Carbo-Iron® particles and, thus, to ensure controlled migration of the reactant in the aquifer. While the flume experiment has been set up and steady state base flow has been obtained the Carbo-Iron® suspension is being optimized. NanoRem milestones require an injection in June of 2015 this deadline will be held and first initial results will be reported in the AQUACONSOIL presentation.

Paul Bardos, r3 environmental technology ltd, UK. Wrap Up and Clinic Offer

A NanoRem brochure “Nanoremediation: what’s in it for me?” will be provided to participants. This will include an enquiry form which can be completed and handed back to the session organisers on the day. The brochure and form will also be available as a link on www.nanorem.eu. The enquiry form offers the chance for delegates to find out more about the NanoRem project, but also to ask specific questions about their own nanoremediation interests which the consortium will endeavour to answer in the weeks following AquaConsoil.

Note: Delegates will be provided with a NanoRem web link for take home materials from special session presentations that they can use within their own organisations to support further decision-making

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Annex 1: Case Study Site: Spolchemie site remediation and NanoRem field site application. From the 2014 NanoRem Newsletter

Case Study Site: Spolchemie site remediation and NanoRem field site application

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Site Remediation

The Spolchemie site was chosen as one of the NanoRem case study sites, to test two types of nanoparticles (NPs) (zerovalent iron - nZVI and iron oxide NPs) for *in situ* remediation of BTEX (Benzene, Toluene, Ethylbenzene, and Xylenes) contamination. Nanoremediation was seen as an opportunity to enhance the *in situ* biodegradation of the BTEX contaminants and to reduce the current remediation method of skimming free product from the groundwater surface waters and contining the use of a pump and treatment system that have been ongoing since 2005. Spolchemie is one of the leading synthetic resin manufacturers in Europe. Besides synthetic resins it also produces other chemicals (e.g. potassium and sodium hydroxide, epichlorohydrin, allylchloride, sodium hypochlorite, perchloroethylene, hydrochloric acid, liquid chlorine). This production site is located in an area of approx. 52 hectares at Usti nad Labem (Czech Republic) in the heart of Europe. The main Spolchemie complex comprises industrial buildings, roads and railway sidings, with a few vegetated areas. The site is in a rural setting. The plant was established in 1856, and began the production of inorganic chemicals followed by the manufacture of organic dyes at the turn of the 20th century, and from the middle of the last century Spolchemie started to produce resins and freons based on tetrachlormethane and tetrachlorethene.

The production, treatment, storage and distribution of these various products has led to extensive contamination of the subsurface by chlorinated ethenes and methanes and organic solvents including BTEX compounds, which in many cases have dispersed widely from the original source areas. Some parts of the subsurface are also contaminated by high concentrations of iron and other inorganics (mainly chlorides and sulphates) which have increased the salinity of the groundwater.

A number of groundwater monitoring campaigns has been undertaken followed by a preliminary site investigation. Based on this work a Conceptual Site Model (CSM) has been developed detailing the subsurface conditions followed by a preliminary risk analysis. This initial CSM was refined by further targeted investigation and subsequent updating of the risk analysis. This work indicated that remediation requirements would be complex. With further funding being secured, the CSM was expanded following delineation of the contamination, geological and hydrogeological surveys, well logging, development of a hydrogeological model of the site and a remediation feasibility study. Exploration of the site is still ongoing to further improve the conceptual site model and review further the most appropriate overall remedial strategy.

Six contamination plumes have been identified at Spolchemie, based on the type of contamination, geology and hydrogeology [see Box 1] of the subsurface areas identified in the conceptual site model.

BOX 1 – Geology and Hydrogeology at the site

The geological formations underlying the site are complex with the lower geological formations consisting of Mesozoic Cretaceous siltstones and claystones (thickness of several tens of metres) overlain by Tertiary Miocene tuffitic clays. From north to south of the site the thickness of the tuffite clays decreases, and is infilled by overburden of Cretaceous sediments. Overlying the Mesozoic and Tertiary sediments is a Quaternary terrace formed mainly by fluvial sediments and deluvio fluvial sediments of the Bilina River, the Elbe River and Klissky Stream. The Quaternary terrace consists of gravel, sand and gravel with large boulders with an average thickness of 6m. The Quaternary terrace is overlain by aolian loess loams, which are located at a depth of 1.5 to 3.5 m below ground level (max. thickness 2.5 m) with made ground overlying that. This consists of backfill of various thicknesses of clay, loam, sand, tarmacadam, pieces of brick and concrete.

The groundwater levels mirror the interface of the loess overburden in the overlying Quaternary terrace deposits. The groundwater level is from 3.0 to 4.0 m below ground level. The general horizontal groundwater flow direction is South East to South East East to the Bilina and Elbe

The general remedial concept is based on a combination of pump and treat technology, a passive reactive barrier and enhancing physical, chemical and biological *in situ* methods. The different methods being applied depending on the character of the contamination. For example permanganate infiltration or *in situ* oxidation accompanied by heating and sparging by a modified Fenton process, supported by venting, are being applied in the source zones, with pump and treat being combined with biological processes such as dehalogenation in a treatment station. This is being monitored in detail by molecular biology analysis in collaboration with the Technical University of Liberec.

The main principle underpinning the remediation design being considered is to pump the contaminated groundwater, treat it above ground and then allow the treated groundwater to infiltrate back into the ground. The costs associated with this type of pump and treat approach tend to be very high, and its operating lifetime tends to be rather long. Nanoremediation may offer a way of dealing with the source terms *in situ* so reducing the requirement for pathway management, and therefore lowering pump and treat costs and treatment time. NanoRem will explore this concept at this site.

The NanoRem case study at Spolchemie

The NanoRem case study at Spolchemie includes two large scale field tests.

Test Site 1: Two contamination plumes in the western part of the Spolchemie area, with Chlorinated Hydrocarbon Contamination (CHCs), are being treated by a 500 m long impermeable underground wall with 10 reactive gates filled with zerovalent iron chips. A pump and treat remedial system was also installed to decrease the concentration of CHCs on the inlet side of the wall. However, routine monitoring showed an overflow of contamination behind the wall from a secondary contamination source (storage tank) was occurring see Figure 1.

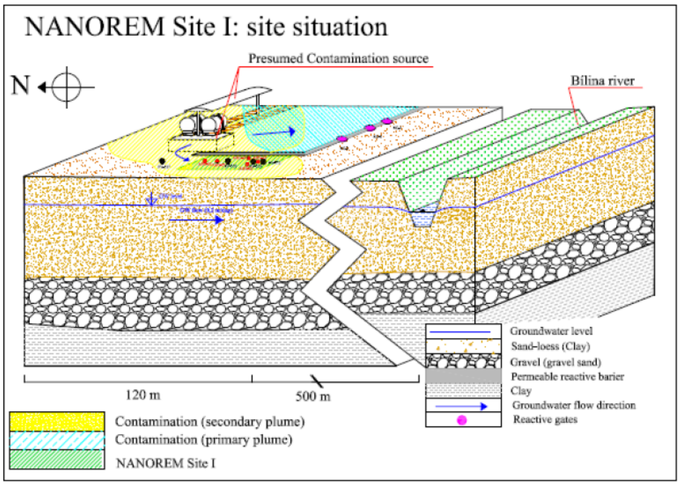

Figure 1 Site Situation (© Aquatest 2014)

The application of nZVI is being evaluated as an *in situ* technology for the clean-up of this secondary source area. A field test will be used to validate its suitability as a full scale remediation option. This field test is being conducted by AQUATEST with participation of several NanoRem partners (TUL, Nanoiron, Palacky University in Olomouc and VEGAS Stuttgart). Detailed monitoring including installation of new wells for vertical contaminant distribution is being carried out in collaboration with VEGAS including the use of micro pumps installed in the original ZVI system for nanoparticle monitoring in the field test. A preliminary tracer test has already been undertaken. nZVI (NanoFer 25S) supplied by Nanoiron will be injected in the autumn of 2014.

Test Site 2: The middle part of the Spolchemie site was also extensively contaminated by BTEXs. A general approach in this area has been to excavate the contaminated soils from the unsaturated zone in the source zone area and then remediate the underlying aquifer by pump and treat. The pumping of free phase from several wells is also ongoing. Treated water is discharged back into the ground. Enhanced *in situ* bioremediation has been identified as a suitable remediation technology to treat residual free phase product and BTEX compounds in this area based on laboratory and pilot tests. Tests confirmed the ability of natural microflora to degrade the present contamination under anoxic conditions with nitrate being used as an electron acceptor. This has created an opportunity for NanoRem to look at nanoremediation and *in situ* bioremediation processes working in tandem, using of oxidic NPs (based on Goethite) as another possible electron acceptor. The NanoRem partners involved in this trial are the Helmholtz Institute in Muenchen, UNIVI and VEGAS Stuttgart.

This area of the site has been investigated in detail. Additional wells have also been drilled and tracer tests undertaken before application to precisely delineate the plume. Undisturbed soil samples were taken for laboratory test verification (reactivity and migration tests) to assist with the NanoRem field test design.

Permitting: Permission for NPs application (for both sites) required negotiation with multiple agencies: the Municipality of Usti nad Labem, the Regional Authority, Czech Inspection of Environment, Ministry of Environment and Ministry of Finance. The permitting process was facilitated by an open process of discussion over many years, which provides information in detail about the whole remediation process, including the preliminary studies of proposed technologies, which are first applied as a small pilot test in the areas covered by the hydraulic barrier.