NanoRem in a nutshell

Hans-Peter Koschitzky, Joachim Roos, Alexandra Gens, USTUTT

NanoRem Final Conference

Nanoremediation for Soil and Groundwater Clean-up - Possibilities and Future Trends

Outline

- Introduction
- Overall Goals
- Project Structure
- Main Results
- NanoRem Toolbox

What is NanoRem?

NanoRem – Taking **Nano**technological **Rem**ediation Processes from Lab Scale to End User Applications for the Restoration of a Clean Environment

NanoRem is a € 14 million international collaborative project with 29 Partners from 13 countries, and an international Project Advisory Group (PAG) providing linkages to the USA and Asia.

- **Industry, research, SMEs, public agencies, technology providers**
- **01.02.2013 – 31.01.2017**

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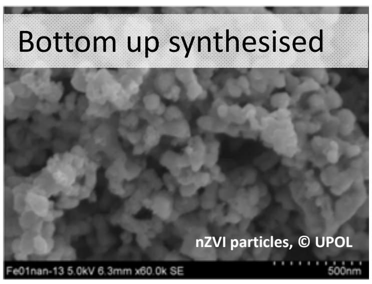
What is nanoremediation?

- The use of nanoparticles (NPs) for treatment (remediation) of contaminated soil and groundwater
- Depending on the use of different particles types nanoremediation processes generally involve reduction, oxidation, sorption or a combination
- NPs usually defined as particles with one or more dimensions <100nm
- Can include larger composite particles with embedded nanoparticles



Advantages of NPs for in situ remediation

- Small size
  ➔ higher surface area
  ➔ very reactive
- NPs (in a carrier fluid) injected into saturated zone via wells
- Focus on source treatment
- Applicable below buildings
- “independent” of application depth
- different NPs
- for various contaminants
- innovative technology

Overall Goals (1)

(1) Identify the **most appropriate nanoremediation technological approaches** to achieve a **step change** in remediation practice

(2) Develop **lower cost production techniques** and production at **commercial scales** of nanoparticles

(3) Determine the **mobility and migration potential of nanoparticles** in the subsurface, and relate these both to their potential usefulness and also their potential to cause harm

Overall Goals (2)

(4) Develop a comprehensive **set of tools for design, application and monitoring practical nanoremediation performance and determine the fate** of nanoparticles in the subsurface

(5) Engage in **dialogue with key stakeholder and interest groups** to ensure that research, development and demonstration meets their needs, is most sustainable and appropriate whilst balancing benefits against risks

(6) Carry out a **series of full scale applications in several European countries** to provide cost estimations and performance, fate and transport findings

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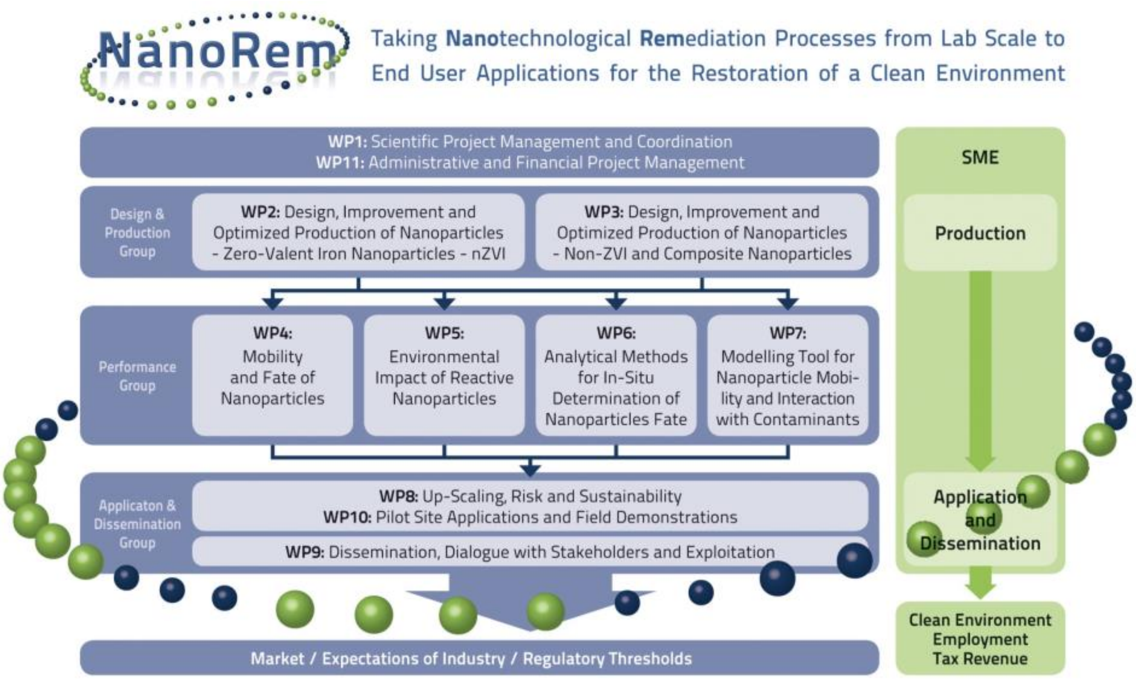
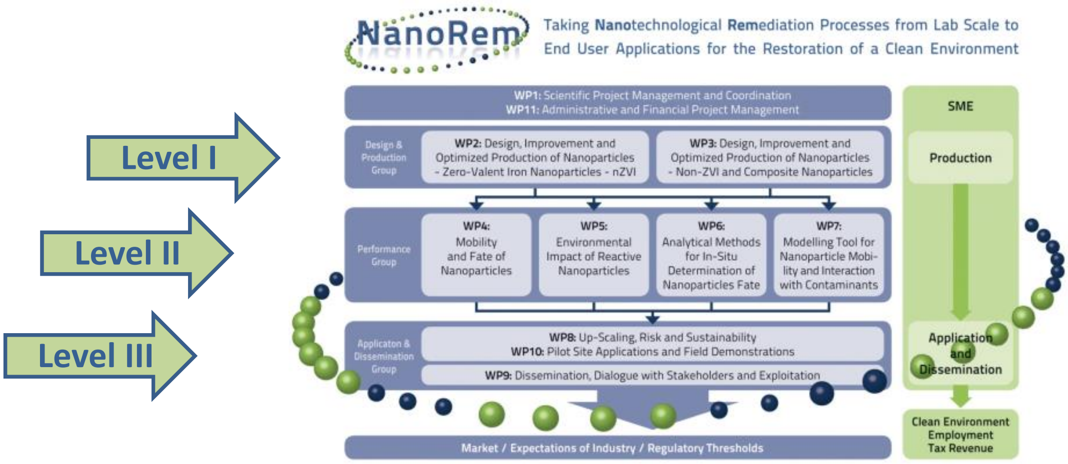
NanoRem Structure



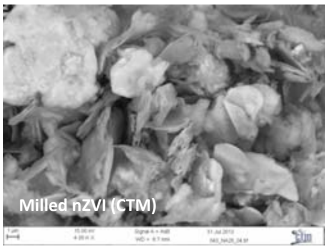
NanoRem‘s three level approach



I	Development and production: **WP2** and **WP3**
II	Properties and behavior in the environment: **WP4** to **WP7**
III	Application, permission (approval) and promotion • Large scale experiments and pilot sites: **WP8** and **WP10** • Dissemination, communication and exploitation: **WP9**

NanoRem Main Results (1)

(1) Identify the **most appropriate nanoremediation technological approaches** to achieve a **step change** in remediation practice



- Model systems have been used to investigate mobility, reactivity, functional lifetime and reaction products
- For NP optimisation, the influence of size, surface chemistry, structure and formulations was investigated

✓ Results led to enhanced NPs and novel NP types
✓ Step change: Extension of practically treatable contaminants

More information: *Bulletin no 4: “A Guide to Nanoparticles for the Remediation of Contaminated Sites”*

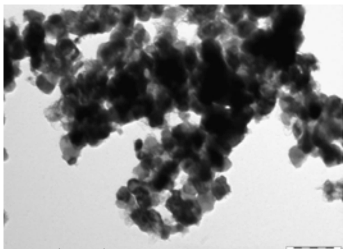
NanoRem Main Results (2)

(2) Develop **lower cost production techniques** and production at **commercial scales** for nanoparticles

- ✓ Laboratory scale production processes were up-scaled to the industrial level, resulting in a commercially available and economically competitive technology
- ✓ nZVI particles have been improved: Surface coating allows for a more convenient handling regarding transport and storage (air-stable)

More information:
Bulletin no 4: "A Guide to Nanoparticles for the Remediation of Contaminated Sites"


Air-stable Carbo-Iron © A. Kuenzelmann, UFZ



nZVI (UPOL)

NanoRem Main Results (3a)

(3) Determine the **mobility and migration potential of nanoparticles** in the subsurface, and relate these both to their **potential usefulness** and also their **potential to cause harm**

- Experiments for mobility and migration potential ranged from laboratory scale (columns), over large-scale contained laboratory systems to field tests

✓ More information:
- *Final Report on Three Large-Scale Experiments and Generalized Guideline for Application*
- *Stability, Mobility, Delivery and Fate of optimized NPs under Field Relevant Conditions* and
- NanoRem site bulletins

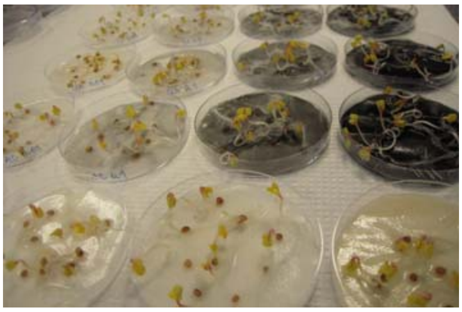

Reactivity studies (VEGAS/USTUTT)

NanoRem Main Results (3b)

- Investigations included unintended secondary effects of NPs application on environment and ecosystems

✓ In the lab, no significant toxic effects were observed on soil and water organisms (tests included effects on earthworms, radish roots, green algae and bacteria)

✓ In three out of four field sites investigated, no toxic effects were observed up to nine months after NP injection. The remaining one was transient



Radish seeds (Claire Coutris, NIBIO)

✓ A positive effect on organohalide-respiring bacteria was observed in two cases

Commercially Available NanoRem Particles

Particle name	Type of particle	Manufacturer	Process of contaminant removal	Target contaminants
Carbo-Iron® (industry)	Composite of Fe(0) and activated carbon	ScIDre GmbH, Germany	Adsorption + Reduction	Halogenated organics (contaminant spectrum as for NZVI)
FerMEG12	Mechanically ground nZVI particles	UVR-FIA GmbH, Germany	Reduction	Halogenated hydrocarbons
NANOFER 25S	Nano scale zero valent iron (nZVI)	NANO IRON s.r.o., Czech Republic	Reduction	Halogenated hydrocarbons and heavy metals
NANOFER STAR	Air stable powder, nZVI	NANO IRON s.r.o., Czech Republic	Reduction	Halogenated hydrocarbons and heavy metals
Nano-Goethite	Pristine iron oxides stabilized with HA	University of Duisburg-Essen, Germany	Oxidation (bioremediation) + Adsorption of HM	Biodegradable (preferably non-halogenated) organics, such as BTEX; heavy metals

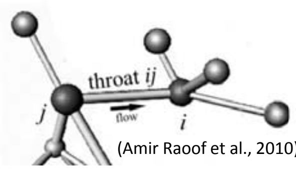
NanoRem Particles under Development

Particle name	Type of particle	Manufacturer	Process of contaminant removal	Target contaminants
Trap-Ox Fe-zeolites	Nanoporous alumosilicate loaded with Fe(III)	UFZ Leipzig, Germany	Adsorbent + Oxidation (catalyst)	Small molecules (dep. on pore size of zeolite) - e.g. BTEX, MTBE, dichloroethane, chloroform, …
Bionano-magnetite	Produced from nano-Fe(III) minerals	University of Manchester, UK	Reducing agent and adsorption of heavy metals	Heavy metals, e.g. Cr(VI)
Palladized bionano-magnetite	Biomagnetite doped with palladium	University of Manchester, UK	Reduction (catalyst)	E.g. Halogenated substances (contaminant spectrum broader than for nZVI)
Abrasive Milling nZVI	Milled iron	Centre Tecnològic de Manresa, Spain	Reduction	Halogenated aliphatics and Cr(VI)
Barium Ferrate	Fe(VI)	VEGAS, University of Stuttgart, Germany	Oxidation	BTEX?, nitroaromatic compounds? (under investigation)
Mg/Al particles	Zero valent metals	VEGAS, University of Stuttgart, Germany	Reduction (reagent)	Halogenated hydrocarbons
Nano-FerAl	Composite of Fe and Al	UVR-FIA GmbH / VEGAS, Germany	Reduction (reagent)	Halogenated hydrocarbons

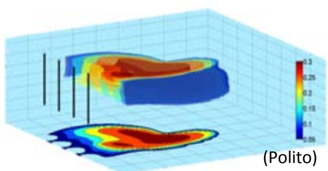
NanoRem Main Results (4)

(4) Develop a comprehensive **set of tools for design, application and monitoring practical nanoremediation performance and determine the fate** of nanoparticles in the subsurface

- ✓ Bulletin No 2: *"Appropriate Use of Nanoremediation"*
- ✓ Bulletin No 3: "*Generalized Guideline for Application*"
- ✓ Bulletin No 5: "*Development and Application of Methods for Monitoring Nanoparticles in Remediation"*
- ✓ Bulletin No 6: "*Forecasting NP Transport for Soil Remediation"*
- ✓ Pre-Deployment Risk Assessment Tool



(Amir Raoof et al., 2010)



(Polito)

Numerical modeling of nanoparticle transport: From the pore scale to the field scale

Monitoring arrays on pilot site (VEGAS/USTUTT)

NanoRem Main Results (5)

(5) Engage in **dialogue with key stakeholder and interest groups** to ensure that research, development and demonstration meets their needs, is most sustainable and appropriate whilst balancing benefits against risks

- Address real market and regulatory interests
- Communicating findings regarding renegade particles and relative sustainability over the life cycle of a typical remediation project

✓ *"Exploitation Strategy, Risk-Benefit Analysis and Standardisation Status"* available on www.nanorem.eu

✓ Life Cycle Assessment Report on production process of 3 NPs included in "*Final Report on Three Large-Scale Experiments and Generalized Guideline for Application"*

✓ *"NanoRem Case Study Sustainability Assessment Background and Workbook"* to provide background, context and procedures for a sustainable remediation

NanoRem Main Results (6)

(6) Carry out a **series of full scale applications in several European countries** to provide cost estimations and performance, fate and transport findings

✓ NPs were applied in both large-scale containers and on pilot sites to provide on-site validation of the lab-scale results

✓ Site results can be found in the site bulletins on www.nanorem.eu

✓ All field trials were carried out within a risk management regime that gained the required regulator approvals

✓ Qualitative sustainability assessment for one NanoRem pilot site and an external one

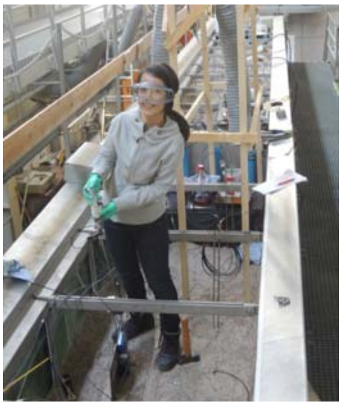

Injection at Hungarian pilot site (Golder)

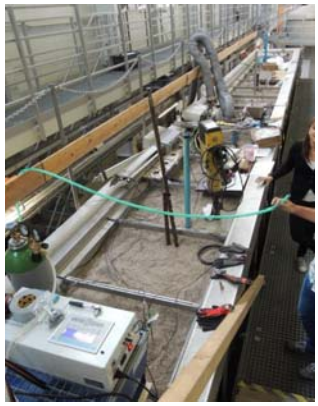
✓ **Spin-Offs:**

- Intrapore UG, Essen, Germany
- Photon Water Technology s.r.o., Liberec, Czech Republic

Large Scale Container (VEGAS/USTUTT)

Large Scale Flume (VEGAS/USTUTT)

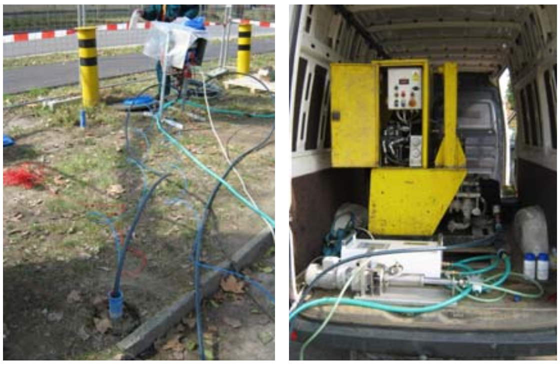




NanoRem Pilot Sites

Site	Country	Site Primary Investigator	Target Cont.	NP-Type	Reaction Principle	Aquifer
Solvay	CH	Solvay	CHC	FerMEG12 (milled nZVI)	Reduction	porous / unconfined
Spolchemie 1	CZ	Aquatest	CHC	NANOFER 25S / NANOFER STAR	Reduction	porous / unconfined
Spolchemie 2	CZ	Aquatest	BTEX	Nano-Goethite (Iron-Oxide)	Oxidation / microbial enhancement	porous / unconfined
Neot Hovav	IS	Negev, BGU	TCE, cis-DCE, toluene	Carbo-Iron®	Adsorption / Reduction	fractured
Balassagyarmat	HU	Golder	PCE, TCE, DCE	Carbo-Iron®	Adsorption / Reduction	porous / unconfined
Nitrastur	ES	Tecnalia	As, Pb, Zn, Cu, Ba, Cd	NANOFER STAR	Reduction	porous / unconfined

Spolchemie pilot site I, micropumps check (VEGAS/USTUTT)



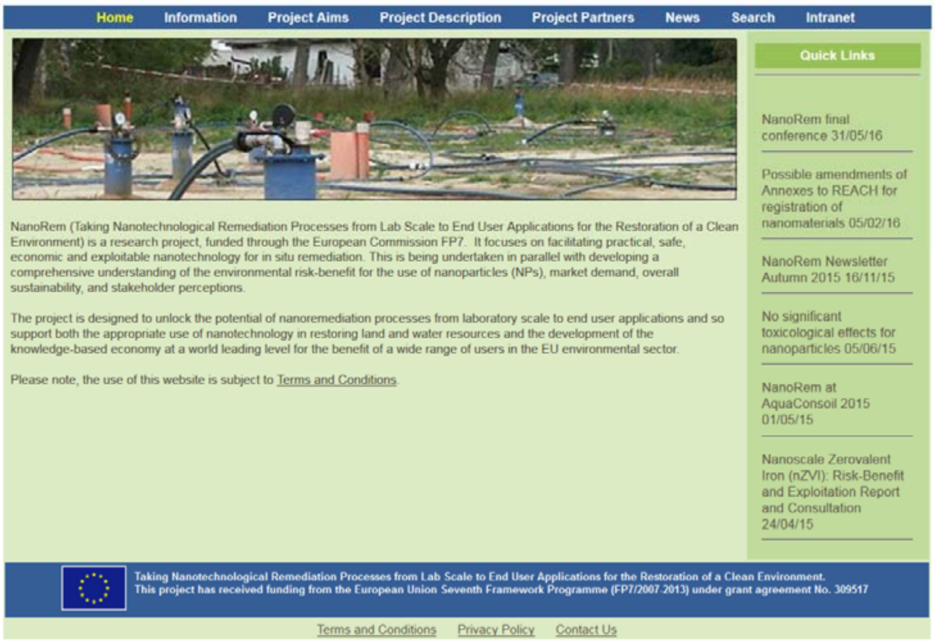
Installations at Solvay site (VEGAS/USTUTT)

Injection at Spolchemie pilot site 1 (VEGAS/USTUTT)

NPs for Solvay pilot site (VEGAS/USTUTT)

www.nanorem.eu

Nanotechnology for contaminated land **Rem**ediation



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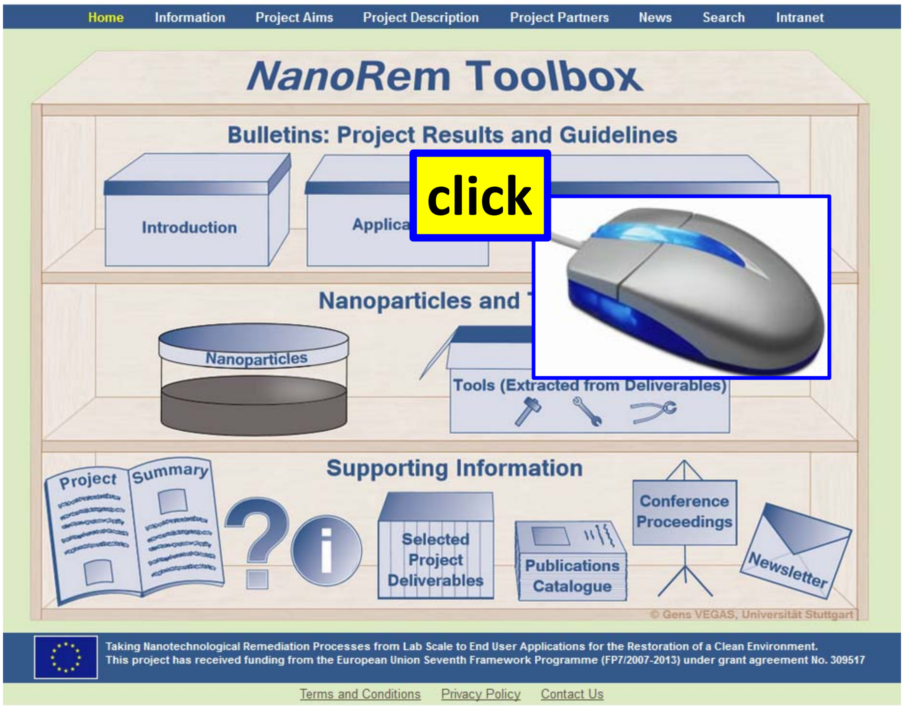

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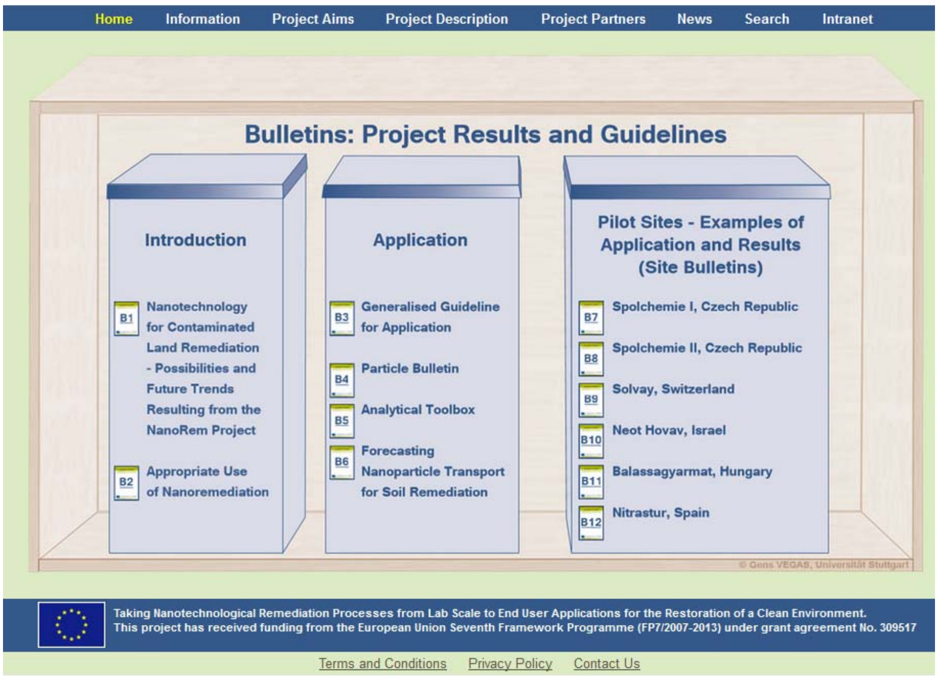

List of NanoRem bulletins

No.	Title
1	Nanotechnology for Contaminated Land Remediation - Possibilities and Future Trends Resulting from the NanoRem Project
2	Appropriate Use of Nanoremediation
3	Generalised Guideline for Application of Nanoremediation
4	A Guide to Nanoparticles for the Remediation of Contaminated Sites
5	Development and Application of Methods for Monitoring Nanoparticles in Remediation
6	Forecasting Nanoparticle Transport for Soil Remediation
7-12	Site-Bulletins

CL:AIRE NanoRem 1 (November 2016)

NanoRem Bulletin

CL:AIRE's NanoRem bulletins describe practical aspects of research which have direct application to the characterisation, monitoring or remediation of contaminated soil or groundwater using nanoparticles. This bulletin provides an overview of the NanoRem project.

Nanotechnology for Contaminated Land Remediation – Possibilities and Future Trends Resulting from the NanoRem Project

Background

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. However, 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 now time to look at nanoremediation as a technology in the European market-place.

Between 2013-2017, the NanoRem project (www.nanorem.eu) carried out an intensive development and optimisation programme for different nanoparticles (NPs), along with analytic and testing methods, investigations of fate and transport of the NPs and their environmental impact.

The aim of this bulletin is to provide an overview of NanoRem, its aims, structure and the main generic results. This overview provides links to other NanoRem outputs where a greater depth of detail can be found.

200 nm

Figure 1. TEM image of nZVI particles injected at the Spolchemie I Site © J. Filip, UPOL, Palacký University in Olomouc, Czech Republic.

What is Nanoremediation?

Nanoremediation describes the *in situ* use of NPs in the treatment of contaminated groundwater and soil. Depending on the use of different particles nanoremediation processes generally involve reduction, oxidation, sorption or their combination. NPs are usually defined as particles with one or more dimensions of less than 100nm. In practice, nanoremediation may apply to particles which are larger, for example composites with embedded NPs. NPs used in remediation are mostly metals or metal oxides, most frequently nano-scale zerovalent iron (nZVI). They may be modified in various ways to improve their performance, for example inclusion of a catalyst (often palladium), use of coatings or modifiers, or emplacement on other materials such as activated carbon or zeolites (for iron oxides).

They are generally applied *in situ* via various injection methods, which may include the use of viscosity control agents or other materials to facilitate targeted emplacement of nanoparticles in the subsurface.

An Introduction to the NanoRem Project

NanoRem was a research project, funded through the European Union Seventh Framework Programme. The NanoRem project focused on facilitating practical, safe, economic and exploitable nanotechnology for *in situ* remediation. This was undertaken in parallel with developing a comprehensive understanding of the environmental risk-benefit for the use of NPs, market demand, overall sustainability, and stakeholder perceptions. The project was designed to unlock the potential of nanoremediation processes from laboratory-scale to end user applications and to support both the appropriate use of nanotechnology in restoring land and water resources and the development of the knowledge based economy at a world leading level for the benefit of a wide range of users in the EU environmental sector.

Taking **Nano**technological **Rem**ediation Processes from Lab Scale to End User Applications for the Restoration of a Clean Environment.
This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 309517.

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NanoRem Bulletin

Figure 6. Heads of monitoring arrays for *in situ* susceptibility measurement (on Spolchemie I pilot site) connected to measuring hardware in protective box © VEGAS/USTUTT, University of Stuttgart, Germany.

Project Results Online – the NanoRem Toolbox

The NanoRem Toolbox (Fig.7), available on www.nanorem.eu, focuses on the needs of decision makers, consultants and site owners. It provides the respective outputs of NanoRem in three levels:

1) The bulletins include the most relevant information in a condensed and concise way.
2) More detailed information on nanoparticles and tools are located in the "Nanoparticles and Tools" shelf.
3) Other dissemination products and selected project deliverables can be found in the "Supporting Information" shelf.

Figure 7. The NanoRem Toolbox.

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Table 3: List of NanoRem project partners.

Organisation Name	Country
University of Stuttgart (VEGAS) - Coordinator	DE
Karlsruhe Institute of Technology	DE
Solvay (Schweiz) AG	CH
Helmholtz-Zentrum für Umweltforschung GmbH, UFZ Centre for Environmental Research	DE
Ben-Gurion University of the Negev	IL
Fundació CTM Centre Tecnològic	ES
University of Vienna	AT
University of Manchester	UK
Fundacion Tecnalia Research & Innovation	ES
HMGU, Helmholtz Zentrum München *Left the consortium 31/03/2015*	DE
NIBIO, Norwegian Institute of Bioeconomy Research *Name change (formerly "Bioforsk")*	NO
Technical University of Liberec	CZ
NMBU, Norwegian University of Life Sciences	NO
Aquatest	CZ
Palacký University in Olomouc	CZ
CNRS, Centre National de la Recherche Scientifique	FR
Politecnico di Torino	IT
Geoplano Consultores, S.A.	PT
DTU, Technical University of Denmark	DK
Stichting Deltares	NL
r3 Environmental Technology Limited	UK
LQM, Land Quality Management Ltd.	UK
CL:AIRE	UK
NANO IRON, s.r.o.	CZ
Golder Associates GmbH	DE
BRGM, Bureau de Recherches Géologiques et Minières	FR
UVR-FIA GmbH	DE
SciDre, Scientific Instruments Dresden GmbH	DE
University Duisburg-Essen *(Successor of HMGU)*	DE

For further information on NanoRem please visit www.nanorem.eu

This bulletin was written by Alexandra Gens, Joachim Roos and Hans-Peter Koschitzky - VEGAS, University of Stuttgart with contributions by Erik Joner and Claire Coutris - NIBIO, Paul Bardos - r3, Jürgen Braun - VEGAS, Pauline van Gaans - Deltares, Deborah Oughton - NMBU, Paul Nathanail - LQM, and Elsa Limasset - BRGM.

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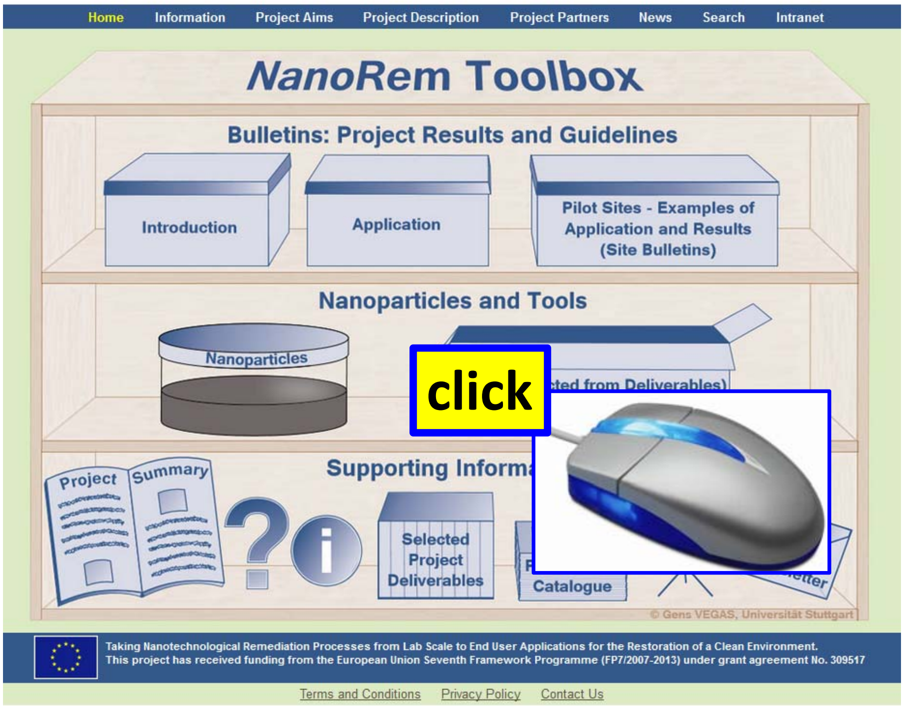
Nanotechnology for contaminated land Remediation



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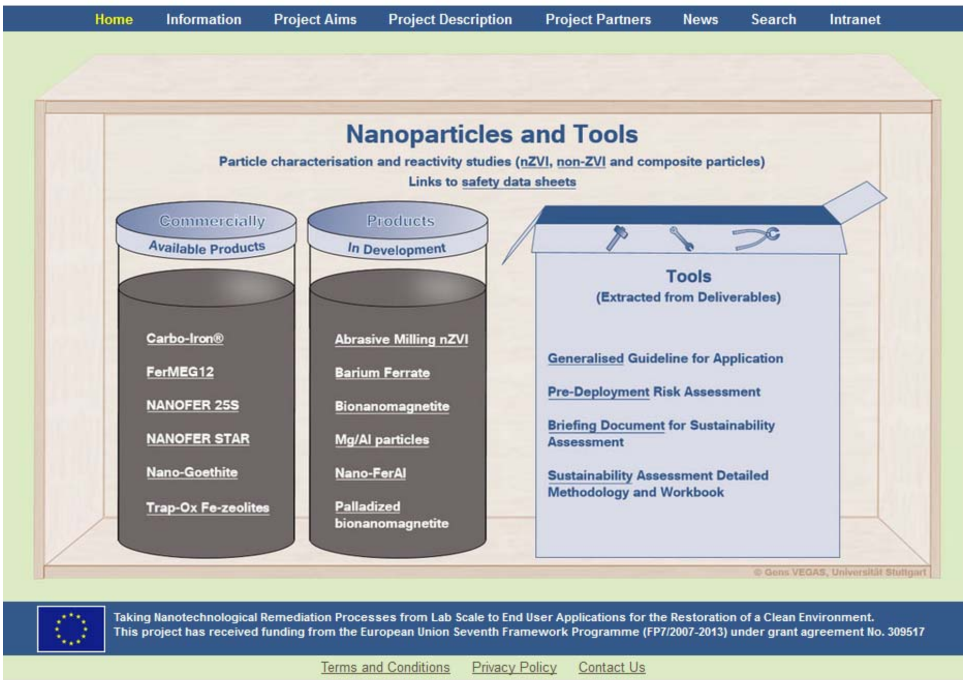

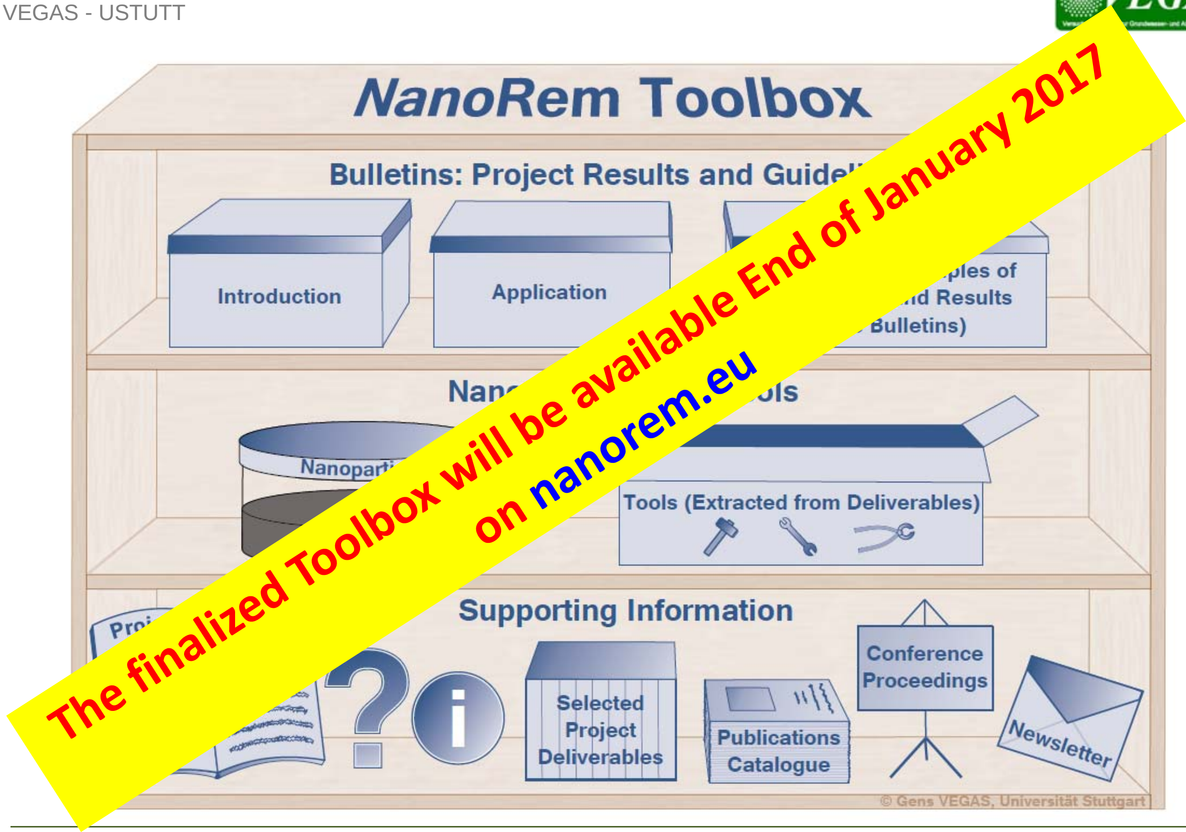

Thank you for your attention

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Hans-Peter Koschitzky
Versuchseinrichtung zur Grundwasser- und Altlastensanierung
Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart
vegas@iws.uni-stuttgart.de www.vegas.uni-stuttgart.de