SNOWMAN NETWORK
Knowledge for sustainable soils

State of the art concerning MNA in Europe – the Netherlands

SNOWMAN network conference on monitored natural attenuation
November 7th 2011
Salon du Relais, Paris

Revised version

Inge Declercq

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Netherlands

1. Regulation and status

1.1. Regulatory context

In the Netherlands, the legislation concerning soils is covered by the “Wet Bodembescherming” (Wbb) from 3 July 1986 (the Soil Protection Act) which was adjusted in January 2006. The adjustment in turn is worked out in the Circulaire “Bodemsanering” 2006. Also important for soil legislation is the “Wet Milieubeheer” (Wm) from 13 June 1979 (the Environmental Protection Act), the Water Act from 2009 and the legislation concerning building materials, more specifically the Decree Soil Quality from 2007.

Between 1995 and 2000, the soil remediation policy in the Netherlands was subjected to a revision, called BEVER (BEleidsVERnieuwing bodemsanering). Important here is the transition towards function-orientated (the remediation goals are coupled to current or planned soil/land use) and cost-effective remediation, combined with minimum after care. The starting point remains that the risks for humans and the environment have to remain at an acceptable level. This “renewal” of soil policy in the Netherlands entails a simplification of soil legislation: there is a standard operation mode, and if that isn’t suitable in a certain case, specific measures can be taken. The BEVER-initiative was officially completed in 2000. In February 2006, BUS or “Besluit Uniforme Saneringen” – the Uniform Remediation Act – came into force, aiming to enable the faster implementation of cheaper soil remediation projects. This adjustment clearly enabled the use of (monitored) natural attenuation ((M)NA). (Website bodem.info; Website Bodemrichtlijn)

In accordance with the laws Wbb and Wm, the “Stichting Infrastructuur Kwaliteitsborging Bodembeheer” (SIKB), developed a protocol concerning the implementation of in-situ remediation methods for contaminated land. This protocol mentions the use of natural attenuation (“natuurlijke afbraak”) as a possible method. (SIKB, 2010)

Thus, national legislation in the Netherlands allows the use of (M)NA as a remediation option. It is, however, subjected to some restrictions. Primarily, the implementation is only possible on the condition that the environment is sufficiently protected. Secondly: the efficacy of NA has to be demonstrated, as well as its sustainability for the future. The goals (stationary or receding plume) have to be reached within a timeframe of 30 years and if at any time it appears as if they won’t be, a fall-back contingency plan has to be available. Furthermore, cost efficiency has to be demonstrated. In the Netherlands, it is possible to allow MNA even when the contamination plume is expanding, but only if it can be demonstrated that contaminant concentrations are stabilized and no further control is necessary. (Slenders, Langenhoff, Ballerstedt, Ter Meer & Sinke, 2005)

1.2. Status: application of NA in the Netherlands

1.2.1. Contaminated sites in the Netherlands

It is estimated that approximately 600.000 contaminated sites exist in the Netherlands. (Unizo, 2005) According to numbers found on the website of Compendium voor de Leefomgeving, approximately 258.000 sites in the Netherlands were severely contaminated[1] at the end of 2009, 180.000 of these haven’t been investigated yet; 78.000 are labelled as “being investigated”, “during remediation” or “in aftercare”.

A governmental initiative called Bodemloket is responsible for the collection of information concerning soil remediation projects. The website of Bodemloket shows at which locations in the Netherlands a soil study has been performed, if further investigation or remediation was necessary and whether remediation has been executed. Historical information is considered separately.

[1] A « grave » contamination is explained as when the intervention value of one or more contaminants has been exceeded in at least 25m^3 of soil or 100m^3 of groundwater.

1.2.2. NA research performed at locations in the Netherlands

A variety of Dutch research programs (as discussed in paragraph 2.2) and scientific articles include the evaluation of NA (processes) at locations in the Netherlands. An overview of locations that have been studied is given in Table 1. The indexes indicate the following: 'n.a.' information not available; '-' no NA present; '+' NA ability; '+/-' unclear results.

Table 1. Overview of Dutch research projects and documents that mention locations in the Netherlands.

Research	***Pub. date***	***Locations included in the program/research***	***NA ability?***	***MNA implemented?***
NOBIS 97-1-08	1997	2 sites located in Overijssel: - Oude Hengelose Dijk - AKZO Nobel Chemical	+	Oude Hengelose Dijk: MNA is suggested for remediation. Implemented? n.a. AKZO Nobel Chemical: groundwater treatment is suggested.
BOS-NA (NOBIS)	1998	6 (Zeist, Arnhem, Tilburg, Petroleumhaven, Achterste Molen, DOW Terneuzen)	+ for 1 site	n.a.
NOBIS 96-1-10	1998	1 (Rozenburg)	+	Proposed remediation strategy: active measures and the monitoring of NA Implemented? n.a.
NOBIS 96-3-04	2001	3 (Coupépolder in Zuid-Holland; Banisveld in Noord-Brabant and Achter de Beukenlaan in Utrecht)	Coupépolder +/- Banisveld + AdB -	Banisveld: extensive monitoring could be an option Implemented? n.a.
SN-002 (SKB)	2002	1 (Veenendaal)	+	No: the site was unsuited for continuation of the project
NAVOS	2002	11	+ for 10 sites - for 1 site	n.a.
SV-213 (SKB)	2003	1 (Hollandsche IJssel)	+	Active measures + NA is suggested. Implemented? n.a.
SV-218 (SKB)	2003	1 (Hoogezand)	+	n.a.
SV-401 (SKB)	2003	2 (Amsterdam and the harbour area of Rotterdam)		n.a.
SV-615 (SKB)	2003	9 (Nieuw Buinen, Apeldoorn, Zeist, 't Gooi, Leiden, Wenum, Bunnik, Budel and Mook)		Natural immobilisation is possible for 7 sites; stimulated immobilisation for the 2 others. Implemented? n.a.
S-NA chlorinated ethenes (SKB)	2003	13	+	NA is considered or applied at 8 sites.
TRIAS 835.80.121 CORONA	2005	1 (Brabant site) and 5 others throughout *Europe*	Brabant: +	n.a.
PT4-120 (SKB)	2006	3 ("Vries-4", Havelte and Roswinkel)	Vries-4: + Havelte: +/- Roswinkel: -	n.a.
TRIAS 835.80.007	2007	3 (Banisveld Boxtel, the Brabant site and the Limburg site)	Boxtel: + Limburg: + Brabant : +	n.a.
TRIAS 835.80.009	2007	2 (Van Velde Buren and Flebo	+	n.a.
PT6416 (SKB)	2008	6 (Eindhoven, Roermond, Veenendaal, Geleen, Deventer, Venlo) +3 (Utrecht, Zwolle, Noord-Brabant)	+ except Venlo: -	n.a.
Cahier "A matter of substance" (SKB)	2010	2 (harbour area of Rotterdam & Haarlem industrial estate)	Rotterdam: + Haarlem: + but slowly	n.a.
Scientific article by Van Nieuwkerk, van Ras, van Hattem and Hartog	2011	5 sites in the harbour area of Rotterdam		

1.2.3. Actual use of NA as a remediation method

In the Netherlands, NA has been applied for remediation since ca. 1997. (Website Bodemrichtlijn) In the SKB Cahier “Natural attenuation, a matter of substance!” (2010), it is mentioned that although natural attenuation is “now regarded as a completely valid remediation variant, it is not yet being fully utilised”. There are still too few contaminations being treated with natural attenuation”. The publication mentions that this is due to the fact that still more confidence exists in conventional methods. This could be related to insufficient use of available knowledge by government and market players or to the perception that NA is an “easy solution”. However, numbers of real-life application of (M)NA are not available in the SKB publication.

An example of application of MNA was found on the website of Bioclear, a Dutch consultant agency. Company activities include e.g. providing environmental guidance; executing biological soil and groundwater remediation; filling out risk assessments, performing feasibility studies and financial cost-benefit analysis. Remediation of a contaminated site located between Grijspkerk and Anjum was carried out by Bioclear. This included the excavation of large contaminations and the use of MNA to remediate smaller residual contaminations. The location is contaminated by benzene. The two monitoring rounds so far (the project started in 2003) have shown a decrease in concentrations conform to the best case scenario. Bioclear expects to reach the remediation goal within a time frame of 10 years.

Seeing that no concrete numbers were found during the internet search, SKB was contacted in order to collect further information about the use of NA as a remediation technique. From this contact, it appeared that (a) there is no database (or information collection) on performed remediation projects in the Netherlands that can be consulted to collect this kind of information and (b) the number of parties which perform biological remediation in the Netherlands is limited. (I. van Reijsen & A. Peekel, personal communication, 2 September 2011) Based on this information the companies BioSoil BV, Hannover Milieu- en VeiligheidsTechniek B.V. (HMVT), Groundwater Technology, Bioclear and Tauw were contacted to gain more insight about the use of NA in the Netherlands.

- *BioSoil BV*

BioSoil responded that it was not possible to provide actual numbers on the use of (M)NA, but it was possible to acquire the “Introduction Document” of the company, which lists the companies activities and some example projects. (S. Wemmenhove, personal communication, 7 September 2011) From the 32 example projects listed in this document, it became clear that BioSoil mostly uses enhanced natural attenuation (ENA). No clear example of MNA is included in this document. (BioSoil BV, n.d.)

- *Tauw bv*

Tauw bv provided us with certain information on their MNA projects in October 2011. The information they were able to give us includes the locations and types of sites that were part of the remediation projects; the contaminants found; whether or not MNA was used in combination with other measures and the results of MNA application. This information is also presented in Table 2. Tauw also provided information on some projects where ENA was used, however, these are not included in this table. Important is that Table 2 is not complete for all MNA remediation projects performed by Tauw bv; it lists 24 of the most complex and most important projects that include MNA. The majority of their MNA projects, however, are smaller in size and not included. (F. Volkering, personal communication, 14 October 2011)

As shown in the table, most locations include industrial sites. MNA is being applied in the Netherlands for the treatment of all kinds of contaminants. From the 24 Tauw cases listed, only five rely on MNA as a stand-alone technique; MNA is mostly used in combination with source removal (16 out of 24 cases). Concerning the obtained results when using MNA for remediation of contaminated sites, this information tells us that MNA has been ‘sufficient’[2] in 12 of the cases (50%) and insufficient in two cases. For the other locations, this is still under evaluation.

Furthermore, Tauw informed us that their first MNA-project that was formally acknowledged by administration was in 1999. (F. Volkering, personal communication, 14 October 2011)

Table 2. MNA projects for the Dutch remediation company Tauw bv.

Location	***Type***	***Contaminants***	***Combination with other measures?***	***Results***
Antwerpen	Industrial site	PCE	Yes: source removal	MNA is sufficient
Amsterdam	Industrial site	PCE	Yes: source removal	MNA is sufficient
Hengelo	Urban area	PCE	Yes: source removal	Being evaluated
Veenendaal	Industrial site	PCE	Yes: source removal	Being evaluated
Eindhoven	Urban area	BTEXN, diesel	No, MNA as a stand-alone Technique	MNA is sufficient
Dordrecht	Industrial site	Cresoles, PAH	Yes: source control	MNA is sufficient
Kampen	Industrial site	TCE	No, MNA as a stand-alone Technique	Being evaluated
Nijkerk	Urban area	BTEXN, diesel	Yes: source removal	Being evaluated
Zwolle	Urban area	BTEXN, diesel	Yes: source removal	Being evaluated
Breda	Industrial site	VOC	Yes: source removal	?
Oss	Industrial site	VOC	Yes: source removal	MNA is not sufficient
Zutphen	Industrial site	VOC	Yes: source removal	Being evaluated
Maarspbergen	Waste deposit	dDCE, VC	No, MNA as a stand-alone Technique	MNA is sufficient
Hilversum	Urban area	BTEX, PAH, CN, etc	Yes: source removal	MNA is sufficient
Ede	Industrial site	VOC	Yes: source removal	Being evaluated
Eindhoven	Industrial site	VOC, BTEXN	Yes: source control	Being evaluated
Hardenberg	Industrial site	Tri	Yes: source removal	MNA is sufficient
Geleen	Industrial site	Benzene	Yes: source removal	?
Eindhoven	Waste deposit	cDCE, VC	No, MNA as a stand-alone Technique	MNA is sufficient
Rotterdam	Industrial site	Diesel	No, MNA as a stand-alone Technique	MNA is not sufficient
Amsterdam	Waste deposit	Mixture	Yes: source control	MNA is sufficient
Terneuzen	Industrial site	VOC, BTEX	Yes: source removal	MNA is sufficient
Deventer	Urban area	Monochlorobenzene	Yes: source removal	MNA is sufficient
Apeldorn	Urban area	BTEX, PAH	Yes: source removal	MNA is sufficient

- *HMVT, Groundwater Technology and Bioclear*

These three companies did not respond to the request to provide information on MNA projects in their care. However, through contacts within the SNOWMAN network it was possible to collect some information on the MNA cases by Bioclear as well.

For Bioclear, certain numbers on the use of (M)NA for remediation were collected for a training course on groundwater remediation through natural attenuation (“PAO cursus grondwatersanering door natuurlijke afbraak”, which took place on 11 and 12 November 2008). Bioclear listed approximately 40 projects at the time where NA was of importance: 10 remediation projects where NA was being applied (nine locations where NA was applied in combination with active measures and one where NA was applied as a stand alone technique); eight projects where investigation or screening of the NA-potential was in process and 20 projects where different remediation methods, including NA, were being compared. (E. de Vries, personal communication, 31 October 2011) These 38 projects don’t stimulate the NA present at the site (so this number does not include ENA projects), they concern the monitoring of the NA-processes (e.g. does NA occur on site, which processes take place, is the NA sustainable? …) either as a preliminary investigation or as part of the remediation plan! Furthermore, it is estimated that since November 2008 about 30 more MNA projects have been started by Bioclear. (N. van Ras, personal communication, 15 November 2011) In addition, Bioclear mentions the rising

[2] Oftentimes a timeframe of five monitoring years is used, however, this is frequently not long enough. (F. Volkering, personal communication, 14 October 2011)

trend to apply MNA in sludge layers of river sediments for the NA of VOC's as well. Currently, this concerns two or three cases by Bioclear. (N. van Ras, personal communication, 15 November 2011)

2. Documents and projects about NA

2.1. Existing documents

This overview of guidelines, methodologies and protocols will be discussed in more detail in paragraph 3.

2.1.1. BOS-NA (1998)

The guideline was developed during a NOBIS project for the assessment of NA of contaminated sites in 1998. Adjustments were made in 2001 (cfr. Paragraph 3.1). This document wants to provide guidance to decision makers when they have to decide on whether or not to use (M)NA as a decontamination- or control measure. This protocol is limited to BTEX and chlorinated hydrocarbons.

Sinke, A.J.C., Heimovaara, T.J., Tonnaer, H. & Ter Meer, J. (2001). *NOBIS 98-1-21 Beslissingsondersteunend system voor de beoordeling van natuurlijke afbraak als saneringsvariant (versie 2.0)*. Gouda: SKB.

2.1.2. Guideline for the evaluation of NA at dump sites (2002)

This guideline was developed within the framework of the NAVOS research program concerning natural attenuation at former dump sites (paragraph 3.2).

Van Vossen, W.J., Frapporti, G., Heimovaara, T.J., de Jong, M.A., van Ras, N.J.P., Slenders, J.L.A., van Verseveld, H.W., van der Waarde, J.J. & Smidt, E.H. (2002). *Natural attenuation en voormalige stortplaatsen: NA-toetsingsmethodiek en set van kenmerkende NA-parameters – Integraal hoofdrapport*. Arnhem: NAVOS.

2.1.3. S-NA protocol for chlorinated ethenes (2003)

This project was initiated by SKB. A protocol was developed to evaluate the sustainability of NA-processes (S-NA), which will be discussed in paragraph 3.3.

Dijkhuis, J.E., van Bemmel J.B.M., Henssen, M.J.C. & van Lotringen, R. (2003). *SV-513 Methodiek voor het vaststellen van de duurzaamheid van natuurlijke afbraak (D-NA) van gechloreerde ethenen*. Gouda: SKB.

2.1.4. Decision support system for the immobilisation of heavy metals (2003)

This SKB project (“SV-615”) developed a general methodology to decide on the use of natural or stimulated immobilisation of heavy metals in the saturated zone of the soil (cfr. Paragraph 3.4).

Steketee, J.J., Nijboer, M.H., Takens, R.C., Dijkstra, J.J. & Comans, R.N.J. (2003). *SV-615 Beslissingsondersteunend systeem natuurlijke en gestimuleerde vastlegging van zware metalen in de verzadigde zone van de bodem*. Gouda: SKB.

2.1.5. ROSA guidebook (2004)

This guidebook was published in 2004 in the Netherlands and deals with decision making for choosing a remediation method for mobile contaminants. Paragraph 3.5 discusses the outline of the ROSA decision making process.

Slenders, A., Haselhoff, A., Leenaers, H., Nijboer, M., Sinke, A. & Volkers, B. (2005). *Praktijkdocument ROSA: handreiking voor het maken van keuzes en afspraken bij mobiele verontreinigingen*.

2.1.6. SKB Cahier

This series of handbooks, published by SKB, focuses on different themes concerning soil contamination and protection. The handbook concerning natural attenuation is the topic of paragraph 3.6.

Van Ras, N., Roosma, A. & Volkers, B. (2010). *SKB Cahier: Natural attenuation – a matter of substance*! Gouda: SKB.

2.2. Research projects

2.2.1. NOBIS projects

- *"Biological degradation of BTEX and chlorinated hydrocarbons during in situ bioremediation"*

This research program for in-situ bioremediation evaluates the bioremediation of BTEX and chlorinated hydrocarbons. By means of literature research, it describes the biodegradation of eighteen components under redox conditions; the techniques for preliminary investigation applied before in-situ remediation and the parameters for the characterization and monitoring of the remediation. (Keuning, van der Waarde & Baten, 1996)

- *BOS-NA*

Within the framework of the NOBIS research program "BOS-NA", six demonstration locations were investigated. The sites were contaminated with were chlorinated hydrocarbons and BTEX (benzene, toluene, ethylbenzene and xylene) and located in Zeist, Arnhem, Tilburg, Petroleumhaven, Achterste Molen and DOW Terneuzen. Only at one site NA was evaluated as "having a chance" after the second traffic light[3]. This project resulted in a guideline, which is discussed in paragraph 3.1. (Sinke, Heimovaara, Tonnaer & Ter Meer, 2001)

- *" In situ bioremediation of soil contaminated with monochlorobenzene and aniline"*

This project (number 96-1-10) studied the conditions and possibilities for NA of monochlorobenzene and aniline. It is based on literature, laboratory analyses and field measurements at a chemical industry site (from ICI Holland BV) in Rozenburg. The proposed remediation strategy included active measures in combination with the monitoring of NA. (Roovers, C., 1998)

- *"Bioremediation of HCH-locations"*

This project (number 97-1-08) started in 1997 and studied the possibilities for natural attenuation of hexachlorocyclohexane (HCH) and its degradation products monochlorobenzene (MCB) and benzene at two contaminated sites in the province of Overijssel (a terrain which is the property of AKZO Nobel Chemicals and the Oude Hengelose Dijk). The existence of NA-processes was confirmed for both sites. A MNA process is chosen for the location at the Oude Hengelose Dijk. For the other site, groundwater treatment is suggested. (Langenhoff, 1999; van Aalst-van Leeuwen et al., 1999)

- *"A step-wise approach in order to assess the occurrence of natural attenuation in groundwater in the vicinity of landfills"*

The topic of this project (96-3-04) is the occurrence NA at dump sites. The project concluded in 1999 but the final summarising report wasn't published until 2001. This report gives a guiding step-wise approach for the evaluation of NA-processes in the groundwater of dump sites. It served as a starting point for the NAVOS program which also studies the occurrence of NA at dump sites (paragraph 3.2). In this NOBIS project three locations were subject to case study investigations: Coupépolder in the province of Zuid-Holland; Banisveld in the province of Noord-Brabant and Achter de Beukenlaan in the province of Utrecht. (Wolbrink & Heimovaara, 2001)

[3] This is explained in paragraph 3.1.

2.2.2. SKB projects

- *SV-206 “Application of isotope analysis in research concerning soil contamination”*

The research project SV-206 started in 2000. The report gives an overview of knowledge about isotope analysis and the relation to soil and groundwater contaminations. (Jonker & Volkering, 2001)

- *SN-002 “NA and distribution of PAH in groundwater”*

Methods were tested for the quantification of NA of polycyclic aromatic hydrocarbons. This included experiments on a test site in Veenendaal. Evidence for biodegradation was found but, however, the test site appeared unsuited for the continuation of the project. This was due to low dispersion of PAH in the groundwater of the test location and the presence of interfering influences. (Menning, Volkering & Beltmans, 2002)

- *SV-213 “Monitoring on-site decontamination processes in the bed of water courses”*

This projected looked at the possibility to apply in-situ methods for the decontamination of the river bed of the Hollandsche IJssel. The combination of NA and active removal of sludge was judged to be most feasible. (Muijs et al., 2003)

- *SV-218 “Demonstration of anaerobic benzene bio-remediation”*

Laboratory analyses and a field test (Flebo site in Hoogezand) were performed to investigate anaerobic degradation of benzene under the influence of nitrate. This project follows the NOBIS project 96-3-05 from 1999 which resulted in the demonstration of anaerobic degradation of benzene under laboratory conditions. The research showed that anaerobic degradation of benzene is present in the groundwater of the contaminated site. (Slik, Hidding, Langenhoff & Griffioen, 2003)

- *SV-401 “NA-interface: NA of oxidisable organic contaminants at the Interface between groundwater and surface water”*

There are indications that the interface between groundwater and surface water can influence NA-processes, especially for mobile contaminants. This project selected locations for site investigations - two of which (Solvay Pharmaceuticals in Amsterdam and LBC in the Rotterdam harbour area) were used for further research - and for the development of monitoring and modelling. Conceptual models were used to describe the NA-interface processes and to quantify their emission to surface water. A new tool was developed for sampling groundwater at the NA-interface: the multi-level sampler. (Middeldorp et al., 2003)

- *SV-615 “Decision making support system for natural and stimulated immobilisation of heavy metals in the saturated zone of the soil”*

Within de framework of this project, a decision support system was developed for the immobilisation of heavy metals, which is discussed in paragraph 3.4. The six step methodology was tested at nine locations (Nieuw Buinen, Apeldoorn, Zeist, ‘t Gooi, Leiden, Wenum, Bunnik, Budel and Mook) contaminated with heavy metals such as zinc, nickel, cadmium, arsenic, cupper and chrome. The project revealed that natural immobilisation is an option in most cases and if not, stimulated immobilisation might be used. (Steketee, Nijboer, Takens, Dijkstra & Comans, 2003)

- *“Sustainability of NA” of chlorinated ethenes*

This SKB project (SV-513) evaluated the sustainability of natural attenuation of chlorinated ethenes at thirteen sites in the Netherlands. This project resulted in the S-NA methodology (D-NA in Dutch) as discussed in paragraph 3.3, which was validated at eight sites where NA-application is considered or performed. (Dijkhuis, van Bemmel, Henssen & van Lotringen, 2003)

- *PT4-120 “Anaerobic degradation of benzene, the ultimate proof”*

This project monitored the natural and stimulated degradation of BTEX at three sites in the Netherlands: “Vries-4”; Havelte and Roswinkel. The project used traditional methods (measurement of concentrations and modelling) as well as e.g. isotope analysis and molecular techniques. The project costs were €40000. NA of benzene was demonstrated at Vries-4; results were unclear for Havelte. (Langenhoff & van Ras, 2006)

- *“Searching for new processes”*

A first aim of project PT6416 (which started in 2006) was to increase knowledge about new NA-processes of chlorinated hydrocarbons, such as abiotic chemical reduction and anaerobic biological degradation. Another aim was to develop and demonstrate an instrument to prove the existence of such processes. The project included the demonstration of the developed instrument on six locations. The groundwater at the sites located in Eindhoven, Roermond, Veenendaal, Geleen, Deventer and Venlo were all contaminated by chloroethenes.

Simultaneous with this project, other sites were evaluated for their natural attenuation potential. The sites at Utrecht, Zwolle and Noord-Brabant were evaluated in a similar way as the other six. (Volkering, van Breukelen, Veld & Gemoets, 2008)

2.2.3. TRIAS projects

The TRIpartite Approach to Soil system processes (TRIAS) is a collaboration between SKB, Delft Cluster and the Dutch Organisation for Scientific Research NOW. The initiative for this project was taken in 2000. The budget was four million euros. The program concluded in 2007 and covers 12 research projects concerning the topics “patterns and processes in the underground” and “ecology and soil quality”. Several of the TRIAS projects included natural attenuation research; they will be discussed hereafter. (Saat & Rogaar, 2007)

- *835.80.002*

This project is called “Multiphase flow and enhanced biodegradation of dense non-aqueous phase liquids” and covers the modelling of NA-processes. The study encompassed e.g. biodegradation and dissolution. It included laboratory analyses and an experimental study in a ‘sandbox’. (Langevoort, 2009; Saat & Rogaar, 2007)

- *835.80.005*

This project is called “Mixing processes in enhanced and natural attenuation”. It started in 2001 and lasted until 2006. The subject is the modelling of dispersion processes in relation to flow movements. This was studied by an experimental arrangement (sandbox) and through field testing of an oil contamination in Perth, Australia. (Ham, 2006; Saat & Rogaar, 2007)

- *835.80.007*

The TRIAS project “Resilience of the groundwater ecosystem in reaction to anthropogenic disturbances” (2001-2005) deals with, among other things, the role of protozoa in degradation processes and characterization of the degradation of chlorinated hydrocarbons by the means of molecular-biological techniques. The aim of this project was to develop a toolbox for the evaluation of the NA capacity of contaminated sites. Three locations were examined: a dump site at Banisveld (Boxtel), the so-called “Brabant site” and the so-called “Limburg site”. Degradation was demonstrated. (Anonymous, 2005; Saat & Rogaar, 2007)

- *835.80.009*

The project called “Anaerobic biodegradation in contaminated soils” studied the anaerobic microbiological degradation of benzene. It lasted from 2002-2004. Degradation of benzene occurred under nitrate and chlorate reducing conditions in batch and column experiments. Soil samples were used from the contaminated site “Van Velde Buren”, which confirmed degradation of benzene. Benzene degradation was also demonstrated for groundwater from the Flebo location. (Saat & Rogaar, 2007)

- *835.80.121 or <u>CORONA</u>*

This project was added to the TRIAS program because the topics were very similar. CORONA or the European project “Confidence in forecasting of natural attenuation” (2002-2004; £1,7M) analysed the degradation of chlorinated hydrocarbons (by micro organisms) in relation to the geochemical conditions and structure of the soil. The project studied microbiology and biodegradation behaviour in laboratory conditions. Numerical models were built for the further interpretation and quantification of the processes and these models were validated through tests in a laboratory sand tank. The project is based on six real sites throughout Europe: the Brabant site (Netherlands), Four Ashes (United Kingdom), Hnevice (Chech Republic), NIT (Italy), Rexco (Mansfield, UK) and Sjoelund (Denmark). The sites were contaminated with a variety of compounds, e.g. phenols, chlorinated solvents and petroleum hydrocarbons. The project resulted in a guidance document, CoronaScreen. (Lerner et al., 2005; Saat & Rogaar, 2007)

2.2.4. <u>Other</u>

- *NAVOS*

According to information found on the NAVOS website, there are about 6000 former dump sites[4] in the Netherlands. After the collection of general information concerning size, contents and locations of former dump sites in the early 1990’s; a research program NAVOS (NAzorg VOormalige Stortplaatsen) started in 1995 to collect information about contamination of the soil and groundwater in proximity of those sites. Research concerning NA-processes at those sites started in 1999. The integral report of these activities was published in 2002. NA-processes included in the research program are aerobic and anaerobic biodegradation; precipitation (chemical immobilisation of heavy metals) and sorption. For the evaluation of NA-processes, basic measurements were performed at every dump site (#:80). These included e.g. exceeding of the intervention values and geochemical analyses. At eleven sites, specific measurements were performed as well, such as gas chromatography, DNA/RNA analysis, batch-experiments and leach tests. Another eleven sites underwent location-specific testing to determine the presence of NA-processes.

This report concluded that NA was insufficient to obtain sufficiently low[5] levels of groundwater contamination in 30% of the 80 dump sites included in the program. This was mostly due to the presence of heavy metals (mainly arsenic and barium). In 70% of the cases, NA was able to sufficiently reduce contamination in the groundwater. The presence of NA was demonstrated for 90-100% (depending on the different contaminant groups) of the eleven sites that underwent location specific assessments.

The research program resulted in a methodology to assess the NA conditions at dump sites, which will be discussed in paragraph 3.2. (van Vossen et al., 2002)

[4] This information was found online in august 2011; the NAVOS report from 2002 refers to the existence of 3800 former dump sites.
[5] Lower than the intervention value.

3. Guidebooks and methodologies

3.1. BOS-NA: the "NA route" with four "traffic lights"

The decision process for the implementation of NA is based on four sequential traffic lights, presented in Figure 1. At each phase, the NA at the contaminated site is evaluated and this results in a green light (when the chances of NA are determined as 'good'), orange ('fair chance', additional information is needed) or red ('no chance'). This decision process however, is limited to BTEX and chlorinated hydrocarbons.

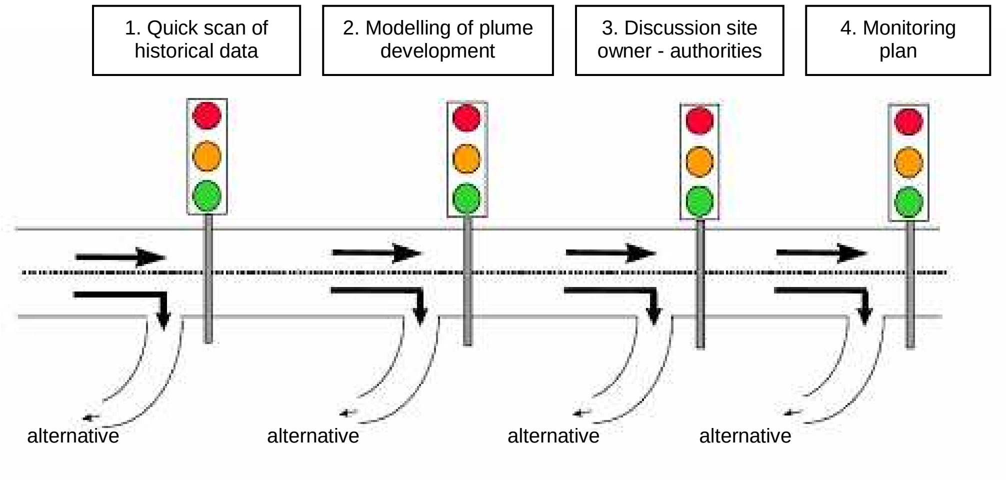

Figure 1. BOS-NA decision support system : four traffic lights when considering NA as a remediation option. (Sinke, Heimovaara, Tonnaer & Ter Meer, 2001, p.4)

3.1.1. The first traffic light: analysis of the current situation

The first traffic light includes a quick scan of historical data in order to estimate the physical possibility of NA-processes as a remediation measure. A spreadsheet was developed to structure this quick scan. The protocol differs in this stage for contaminations with chlorinated ethenes (Figure 2) and BTEX (Figure 3).

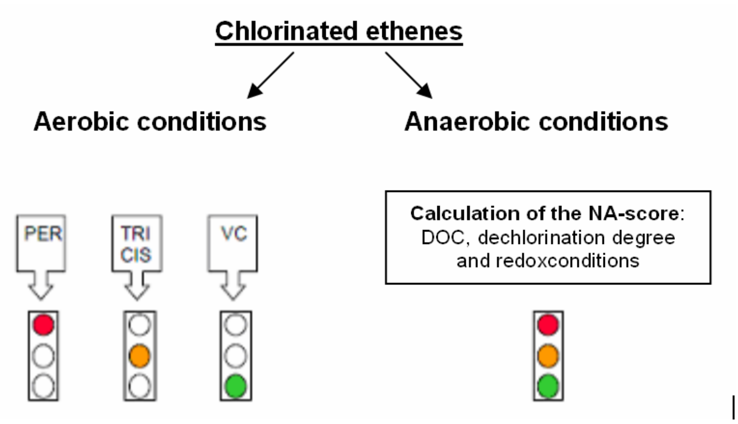

Figure 2. Decision schedulet for the first traffic light in the case of a contamination with chlorinated ethenes. (Sinke, Heimovaara, Tonnaer & Ter Meer, 2001, p.11)

For the calculation of the NA-score (for chlorinated ethenes under anaerobic conditions) several elements have to be taken into account, namely: the oxidation-reduction conditions, the degree of dechlorination and the grade of dissolved organic carbon in the groundwater. The NA-score determines further evaluation: NA-score ≥8 means a green light, a NA-score 5-7 stands for an orange light and a red light equals a score ≤4. This calculation has to be made for every monitoring well.

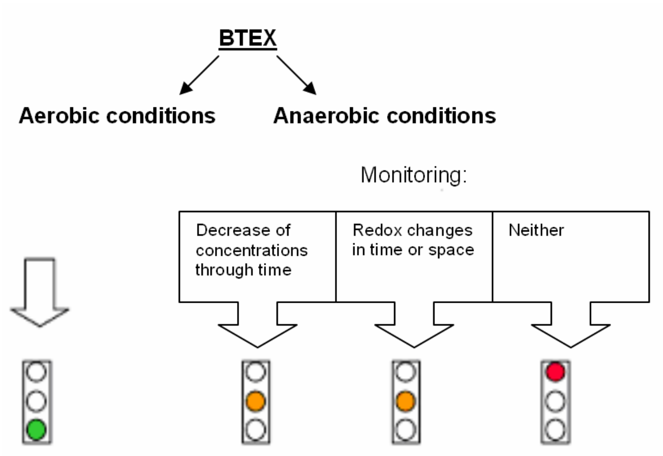

Figure 3. Decision schedule for the first traffic light in the case of a contamination with BTEX. (Sinke, Heimovaara, Tonnaer & Ter Meer, 2001, p.15)

Under anaerobic conditions for BTEX, monitoring is required to determine whether NA is present. If the concentrations decrease or the oxidation-reduction conditions change, an orange light is given; if not, then NA is not a good choice as a remediation technique. This consideration is done for entire location.

3.1.2. The second traffic light: expectations for the future

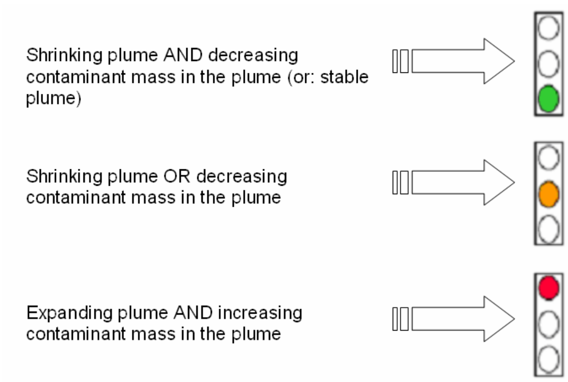

Figure 4. Interpretation of the second traffic light. (Sinke, Heimovaara, Tonnaer & Ter Meer, 2001, p.23)

This second phase includes the modelling to estimate evolutions of contaminations and development of the contamination plume. The interpretation of the traffic lights is presented in Figure 4.

3.1.3. The third traffic light: consultation between the involved parties

Discussion between site owner and the authorities takes place during the third phase: will MNA be implemented? In order to simplify the decision making, a checklist was developed containing practical and managerial points of interest. When it is decided that the choice for the implementation of NA is accepted, a “packet of demands” has to be drawn up, the timeframe during which NA will be monitored has to be set as well as what should happen if NA doesn’t live up to the expectations.

3.1.4. The fourth traffic light: implementation and monitoring

Development of a long term monitoring plan. When the defined time of monitoring has passed, an evaluation of the occurred NA has to be performed. There are three possible results:

(1) If NA took place as accepted and the monitoring can be reduced (green light);

(2) Another possibility is that NA has failed to reach the expectations (red light). The fall-back contingency plan then has to become operative;

(3) When there are doubts (orange light), all conditions have to be considered when deciding which action should be taken.

If at any time it appears that there is no possibility for the implementation of NA-processes as a remediation measure, the search for an alternative has to be initiated.

(Sinke, Heimovaara, Tonnaer & Ter Meer, 2001)

3.2. Guideline for the evaluation of NA at former dump sites

A NOBIS research program (96-3-04) was performed concerning NA at dump sites. This resulted in a step-wise approach for the evaluation of NA at dump sites, as presented in Figure 5. However, as the report of the 96-3-04 project states, this approach is only meant to give direction, it isn't intended as a protocol. Nonetheless, this served as a base for the NAVOS research program, discussed here, which does include a methodology for the evaluation of NA at dump sites.

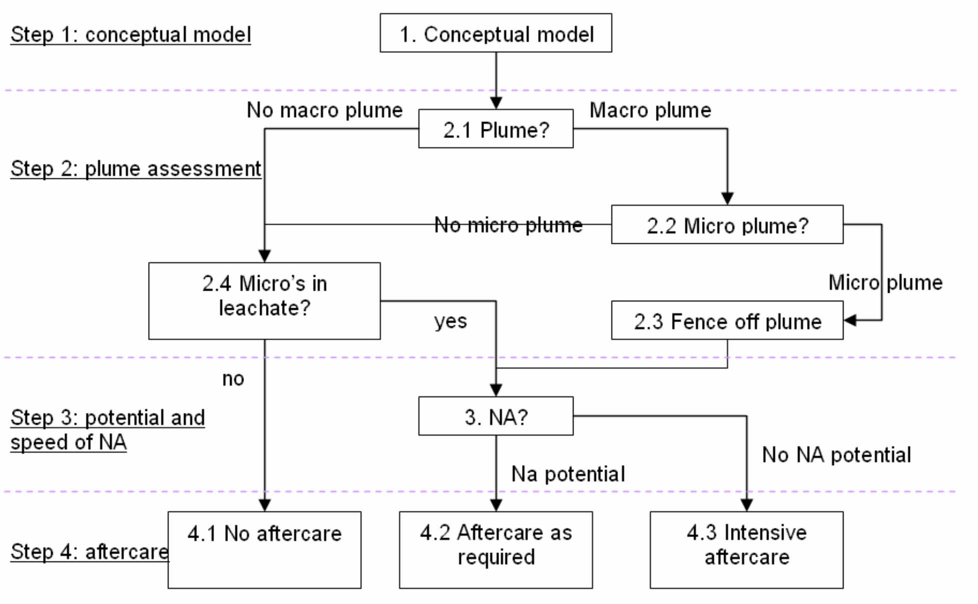

Figure 5. Step-wise approach for the evaluation of NA at dump sites, as suggested in the NOBIS research project. (Wolbrink & Heimovaara, 2001, p.12)

The guideline published as a result of the NAVOS research program includes a methodology for the assessment of NA conditions at dump sites, which consists of six steps:

1. Determination of the presence of a macro plume[6]
2. Determination of the presence of a micro plume[7]
3. Determination of whether or not the contaminations fulfil the “NA model dump” (in other words: are they degradable under oxidising conditions?)
4. Determination of whether or not the oxidation reduction conditions fulfil the “NA model dump”
5. Determination of whether or not the environment allows NA
6. Assessment of NA as an aftercare option

This methodology uses measurements of two sets of parameters characteristic of NA: (a) basic parameters (e.g. volatile aromatic hydrocarbons; ammonium; arsenic; cadmium; oxygen; nitrate; sulphate; ethane; barium; pH and total organic carbon) and (b) specific measurements: batch experiments, leach tests and fermentation tests.

(van Vossen et al., 2002; Wolbrink & Heimovaara, 2001)

[6] Macro plume: surface that is influenced by macro parameters. Macro parameters are those parameters that are deterministic for the characteristics of the groundwater.
[7] Micro plume: presence of (in)organic contaminations in the form of a cigar, situated in the macro plume.

3.3. S-NA protocol

This methodology describes how the sustainability of natural attenuation of chlorinated ethenes, or in other words, the future natural attenuation activity can be evaluated. This methodology contains two large parts: a quantitative approach to determine the expectations for the future, and an “attention list” (“attenderingslijst”) which asks questions relating to possible influences on the NA-processes.

3.3.1. Quantitative approach

This part of the S-NA protocol includes the following steps:

1. Checking preconditions for each monitoring well
    a. Evaluation of oxidation-reduction conditions
    b. Evaluation of the ED potential
    c. Evaluation of the microbial population
    d. Are the three conditions (a-c) fulfilled for each monitoring well? Then the evaluation proceeds to step 2
2. Checking preconditions at location scale. This means an integration of the scores of the individual monitoring wells from step 1. If conditions hold, the evaluation proceeds to step 3
3. Determining future prospects
    a. Measurement of nitrate and sulphate in the groundwater upstream from the contamination. If present follow (c); if not[8], (b)
    b. Nitrate or sulphate supply to the contamination:
        i. Characterisation of the organic material: identification of natural and anthropogenic ED
        ii. Formulation of the ED balance: if there are sufficient ED available, the NA is categorised as ‘sustainable’ and the evaluation ends here
    c. No nitrate or sulphate supply to the contamination:
        i. Characterisation of the organic material: identification of anthropogenic ED
        ii. Formulation of the ED balance: if there are sufficient ED available, proceed to (iii)
        iii. Calculation of the ED-use due to the infiltration of nitrates and sulphates, as well as attenuation of chlorinated ethenes. If the time that is necessary for the natural attenuation is lower than the time during which the contamination plume remains reduced, NA is classified as ‘sustainable’

All of this has to be in accordance with measuring strategies as described in BOS-NA 1998.

3.3.2. Attention list

Aspects that can influence the NA-processes have to be taken into account. For this, an “attention list” has been drawn up. It includes several elements e.g. are the current or past use of other remediation methods at the site; time availability; the presence of a fall-back plan; financial responsibility and limitations in use of the terrain.

(Dijkhuis, van Bemmel, Henssen & van Lotringen, 2003)

Furthermore, the Network for Contaminated Land in Europe (NICOLE) studied the sustainability of natural attenuation of aromatics (BTEX). The research program was based on the S-NA protocol for

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[8] « Not present »: <1mg nitrate /l and <20mg sulphate /l.

chlorinated ethenes. The protocol that resulted from that research program was published in 2007. (Van Ras, Winters, Lieten, Dijkhuis & Henssen, 2007)

3.4. Decision support system: immobilisation of heavy metals

The SKB project “SV-615” developed a decision support system for the use of natural or stimulated immobilisation of heavy metals in the saturated zone of the soil. The basic methodology is presented in Figure 6. The basic steps of the methodology are:

1. Assessment of the base of support and of the risks
2. Indicative assessment of technical feasibility
3. Indicative assessment of policy feasibility
4. Additional research when necessary and consultation with competent authorities
5. Final technical evaluation
6. Final policy evaluation

(Steketee, Nijboer, Takens, Dijkstra & Comans, 2003)

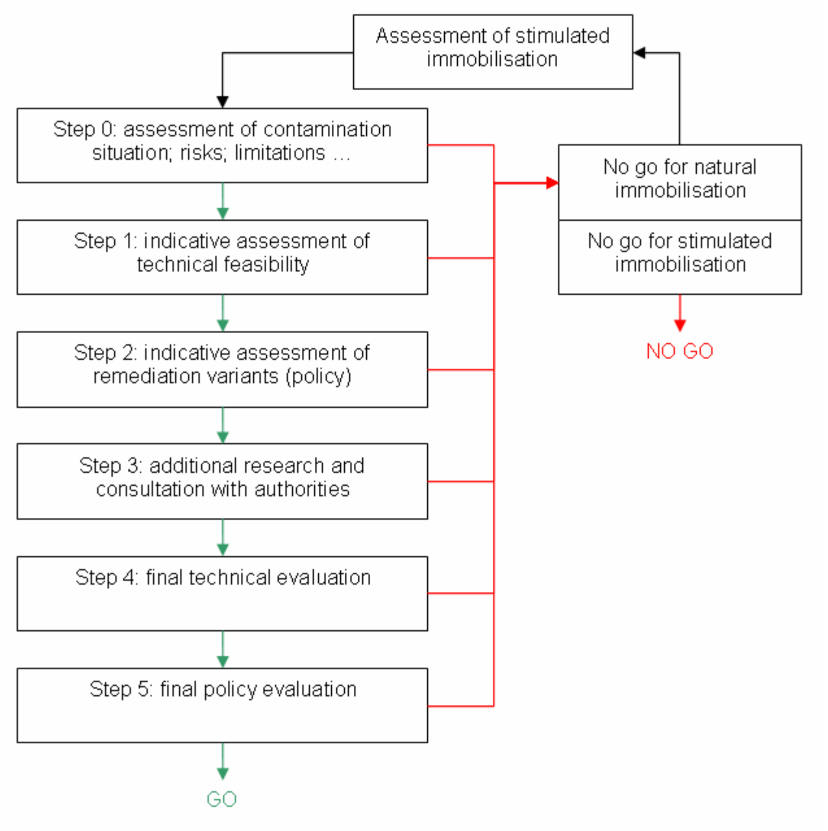

Figure 6. Decision support system for natural or stimulated immobilisation of heavy metals: methodology. (Steketee, Nijboer, Takens, Dijkstra & Comans, 2003, p.5)

3.5. ROSA

3.5.1. “Doorstart A5”

The ROSA guidebook builds on the 2001 report “Doorstart A5”. This includes the basic decision process for remediation methods for mobile contaminants, as presented in Figure 7.

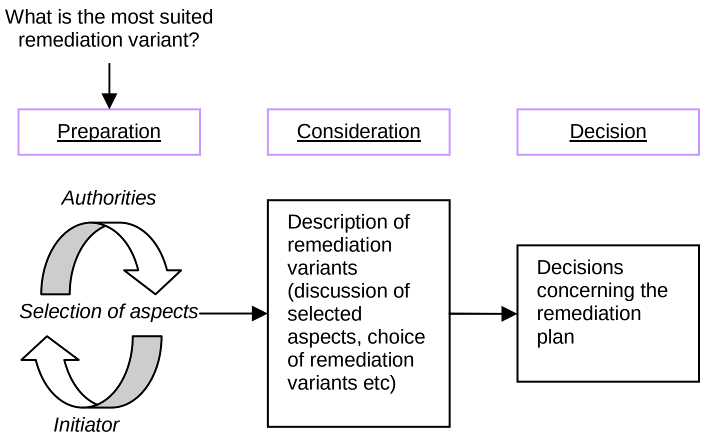

Figure 7. Decision process for remediation methods for mobile contaminants, as described in « Doorstart A5". (Slenders, Haselhoff, Leenaers, Nijboer, Sinke & Volkers, 2005, p.1)

3.5.2. ROSA

The ROSA guidebook covers the decision making process (steps A-D) and agreements on care and aftercare (steps E-G):

A. Preparation of the decision process: authorities, initiator and stakeholders
B. Development of remediation options
C. Assessment: costs and benefits (e.g. remediation costs, remediation duration and aftercare, risks and uncertainties, effect on the environment, risk reduction, recovery of soil functions, behaviour of the plume, reduction of liability, reduction of contamination)
D. Choice of the remediation method
E. Establishing agreements in the remediation plan
F. Perform, monitor and evaluate
G. Registration and aftercare

(Slenders, Haselhoff, Leenaers, Nijboer, Sinke & Volkers, 2005)

3.6. SKB Cahier "Natural attenuation, a matter of substance!"

3.6.1. NA as a remediation measure

This handbook discusses the need for a reliable decision making system for the evaluation of NA-processes. It mentions the four traffic lights from BOS-NA and the three lines of evidence. The sustainability of the degradation process is also discussed. This can be evaluated through a method which includes a quantitative mathematical approach, which tries to answer the question "are NA preconditions being met?" It also includes a reminder list that alerts the user to aspects that can influence NA.

3.6.2. A stable end situation

The handbook also mentions the evaluation of the feasibility of a stable end situation. This includes three factors (spreading of the contamination, degradation process and residual concentrations of the contamination). The calculation of a "remediation value" allows concluding whether the situation will be stable or not.

3.6.3. Modelling

To predict the development of the contamination plume; transportation modelling can be used. It is important that the modelling itself is also evaluated. The SKB Cahier mentions that, for the reliability of a model, the model input has to be studied (e.g. hydrology, rise height measurements, organic matter content, influx concentration, degradation rate). As part of a sensitivity analysis, several scenarios can be calculated.

3.6.4. Monitoring

The publication from van Ras, Roosma and Volkers mentions several reasons for monitoring: insight into the spreading of the contamination; control and adjustment of the modelling; anticipation of changes (e.g. groundwater, organic carbon) and to guarantee the protection of the nearby environment.

The handbook discusses a few aspects of the monitoring:

- What? A monitoring network (in the source, along the plume axis, longitudinally over the plume, upstream and downstream of the plume).
- When? An annual frequency is mentioned for the first period of the monitoring. After some time, when more information concerning the NA-processes becomes available, the frequency can be optimised.
- A monitoring plan should be drawn up which includes calibration points and testing criteria. It most also be registered when interventions must occur.

Compliance monitoring refers to the demonstration that the contamination development meets the requirements. The monitoring plan must include among others the check for an expanding plume, the detection of changes in conditions which may affect NA-processes and verification that the remediation goal has been achieved. It is necessary to have a fallback plan.

(Van Ras, Roosma & Volkers, 2010)

3.7. Techniques

3.7.1. Preliminary investigation

Different test methods for the investigation preliminary to in-situ remediation are discussed in the NOBIS publication 96-608 from 1996.

Table 3. Test methods for preliminary investigations of in-situ remediation. (Keuning, van der Waarde & Baten, 1996)

Goal	***Investigation method***				
	literature study	***biodegradation tests***	***batch tests***	***column tests***	***pilot tests***
Demonstrate biological degradability	+	+	±	-	-
Maximum remediation speed in the soil	-	-	+	-	-
Simulation of field remediation speed	-	-	-	+	-
Real field remediation speed	-	-	-	-	+
Biological vs. non-biological processes	-	+	±	+	-
Nutrient consumption	-	-	+	+	-
Residual concentrations	-	-	+	±	-
Biological availability	-	-	+	±	-
Soil permeability	-	-	-	±	+
Selection of monitoring techniques	±	-	±	+	±

Table 3 shows the different investigation methods and their goals (index '+'). For example: literature studies are performed in order to demonstrate biological degradability, a possible side goal (index '+/-') of this technique is the selection of monitoring techniques. Techniques for preliminary investigations (mentioned in Table 3) are:

(1) Literature study;

(2) Degradation tests;

(3) Batch tests;

(4) Column tests;

(5) Pilot tests;

(6) Transitional forms of the above.

This publication also discusses methods for the characterization and monitoring of remediation processes. (Keuning, van der Waarde & Baten, 1996)

3.7.2. Demonstration and evaluation of NA

The BOS-NA protocol (1998) mentions the possibility for additional measures to the ones supporting the four traffic lights in order to confirm or to gain more insight into the NA-processes of BTEX and chlorinated ethenes. (Sinke, Heimovaara, Tonnaer & Ter Meer, 2001)

(1) BTEX

- Degradation in batch or column-experiments
- Degradation in the field:
    - Measurement of the isotope ratio $^{13}C/^{12}C$;
    - Push-pull experiments;
    - Molecular techniques for DNA and RNA analysis.

(2) Chlorinated ethenes: measurements of hydrogen in the groundwater

The TRIAS project 835.80.007 developed a toolbox for the evaluation of the NA capacity. (Anonymous, 2005) Elements of this toolbox are:

(1) Evidence for in-situ anaerobic BTEX degradation;

- Microcosm
- Groundwater samples

(2) Identification of specific bacterial organisms;

(3) Molecular analysis using functional markers;

(4) Mathematical models.

The 96-3-04 NOBIS report summarises a few possible techniques for the evaluation of NA at dump sites. (Wolbrink & Heimovaara, 2001)These include:

(1) To be able to formulate a conceptual site model: collection of information concerning dump history; dimensions of the dump site; information concerning licences; information about the soil structure and geological environment and so on

(2) To determine the presence of a plume

- Geophysical methods to investigate soil properties
    - Direct describing methods: satellite images, aerial photographs …
    - Indirect describing methods
        - Active methods: electromagnetic probes and soil radars
        - Non-active methods to investigate temperature, conductivity … e.g. probing
- Samples
    - Geochemical analyses
    - Biological analyses

(3) To determine the existence of NA-processes

- Chemical analyses of the sediment (oxidation reduction parameters)
- Microbiological analyses e.g. BIOLOG
- DNA/RNA analysis

The 2002 SKB project "SN-002" applied four methods for the demonstration of NA of PAH. (Menning, Volkering & Beltmans, 2002)

(1) Number of PAH degrading organisms;

(2) Enzyme activity;

(3) Presence of degradation products;

(4) $^{12}C/^{13}C$ analysis.

The SKB publication "PT6416" (Volkering, van Breukelen, Veld & Gemoets, 2008) discusses a few techniques for the demonstration of "new NA-processes":

(1) Analysis of acetylene (degradation product) through gas chromatography;

(2) Stable isotope analysis for demonstration of *other* NA-processes than the "new" processes.

The SKB Cahier "Natural attenuation, a matter of substance!" (2010) mentions the following techniques to support the three lines of evidence:

(1) First line of evidence: demonstration of the reduction of the contamination

- Measurements of groundwater and soil;
- Trend analysis;
- Degradation products.

(2) Second line of evidence: geochemical and biochemical indicators of NA-processes

- Field analysis of pH, conductivity, oxygen and oxidation-reduction potential;
- Groundwater samples for laboratory analyses of macro parameters;
- Isotope analysis (fractioning).

(3) Third line of evidence: microbiological activity

- Bacteria counts;
- Degradation tests;
- Molecular analysis of genes;
- In-situ microcosms ("bacterial trap" or Bac-Trap®)

(Van Ras Roosma & Volkers, 2010)

3.7.3. Sampling

The SKB project SV-401 used different sampling techniques listed below. (Middeldorp et al., 2003)

(1) "Peeper";

(2) Environfilters

(3) Multilevel sampling device;

(4) Control buckets.

3.7.4. Isotope analysis

In the 2001 SKB publication “SV-206”, the use of isotope analysis within the framework of soil and groundwater investigation is discussed. The document mentions four application areas. (Jonker & Volkering, 2001)

(1) Characterization of groundwater flows and compound transportation;

(2) Geochemical characterization;

(3) Contamination characterization;

(4) Demonstration of the attenuation of contaminations.

4. Lessons from the application of NA

As Table 1 shows, a few (Dutch) research projects were found through the performed internet search that suggested MNA as a remediation strategy or as a part thereof (NOBIS 96-1-10, 97-1-08 and 96-3-04; SKB SV213, SV615 and S-NA). Only one project mentioned that NA was actually applied at the studied sites (S-NA project).

The SKB report of the PT4-120 project discusses the applicability of certain techniques for the demonstration of anaerobic degradation of benzene. Cost estimations for MNA projects were found online and in the SKB Cahier. Costs for analysis of groundwater samples were found in the SKB report of the SV-513 project.

- *Applicability of techniques for the demonstration of anaerobic degradation of benzene*

The PT4-120 report states that the use of degradation tests (measurements of concentrations over time at the site) are a first indication for benzene degradation. The advantage of such tests is their reliability of results; a disadvantage is the waiting time necessary to obtain results. This technique requires accurate sampling at the site of soil and groundwater. Following this technique, the use of electron acceptors should be determined through oxidation-reduction characterisation. Thirdly, stable isotope analysis is a method to determine whether degradation of components has occurred. Advantages of this technique are the possibility for quantification and the quick results; a disadvantage is that the output only provides useful information when there are positive results. Furthermore, isotope analyses are specific tests and thus require specific knowledge to interpret the results correctly. This can prove to be a disadvantage as well. (Langenhoff & van Ras, 2006)

- *Costs*

The costs of an *MNA project* are discussed on the website Bodemrichtlijn (http://www.bodemrichtlijn.nl/). The preliminary investigation (which includes characterisation and determination of the NA ability) is estimated to a cost of €20000 - €75000, depending on case specific factors. Determining factors are e.g. complexity, size and depth of the contamination. If monitoring is assumed to last for a period of 10 - 30 years, the costs for this are estimated to be €100000 - €450000, again depending on specific case factors. Another determining factor for the monitoring cost is the set of parameters that will be analysed during the monitoring period. The same estimations are mentioned in the SKB Cahier “Natural attenuation: a matter of substance!”. (Van Ras, Roosma & Volkers, 2010)

In the SKB project SV-513 report it is mentioned that the global costs for analysis of groundwater samples varied from €720 – €1140. These analyses included e.g. screening for the presence of *Dehalococcoides ethenogenes* and spectrophotometry. (Dijkhuis, van Bemmel, Henssen & van Lotringen, 2003)

5. Return on experience

Through internet research, one example was found where MNA was used in practice (as discussed in paragraph 1.2.3). The remediation project was carried out by Bioclear and started in 2003. Bioclear expects to reach the remediation goal within a time frame of 10 years. In this project, MNA is applied in combination with active excavation of the location. The two monitoring rounds so far have shown a decrease in concentrations conform to the best case scenario.

Furthermore, Tauw bv provided us with information concerning their MNA-remediation projects. This information shows that:

- MNA is being used for all kinds of contaminations;
- MNA is being used most often in combination with source removal;
- In half the cases; MNA is found to be sufficient after a standard monitoring period of five years (although this period is often found to be too short).

Additional information provided by a contact from Bioclear confirms the preference to use MNA in combination with active source treatment. Some additional remarks concerning NA in general are listed below (E. de Vries, personal communication, 31st October 2011).

- there are relatively many measurements needed to demonstrate sufficiently that the NA processes are able to degrade contaminations in the soil/groundwater;
- patience is a key element to an (M)NA approach;
- the trend for the application of natural attenuation is growing from a case-by-case application towards a regional or area-orientated remediation approach;
- there is also a growing trend to apply natural attenuation in sediments of river beds (for VOC's)
- the interest to use NA processes within so-called "WKO-systems[9]" is also increasing;
- the authorities in general accept NA as a remediation variant; however, the monitoring approach apparently differs between the different authorities.

For the different companies that were contacted, indications show approximately 85 MNA cases in the Netherlands. This, however, is not an exhaustive count of the existing MNA cases in the Netherlands! Thus, the collected information on real-life cases shows that MNA is indeed being applied in the Netherlands; however, it is not easy to obtain return on experience from these cases. Important feedback on e.g. possible obstacles during implementation, on reasons for success or failure of the applied MNA program, on actual costs and duration and, most importantly, on the achieved results of remediation, is very limited.

[9] « Warmte-koude opslag »: this is a method to store energy in the soil under the form of heat or cold. This is used for e.g. heating or cooling of buildings and in horticulture.

6. Timeline

Figure 8 represents the timeline for the Netherlands. As shown in the timeline, research projects were performed through in the period 1997-2007; several methodologies were published until 2004. The SKB Cahier followed in 2010. Limited return on experience was found but we do know for sure that MNA has been applied in the Netherlands since approximately 1999.

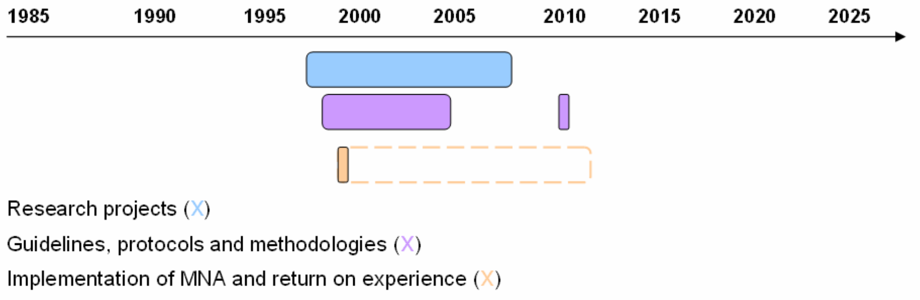

Figure 8. Timeline for the Netherlands.

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NAVOS http://www.nazorgstortplaatsen.nl/Default.aspx.

8. List of abbreviations

AFCEE	Air Force Centre for Environmental Excellence (US)
ASTM	American Society for Testing and Materials
BOS-NA	Refers to the NOBIS project “Ontwikkeling van een BeslissingsOndersteunend Systeem voor de beoordeling van Natuurlijk Afbraak als saneringsvariant” as well as to the result of that project, the “Decision supporting system for NA”
BTEX	benzene, toluene, ethylbenzene and xylene (volatile organic compounds)
BTEXN	BTEX and naphtalene
BUS	Besluit uniforme saneringen
CAH	chlorinated aliphatic hydrocarbons
CORONA	Confidence in forecasting of NA as a risk-based groundwater remediation strategy
EA E&W	Environment Agency of England & Wales
ED	electron donors
ENA	enhanced natural attenuation
HCH	hexachlorocyclohexane
HMVT	Hannover Milieu- en VeiligheidsTechniek B.V.
MCB	monochlorobenzene
(M)NA	(monitored) natural attenuation
n.a.	information not available
NAVOS	NAzorg VOormalige Stortplaatsen
NICOLE	Network for Contaminated Land in Europe
NOBIS	Nederlands Onderzoeksprogramma Biotechnologische In-situ Sanering
OSWER	Office of Solid Waste and Emergency Response (US)
PAH	poly aromatic hydrocarbons
RTDF	Remediation Technologies Development Forum (US)
SIKB	Stichting Infrastructuur Kwaliteitsborging Bodembeheer
SKB	Stichting Kennisontwikkeling en Kennisoverdracht Bodem
S-NA	sustainability of NA
TRIAS	TRIpartite Approach to Soil system processes (soil research program Netherlands)
US EPA	United States Environmental Protection Agency
Wbb	Wet bodembescherming (Netherlands)
Wm	Wet milieubeheer (Netherlands)