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Review

Application of monitored natural attenuation in contaminated land management—A review and recommended approach for Europe

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ABSTRACT

The prospect of more efficient, economically advantageous management strategies has driven the development of contaminated land management concepts particularly for large and complex contaminated sites during the last years. Consequently, the conscious and controlled use of naturally occurring degradation and retardation processes of pollutants in the subsurface (monitored natural attenuation—MNA) has gained increasing attention. Today, there are in principle two different MNA concepts available: risk-based MNA concepts as used, for example, in the USA, and MNA concepts which rely on a precautionary principle of soil and groundwater protection as developed, for example, in Germany. Based on a discussion of the virtues and limitations of these concepts, the manuscript provides a review and a synthesis of these concepts as well as recommendations for further improvements.

1. Introduction

The term natural attenuation (NA) refers to the observed reduction of contaminant concentrations (Wiedemeier et al., 1999) and/or contaminant mass flow rates (Teutsch and Rügner, 2000) as contaminants migrate away from their source in aquifers or other environmental media. Concepts have been developed to make use of monitored natural attenuation (MNA) as a management option for contaminated land and groundwater. It has become a widely accepted approach in the United States (ASTM, 1998) and attempts have been made in recent years to promote the use of MNA in European Countries as well (e.g., Sinke et al., 1998; Teutsch and Rügner, 2000; Carey et al., 2000; Christensen et al., 2000a).

However, before using MNA as a contaminated land management option, it must be clearly demonstrated that NA processes protect the environment from harmful impacts efficiently and persistently, which may be the case under favourable conditions mainly depending on the contaminant properties and the specific hydrogeological settings. For this

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purpose guidelines are needed (U.S. NRC, 2000). Even though these guidelines exist in some countries, the discussion regarding the best practice of employing MNA as a contaminated land management option, particularly at very large and complex contaminated sites (so-called megasites), is still ongoing. However, as it is nowadays widely accepted that a complete restoration of contaminated land and groundwater may not be achieved at such sites at reasonable costs, the controlled use of naturally occurring degradation and retardation processes of pollutants becomes more important. Thus, a novel concept (the receptor-oriented multi-compartmental approach for natural attenuation—ROMANA) is proposed, which is – in our opinion – suitable for the principle use of MNA in Europe and which is also applicable at megasites.

2. Existing concepts for the use of MNA in contaminated land and groundwater management

This chapter briefly discusses the presently existing concepts for the use of MNA as a contaminated land management option in Germany (D), the United States (USA), Denmark (DK), The Netherlands (NL) and the United Kingdom (UK). In principle, the approaches may be divided into two groups (see Table 1):

(1) MNA concepts which rely (at least partly) on contaminated land management concepts which are based on the precautionary principle of soil and groundwater protection (D, DK): These concepts are usually ‘‘limit-based’’, that is, groundwater in itself is regarded as the principal receptor and decision making is mainly controlled by fixed compliance criteria for groundwater. A typical example is the MNA concept of the German federal/state-run working group on soil protection (LABO, 2005).
(2) MNA concepts which rely (mainly) on risk-based and human health-oriented contaminated land management concepts (USA, UK, NL): These concepts generally focus on existing risks and do not, in most cases, define groundwater as a principle receptor. The prototypical example is the use of MNA by the U.S. EPA (1999).

2.1. *The use of MNA in Germany (concept of the German federal/state-run working group on soil protection, LABO)*

Contaminated land management in Germany is regulated by the Federal Soil Protection Act (1998) and Federal Soil Protection Ordinance (1999). According to this legislation, groundwater is regarded as a receptor and decision making is – among other things – controlled by compliance criteria for groundwater (groundwater trigger values). NA processes are considered concerning pollutant transport in the unsaturated soil zone (risks to underlying groundwater resulting from seepage water). Groundwater damage is established if the crucial criteria, namely a ‘‘limited (spatial) occurrence of increased pollutant concentrations’’ and corresponding ‘‘small pollutant loads’’, are not achieved at the seepage water-groundwater interface or in groundwater which is in close contact with contaminated soil or waste. In such cases the need for remediation has to be assessed. However, the final decision of if, where, and which remedial action is necessary depends on the ‘‘principle of proportionality’’, a mainly administrative decision, which implies that any kind of measure has to be feasible in terms of effort and costs. Only in very unfavourable cases, where the criteria for a ‘‘successful’’ remediation cannot be achieved due to either economical or technical limitations, may it be necessary to tolerate groundwater damage.

Although MNA draft guidelines exist today at the federal level, there are only a few field sites where MNA has been implemented. Funded by the state-run EPA of Baden-Wuerttemberg (LfU), a number of case studies has been performed at the University of Tuebingen, which focused on the quantification and evaluation of NA processes at contaminated reference field sites (Rügner et al., 2004a,b). NA processes where quantified based on the measured decrease in contaminant mass flow rates at consecutive control planes (the first control plane was located close to the source zone, the second at a distance of several hundreds of meters) using a new integral groundwater investigation technique (Bockelmann et al., 2001). Numerical reactive transport modelling was used to assess the present contaminant plume extension and to predict the future plume behaviour. In addition, a general (non-NA-specific) site investigation was performed, as the German Soil Protection

Table 1 – Overview of existing MNA concepts

	Country				
	USA	UK	NL	D	DK
Publishing regulating agency	U.S. EPA U.S. Air Force	UK EA	NOBIS	LABO	DK-EPA
Contaminated land and groundwater management concepts:	Human health-oriented/risk-based			Groundwater-oriented/limit-based	
Demonstration of the efficiency of NA processes	Three lines of evidence	Three lines of evidence	Three lines of evidence	Decrease in MFR[a]	Three lines of evidence
Max. acceptable stable plume length	–	–	–	–	1 y/100 m[b]
Acceptable time frame[c]	Comparable	30 y	Comparable	–	–

[a] Demonstration of NA at the reference field sites in Baden-Württemberg was based on decreasing contaminant mass flow rates (MFR) with increasing distance from the source.
[b] Valid in groundwater restriction areas in Denmark.
[c] The definition of a time frame for MNA usually requires source control measures in conjunction to MNA.

Ordinance (1999) requires a scientific and economical comparative assessment of adequate remediation measures prior to a final decision on which approach to use. As NA processes were found to be sufficiently effective and active remediation measures (in these cases: pump and treat) were not considered to be "proportionate", the responsible regulators decided in favour of using MNA as a contaminated land management option at these sites. The crucial decision criterion was that the contaminant plumes (reactive zones) were found to have, now and in the future, a limited and tolerable extension (steady-state conditions). NA processes are monitored and back-up options have been foreseen.

2.2. *The use of MNA in the USA*

In the USA, a risk-based approach is used for contaminated land management and in particular for defining remediation targets (Risk Based Corrective Action—RBCA: U.S. EPA, 1996; ASTM, 2000). The risk resulting from different exposure scenarios and along the pathways of concern is calculated (quantitative risk assessment) by comparison of the additional daily intake dose with the tolerable or acceptable (contaminant specific) daily intake dose. Remediation targets are defined in order to eliminate concentrations (in the source, along pathways and at the receptor) which would cause the contaminant levels to exceed the acceptable daily intake dose at the receptors of concern. NA processes are considered in the quantitative risk assessment and therefore MNA may – where suitable – be accepted as the remedial option as a stand alone approach or, more likely, in conjunction with other, more active measures (ASTM, 1998; U.S. NRC, 2000; Chapelle et al., 2001).

The U.S. EPA's policy regarding the use of MNA for the clean-up of contaminated soil and groundwater is clarified in the OSWER-Directive (U.S. EPA, 1999). Recommendations concerning MNA specific site investigations and evaluations are given in the U.S. Air Force protocols (Wiedemeier et al., 1995, 1998). The demonstration of the efficiency of NA processes is performed by the so-called "three lines of evidence-approach", which requires (1) an observed decrease in contaminant concentration with increasing distance from the source and a decrease of contaminant mass in the plume. The latter is achieved either by (2) the interpretation of geochemical indicators such as occurrence of metabolites, changes in redox conditions or comparison of concentrations of tracer compounds, or by (3) a demonstration of the microbial activity by in situ or laboratory experiments. After the decision to rely on MNA as remediation option has been adopted, the efficiency of NA processes has to be monitored. As MNA has to be effective within a "reasonable" time frame (i.e., comparable to other more active measures), short-term source treatment or source control measures may have to be undertaken in addition to MNA (Table 1). This means that the source will be (partly) removed or contained (e.g., hydraulic barriers or encapsulation).

2.3. *The use of MNA in Denmark*

In Denmark, guidelines on remediation of contaminated sites (1998) and the new Danish Soil Contamination Act (1999) refer to risk assessment and the use of MNA. Major goals in contaminated land management are the protection of residential areas and water restriction areas. As Denmark relies on groundwater resources for approximately 99% of the drinking water supply (drinking water originates from numerous groundwater wells, which are spread across the country and are not usually in need of treatment), about 35% of the country's area has been defined as water restriction areas (here, groundwater standards were set according to drinking water standards; Table 1). Inside these areas, a risk for groundwater resources arises if compliance criteria for groundwater are exceeded at a distance equalling 1 year of groundwater travel time or a distance of 100 m downstream of the source zone (therefore, this is not a risk-based, but rather a groundwater-oriented and "limit-based" approach). NA processes are considered in risk assessment procedures for a limited number of contaminants. If these processes lead to a sufficient contaminant reduction, MNA may be accepted as a contaminated land management option (Edelgaard and Dahlstrom, 1999). The demonstration of the efficiency of NA processes is performed by field measurements and laboratory experiments. Usually methodologies comparable to the "three lines of evidence-approach" and/or additional methodologies developed in the investigation programmes at Danish landfill sites are used (e.g., Christensen et al., 2000b, 2001).

2.4. *The use of MNA in The Netherlands*

In The Netherlands, the management of contaminated sites is regulated by the Dutch Soil Protection Act (1994). Contaminated land management has traditionally been based on concrete compliance criteria for soil and groundwater (the famous so-called "Holland List", which originated from the "Guideline for Evaluation and Remediation of Soils" in The Netherlands and was subsequently used for contaminated land management in many other European countries in the eighties and nineties). However, in recognition of the problems arising from heavily contaminated sites, more and more risk-based approaches are now being used in contaminated land management in The Netherlands as well. To make use of MNA as a contaminated land management option a decision support system was developed (Sinke et al., 1998). It consists of a tiered approach to decision making regarding the use of MNA as a contaminated land management option for BTEX and chlorinated solvents. The demonstration of the sufficiency of NA processes is based on chemical and microbiological analyses (comparable to the approaches used in the USA). A modelling of future plume behaviour is required, which may be performed using simple analytical models (e.g. BIOSCREEN, U.S. EPA, 1997a). Similar to the U.S. concept, the time frame for clean-up using MNA has to be "reasonable" (i.e., comparable to active measures).

2.5. *The use of MNA in the United Kingdom*

In the United Kingdom, risk-based contaminated land management approaches are similar to the ones used in the USA. As the majority of the drinking water supply relies on surface water, groundwater is usually not regarded as a principle receptor. For the evaluation of MNA as a contaminated land management option, a multi-stage risk-based concept (including a screening, demonstration, implementation and monitoring phase; Carey et al., 2000) was prepared for agency staff, problem holders and consultants. Demonstration of NA efficiency is carried out in analogy to the U.S. approach (''three lines of evidence''). The required time frame of 30 years for the achievement of the remedial goals implies that source control measures are needed.

3. A synthesis of the different concepts—what is most suitable from a European perspective?

Being developed against different country-specific legislative backgrounds the diverse MNA concepts bear on different motivations, thus focussing on particular goals and intentions. Therefore, though exhibiting features that are meaningful in their defined context, none of the described concepts appears to be flexible enough from a European perspective, particularly if the management of megasites is addressed. However, individual features of the different concepts may be combined to synthesise a more general concept that is capable of taking the diversified needs and site-specific requisites into account. The main features of a synthesised concept are:

(1) *Different types of remediation targets*. All existing concepts employ remediation targets of specific nature, either expressed as concentration, mass flux, or risk level. However, neither a concept that is solely based on precautionary groundwater-oriented targets nor a pure human health risk-based concept seems to be appropriate. While the latter does not consider groundwater as a receptor and thus will not coincide with the principle legal requirements in some countries (e.g., DK, D), the former will not be applicable in large and heavily contaminated areas.

   As a consequence, a case-specific flexible definition of remediation targets, in terms of either maximum mass flow rates, and/or precaution-driven concentration targets, and/or concentration-based human risk levels, should be taken into consideration. Mass flow rate based remediation targets (as considered in the German approach) allow for the consideration of a sustainable management of groundwater resources as required by the European Water Framework Directive (EU-WFD, 2000) as this method enables a direct consideration of mass load to the groundwater body, preventing simple dilution (by dispersion) from being regarded as an equivalent to NA processes (comparable to biodegradation or volatilisation) and allows for an assessment of water quality goals on a river basin or catchment scale. Strictly precautionary-oriented remediation targets might be applied to previously defined groundwater restriction areas, as is the case, for example, in Denmark. Concentration targets are required to assess MNA for its effectiveness to guarantee, for example, the functional usage of groundwater as drinking water at defined locations of compliance.

(2) *No categorical time frame for clean-up*. Any categorical requirements concerning the time frame for clean-up of a site (e.g., UK approach) are believed to be inappropriate since they obviously ignore any site-specific circumstances that may call for longer remediation time frames. In fact, a complete source removal, although principally desirable, is in most cases not possible in reality due to the inability to quantify the size, distribution and composition of the source zone in heterogeneous natural environments. Parts of the source zone will be left untreated or only partially treated after source treatment. Acknowledging this fact, it must be reasonably expected that contaminant releases from source zones may last for hundreds of years (Eberhardt and Grathwohl, 2002). Although a careful evaluation of possible benefits of active source depletion measures is required, source control measures should not be claimed if economically and/or technically infeasible and if a considerable reduction of MNA time scale is questionable.

(3) *Proving MNA by a tiered evaluation and multiple lines of evidence*. A reliable examination of the efficiency of NA processes is based on chemical and microbiological indicators. The lines of evidence to consider are the decrease in contaminant concentrations and the decrease of contaminant mass in a plume (either by a decrease of contaminant mass flow rates or geochemical or biological indicators; see Table 1). Since the efforts for the corresponding investigation and evaluation of MNA and possible accompanying remedial activities might be considerable, particularly at large and complex contaminated sites, a tiered or multi-stage approach (as implemented in the guidelines of UK and in The Netherlands) is an essential prerequisite. Based on scientific-technical investigations the lines of evidence may be evaluated on a qualitative, semi-quantitative level (screening stage—based on generic and preliminary site-specific information and modelling) and on a quantitative level (demonstration stage—based on detailed site investigations) and have to be proven by monitoring (monitoring stage; long-term performance).

(4) *Comparative assessment of MNA and other alternatives*. In order to guarantee an efficient contaminated land management, both the effectiveness and costs of MNA need to be assessed in comparison to other alternative management options, including combinations of MNA and active remedial measures. A technology selection should then be based on factual, site-specific issues such as cost-efficiency and available financial resources rather than on general, formal requirements. An important and still open question in this context is how to define the demands which will be made on the level of confidence and reliability of such a comparative assessment. Stringent demands may entail intensive site investigations, leading to excessive costs for the quantitative evaluation of both the NA processes and the effectiveness of other remediation options, particularly at megasites (Kaschl et al., 2003). In Germany, for example, the proportionality of any remediation measure (and MNA) has to be proven based on a sufficiently reliable database. Thus, MNA was so far only applied at smaller or medium-sized contaminated sites where required data could be obtained at reasonable costs.

4. What is still missing—recommendations for further conceptual improvements

Although a synthesised approach as outlined above would mean a big step forward, there is, in the authors' view, still scope for improvements. Important aspects that should be explicitly addressed in a European MNA concept are:

(a) *Tailored decision and investigation concepts and methods for early decision making*. Specific site investigations are mandatory for the evaluation of NA processes as well as of the effectiveness of alternative or accompanying measures. Especially at large and complex contaminated sites there are usually a great number of possible management solutions to be considered. A detailed investigation of all these options, however, is not economically feasible. Hence, the streamlining of the planning and decision process is a mandatory requirement. Decisions to be taken should be made as early as possible in order to reduce expenditures on site investigation. Therefore, a tiered decision-making procedure is required, including (i) an identification and prioritisation of focal areas (origin) of risks, (ii) a feasibility screening of remediation targets as well as of available management options to narrow the range of possible options for (iii) subsequent detailed investigations of only a few preferable options. For each of these elements tailored decision and investigation concepts are required. These concepts and employed methods should be specifically adapted to the type and scale of the particular decision to be taken—i.e., more target oriented, and cost-efficient investigation programmes as well as model-based assessment methods are needed. Useful procedural elements can be found here in the so-called TRIAD approach (U.S. EPA, 2003a), an upcoming dynamic procedure to hazardous waste site clean-up, which improves the liability of risk related decisions.

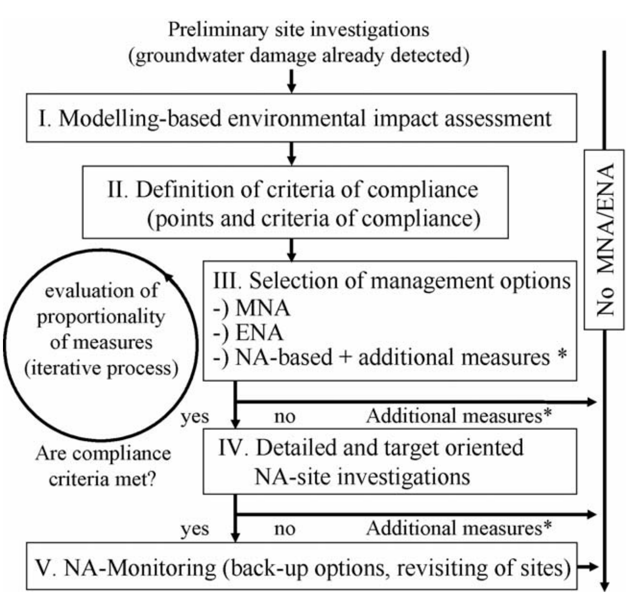

Fig. 1 – NA-concept (asterisk (*) indicates additional measures include conventional technical measures as well as restrictions/changes concerning land use).

(b) *Long-term perspective*. A direct implication of the inability to completely remove the contaminant source in many cases is the need for long-term management options for contaminated land which go beyond one-time removal/ remediation activities. In fact, this holds not only for MNA but also for other plume management techniques. Possible solutions might include revisiting these sites after an adequate time period as a follow-up measure and reconsidering any decisions taken previously.

Taking the above-mentioned aspects into account, we propose a new, receptor-oriented, multi-compartmental MNA concept (ROMANA). The concept is based on scientific-technical investigations of gradually increasing sophistication and a corresponding consecutive evaluation of the obtained results. It differs from existing contaminated land management concepts in terms of a modified sequence of work steps and an increased emphasis on modelling. The concept comprises the following procedural steps (Fig. 1):

Table 2 – Examples of tools to be used for a modelling based environmental impact assessment and cost estimates

Release rates from contaminant sources and time frame of contaminant release
Analytical solutions for calculating release rates from source zones as well as time frames of NA (Grathwohl, 1998; Grathwohl, 2003; Eberhardt and Grathwohl, 2002; Huntley and Beckett, 2002)
Contaminant transport in groundwater
One-dimensional analytical solutions of equations describing reactive transport in groundwater incl. biodegradation rates and/or attenuation factors (Domenico, 1987; see also: Wiedemeier et al., 1998; Carey et al., 2000)
One-dimensional and two-dimensional numerical models for calculating reactive transport. Examples: *BIONAPL* (Frind et al., 1999), *SMART* (Finkel et al., 1999), *MIN3P* (Mayer, 1999), *PHT3D* (*MT3DMS* + *PhreeqC*; Prommer et al., 1999), *TBC* (Schäfer et al., 1998), *Geosys* (Kolditz and Bauer, 2004), *Bioplume III* (USEPA, 1997b)
Empirical equations for calculating plume length (Cirpka et al., 2006; Ham et al., 2004; Liedl et al., 2005; Maier and Grathwohl, 2006)
Multi-compartmental conceptual models
Calculation of inter-compartmental pollution fluxes and resulting concentrations in compartments based on analytical solutions. Examples: *3MRA* (U.S. EPA, 2003a,b), *ARAMS* (U.S. Army Engineer Research and Development Center, 2006)
Calculation of inter-compartmental pollution fluxes using analytical solutions based on the fugacity concept (Mackay, 2001), Multimedia Total Exposure Model *CalTOX* (Lawrence Berkeley National Laboratory 2002)
Guidelines/models for calculating exposure scenarios
Guidelines for calculating additional daily doses for relevant receptors and compilations of toxicological and eco-toxicological reference data (European Economic Commission, 1996; Total Petroleum Hydrocarbon Criteria Working Group, 1999; U.S. EPA, 2005). Algorithms: *SADA* (University of Tennessee, 2005), *FRAMES 2.X* (Pacific Northwest National Laboratory 2006)
Cost estimation tools
Examples: *Cost Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents* (U.S. ESTCP, 2005); *MCACES* (U.S. Army Corps of Engineers, 1996); *RACER* (Earth Tech, Inc., 2005); *CAROPlus* (Serapiglia et al., 2005; McKnight et al., 2006)

(I) As a first step a *modelling-based environmental impact assessment* is performed. Modelling is based on generic data, for example plume length statistics, data on degradation/retardation constants, etc. and takes into account the already existing information (a preliminary site investigation to create a first conceptual site model being a major prerequisite) and may be performed using conceptual, but process-oriented analytical or numerical models (examples are given in Table 2). This allows the prediction of contaminant spreading in time and space considering realistic spreading scenarios along relevant pathways (in groundwater and across compartment boundaries, e.g., transport into soil air by volatilisation, transport into surface waters, etc.) and the assessment of possible contaminant input into final sinks (atmosphere, river basins, etc.). Modelling also allows for the identification of presumably relevant receptors (groundwater, plants, human health, outdoor and indoor air, the ecosystem quality, etc.) and the assessment of impacts (over time) on the relevant receptors (e.g., by the methodologies given in Table 2). Of course, existing and future land use and spatial planning objectives have to be considered.

(II) Based on the results of the environmental impact assessment, *points of compliance and corresponding compliance criteria* are to be determined by the regulating authority at a very early stage of the investigation programme. Possible points of compliance (POC) and compliance criteria are listed in Table 3. As receptor-relevant concentrations and/or mass flow rates are related to concentrations and/or mass flow rates in groundwater, the POC may be located at the concerned receptor itself or at a certain location along the groundwater pathway. In fact, this so defined set of criteria serves as a preliminary definition of remediation targets. These targets may be reconsidered later on if subsequent steps reveal that one or more criteria cannot be met by proportionate means (i.e., none of the available remediation options will achieve the goals at reasonable costs).

(III) Here, *suitable management options* are selected, on the grounds that they are able to conform to the previously defined criteria. NA-based management options include MNA, ENA or any combination of MNA/ENA and other measures (technical measures and/or restrictions/changes concerning land use; see Fig. 1). For performance assessment of management options the modelling approaches developed during the environmental impact assessment may be used. In addition to the performance assessment, possible management options are also compared with respect to economic cost (see Table 2 for a selection of cost estimation tools). The suitability of investigated options is then evaluated in terms of cost-efficiency. Any option which is not "proportionate" compared to alternative options should not be considered further. If, according to the environmental impact assessment, the compliance criteria may not be met using only NA based management options, other (more active) measures must be implemented. For megasites with many different sources, pathways and receptors, the definition of so-called "risk clusters" allows for the convenient structuring of the site. Existing risks may also be addressed by employing different, cluster-specific measures (including MNA/ENA; Kaschl et al., 2003).

(IV) If MNA/ENA (unassisted or in combination with other measures) are estimated to represent possible manage-

Table 3 – Examples of possible points of compliance (POC) and corresponding compliance criteria

Receptor	Possible POC	Corresponding compliance criteria
Drinking water supply	Water supply wells (or control wells at a certain distance)[a]	Drinking water standards (legal limits)
Human health (working/housing)	Indoor air (at work)[a]	"Max. allowable concentrations" (e.g., as defined in Germany)
	Indoor air (housing)[a]	Tolerable concentration in indoor air
Groundwater at the local scale[b]	Groundwater directly downstream of a site ("only locally increased concentrations/small pollutant loads")	Max. concentrations and tolerable mass flow rates (e.g., German soil protection ordinance)
Groundwater at the regional scale[b]	Groundwater at a certain distance or at the front of contaminant plumes	Groundwater "no observed effect values" (defined e.g. in Germany)
Groundwater at the river basin scale[c]	Reference monitoring wells within groundwater monitoring programmes	Quality criteria "of a good chemical status" according to the EU-WFD
Surface waters[c]	Lakes, rivers, etc.	

[a] Corresponding concentrations in groundwater and/or soil air may be calculated by an inverse quantification, for example, based on the tolerable daily dose (for a non-carcinogenic pollutant) for residents in a housing area (receptor).
[b] Regarding MNA as a decision option, groundwater in general may not be considered as a principal receptor. Whether groundwater at the local scale or regional scale is considered as a receptor has to be decided by the regulators based on the principle of proportionality of measures. However, it may be useful to consider whether compliance criteria (e.g., depth averaged concentrations and corresponding mass flow rates) are exceeded in groundwater at a certain distance from the source zone (Bannick et al., 2000; LfU, 2002).
[c] As the European Water Framework Directive (EU-WFD) does not explicitly address the issues of "contaminated land management" these criteria may be considered as additional ones if, for example – due to heavily contaminated area(s) – the quality criteria "of a good chemical status" cannot be preserved within a river basin or catchment area.

ment options, *detailed NA investigations* are performed. This may now be conducted in a very cost-effective manner, as only target-oriented management options have to be considered in a detailed but ''tailored'' site investigation. For this purpose, a number of methodologies are already available (such as the studies on NA by Christensen et al. (2000b) and Rügner et al. (2001), the U.S. Air Force protocol by Wiedemeier et al. (1998) or the UK EA protocol by Carey et al. (2000). The detailed investigations may also include elaborate modelling activities to confirm and improve the environmental impact assessment and the assessment of future contaminant behaviour. Only if these detailed NA investigations confirm that the defined criteria are met, may NA based measures finally be selected as a management option at the site. If it cannot be demonstrated that NA processes are active to a sufficient degree, the selection of management options has to be reconsidered (according to the iterative process illustrated in Fig. 1) and detailed investigations regarding the newly chosen management options have to be performed.

(V) Subsequently, a *monitoring programme* and/or *follow-up/back-up management options* are defined. This includes the time, locations and techniques of control measurements to prove that the defined requirements are fully met. For the case that monitoring reveals that NA processes do not perform as predicted, back-up management options according to the requirements of the regulating authority needs to be defined.

5. Final remarks

The proposed MNA concept ROMANA offers major advantages for an increased use of MNA in contaminated land management in Europe for the following reasons: It is (i) applicable to large and complex contaminated sites, as detailed (and expensive) investigations with respect to (presumably) non-relevant decision options (or at least for the most of them) are excluded; it (ii) allows for straightforward and more flexible decision making, since the compliance criteria will be directed both towards human health and groundwater protection; it (iii) guarantees the necessary level of quality and reliability of the evaluation of NA processes since detailed investigations geared towards the quantification and monitoring of NA processes are performed; it (iv) allows the regulating authorities to decide in favour of complete or limited risk reduction through conventional, active remediation measures according to the technical and economical feasibility of measures; it (v) does not include any restrictions concerning the time frame of MNA but foresees, if necessary, the revisiting of sites after a certain time period; it (vi) considers possible harmful impacts on finals sinks like surface waters or the atmosphere, which are not taken into account in many present-day contaminated land management programmes; and finally it (vii) allows the linking of objectives and strategies of risk management with those of land and spatial planning. This is a major prerequisite for integrated land management concepts and the revitalisation of contaminated sites.

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