The sustainability of natural attenuation for the remediation of contaminated sites

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ABSTRACT
As long-term environmental strategies are required to protect and enhance the environment, what role can nature play in sustainable development and specifically in a sustainable geoenvironment? Natural attenuation is being advocated for use as an integral tool in sustainable geoenvironmental practice-through mitigation and management of impacts from physical and chemical stressors in the subsoil. Procedures are being developed to effectively use natural attenuation and specify macro and material-status indicators. The long term performance of mechanisms and processes in the natural attenuation of pollutants must be ensured. Lines of evidence and methods for evaluating the sustainability of remediation by natural attenuation will be presented.

RÉSUMÉ
Dès que les stratégies à long terme sont requises pour protéger et améliorer l'environnement, quel est le rôle que l'atténuation naturelle peut jouer dans le développement durable ou plus spécifiquement dans un géo-environnement durable? L'atténuation naturelle pourrait être utilisée comme un outil intégral en pratique géo-environnementale par la mitigation et le ménagement des stresses physiques et chimiques dans le sol. Des procédés sont en cours de développement pour l'utilisation effective de l'atténuation naturelle et pour spécifier les indicateurs macro et le statut matériel. La performance à long terme des mécanismes et des procédés de l'atténuation naturelle doit être assurée. Les lignes d'évidence et les méthodes d'évaluation de la durabilité de la restauration par l'atténuation naturelle seront présentés.

1 INTRODUCTION

The ultimate goal for all of humankind is to obtain both a sustainable society and sustainable development. It therefore follows that until a sustainable society is obtained, *sustainable development* will not be achieved. The term *sustainable development* is used to mean that *all the activities associated with development in support of human needs and aspirations, must not compromise or reduce the chances of future generations to exploit the same resource base to obtain similar or greater levels of yield.*

The g*eoenvironment* includes the land environment with all the geophysical (geological and geomorphological) features, together with the aquatic elements classified as receiving waters. The geoenvironment thus contains all the elements that are vital for the sustenance and well-being of the human population. Commoner (1971) states that the ecosphere, together with the earth's mineral resources, is the source of all goods produced by human labour or wealth. Any degradation of the ecosphere will this impact negatively on the capability of the ecosphere to provide the various goods produced by human labour or wealth.

The Johannesburg World Summit on Sustainable Development (WSSD, year 2002) identified 5 priority theme areas that needed to be addressed. These five *thematic areas* have the acronym of WEHAB – which are: (a) Water and Sanitation, (b) Energy, (c) Health, (d) Agriculture, and (e) Biodiversity. How the various industries (life-supporting and manufacturing-production) and their associated activities interact with the geoenvironment can be viewed as follows:

1) Resource extraction and processing
2) Utilization of land and soil as a resource material in aid of production
3) Water, groundwater and aquifer harvesting
4) Use of land as a facility.

From the viewpoint of the geoenvironment and ecosphere, the pressures from *development stresses* and WEHAB, combined with the processes necessary to satisfy sustainable development objectives are summarize in Figure 1.

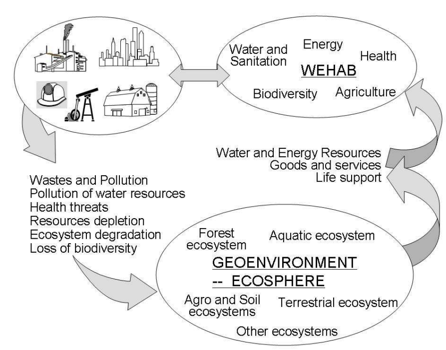

Figure 1. Interaction of industry, WEHAB, and the geoenvironment

Potential sources of pollution of subsurface water or groundwater (pore water and aquifers) other than inadvertent spills and deliberate dumping of hazardous materials, include landfills, underground storage tanks, waste piles and waste sites, underground injection wells, unplugged oil and gas wells, various kinds of surface impoundments and settling ponds, lands treated with pesticides, insecticides, fertilizers, and pipelines transporting carbon resources. The types of pollutants, their concentrations and proportions, and the transport of these in the subsoil and their fate are critical to the structuring of protective measures necessary for the protection of public health and the health of the terrestrial environment. The need for predictive tools is obvious.

For remediated sediments to remain remediated, the input rate of contaminants ≤ remediation rate and is determined by:

(a) by natural remediation or recovery processes in the remediated sediment, or
(b) by human intervention

The requirements for this to happen include:

- Elimination or reduction of rate and-or quantity of input contaminants
- Natural and-or technological remediation processes capable of decontaminating and-or detoxifying the incoming contaminant load
- Restoration of habitat, breeding grounds and natural species.

In this paper, the objectives are to examine and evaluate the role of natural attenuation in the sustainable remediation of contaminated soils.

2 NATURAL ATTENTUATION

According to the US EPA (1999), natural attenuation is the "use of natural processes to contain the spread of the contamination from chemical spills and reduce the concentration and amount of pollutants at contaminated sites". It can also be termed as intrinsic remediation, bioattenuation and intrinsic bioremediation. In this case, the contaminants are left on site and the naturally occurring processes are left to clean up the site. The natural processes include biological degradation, volatilization, dispersion, dilution, radioactive decay, and sorption of the contaminant onto the organic matter and clay minerals in the soil. It is mainly used for remediation of the aquifer when the contamination source has been removed but can also be used when the source is still present or if some hot spots are removed.

As long-term environmental strategies are required to protect and enhance the environment, what role can nature play in sustainable development and specifically in a sustainable geoenvironment? Natural attenuation is being advocated for use as an integral tool in sustainable geoenvironmental practice-through mitigation and management of impacts from physical and chemical stressors in the subsoil. Procedures are being developed to effectively use natural attenuation and specify macro and material-status indicators (Yong et al. 2006). The long term performance of mechanisms and processes in the natural attenuation of pollutants must be ensured. Some of these processes are indicated in Figure 2.

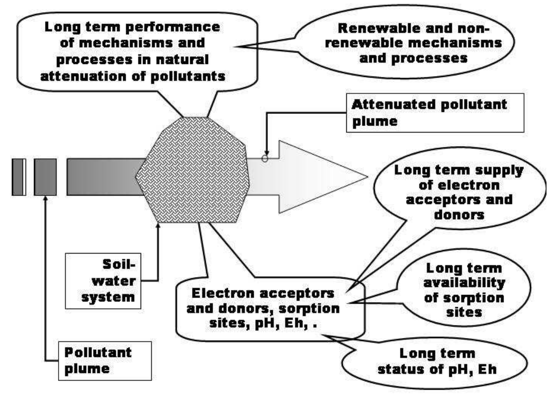

Figure 2. Sustainability of natural attenuation.

The natural attenuation capacity of soils has long been recognized and described by soil scientists as the assimilative capacity of soils. It is now a tool that can be used as a passive treatment process in the remediation of sites contaminated by organic chemicals. The US EPA has integrated it with the requirement for continuous on-site monitoring of contaminant presence whenever natural attenuation is to be used as a tool for site remediation. The procedure for application of this attenuation process is called *Monitored Natural Attenuation (MNA)*. Guidelines and protocols for application of MNA as a treatment procedure in remediation of contaminated sites have been issued. A general protocol, from Yong and Mulligan (2004) for considering MNA as a remediation tool is shown in Figure 3. A very critical step in the application of MNA as a site remediation tool is to have: proper knowledge of: (a) *lines of evidence* indicating natural or intrinsic remediation, (b) contaminants, soil properties and hydrogeology, and (c) regulatory requirements governing *evidence of success* of the MNA remediation project.

The data and information inputs shown in Figure 3 tell us what is required to satisfy site specific conditions, and whether the *indicators* for natural bioremediation are sufficient to proceed to satisfy the use of MNA as a viable treatment option. If the responses are not satisfactory for first two decision steps, technological and/or engineered solutions to the remediation problem will be required. Laboratory research and transport and fate modelling are needed to determine the ability of the site materials and conditions to attenuate the pollutants.

The term *Lines of evidence (LOE)* is associated with the use of NA as a tool for mitigation and management of impacts from waste and pollutant discharges to the land environment. It refers to the requirement to determine whether a soil has the capability for in situ attenuation of contaminants. This requirement originates from procedures associated with the use of monitored natural attenuation (MNA) as a treatment procedure. This is a prudent course of action, since there is need to determine how effective a particular soil will be in attenuating contaminants. The types of information and analyses required for LOE indicators are shown in Figure 3. Site and problem specificities will dictate how much information and what specific kinds of analyses will be needed. The type of information needed to define the site characteristics is shown in the top right-hand corner of the diagram. The physical (geologic and hydrogeologic) setting sets the parameters of the problem to be resolved. Whether the natural attenuation capability of the subsoil is capable of mitigating and managing the pollutant plume anticipated within the site boundaries will be established by the other two categories; patterns of natural attenuation and supporting laboratory tests and analyses.

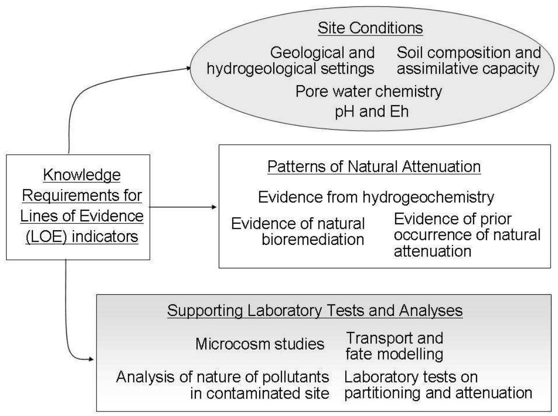

Figure 3. Lines of evidence indicators.

To determine evidence of previous natural (intrinsic) remediation of contaminants, it is necessary to establish the various mechanisms and processes related to retention and transformation of the various kinds of pollutants generally found in the subsoil. In addition, one needs to determine or assess the environmental mobility of the contaminants in the site under consideration. These are necessary for the lines of evidence (LOE).

The use of natural attenuation (NA) as an active tool in the management of contaminant impact and transport, as opposed to the use of MNA as a passive tool, has been hampered because of insufficient knowledge of the many processes that contribute to the natural attenuation process. The designation of MNA as more of a passive tool as opposed to an active tool is based on the fact that except for the monitoring requirement, the use of natural attenuation processes as existent in situ is essentially a "do-nothing" solution. The "do-nothing" part refers to human contribution to the processes resulting in natural attenuation of contaminants. To make NA an active tool, it is possible to: (a) enhance the processes that contribute to natural attenuation capability, (b) incorporate NA as part of a scheme to mitigate and manage the geoenvironmental impacts from discharge and/or containment of waste products and pollutants.

3 ANALYTICAL AND PREDICTIVE TOOLS

Analytical and predictive tools dealing with the fate and transport of pollutants must account for the following:

- concentrations of the various target pollutant species,
- hydraulic conductivity of the subsurface material (soil),
- diffusive capabilities of the target pollutants,
- hydrogeologic setting,
- partitioning potential of the target pollutants,
- solubility of the target pollutants,
- speciation, complexations and products formed,
- abiotic and biotic reactions and transformations.

The factors and elements to be considered fall conveniently into two groups: (a) transport, and (b) reactions. Two types of analytical-computer models have been developed: (a) models dealing with fate and transport of pollutants, and (b) models that take into account geochemical reactions and their products. Mainly partitioning coefficients are used to account for sorption of pollutants from the pore water, with little or no attempt to account for the chemical reactions in the soil-water system. In particular, speciation and complexation are not included in the structuring of the basis functions. Attempts have been made, (and are being made), to develop reactive fate and transport models. In the second type of models, geochemical models address geochemical speciation equilibria between the various phases (solids, liquid and gaseous) in the subsurface setting. This includes the dissolved and adsorbed elements in the various phases.

Assessment and prediction of the transport and fate of pollutants commonly rely on analytical and/or numerical (computer) models designed to take into account the various processes, site contamination situations, and properties of the pollutants and subsurface materials. These models are useful for regulatory agencies in risk management and performance assessment of target sites and situations, for those involved in site remediation (Figure 4). The quality of models, i.e. how accurately their predictions accord with real performance, depends on how well they represent the real problem situation and processes involved.

4 THE USE OF STATUS INDICATORS

Material performance and system status indicators are specified or determined on the basis of how or what one needs to know and undertake to meet the specific targets identified in *sustainability status indicators*. There are two starting points for delineation of indicators.

With the objective of maintaining the quality of the soil in a tract of land or a particular site, an important aspect is the life-support role of the specific tract of land. Defining or establishing indicators are needed as sustainability status indicators such as soil quality aspects as shown in Figure 5. The sources and nature of interactions with the tract of land and their impacts, and the required actions must be established to ameliorate, mitigate, avoid and protect the desired soil quality.

Material and macro status indicators are established to determine and track the results of the corrective and protective measures. Figure 6 shows the use of status indicators in tracking anticipated or predicted outcomes from analyses or modelling of the processes initiated by the corrective actions. Failure to meet tracking results from the status indicators requires one to decide: (a) to ignore indicators, or (b) modify or add or correct the actions previously prescribed to manage the impacts.

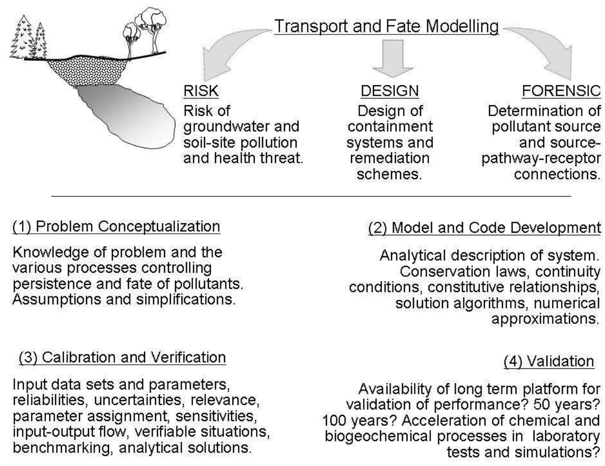

Figure 4. Pollutant transport and fate modelling

Starting with the external sources of interactions with the terrestrial environment itself, a reverse sequence is followed. Figure 5 shows a typical protocol to determine or evaluate sustainability capabilities for the actions or impacts resulting from a specific project, activity, or industry. The status indicators *(1)* and *(2)* are indicators that may refer to different time periods, intervals, circumstances, or locations. Prediction of the outcome of preventative or ameliorative actions (corrective actions) is generally obtained via modelling of the processes involved in the impact and corrective interactions – as also in the case of the actions shown in Figure 6.

The importance of system status and material performance indicators is evident in the *soil quality indicators* shown in the left-hand side of Figure 5. The list of physical, chemical and biological indicators shown in the diagram is not comprehensive. The specifics of the natural capital component must be considered. The status indicators (1) and (2) accord with monitoring requirements. These are both spatial and temporal in nature and can include more than the numbers shown in the diagrams. Even though true sustainability may not be attained, it is necessary for the objectives and goals for sustainability to be properly articulated. These will serve to establish what, where, how many and how often status indicators will be used or required.

Laboratory research and modeling (transport and fate) are used to evaluate the site material capability and conditions for attenuation. Yong and Mulligan (2004) proposed three main lines of evidence including site conditions, supporting laboratory research and patterns of natural attenuation. The contaminants, soil properties and hydrology, in addition to the regulatory aspects regarding evidence of natural attenuation must all be addressed.

The distribution coefficient k_d obtained from the adsorption isotherms refers directly to a maximum reactive surface reaction process. Equation 1 is obtained if a linear adsorption isotherm is assumed:

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 x}{\partial x^2} - v\frac{\partial c}{\partial x} - \frac{\rho}{n\rho_w}\frac{\partial (k_d c)}{\partial x} \qquad [1]$$

where: c = concentration of pollutants or contaminants of concern, t = time, D_L = diffusion coefficient, v = advective velocity, x = spatial coordinate, ρ = bulk density of soil media, ρ_w = density of water, and n = porosity of soil media.

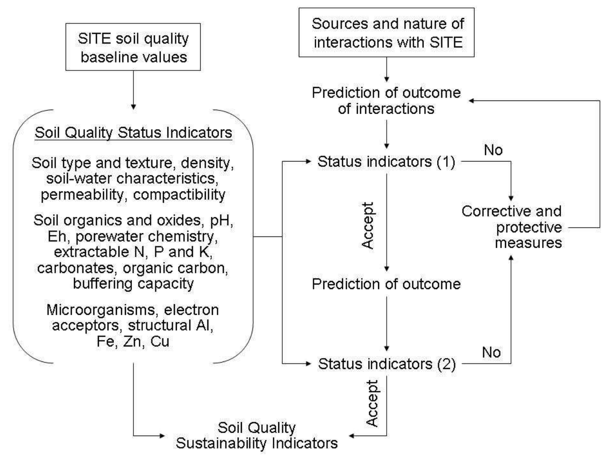

Figure 5. Use of system status and performance indicators.

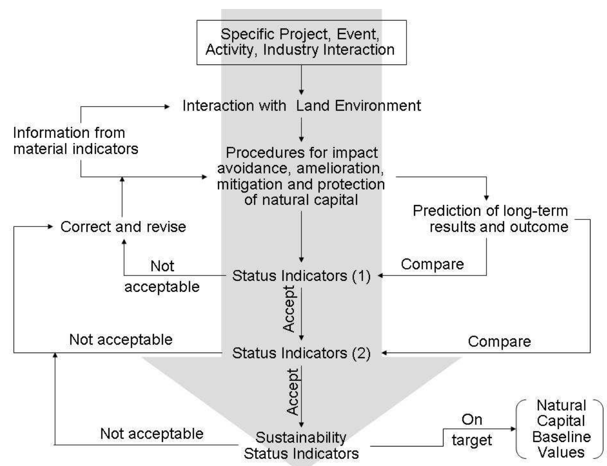

Figure 6. Evaluation of sustainability requirements using indicators

4.1 Chemical Reactions and Transport Predictions

To meet the objectives of sustainability of the terrestrial environment, proper prediction of transport and fate of pollutants requires knowledge of how the abiotic and biotic reactions affect the long term health of the terrain system – especially the subsoil system. From the myriad of possibilities in handling the complex problem of chemical reactions and reaction rates, and transformations, there exist at least four simple procedures that provide some accounting, to a greater or lesser degree, of the various processes controlling transport. These include: (a) the addition of a reaction term r_c in the commonly-used advection-diffusion equation given as Eq. 1, (b) accounting for the contaminant adsorption-desorption process, (c) use of first or second-order or higher-order reaction rates, and

(d) combining transport models with geochemical speciation models..

Addition of a reaction term r_c to Eq.1 is the most common method used to accommodate a kinetic approach to fate and transport modelling. The result is as follows;

$$R\frac{\partial c}{\partial t} = D_L\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x} + r_c$$

R is defined as the *retardation* = $\left[1 + \frac{\rho}{n\rho_w}k_d\right]$ (2)

The use of an adsorption-desorption approach to fate and transport modelling recognizes that in field situations, desorption (or displacement) occurs as part of the ion exchange process. Curve fitting procedures are commonly used to deduce information obtained from batch equilibrium and/or flow-through (leaching column) tests. The Freundlich and Langmuir curves, for example, are specific cases of such procedures.

Prediction and modelling for biotransformation and biodegradation and their effects on fate and transport require a different approach. Yong and Mulligan (2004) have provided an accounting of some of the more popular analytical-computer models used in application of natural attenuation schemes. These in effect are fate and transport models since biotransformation and biodegradation are the primary attenuation processes – a principal feature in fate and transport of organic chemicals. For example, the analytical model BIOSCREEN (Newell et al., 1996) developed for the Air Forces Centre for Environmental Excellence by Groundwater Services Inc. (Houston, TX) assumes a declining source concentration with transport and biodegradation processes for the soluble hydrocarbons that include advection, dispersion, adsorption, aerobic and anaerobic degradation. Most of the available analytical-computer models developed to handle biotransformation and biodegradation in fate and transport modelling have the essential items contained in BIOSCREEN. The principal distinguishing factors between the available computational packages such as BIOPLUME III (Rifai et al. 1997), MODFLOW and RT3D (Sun et al.,1996), BIOREDOX (Carey et al. 1998), and BIOCHLOR (Aziz, et al. 2000), include: (a) structure of the outputs, (b) manner in which degradation is handled, such as order of degradation and degradation rates, (c) types of organic chemicals, (d) inclusion of heavy metals and some other inorganics , (e) availability and types of electron acceptors, and (f) adsorption-desorption.

Solution of the transport relationships shown as Equation 1 and other similar relationships can be achieved using analytical or numerical techniques. For well defined geometries, initial and boundary conditions, and processes, analytical techniques provide exact solutions that can further insight into the processes involved in the problem under consideration. Numerical techniques such as finite difference, finite element and boundary element are useful and are perhaps the techniques favoured by many because of their capability to handle more complex geometries and variations in material properties and boundary conditions.

Abiotic reactions and transformations, together with the biotic counterparts, form the suite of processes that are involved in the transport and fate of contaminants in the subsoil. The reactions between the chemical species in the pore water and also with the reactive soil particle surfaces discussed in the previous sections and chapters constitute the basic platform. Because individual chemical species have the ability to participate in several types of reactions, the equations to describe the various equilibrium reactions can become complicated, particularly when all the reactions are captured.

Geochemical modelling provides a useful means for handling the many kinds of calculations required to solve the various equilibrium reactions. Specific requirements are a robust thermodynamic database and simultaneous solution of the thermodynamic and mass balance equations. Appelo and Postma (1993) provide a comprehensive treatment of the various processes and reactions, together with a user guide for the geochemical model PHREEQE developed by Parkhurst et al. (1980). As with many of the popular models, the model is an aqueous model based upon ion-pairing, and includes elements and both aqueous species and mineral phases (fractions).

Other available models include the commonly used MINTEQ (Felmy et. al. 1984) and the more recent MINTEQA2 that includes PROFEFA2 (Allison et al. 1991), a preprocessing package for developing input files, GEOCHEM (Sposito and Mattigod 1980), HYDROGEOCHEM (Yeh and Tripath 1990), and WATEQF (Plummer et al. 1976). Most of the geochemical codes assume instantaneous equilibrium, partly because reactions such as oxidation-reduction, precipitation-dissolution, substitution-hydrolysis and to some extent, speciation-complexation, can be relatively slow. To overcome this, some of the models have been able to provide analyses that point towards possible trends and final equillibria. The code EQ6 (Delaney et al. 1986) does however provide for consideration of dissolution-precipitation reactions. Transformations however are essentially not handled by most of the codes.

4.2 Organic Chemical Compounds

The various results of transformations and biodegradation of organic chemicals have been discussed in various forms (Yong et al. 2006). The significant outcome of NA as a tool for mitigation of impact is the evidence of occurrence of biodegradation and transformation of the target organic chemicals in the NA process. The *indicators* that need to be prescribed in the LOE relate to specific decreases in concentration of the pollutants and transformations (conversions and biodegradation) of organic chemical pollutants. Determination of the nature and composition of the transformed products of the original organic chemical pollutants is required. Knowledge of the products obtained via abiotic and biotic processes is essential. A good example of this is, for example, recognizing that abiotic transformation products are generally other kinds of organic chemical compounds, whereas transformation products resulting from biotic processes are mostly seen as intermediate products towards mineralization of organic chemical compounds. Biologically mediated transformation processes are the only types of processes which can lead to mineralization of the subject organic chemical compound. Complete conversion to CO_2 and H_2O (i.e., mineralization) does not always occur.

4.3 Metals

At the very least, prescription of the indicators for the lines of evidence in respect to heavy metals requires determination of: (a) the nature and concentration of sorbed metal ions, (b) pore water chemistry including pH and Eh, and (c) the environmental mobility of heavy metals. The environmental mobility of heavy metals is dependent to a very large extent upon whether they are in the pore water as free ions, complexed ions or sorbed onto the soil particles. Prescription of *indicators* for LOE should take into account the assimilative capacity of the subsoil and the nature and fate of the heavy metals in the subsoil. So long as the full assimilative potential of the soil for HM is not reached, attenuation of the heavy metals will continue. Metals that are sorbed onto the soil particles to a large extent by the soil fractions. The various types of soils and their different soil fractions have different sorption capacities, dependent on the nature and distribution of the heavy metals and pH of the system.

Precipitation of heavy metals as hydroxides, sulphides and carbonates generally classify as part of the assimilative mechanism of soils because the precipitates form distinct solid material species, and are considered as part of the attenuation process. Sequential extraction can thus be used to evaluate the capability of the soil to retain the heavy metals as shown in Figure 7. The weaker bound exchangeable fractions of zinc and lead have already leached out whereas the stronger bound oxide and organic fractions remain. Acid rain, however, could enhance the solubilisation of the oxide fraction.

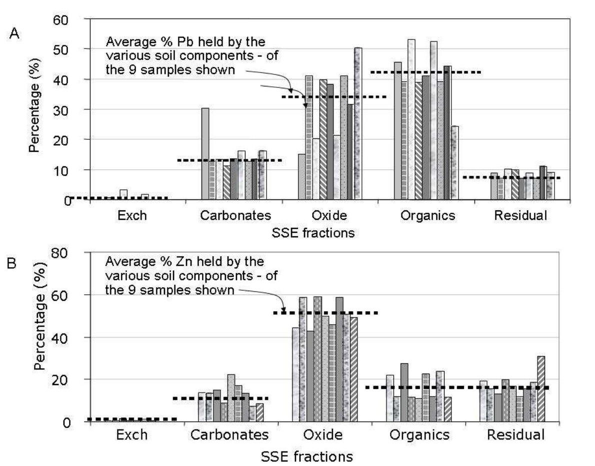

Figure 7. Selective extraction characterization of (A) Pb and (B) zinc (Huang, 2005)

5 EVIDENCE OF SUCCESS

Evidence of success (EOS) is a requirement specified by Yong and Mulligan (2004) as testimony to the success of utilization of NA as a tool for remediation of contaminated sites. Whilst monitoring is required in the application of MNA, there is a need to have knowledge of whether the “signs and signals” registered in the monitoring programme testifies to a successful MNA treatment programme. In essence, EOS takes the role of *indicators* of success or steps towards success by MNA in remediation of contaminated sites.

With the same rationale, EOS can be used in impact mitigation and management programs. Figure 6 shows the basis for determining whether NA can be successfully used as an impact mitigation and management tool. The first two levels of protocol are similar to the MNA steps. At the third step or level, a clear knowledge of the kinds of impact, and mitigation and management requirements need to be determined. These are combined with information from laboratory tests that are designed to provide the kinds of information necessary to determine material parameters and interaction processes. Supporting predictions on fate and transport are necessary pieces of information. All of these provide the tools to determine whether NA can be successfully used to meet the requirements for impact mitigation and management. Negative responses will require that NA be rejected as a tool, or used in conjunction with other technological tools to provide the necessary impact mitigation and management solution.

A positive response will require structuring implementation procedures and strategies in combination with an appropriate monitoring scheme to track progress and determine the sustainability of the natural attenuation processes. A very necessary part of the implementation scheme is the specification or prescription of *success indicators* shown in the ellipse at the bottom right-hand corner of Figure 8. These indicators also serve as markers for performance assessment of the impact mitigation scheme. Since the time required for processes contributing to the natural attenuation to fully complete their functions can be extensive, it is necessary to prescribe intermediate indicators as tracking indicators and as performance assessment markers.

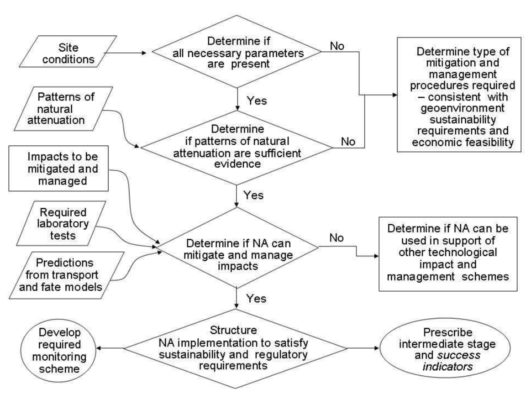

Figure 8. Tool for evaluating the sustainability of NA for sustainable mitigation and management of a site.

Monitoring and sampling of pore water and soils are needed in the contaminant attenuation zone. The choice of type of monitoring wells and sampling devices and their spatial distribution and/or location will depend on the purpose for the wells and devices. At least three separate and distinct monitoring-sampling schemes need to be considered:

- Initial site characterization studies. Site characterization monitoring and sampling provide information on site subsoil properties and hydrogeology.
- Verification monitoring – this requires placement of monitoring wells and soil sampling devices within the heart of the pollutant plume and also at positions beyond the plume.
- Long term conformance monitoring. This is essential to verify success of mitigation scheme and for long term management of the potential impact.

Analyses of samples retrieved from monitoring wells will inform one about the concentration, composition, and toxicity of the target pollutant. Knowledge of the partition coefficients and solubilities of the various contaminants, together with the monitoring well information will provide one with the opportunity to check the accuracy of predictions from transport-fate models. For organic chemicals detected in the monitoring-sampling programme, laboratory research may be required to determine the long term fate of the transformed or intermediate products and the availability of the appropriate microorganisms, essential nutrients, co-factors and electron donors. This is not a necessary requirement if modelling predictions and especially if the *indicators* for the intermediate show good accord with the sampling values of pollutant concentrations. Tests on recovered soil samples from the sampling programme should determine the environmental mobility of the pollutants and also the nature and concentration of pollutants sorbed onto the soil particles (soil solids). Detailed discussions of many of the bonding mechanisms and their reactions to changes in the immediate environment have been developed in Yong et al. (2006).

6 CASE STUDY

In a case study, a former oil refinery was converted to a business and recreational opportunity in Casper, Wyoming (Applegate et al. 2005). The refinery had operated since the early 1900's but closed in 1991 due to environmental liabilities. The cost of the site remediation was estimated at $350 million US. Various risk assessments were undertaken. To protect the river and remediate the groundwater, a horizontal wall for air sparging and venting was designed and installed, in addition to a sheet-pile barrier wall. Pipes were also removed to eliminate the pollution source. Final remediation strategies included: (a) removal of sediment from the lake, (b) removal of tanks, pipes, concrete and other material from the refinery area. Cleaning of the groundwater involved oil recovery, sparging, venting, phytoremediation, and monitored natural attenuation in the refinery and tank farm areas. All concrete (nearly 272,000 tonnes) that was removed was crushed for reuse at the site and most of the pipes were sent to recyclers. Concrete was recycled for: (a) use as drainage in the water treatment system, (b) construction of a barrier that prevented animals from entering the waste depository near the lake, and (c) construction of roads. It is estimated that oil recovery at the site will take approximately 25 years – on the basis of analysis of the mobility of the oil strongly adsorbed to the alluvium. Due to the construction of a golf course, oil recovery wells had to be designed so that they would not be placed in the fairways and greens.

Water at the site was also to be reused. Therefore a system was set up that included management of the storm water, irrigation of the golf course, and pumping of the water into the lake for the migratory birds. The water management system, shown in Figure 9, can handle between 1890 to 5670 L/min. It is mainly hidden and integrated in the golf course. A kayaking course will also be placed in the river.

6.1 Sustainability Indicators – Observations and Comments

From a land use sustainability perspective, the remediation of the contaminated site with MNA in this example and use of recycled materials, it appears that improved land use has been obtained. The remediation-rehabilitation plan provides opportunities for prescription of indicators for sustainability. It appears that site restoration will be performed that will return the site to conditions and usage beyond initial sandy beach conditions. From a land use stand point, the remediation-rehabilitation scheme is a positive step. However, ultimate sustainability would lead to the restoration of species biodiversity at the site.

7 CONCLUSIONS

In conclusion, natural attenuation can be used as a tool for the mitigation and management of contaminant due to the capability for contaminant and toxicity reduction. For pollutants that can partition between the aqueous phase and the soil solids in the subsoil system, we have well-developed advection-diffusion transport models that can address the problem. The pitfalls in implementation of such models include the availability of appropriate and realistic input parametric information (especially partition and distribution coefficients), and chemical reactions that affect the status of the pollutants in the system.

The use of geochemical speciation modeling allows one to determine these reactions. However, since kinetic reactions are not readily handled in the present available geochemical models, and since most of these models are not coupled to the regular transport models, much work remains at hand to obtain a reactive prediction model that can tell us about the fate and transport of pollutants in the subsoil system. Present research into coupling between geochemical models and advection-dispersion models has identified the complex and highly demanding computational requirements for a coupled model. Nevertheless, a realistic reactive coupled model is needed if we are to reach the stage where knowledge of the fate and persistence of pollutants in the subsoil system is to be obtained.

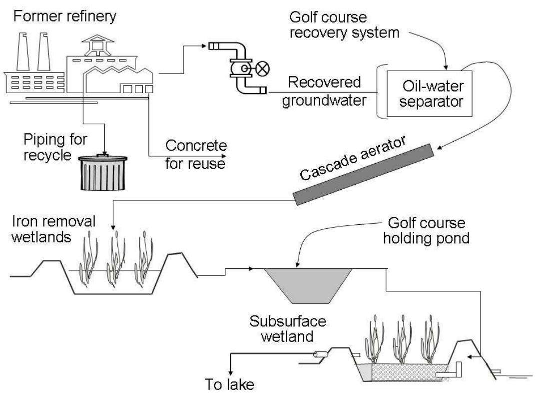

Figure 9. Recovered groundwater treatment at a former refinery and tank farm (adapted from Applegate et al. 2005)

Natural attenuation can subsequently be integrated into sustainable land redevelopment schemes. If the goals and objectives of the remediation plan cannot be met by natural attenuation, as a passive approach, then a more active approach in combination with pre- or post-treatment treatments at a site may be necessary.

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