Modelling of Remediation Technologies at the Performance Assessment Level – 8030

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ABSTRACT

This paper presents approaches to modelling three different remediation technologies that are designed to support site operators during their assessment of remediation options for the management of radioactively contaminated land on nuclear licensed sites in the UK. The three selected technologies were soil washing, permeable reactive barrier and in-situ stabilisation. The potential exists to represent electrokinetics in the future. These technologies were chosen because it was considered that enough information already existed for site operators to assess mature technologies such as soil dig and disposal and groundwater pump and treat. Using the software code GoldSim [1], the models have been designed to allow site operators to make both a reasonable scoping level assessment of the viability of treatment and understand the cost-benefits of each technology.

For soil washing, a standard soil leaching technique was simulated whereby the soil is separated into fines and oversize particles, and subsequently a chemical reagent is used to strip contamination off the soil. The cost benefit of this technology in terms of capital costs for the plant and materials, operational costs and waste disposal costs can also be assessed.

The permeable reactive barrier (PRB) model can represent either a continuous wall or a funnel and gate system. The model simulates the transport of contaminants through the reactive material contained in the PRB. The outputs from the model include concentration of contaminants in the groundwater flow downstream of the PRB, mass of contaminants retained by the PRB, total mass and volume of waste and the various costs associated with the PRB remediation technology.

The in-situ stabilisation (ISS) model has the capability to represent remediation by the addition of reagents that immobilise contaminated soil. The model simulates the release of contaminants from the treated soil over time. Performance is evaluated by comparison of the mass of contaminants retained and released to the area outside the treatment zone. Other outputs include amount of spoil generated (to be treated as waste) and the costs associated with the application of the ISS technology.

These models are aimed to help users select a technology or technologies that are potentially suitable for a particular site. It is anticipated that they will prompt the user to undertake more detailed assessments to tailor the selected technology to their site specific circumstances and contaminated land conditions.

INTRODUCTION

The majority of civil nuclear licensed sites in the UK are nearing the end of their operational lives and entering the decommissioning phase of their lifecycles. On these sites, land contaminated by nuclear and historical (non-nuclear) land-uses may pose a significant hazard to present day and future environmental receptors. If an assessment has shown that there are significant risks that must be managed, then in some cases, the Best Practicable Environmental Option (BPEO) for managing the risks may involve the use of remediation technologies. Remediation technologies may assist in reducing the potential risk posed to environmental receptors by reducing the degree of contamination on the sites whilst also reducing the volume of radioactive and non-radioactive waste requiring further treatment or disposal.

In the UK on nuclear licensed sites controlled by the Nuclear Decommissioning Authority (NDA), site licence companies must select viable and cost effective technologies to manage any risks posed by radioactively contaminated land. A wide range of technologies are available to potentially remediate radioactively contaminated land. A key initial step in the management of radioactively contaminated land is the screening of a wide range of technologies to produce a limited list of options that may be viable and cost-effective, given the type, concentration and volume of contamination and the site setting. Feasible options may then be evaluated in detail to develop cost-effective solutions that will form part of contaminated land management strategies for the site.

This study focuses on providing site operators with tools that support the screening of generic technologies. The tools cover a range of remediation technologies at a performance assessment level, to enable site operators to assess the potential suitability of a technology. These simple performance assessment models were designed to enable users to efficiently assess whether each technology is feasible for a particular contaminated land scenario and to calculate likely associated costs. These tools have been deliberately designed to be as simple as possible to enable them to be used with minimal site information, conducive to use within screening level evaluations. To date, models have not been prepared for certain widely used remediation options such as dig and disposal and groundwater pump and treat. These are regarded as mature technologies for which site operators may already be able to obtain sufficient information.

The technologies selected for representation at the performance assessment level were: soil washing, permeable reactive barrier and in-situ stabilisation. Each of these technologies was simulated at the performance assessment level using the GoldSim software and each of the models is available for use using the free GoldSim Player software [2].

REMEDIATION TECHNOLOGIES

The overall aim of the project of which this is study is a part was to increase the availability of data and decision support tools for remediation technologies, encouraging a wider range of cost effective technologies to be considered in contaminated land management strategies. The technologies selected for this study were selected on the basis of a review of the range of likely radioactive contaminants, their volumes, concentrations, cost of implementation and the environmental conditions associated with nuclear licensed sites that are the responsibility of the NDA.

On this basis, technologies such as pump and treat, standard particle separation/soil washing and dig and disposal options have not been considered as a great deal of information exists already to support site operators. Some technologies such as in-situ vitrification and the use of supercritical fluids have been used on specific sites but were considered to need a reasonable amount of development in order to produce a larger matrix of data (for instance of soil and contamination types) and more on-site demonstrations than existed to date in order for this study to justify their inclusion.

However, chemically enhanced soil washing, permeable reactive barrier and in-situ stabilisation were considered as technologies that with a relatively small amount of development work could lead to increased consideration of the technologies within radioactively contaminated land management strategies on nuclear licensed sites. Performance data for these technologies are being experimentally studied within the wider project of which this study is a part. The work reported in this paper is the development of an initial set of optioneering support tools. This first iteration of tools will inform the experimental studies of the key parameters and processes that should be studied. On the conclusion of experimental studies these tools will be updated on the basis of the results from the experimental studies.

PERFORMANCE ASSESSMENT MODELLING

Performance assessment modelling refers to the level of modelling commonly undertaken to allow complex decisions to be made and supported. In the context of contaminated land, this level of modelling is typically able to assess the migration of soil and groundwater contamination and its impact on potential receptors through the representation of basic environmental effects and processes such as solubility limits, retardation, decay, advection and diffusion. In some cases this level of modelling is supported by detailed underpinning codes which are specifically designed to represent sophisticated processes such as microbial degradation, gas generation and other biogeochemical effects. The overall effects of these detailed models and/or processes are often simulated at the performance assessment level, sometimes probabilistically, to allow for robust decisions to be made.

Various commercially available performance assessment modelling software tools exist on the marketplace. GoldSim was selected for use here as it is flexible enough to allow a wide variety of processes to be represented whilst allowing for a simple model to be constructed for use by decision makers not from an environmental modelling background. GoldSim is also unit and dimensionally aware and automatically performs conversions (*e.g.* kg to tonne or litres to m^3).

REMEDIATION TECHNOLOGY DEMONSTRATORS

Soil Washing

Soil washing is an ex-situ technology applied to excavated contaminated soils and can be sub-divided into 3 techniques [3]:

i. **Standard Soil Washing:** fine soil particles have a greater surface area-to-volume ratio than the equivalent coarse (or ‘oversize’) particles. Consequently contamination tends to accumulate more in the ‘fines’ fraction than in any other part of the soil. Standard soil washing uses this property and employs adapted minerals processing techniques to separate the ‘fines plus contaminants’ from the rest of the soil components. For non-nuclear applications of soil washing, the coarse fractions (gravels and sands) are sold as by-products and the fines fraction only disposed of as contaminated waste. Clean fill is imported to backfill the excavated volume.

ii. **Standard Soil Leaching:** soil leaching is the chemical equivalent of standard soil washing. A chemical leaching agent (or ‘reagent’) is used to remove the target contaminants from the soil particles. Leaching agents include mineral acids or alkalis, and contaminant specific leachants such as carbonates for uranium ions. Standard soil leaching employs adapted mineral processing techniques used for ore processing to recover the contaminants into the leachant solution. Depending on the concentrations of the contaminants, they are then recovered as a by-product or removed from the spent leachant for separate disposal. Depending on the effects of the leachant and its residual concentration in the leached soil, the treated soil is either returned as backfill or sent for disposal as more lightly contaminated material.

iii. **Enhanced Soil Washing:** soil washing combines the advantages of standard soil washing with those of soil leaching. The spent leachant is used to provide the physical separation of the fines fraction, and fresh leachant used to extract the contaminants from the contaminated fines. As a consequence, the fines can be recombined with the coarse fractions and the whole soil can be returned as backfill. This also removes the need for importation of clean fill onto the site. Unlike standard soil leaching, soil washing uses a multi-component leachant that is less aggressive than the harsh acids or alkalis.

Version 1.0 of this model was designed to represent the fundamental nature of this type of technology at the performance assessment level in order to demonstrate that it is possible to model this technology in this way and to provide a set of key data requirements for further research. The basic costs associated with this technology were also represented in order that a total cost of remediation could be derived.

The first version model developed represents ‘standard soil leaching’ using the simplified process outlined in Figure 1. The generic term ‘soil washing’ is applied to this demonstrator model here.

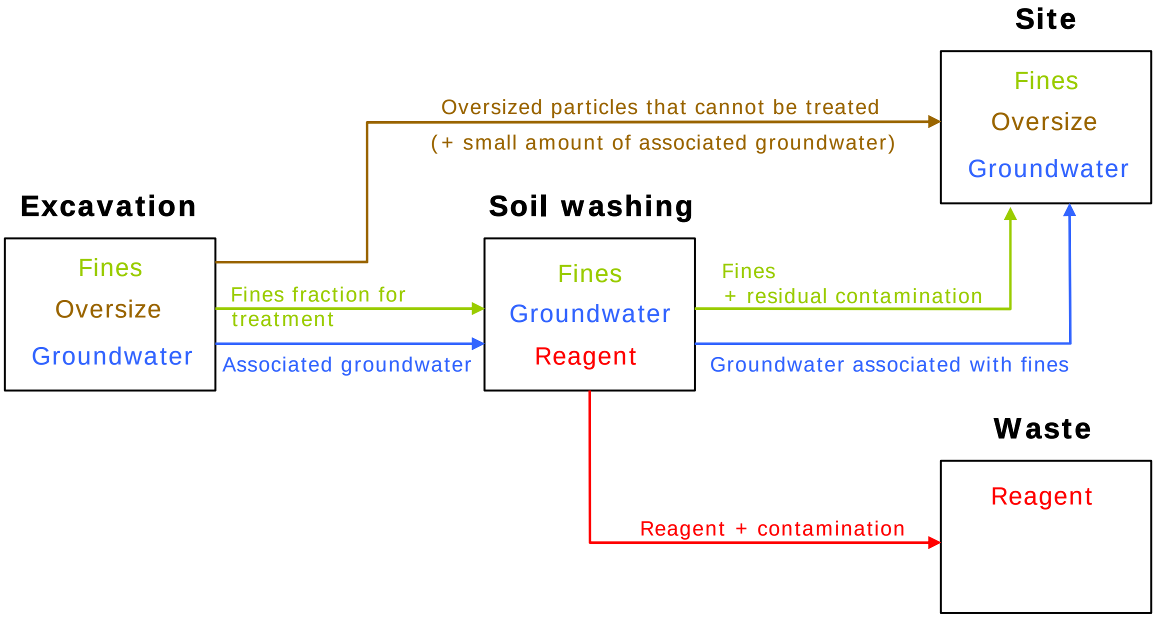


Figure 1. Simplified soil washing process.

The potential exists to extend this work in the future to provide a more complete and robust model, incorporate further cost elements and to possibly extend the functionality to include Enhanced Soil Washing (*e.g.* recycling of reagent).

Figure 1 outlines the simplified soil washing process represented in the GoldSim model developed here. Several key process are represented at 4 stages:

i. **Excavation:** contaminated soil is excavated from the site and separated into fines (silt/clay, less than 63μ) and oversize fractions. A quantity of groundwater is assumed to be associated with both. The oversize material (and associated groundwater) is not treated and is returned to the site as infill.
ii. **Soil Washing:** the fines fraction (and associated groundwater) enters the soil washing stage where it is mixed with a reagent. The reagent 'leaches' a proportion of the contamination off the fines material. The proportion of contamination removed from the fines and accumulated by the reagent is controlled by the partitioning of the contamination between groundwater, fines and reagent materials. The lower the fines partition coefficients are and the stronger the partitioning of contamination from groundwater to reagent, the more effective the soil washing will be.
iii. **Site:** the treated fines, oversize material and associated groundwater are all sent back to site as infill.
iv. **Waste:** the reagent introduced at the soil washing stage is extracted along with the accumulated contamination and removed from the site as waste.

Overall and at each of the above stages, there are costs associated with this remediation technique. In this model, these are assumed to be:

- Plant capital cost (£).
- Materials capital cost (£).
- Plant operational unit cost (£/day).
- Reagent treatment (or disposal) unit cost (£/m^3).

These simple assumptions allow an overall cost for the technique to be derived once the user has predicted and entered the duration (days) of the remediation.

In order to represent a soil washing technology efficiently at the performance assessment level, it is necessary to make a series of assumptions. These assumptions are a mixture of simplifications for ease of modelling, necessary simplifications due to the capability of the GoldSim software and time/budgetary constraints. The following assumptions were made:

- The excavated soil is fully saturated throughout its pore space.
- There are no adhered fines within oversize material.
- Radioactive decay and ingrowth are not important over the timescale of remediation (365 days by default). No half-lives are specified by default as it is not considered likely that any radionuclides requiring remediation would have half-lives of less than several years (*i.e.* several times longer than the default model duration). This is considered a reasonable assumption for radionuclides with a half-life >10 years. It is considered unlikely that radionuclides with shorter half-lives would be targeted for remediation.
- The user is responsible for selecting the most appropriate soil partition coefficients taking into account contaminated (feed) soil and groundwater concentrations.
- The only waste produced is contaminated reagent.
- All the groundwater, oversize and fines excavated from the site are returned as infill.
- No clean infill is imported to the site.
- The reagent is not recycled.
- The reagent disposal costs are purely a function of volume of reagent and do not account for the levels of contamination in the reagent.
- Contaminants are not solubility limited by default. This is not considered to be an unreasonable assumption given the low molar concentrations of radionuclides likely to be encountered.
- Contaminants are not volatile.
- Fines and oversize fractions of the soil share the same partition coefficients and are initially contaminated to the same degree.
- The overall efficiency of the technology is a mean function of the individual contaminant concentrations in the infill returned to site (fines and oversize) compared with the excavated soil unit contaminant concentrations (and is not a function of cost).

It is intended to re-visit some or all of the above assumptions in future versions of the model.

The costs associated with this remediation technique are calculated using user provided basic cost data for the capital cost of the plant, capital cost of the materials, plant operational cost per day and the reagent treatment or disposal cost (per m^3) via the 4 data elements. The plant operation cost and the reagent treatment or disposal costs are multiplied by the remediation duration to calculate a total cost for each. A sum element then adds all the total costs together to provide an overall cost which is displayed on the dashboard.

To demonstrate the capability of the soil washing model, a trial run using arbitrary values was undertaken. The model contained two contaminants (A and B). Key input values were:

- Feed soil concentrations of 1000 and 500 mg/kg (respectively).
- Feed groundwater concentrations of 650 and 300 mg/l.
- Soil partition coefficients of 20 and 10 m^3/kg.
- Both contaminants not solubility limited.
- Reagent partition coefficients of 500 and 100 (dimensionless).
- Duration of 365 days.
- Total mass of soil: 100,000 tonnes.
- Proportion of fines: 25%.
- Porosity of fines: 0.2.
- Porosity of oversize material: 0.5.
- Bulk density of fines: 1200 kg/m^3.
- Bulk density of oversize: 1800 kg/m^3.
- Plant capital cost: £1 million.

- Materials capital cost: £50,000.
- Plant operational cost: £100/day.
- Reagent treatment unit cost: 10 £/m^3.
- Reagent injection rate: 50 m^3/day.

The results of the model showed that the reagent is not powerful enough to strip a lot of contamination of the fines, with an overall efficiency of just 2.41% costing a total of £916,500. Re-running the model with a more powerful reagent would increase the efficiency of the remediation, however the model was found to be far more sensitive to the effects of soil partition coefficients. Reducing the soil partition coefficients by similar order of magnitude as increases in reagent partition coefficients results in a much high overall effectiveness. The model therefore suggests that this remediation technique is potentially more suited to inert soil types such as those consisting of high proportions sands and gravels.

Permeable Reactive Barrier (PRB)

PRB remediation is an *in-situ* process, defined as "an engineered treatment zone of reactive material(s) that is placed in the subsurface in order to remediate contaminated fluids as they flow through it" [4]. Thus, PRBs are used to prevent contaminants from spreading, usually through an aquifer.

Due to natural hydraulic gradients, contaminants are transported through the reactive material where a range of physical, chemical or biological processes can be used to degrade, sorb, precipitate or remove the contaminants from the groundwater. The contaminants are then retained within the reactive zone itself. Redox reactions and sorption or substitution reactions (e.g. with the use of zero valent iron) are examples of treatment methods applied within the reactive medium to remove contaminants from the groundwater [5].

PRB design can be categorised into three main configurations [6]:

i. **Continuous Wall:** this technique involves the insertion of a wall containing the reactive medium into a trench that intersects the contamination plume(s). The wall is simple to install and has reactive material along its entire length, making it difficult for groundwater to bypass the reactive zone. Maintenance and recovery of the spent material is difficult with this type of PRB. However, it is still the favoured configuration in the USA.

ii. **Funnel and Gate:** groundwater is channelled through a central permeable zone or 'gate' by means of impermeable cut off walls (a funnel) either side of the gate. This permits maintenance and recovery of the spent material. The installation process is more complex than that of the continuous wall, due to the requirement that the funnel is sealed into the reactive zone and it is not bypassed. The technology is also subject to patents where zero valent iron is used in the reactive media. This configuration is, however, more widely used in Europe than the continuous wall.

iii. **Drain and Gate:** groundwater is captured via a funnel and/or a permeable trench and fed into a purpose built drain where the reactive material is held in tanks. The groundwater passes through the reactive material in the same way as it passes through the gate in the funnel and gate system, but can also be driven by additional external pumping. Other advantages over the funnel and gate system are that the drain system can be isolated by using non-return valves, it can be taken offline to replace spent material, the reactive material used can be varied with time and the funnel walls can be arranged so that they surround the contamination source. The increased design complexity will, however, increase costs.

Version 1 of this model is aimed at representing the technology behind PRB remediation in order to derive a performance assessment and cost analysis of the remediation. The first version model developed has the capability to represent either a continuous wall or a funnel and gate system, depending on the user inputs. In both cases, the reactive material has associated user specified removal efficiencies for each of the contaminants to be treated.

Future iterations of this model could aim to represent the removal efficiencies of specific reactive materials for specific contaminants, thus allowing the user to assess the effectiveness of the remediation process with a range of reactive materials present in the gate. In addition, representation of a pumped system such as the drain and gate configuration could be included, as well as the option for maintenance, replacement or variation of the reactive material.

Figure 2 outlines the permeable reactive barrier remediation process to be assessed in the GoldSim model developed here. The process is represented in 4 stages:

i. **Contaminant plume:** the contaminants occupy a specific volume of soil and an associated volume of groundwater. Groundwater flow upstream carries the plume of contaminants towards the permeable reactive barrier.
ii. **Remediation in PRB:** the dimensions of the gate (and funnel) determine the effective plume capture area of the PRB. The fraction of the plume captured for treatment by the PRB is then calculated by the dimensions of the plume relative to the effective capture area. Contaminant removal in the PRB is calculated using percentage removal efficiencies.
iii. **Downstream groundwater flow:** Groundwater flow that is not captured by the PRB, along with the out-flowing groundwater from the PRB, accumulates downstream.
iv. **Waste:** the reactive material in the gate along with the retained contaminants is excavated and treated as waste.

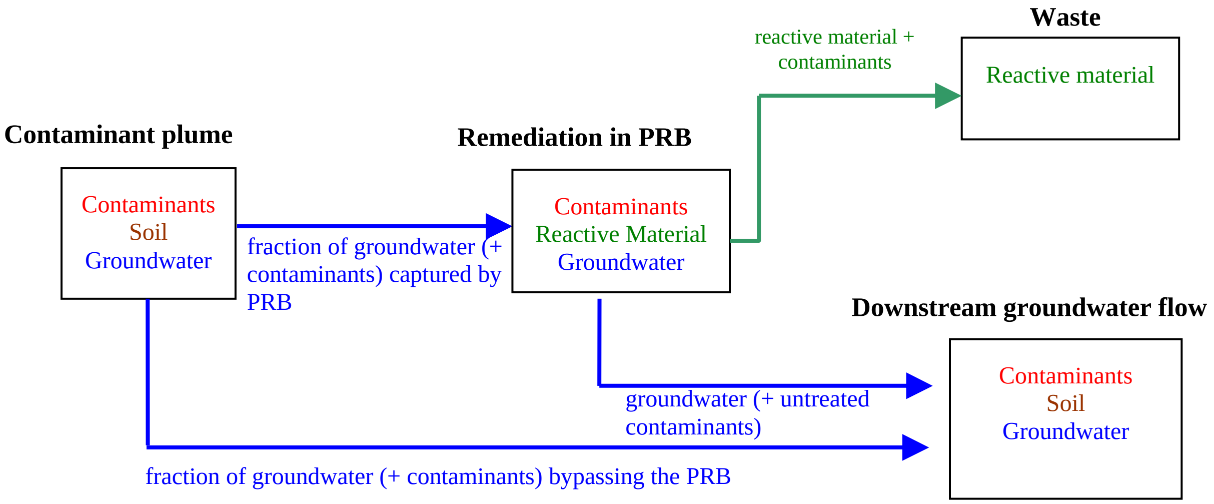


Figure 2. Simplified PRB remediation process.

The costs associated with the remediation technique are simplified in this model and are assumed to be:

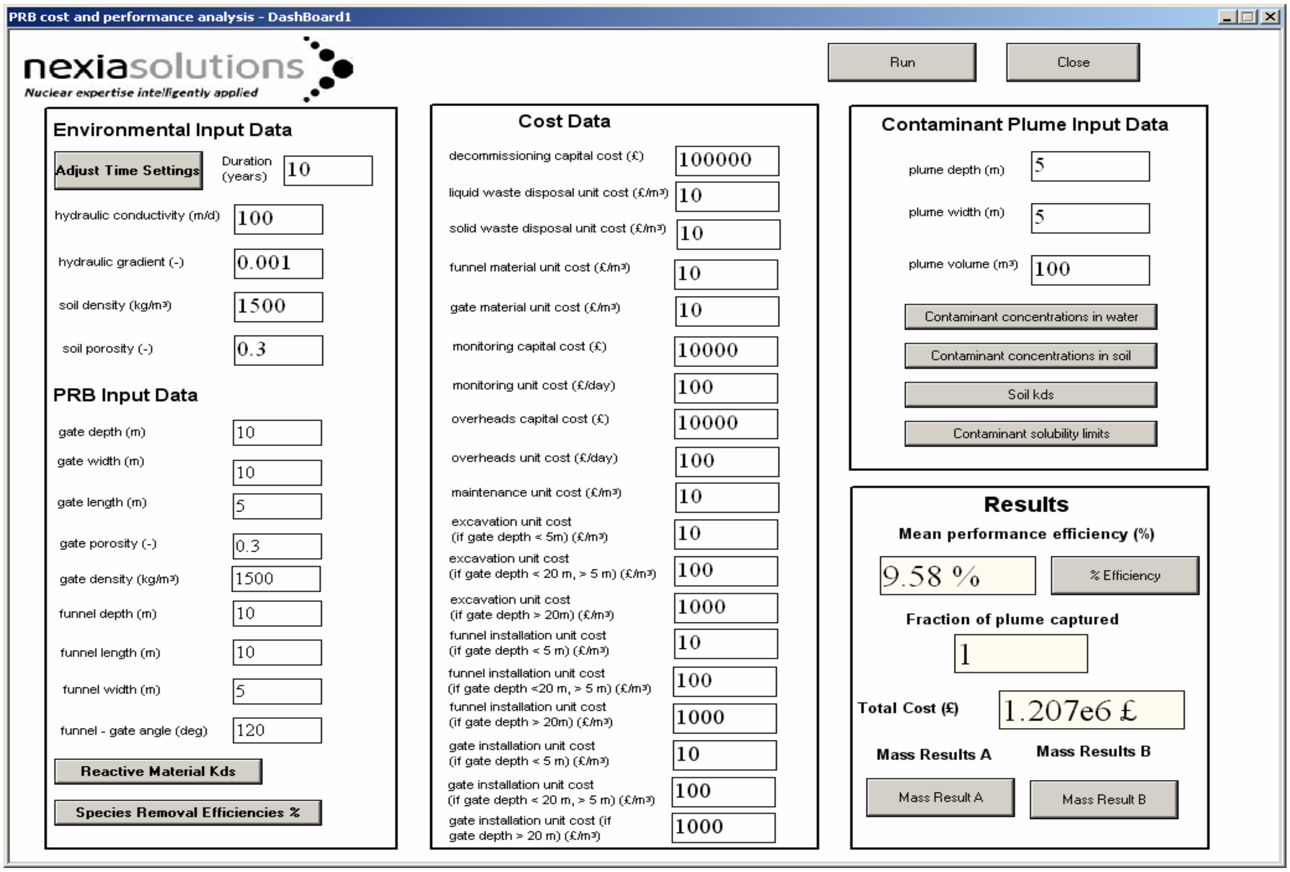
- Excavation unit cost (£/m^3).
- Gate (and funnel) materials unit cost (£/m^3).
- Gate (and funnel) installation unit cost (£/m^3).
- Maintenance unit cost (£/day).
- Monitoring capital cost (£) and unit cost (£/day).
- Overheads capital cost (£) and unit cost (£/day).
- Reactive material treatment (or disposal) unit cost (£/m^3).
- Decommissioning capital cost (£).

User inputs for these parameters along with the predicted duration (days) for the remediation and the PRB volume (m^3) can be input to the GoldSim Player model via the “dashboard” facility and allow an overall cost for the technique to be derived.

A series of assumptions has been made in order to efficiently represent the PRB remediation technology at the assessment level. These assumptions are simplifications that are necessary due to the capability of the modelling package, time/budgetary constraints or for general ease of modelling. These assumptions can be revisited in later versions of the model. The assumptions made for version 1.0 are:

- The soil in the contaminant plume is fully saturated throughout its pore space.
- Contaminants are not solubility limited by default.
- Contaminants are not volatile.
- The fraction of the contaminant plume that flows through the reactive material is proportional to the ratio of the cross sectional area of the contaminant plume to the effective capture area of the gate (and funnel). It does not take into account any effect of groundwater flow within the vicinity of the PRB. The cross sectional area of the contaminant plume is assumed to be ellipsoidal and is calculated from the plume depth and width.
- Groundwater flow is a function of the capture area of the PRB and is assumed to be constant throughout the model.
- The excavation volume required for installation of the PRB is equal to the volume occupied by the PRB.
- The unit cost of excavation and PRB installation and is a function of the depth of the gate. The unit costs for each specified gate depth range must be input by the user.
- The reactive material disposal costs are a function of the volume of reactive material and do not account for the levels of contamination in the material. No additional costs are added for excavation and gate removal. If the reactive material is to be left *in situ*, user inputs for the cost of disposal and decommissioning should be zero.
- The removal of contaminants by the reactive material in the PRB is represented by a percentage removal efficiency for each individual contaminant.
- The overall efficiency of the technology is a mean function of the individual contaminant mass removed from the plume compared to the initial contaminant mass in the plume at the start of the simulation, and is not a function of cost.
- The groundwater bypassing the PRB is assumed to join the outflow from the PRB in the overall downstream flow. The total mass of contaminants from these two flows is then considered in the calculation of the PRB efficiency.

A trial run of the PRB remediation technology GoldSim model version 1.0 has been undertaken to demonstrate its capability. Figure 3 shows the key input values selected via the GoldSim dashboard. The model contains two contaminants (A and B). The key values associated with these contaminants that are not shown on the dashboard are initial concentration in water; 800 and 500 mg/l, concentration in soil; 350 and 150 mg/kg, soil *kd*s; 3 and 2 m^3/kg, reactive material *kd*s; 3 and 2 m^3/kg and the removal efficiencies in the reactive material; 50 and 30 % respectively.



Environmental Input Data

Duration (years) 10
hydraulic conductivity (m/d) 100
hydraulic gradient (-) 0.001
soil density (kg/m³) 1500
soil porosity (-) 0.3

PRB Input Data

gate depth (m) 10
gate width (m) 10
gate length (m) 5
gate porosity (-) 0.3
gate density (kg/m³) 1500
funnel depth (m) 10
funnel length (m) 10
funnel width (m) 5
funnel - gate angle (deg) 120

Cost Data

decommissioning capital cost (£) 100000
liquid waste disposal unit cost (£/m³) 10
solid waste disposal unit cost (£/m³) 10
funnel material unit cost (£/m³) 10
gate material unit cost (£/m³) 10
monitoring capital cost (£) 10000
monitoring unit cost (£/day) 100
overheads capital cost (£) 10000
overheads unit cost (£/day) 100
maintenance unit cost (£/m³) 10
excavation unit cost (if gate depth < 5m) (£/m³) 10
excavation unit cost (if gate depth < 20 m, > 5 m) (£/m³) 100
excavation unit cost (if gate depth > 20m) (£/m³) 1000
funnel installation unit cost (if gate depth < 5 m) (£/m³) 10
funnel installation unit cost (if gate depth <20 m, > 5 m) (£/m³) 100
funnel installation unit cost (if gate depth > 20m) (£/m³) 1000
gate installation unit cost (if gate depth < 5 m) (£/m³) 10
gate installation unit cost (if gate depth < 20 m, > 5 m) (£/m³) 100
gate installation unit cost (if gate depth > 20 m) (£/m³) 1000

Contaminant Plume Input Data

plume depth (m) 5
plume width (m) 5
plume volume (m³) 100

Results

Mean performance efficiency (%) 9.58 %
Fraction of plume captured 1
Total Cost (£) 1.207e6 £
Mass Results A
Mass Results B

Figure 3. GoldSim Player Dashboard and inputs for demonstrator model trial run.

The results of the model show that the capture area of the funnel and gate is big enough to capture the whole plume. However, the overall mean efficiency of the PRB is 9.58 % which indicates that the model has not been run long enough to allow the entire contaminant plume to flow through the gate. If the simulation duration is increased from 10 years to 20 years, the PRB efficiency is increased to 16.8 %.

The model results are also particularly sensitive to the soil *kd*s, the reactive material *kd*s and the groundwater flow (which depends on hydraulic conductivity and hydraulic gradient). The inputs for these parameters should therefore be carefully considered so that the model is a true representation of the situation to be assessed.

In-situ Stabilisation (ISS)

In-situ immobilisation as a technology covers a wide variety of techniques that rely upon solidification or stabilisation processes [7]. Stabilisation involves the addition of reagents to a contaminated material to produce more chemically stable constituents. Solidification involves the addition of reagents to a contaminated material to impart physical/dimensional stability to contain contaminants in a solid product and reduce access by external reagents. This paper uses the term in-situ stabilisation or ISS, to encompass both of these processes.

Key to the success of the ISS remediation technology is the use of binders (reagents and additives) used in the process. Binder materials are delivered to the soil to be treated by way of an emplacement technique, typically, near surface mixing (rotovation) or by use of modified augers. ISS can be described on the basis of binder type, which can cover a wide range of substances applicable to different contaminants and desired end points. Three categories of binders used for ISS [8] in order of importance:

- Hydraulic binders (variants of Portland cement, variants of lime and proprietary additives).
- Organic binders (bitumen, asphalt and polyethylenes).

- Others (apatite and applications of clays such as illites and bentonites).

Hydraulic binders require reaction with water to enable solidification of the binder. Both chemical reactions with the contaminants (stabilisation) and encapsulation processes (solidification) occur. Organic binders typically perform by encapsulating contaminants (solidification) and do not bind to contaminants. A typical example for the remaining binder category is to use apatite as a source of phosphate that induces inorganic phosphate precipitation (stabilisation).

Version 1.0 of the ISS remediation technology demonstrator model was designed to represent the fundamental nature of this type of technology at the performance assessment level in order to demonstrate that this is possible and to provide a set of key data requirements for further research. The basic costs associated with this technology were also represented in order that a total cost of remediation could be derived. The version 1.0 model is capable of simulating effects of this remediation technology on groundwater flow, sorption and solubility properties of contaminants.

The first version model developed represents the impact of in-situ stabilisation when applied to contaminated land using the simplified process outlined in Figure 4. The generic term ‘soil treatment’ is applied to this demonstrator model. The ISS process is represented in 6 stages:

1. **Contaminant transport in untreated soil:** the contaminant plume occupies a specific volume of soil and an associated volume of groundwater. Groundwater flow upstream and infiltration from rainfall has the potential to transport the contaminants to the downstream area of soil (not contaminated). Soil properties (porosity, density and hydraulic conductivity) are characteristic to that of untreated soil. Contaminant properties describing mobility and solubility are characteristic to those in untreated soil.
2. **Remediation by ISS:** the full volume of the contaminated zone is treated by addition of a binder material or materials. The intention of treatment is that groundwater has a reduced potential to transport contamination outside the treated area. This is achieved by changing soil properties and contaminant specific properties at the time of remediation.
3. **Transport in treated soil:** soil properties are altered to those of the treated soil. Contaminant properties describing contaminant mobility are altered to those of in treated soil. General hydrological conditions (rainfall and hydraulic gradient) remain unchanged.
4. **Release of contaminants to downstream area:** an arbitrarily large volume of soil is considered as a ‘sink’ to receive all groundwater flowing from the contaminated area and thus representing a potential receptor for contaminants. This volume of soil is assumed to be uncontaminated at the time when remedial action is taken. Soil and contaminant properties are the same as for untreated soil.
5. **Waste generation:** any spoils generated during implementation of the remediation technology is treated as waste.

The costs associated with the remediation technique are simplified in this model. They are assumed to be:

- Unit cost for application of technique (function of installation depth) (£/m3).
- Binder materials unit cost (£/m3).
- Overheads capital cost (£) and unit cost (£/m3).
- Monitoring capital cost (£) and unit cost (£/year).
- Spoil material treatment (or disposal) unit cost (£/m3).

User inputs for these parameters along with the soil to binder ratio (-) and remediation overreach (m), allow an overall cost for the technique to be derived. Remediation overreach is essentially a safety factor measuring the length/width/depth of soil excavated in excess of the assumed dimensions for contaminated soil. Higher numbers signify higher levels of safety, allowing for the practical limitations of soil excavation at a real site.

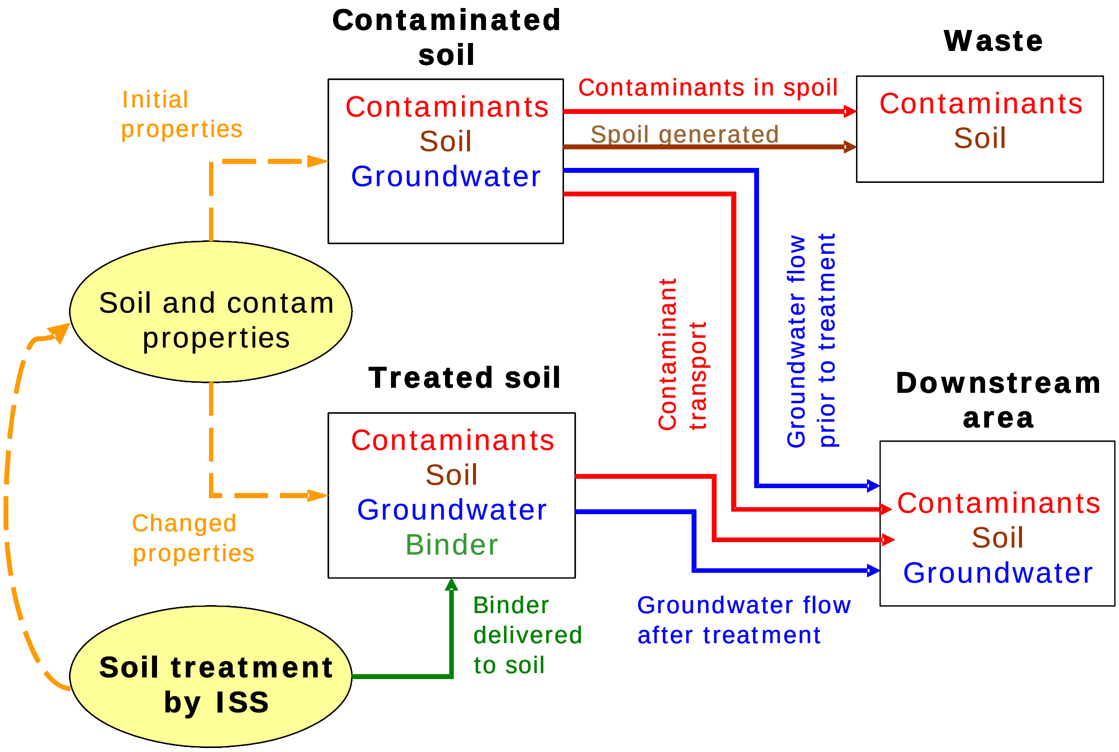


Figure 4. Simplified in-situ stabilisation remediation process.

A series of assumptions has been made in order to efficiently represent the ISS remediation technology at the assessment level. These assumptions are simplifications that are necessary due to the capability of the modelling package, time/budgetary constraints or for general ease of modelling. The assumptions made for version 1 are:

- The soil in the contaminant plume is fully saturated throughout its pore space.
- Contaminants are not solubility limited by default.
- Contaminants are not volatile.
- Groundwater flow through the contaminated sol is a function of the hydraulic gradient, hydraulic conductivity of the soil and the cross sectional area of the contaminated area.
- Vertical flow through the contaminated soil is from rainfall only, and is a controlled by hydraulically effective recharge (HER) or hydraulic conductivity of the soil, whichever is smaller.
- The hydraulic gradient is constant throughout the model and over the time of simulation.
- Both untreated and treated soil is homogeneous (*i.e.* can be characterised by uniform properties).
- Properties of both the treated and untreated soil are constant over time.
- The process of production of the reagent mix is not considered.
- ISS application (*e.g.* soil mixing by grouting) is instantaneous. The technique to deliver the reagent mix into the soil is not distinguished in terms of outcome or costs.
- The only waste product generated as a result of the remediation is spoils generated from injection or reactive material into the ground. No liquid effluents is produced (*e.g.* from production of the reagent mix).
- Disposal costs of spoil material (if any) are a function of the volume of material and do not account for the levels of contamination in the spoil.

It is intended to re-visit some or all of the above assumptions in future versions of this model.

To demonstrate the capability of the model, a trial run using arbitrary values was undertaken. The model contained four contaminants (A, B, C and D). Contaminant specific input values (concentrations, sorption and solubility) selected for the demonstrator run are given in Table 1. Other key input values were:

- simulation time: 100 years.
- time to remediation: 10 years.
- contaminated area dimensions (length /width /depth): 10 m / 10 m / 10 m.
- soil density (untreated → treated): 1800 kg/m^3 → 2200 kg/m^3.
- soil porosity (untreated → treated): 0.3 → 0.3.
- hydraulic conductivity (untreated → treated): 1 m/day, → 0.001 m/day.
- hydraulic gradient: 0.01 m/m.
- infiltration from rainfall 500 mm/day.
- binder to soil ratio 0.3.
- spoil return: 0.05.
- remediation overreach: 0.5 m.
- soil treatment unit cost for application to < 5m depth: 10 £/m^3.
- soil treatment unit cost for application to 5m – 20m depth: 50 £/m^3.
- unit cost for main binder component used in soil treatment: 2 £/m^3.
- overheads capital cost: £20,000.
- overheads unit cost: 10 £/m^3.
- monitoring capital costs: £5000.
- monitoring annual costs: £1000.

Table 1. Contaminant specific input values selected for demonstrator run.

	Contaminant A	Contaminant B	Contaminant C	Contaminant D
Initial concentration in water (mg/l)	10	10	10	10
Concentration in soil (mg/kg)	10	10	10	10
Soil K_d (m^3/kg)	0.15	0.01	0.25	3.5
Treated soil K_d (m^3/kg)	0.15	0.001	1	0.5
Solubility limits in soil (mg/l)	1000	1000	1000	1000
Solubility limits in treated soil (mg/l)	1000	0.001	1000	1000

The parameter values shown Table 1 are generic, and were intended to represent a range of contaminants. According to Table 1, in-situ stabilisation was assumed to have the following effect on the various contaminants:

- Contaminant A: no effect on sorption and solubility properties.
- Contaminant B: reduced sorption, but become solubility limited.
- Contaminant C: increased sorption and no solubility control.
- Contaminant D: reduced sorption and no solubility control.

The impact of remediation by ISS was calculated for contaminant release from the treated zone. For all contaminants, there was a continuous increase in the amount of contamination released from the source zone until the time of remediation (assumed at 10 years). Following remediation. there was a marked change (reduction) in the shape of the release profile at 10 years for all contaminants. The nature of this reduction reflects the effectiveness of the remediation.

ISS remediation was shown to be effective for contaminants A, B and C, and less effective for contaminant D. These results showed that without solubility control (contaminants C and D) ISS can be effective in retaining contaminants with moderate mobility (contaminants A and C), but may be relatively less effective if it causes a relative increase in the mobility of the target contaminant (contaminants D). The technology can also be effective for mobile contaminants that become solubility controlled as a result of soil treatment (species B). Effectiveness of the technology for contaminant A demonstrates the importance of reduced flow achieved as a result of soil treatment. In the demonstration example, reduction in hydraulic conductivity of the treated soil was taken to be 3 orders of magnitude. Results for contaminant D represent a balance between competing influences (reduced flow but increased mobility).

These results demonstrated that the results are sensitive to sorption and solubility controls, and to groundwater flow (which is in turn a factor of hydraulic conductivity and hydraulic gradient). Inputs for these parameters should therefore be carefully considered so that the model is a true representation of the situation to be assessed. The model provides a useful tool to investigate the possible outcome of a combination of system parameters which will interact in a complex manner.

CONCLUSIONS

A set of remediation technology demonstrator models were developed with the GoldSim software to represent three remediation technologies potentially applicable to radioactive contamination on NDA sites in the UK. These models were designed to be simple to support high level decisions for which technology or technologies are potentially suited to the remediation of a specific site and contaminants.

The remediation technologies simulated were standard soil leaching, permeable reactive barrier and in-situ stabilisation. It was considered that sufficient information already existed for existing remediation techniques such as soil dig and disposal and groundwater pump and treat to allow such decisions to be made.

All three models effectively demonstrate the effects of basic site specific and generic data on the effectiveness of the remediation to specific circumstances and also allow the calculation of likely associated costs and timescales.

These models will allow a high level comparison of the three remediation technologies in order that their potential application to specific contaminated land situations can be assessed.

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REFERENCES

[1] GoldSim Technology Group LLC. User’s Guide GoldSim Probabilistic Simulation Environment (2007).

[2] GoldSim Technology Group LLC. User’s Guide GoldSim Player (2007).

[3] Claxton, D. and Paksy, A. Application of Enhanced Soil Washing – a Review. Nexia Solutions Report (05) 6223 Issue 01 (2006).

[4] Carey, M. A. Carey, B., Fretwell, A., Mosely, N. G. and Smith, J. W. N. (2002), *‘Guidance on the Design,* Construction, *Operation and Monitoring of Permeable Reactive Barriers’*. National Groundwater and Contaminated Land Centre Report NC/01/05. Entec (UK) Ltd and Environment Agency, September 2002. http://www.environment-agency.gov.uk/commondata/acrobat/prbdraftguidance.pdf

[5] Vidic, RD (2001), *‘Permeable Reactive Barriers: Case Study Review’*, Groundwater Remediation Technologies Analysis Center Technology Evaluation Report GWRTAC TE-01-01, November 2001.

[6] Claxton, D. and Paksy, A. 2006. Application of Permeable Reactive Barriers – a review. Nexia Solutions Report (05) 6634 Issue 01.

[7] Environmental Agency (2004). Guidance on the use of solidification/stabilisation for the treatment of contaminated soils. Science report SC980003/SR01. Bristol.

[8] Trivedi, D., 2005. Application of In-Situ Stabilisation – a review. Nexia Solutions (05) 6635. September 2005.