Final Meta Model of integrated prognosis/monitoring model

Deliverable 6.4

Sjoerd van der Zee, Helen K. French
**Soil Contamination:** Advanced integrated characterisation and time-lapse Monitoring

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Summary

A meta model comprises of a number of involved aspects putting into system knowledge about contaminant situation, geological setting and how various forcing conditions affect may affect the future situation of a particular site. Whereas the SoilCAM project aims at presenting a meta model for the two investigated sites Gardermoen (NO) and Trecate (IT), its scope is broader. This report is structured in two main parts, first a description of Meta models for the specific SoilCAM sites, the second part a General meta model for employing the three instruments (invasive, non-invasive field methods and modelling). The site specific meta models are developed upon a request of the stakeholders, and are therefore written for them. In general the Meta Model concept consists of 6 steps: 1.Problem statement, 2.Objective(s), 3.Development of a conceptual model (set of hypotheses), 4. Modelling, 5.Experimental design and 6.Analysis.

These phases are illustrated, by two case study sites. The common feature of the two sites and also the focus of the SoilCAM project is that there is a degradable organic component is found in a permeable aquifer system. This also constrains the use of the Meta Model to such cases. Case site 1) Gardermoen is the main airport in Norway with the use of large amounts of de-icing chemicals for winter maintenance and  Case site 2) Trecate with an accidental crude oil blow and leakage down to the groundwater.

The following general aspects need to be addressed at contaminated sites to be able to develop and test conceptual site models: Stratigraphy, Environmental conditions, Transport, Contaminant fate and Biogeochemical interactions. In this report we address the methodological requirements of these topics based on the experiences of the SOILCAM project, hence a limited point of view and probably not valid for all types of contaminants, sites and methods. A decision tree is suggested as a framework to help decide which methods (invasive and non-invasive) are most appropriate for a given contaminated site depending on geological and contamination characteristics. The frame work outlines how a web-site could be constructed and how it could be extended progressively as more knowledge and experience on characterisation and monitoring of contaminated sites by combining different technologies becomes available.

Some of the information and experience gained through EU projects reported in Deliverables may be of more practical use for site managers, stakeholders and policy makers than knowledge that is “conserved” through peer reviewed publications, hence an overarching structure on a European level is required. The outlines illustrated in this report could be used for further development of such a pan-European web tool maintained by a European organisation, such as JRC or similar.
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1. Introduction

In the 2011 Annual SoilCAM meeting in Bucharest, Romania, discussions were held with regard to one of the major practical results of the project, i.e., the meta model. The meta model should be visualized as a guide for the systematic thinking with regard to the characterization of a site, to support decision making and management of that site, by stakeholders that are not research scientists.

A meta model comprises of a number of involved aspects, that Dr. Laurence R. Bentley, member of the SoilCAM Scientific Advisory Board, was so kind to delineate for the participants. From his notes, we adopted the organization of our meta model below.

Whereas the SoilCAM project aims at presenting a meta model for the two investigated sites Gardermoen (NO) and Trecate (IT), its scope is broader. In compliance with the aims of the project, the guidelines for systematic thinking must be formulated in such a way, that choices with regard to the suitability of non-invasive techniques, as well as regarding how to combine the three instruments under SoilCAM investigation (invasive & non-invasive measurements, and mathematical modeling).

This report is structured in the following way:

- Meta model for a specific SoilCAM site
- General meta model for employing the three instruments

These parts are now described.
2. Meta Model Site Analysis

The site specific meta models are developed upon a request of the stakeholders, and are therefore written for them. In general the Meta Model concept consists of 6 steps:

1. Problem statement
2. Objective(s)
3. Development of a conceptual model (set of hypotheses)
4. Modelling
5. Experimental design
6. Analysis

These phases are now illustrated, by two case study sites. The common feature of the two sites and also the focus of the SoilCAM project is that there is a degradable organic component found in a permeable aquifer system. This also constrains the use of the Meta Model to such cases. Case site 1) Gardermoen is the main airport in Norway. It is situated on a large rain fed aquifer of glaciofluvial sediments. Degradable de-icing chemicals are supplied to the permeable surfaces along the runway due to winter maintenance every winter. Case site 2) Trecate is an agricultural area with rice production. In 1994 a crude oil blow-out caused a large surface area to be contaminated and considerable amounts of leakage down to the groundwater.

2.1 Problem statement

The stakeholder(s) have experienced problems that lead them to investigate their site. Nevertheless, this problem statement is necessary, to ascertain whether or not the problems are perceived the same by stakeholders, the pollution authorities and consultancy/research group, and to identify possible discrepancies in perception as early as possible. This problem statement is agreed upon as early as possible in the process. Special attention should be given to ‘the possible’. Too high demands by stakeholders, that cannot be met by the project, should be recognized early, to avoid frustration.

**Gardermoen:** De-icing chemicals are considered to be contaminants that may not reach groundwater. Hence, past experiences where this occurred have motivated research on the fate of de-icing chemicals in the unsaturated zone. The SoilCAM project may provide understanding on two basic issues, i.e., the natural microbial degradation that is mobilized in the subsoil system, and early warning systems that indicate that contaminants are going to be leached. In particular, the project results should support the management decisions on whether or not to take preventive or remedial action. Practical aspects are therefore: should the monitoring program be changed (optimized), preferably reduced with smaller costs, while maintaining an international (say EU) standard of quality? In particular, questions on how water and chemicals move through the snow pack and whether indeed PG gets a head start, have been raised. At this moment, the interactions between biogeophysical transport and degradation processes, the (only partly known) subsurface complexity, and type and location of monitoring equipment is too poorly known, leading to questions such as: How should remediation be done (differently)?

**Trecate:** The site in the past 10 years has been subjected to the monitoring of the groundwater quality and soil pollution; it has been assessed that the transport of dissolved phase in groundwater in concentration of mg/l (total hydrocarbon) doesn’t affect any sensitive target downstream the groundwater flow. The residual phase of hydrocarbon is partially located in the unsaturated zone and partially in the smear zone, affected by the groundwater table fluctuations. Risk analysis pointed out the negligible impact on environment and human health due to the residual hydrocarbon still trapped in the vadose zone. The low mobility and reduced solubility of the non-miscible NAPL phase provide a slow release of the contaminants as dissolved phase in the groundwater; the mass balance between
the concentration of dissolved phase at the source, degradation, and mechanical dispersion determines a plume that can vary seasonally but affects a well restricted zone. In the last years, stakeholders didn’t observe any contamination levels greater than the admitted values at the monitoring wells.

The action undertaken is the monitoring of the groundwater quality at the existing controlling network of boreholes; the open question is how much integrated approach (invasive, non-invasive, modelling) can be effective in monitoring the time-varying effects of natural degradation of the residual contaminants. At similar sites, which are still incompletely investigated and risk and remediation action analysis is yet to be done, several other questions may arise. In particular the mobility of in phase, colloidal and dissolved contaminants, the geometry of source and plume and the processes of retention and natural attenuation require attention. The answers to these questions should then lead to management decisions.

2.2 Objectives

The problem statement describes the history of the contaminated site and the spatial and temporal scale of the problem, i.e. whether the contaminant has a large or small distribution, sorption processes and whether the degradation process is fast or slow compared to the velocity of the groundwater in the area. It is also stated whether the contaminant source is continuous or caused by a one off situation. The general objective is to integrate experimental, monitoring, and modeling results, to improve decisions on management of the sites in the future.

The objectives could be classified in three classes:

1) Natural process can reduce the contaminant concentration to an acceptable level within a set spatial scale – and the objective is to set up a monitoring system to ensure this is the case
2) The contaminant situation is unacceptable and the objective is to choose and implement optimal remediation techniques as well setting up a sufficient monitoring system.
3) The contaminant situation is unacceptable and the objective is to find and implement the best removal techniques and post effects monitoring programme.

The two case sites have different problem statements, so the specific objectives differ where the general objectives may still be the same. Site specific objectives

Gardermoen: (i) to provide guidelines, specific for Olso Airport, with regard to monitoring contaminant status (distribution and spreading) in general and for early warning, (ii) to give an integrated understanding of aspects that determine whether or not management of de-icing chemical use in situ is sustainable, and how it can be made sustainable.

Trecate: (i) to provide technology for cost-effective monitoring of the degradation activity (ii) to furnish a more accurate conceptual model of the site in general and the evolution of degradation in particular (iii) to establish robust model to predict the evolution of the (de-)contamination.

2.3 Conceptual Model of the site

The information that we have received from different sources must be integrated into an interpretation of the site, that can be tested with respect to its consistency, both internally and with respect to the data at hand. Several aspects and the acceptable degree of simplification of these needs to be reconciled:

- Stratigraphy: different layers and horizons till the basis of the site; an argumentation for this basis; textural & porosity, physical, and chemical properties of the strata
• Environmental conditions: climate/meteorological data (rainfall, snow, temperature patterns and statistics), vegetation/land use
• Hydrology: variation of water fluxes (infiltration, runoff, evapotranspiration, leaching, capillary up-flow/seepage, groundwater level pattern
• Transport: chemical boundaries at top and bottom, important chemical concentration, direction of fluxes in water and gas phases, to atmosphere, groundwater, in groundwater.
• Contaminant distribution: all available information regarding spatial and temporal variation of concentrations for the site, i.e.
• Load/concentration and which form aqueous-, gas-, solid- and possibly nona-queous phase;; contaminant properties. Biogeochemical interactions: equilibrium and non-equilibrium chemical and transformation processes, plus involved native chemicals.

The conceptual model of the site is based on a dialogue between the stakeholder and independent ‘experts’ integration of a variety of data, that can be updated as additional information becomes available.

2.3.1 Gardermoen

Geology and hydrogeology

For the stratigraphy, the different detailed descriptions of layers and horizons can be simplified to that of coarse poorly sorted sand to gravel in the northern and eastern parts of the airport area, finer sediments towards the south and south-western parts as well as vertically. The particular area of study in SoilCAM next to the runway is an area of finer sandy soils, the experimental station is located in an area of coarser material. Soil organic matter is found to be present from soil forming processes in the top 0.5m. Layering due to the sedimentation regime at the time of deposition can locally be characterized as random, with layer interfaces that may be tilted or horizontal.

The layers have been characterized physically, and biogeochemically.

Hydrology and Climate

Environmental conditions comprise of impermeable runways and built up structures, grassland, and further from the runways also woodland. For in soil processes, the grassland is important for the behaviour of the de-icing chemicals in the subsoil. For grassland, good default values are available to translate potential transpiration demand into actual transpiration. Atmospheric forcing is determined by the change from winter to summer. In winter, several situations may be relevant. Depending on the possible alternation of frost and non-freezing conditions, and snow cover or its absence, the upper soil may have been frozen to several dm (absence of snow) or only shallowly (insulating snow cover). Upon start of spring and infiltration of snow melt water, depending on the soil frost conditions, melting water may flow over significant horizontal distances within/on the snow cover, and on the frozen topsoil surface, until it arrives at unfrozen spots where it can infiltrate. The melting period may be relatively short (small snow cover, sharp increase in temperature), or long. The increase of soil temperatures may be slow (wet soil, initially severely frozen) or fast, which is important for degradation rates.

Potential evapotranspiration can be calculated for any latitude from the incoming radiation, and corrected if necessary for the ‘average’ cloud cover conditions. As the soil is under grassland, the actual transpiration can be readily calculated from the potential value. The moment of snow melting can vary over several weeks in March/April, and can be almost instantaneous or smeared out over several weeks. Relatively dry conditions typically follow shortly after melting, leading to a rapidly
increasing precipitation deficit. Simplified, this gives a short period (say one month) with significant water supply at the soil surface, followed by summer where net infiltration is insignificant.

Atmospheric forcing is one of the predominant aspects of water flow, since, due to the relatively deep groundwater (4-6 m – soil surface) and coarse soil material, capillary upward transport is negligible. However, flow does not only depend on the amount of water present in the snow cover, the rate of snow melt, and the rainfall pattern of spring. Due to the snow cover, and low permeability of the frozen topsoil, locally generated melt water may displace horizontally over significant distances (meters) before finding a place where it can infiltrate. Whereas this runoff redistribution occurs over distances much smaller than the airport, it may have strong implications: (i) due to very localized infiltration, a large fraction of melt water may move downward rapidly, shortly after onset of spring, (ii) this fraction of water may contain a large fraction of de-icing chemicals, that due to its de-icing capacity may tend to be in the first melt water, and (iii) contaminated water may arrive at sufficient depths, so that it will be too deep to be transported upward again by capillary forces. This latter issue is important, because temperatures may rise rapidly in the Gardermoen area, in which case evapotranspiration may pull shallow soil water upward again, towards the root zone, to be taken up by the vegetation.

Using data from the Gardermoen and Moreppen locations, a DEM was created and water redistribution was calculated similar to Appels et al. (2012), revealing that the 70% of supply of water in spring may be redirected towards 30% of the soil surface. This leads roughly to a cumulative infiltration that varies easily by a factor of 7. This bypass water of part of the soil volume is smeared out by capillary forces, but a factor of 5 may be possible. A typical horizontal distance of redistribution is estimated as 2 m at maximum. As this distance is larger than the resolution of the MCS (Multi Compartment Sampler), such preferential lateral movement at the surface is not well observable with the MCS. The supply of spring water for the two years of monitoring by SoilCAM seems to have varied less http://www.hydrol-earth-syst-sci.net/16/2871/2012/hess-16-2871-2012.pdf. A better long term average can be obtained from the OSL data bases. Snow removal from the runway causes additional re-allocation of snow and hence a potential doubling the available water for infiltration in the area next to the runway.

Besides water flow, which is the main transport pathway of the de-icing chemicals, also gas phase exchanges are important. De-icing chemicals may readily degrade, if temperatures are high enough and microbes are present, provided that also oxygen as the major electron acceptor is present. The presence of oxygen depends therefore critically on the absence of snow, and the presence of sufficient air filled (continuous) pores. The latter requirement implies that the soil should not be too wet, so that oxygen can readily diffuse into the soil. How much oxygen is needed, depends of course on the degradation demand: how much of which de-icing chemical (and other degrading compounds) is present, what is the temperature, and the presence of other electron acceptors.

Highly preferential infiltration of water causes it to reach a fivefold larger depth at some places than at others. Two extreme visualizations are possible, i.e., perfect piston displacement of resident water and complete bypass of resident water.

- Flow is vertical
- Snow & rain determines the depth of penetration, but does not seem to cause much lateral flow in the snow pack
- PG moves ahead of tracer
- Under natural forcing conditions in the field, PG has not been observed to move deeper than 1.5 m in spring.
- With a 2-3 times increase of infiltrating melt water, simulations show a deeper penetration, especially along a membrane along the runway. This is consistent with observations made with electrical resistivity measurements.
Fate of Contaminants

Anaerobic degradation of de-icing chemicals causes formation of unwanted gases (mercaptans and methane in the case of glycol degradation) and strips the soil of iron and manganese oxides. Since such conditions are environmentally unwanted, degradation should occur before these chemicals arrive at the groundwater. This is one of the crucial aspects of environmental sustainable use of de-icing chemicals, as the rate of movement depends on soil and atmospheric conditions. These also affect the rate of degradation, and in combination with PG additions, the leached quantities of PG. The latter depends on alternative electron acceptors in the case that the oxygen supply from the atmosphere is not fast enough to where chemicals are located. How fast oxygen is supplied depends on the continuity of air filled pores, which is a highly nonlinear function of water content. If water infiltration rates are large, it is plausible that the oxygen supply to the subsoil is adversely affected. This effect was supported by two dimensional model of flow in the unsaturated zone along the runway. In case of significant spatial variability, partial anaerobiosis (pockets with de-icing chemical, much water, low oxygen) may occur and alternative electron acceptors such as nitrate, manganese, or iron may take over the role of oxygen. As the pockets with anaerobic conditions are difficult to identify and parameterize, it may be that we have to resort to measuring how much Mn and Fe outputs in drainage water are, and perhaps to correlate this to varied infiltration rates. This is, however, quite involved and expensive work.

The working hypothesis is that the drainage of Mn and Fe on average leads to gradual depletion of these compounds, which may take years to decades, and could render the self-rinsing capacity of soil to disappear because of deterioration of soil functions. Reason is that each time anaerobic conditions occur, this may lead to reduction to Mn$^{2+}$ and Fe$^{2+}$, which are mobile in draining water. The natural supply of these metals to the soil is negligible. Hence, the mobilization has to be avoided. An alternative electron acceptor is nitrate, if oxygen is poorly present, which could be supplied with the infiltrating melt water. So far, the results of nitrate addition are inconclusive and may even result in adverse effects. As yet, much is unknown regarding the rates of degradation, as a function of electron acceptor concentrations, temperature and soil changes. It is possible that repeated (over the years) supply with de-icing chemicals also the microbial community (particularly mass) changes, causing degradation rates to increase over the years, at least initially. As Mn and Fe become depleted, these rates might decrease again.

Identification of widespread bacteria able to degrade aerobically propylene glycol in soil samples taken at Gardermoen site proves the potentiality for bioremediation. Specific molecular functional probes can aid the quantification of competent microorganisms without culturing. Cometabolism of formate and PG has been proved possible in lab cultures.

The laboratory tests suggest the use of biostimulation (addition of nutrients, in this case ammonia) for increasing microbial population to overcome the effect of low temperatures. Nitrate addition is not expected to be effective as ammonia in aerobic conditions.

Anaerobic pockets and partial anaerobiosis are difficult to predict, however, it is quite obvious that high infiltration rates can rapidly increase local anaerobic conditions. Two conclusions can be drawn, namely that if the leached metals comprised significant fractions of amorphous oxides in the experiments so far, sustainability of relying on the soil’s capacity to rinse contaminated water is questionable. The second conclusion is that engineering solutions are needed. One may think of: subsurface air injection (low rates, as the intention is to generally increase subsoil oxygen partial pressures, recognizing that there is no possibility to steer where exactly injected air moves to), irrigation/injection of solutions with nutrients such as ammonia and phosphate salts, and limiting the rate of water infiltration from snow melt (e.g. by puddling). If that appears to be an option, removal of contaminated snow towards engineered soil-based filters may be investigated (higher temperatures, electron acceptor and nutrient injections, controlled effluents) or the possibility of temporary storage of contaminated snow/water for sprinkling under warmer summer conditions. Unfortunately, and a major result of the SoilCAM research is that additions of electron acceptors (e.g. nitrate) may not sort...
a beneficial effect: Complete removal of PG is difficult to steer, and this is also the case concerning the leaching of applied nitrate (which then becomes a pollutant).

2.3.2 Trecate site (conceptual model)

Geology and hydrogeology

The regional geology of the area corresponds to the fundamental level of the Po plain and consists of alluvial areas deposited during the last glacial period (Wiirm), which in this area is essentially represented by large gravelly fans (LG) with an almost level or slightly convex morphology, consisting of coarse, unaltered fluvio-glacial materials. More recent alluvial deposits can be found along the Holocene water courses network, mainly along the Ticino river valley. These deposits consist of erosion terraces (VT), constituted by ancient or moderately old alluvium (ancient Holocene) and flat, often flooded alluvial areas (VA) with essentially depositional dynamics, consisting of recent fluvio-glacial deposits (recent Holocene); the VT are found in correspondence to the VA and they are separated by escarpments.

Locally the area is characterised by fluvio-glacial and fluvial deposits, with sequence of poorly sorted silty sands and gravel in extensive lenses, which is typical of braided river sediments. An artificial layer of clayey-silty material, less than 1 m thick, which was originally placed as a rice paddy liner, covers most of the site.

The unsaturated zone is characterized by a silty and sandy topsoil with a hydraulic conductivity in the 1-100 cm/d range (in saturated condition); the unit is characterised by a water content of 0.05 up to 0.15 in wet conditions; the second medium is mainly composed of silty sand with gravel, and it exhibits a hydraulic conductivity in the 10-1,000 cm/d range; the third unit is characterized by gravel in a silty and sandy matrix with similar hydraulic behaviour as the previous unit.

The local unconfined aquifer is characterized by sandy gravel and sandy sediments. This aquifer reaches a depth of 55-60 m. Data on hydraulic conductivity shows great uncertainties according to the procedure adopted for estimating the parameters: a hydraulic conductivity about $10^{-2}$ (m/s) has been estimated with standard well-tests, while slug tests with direct push technology inferred hydraulic conductivity values in the range of $5*10^{-3}$-$5*10^{-4}$ m/s.

The groundwater levels seasonally fluctuate by 6 m with higher levels at the end of summer, because of the local recharge due to the infiltration of the water used for agricultural irrigation purposes. A decreasing groundwater level trend was observed from 1995 to 2007, due to a decrease in the overall amount of water used for field irrigation. As a consequence, the oil lens just above the water level has fluctuated in the past years from a depth of -8 m to -12 m. During the SoilCAM project the maximum level occurred at the beginning of September, 2009, while the minimum level was at the beginning of April, 2010. The general trend shows a seasonal fluctuation with a gradual decrease of the groundwater level during the autumn 2009 and the spring 2010. The groundwater level appears rather sensitive to the rainfall with a sharp increase and decrease of the groundwater level which usually lasts few days (e.g. the several events occurred in February, 2009). The long term fluctuation is mainly related to the infiltration of the water used for irrigation purposes; the flooding of the cultivated area lasted from April, 2009 till September, 2009, which corresponds to the major increase of the groundwater level.

Hydrology and Climate

The surface hydrographical network of the area is influenced by the Ticino River, which is the main natural water course in the area. In addition, there are numerous artificial water canals that supply the fields in the area. The low density of the natural water courses is a consequence of the generally high
permeability of most of the surface deposits (i.e. gravel and sands). In these conditions, water percolates through the substrate.

The climate is humid, of a meso-thermic type, with a slight water deficiency in summer. The zone is characterized by a marked seasonal thermal range with cold winters (mean temperatures of 2 °C) and hot summers (mean temperatures of 20.6 °C). The distribution of the rainfall is characterised by peaks in the spring and autumn and minimums in winter and summer. The annual precipitation ranges from 1000 -1500 mm. The summer water deficit is concentrated in the months of July and August, with a significant depletion of the ground water reservoir.

**Contaminations**

The soil contamination has mainly been observed in three hot-spots, close to boreholes B-I, B-H, and B-D (Deliverable D3.1). At a deeper level (-8 m) total petroleum hydrocarbon (TPH) concentrations of more than 500 mg/kg have been observed in an elongated shaped area, which covers an area of about 200 m in the east-west direction and 250-300 m in the south-north direction. In the profiles analysed during the SoilCAM project a maximum TPH concentration of 26000 mg/kg was observed.

Residual free phase still trapped in the uppermost subsoil (depth of -2/-3 m) has been detected during direct push survey of 2011.

The groundwater contamination (dissolved phase) is limited to an area between boreholes B-J and B-O on the south and boreholes B-I and B-M to the north (hydraulically up-gradient); this area is contaminated by a concentration of TPH of 10 mg/l. In the multilevel piezometers sampled during the SoilCAM project a maximum of 440 mg/l was observed.

**Effects of hydrocarbon degradation**

Since 1998, the natural attenuation of pollution has been monitored in the groundwater as a follow-up remediation strategy. Measurements of TPH, oxygen, nitrate, ferrous iron, and sulphate have been collected at a several wells to follow the core-plume evolution over time and the bio-degradation process. The monitoring of the chemical and physical parameters at this site is still under way, in order to assess the effectiveness of the natural degradation. The respiratory activity of bacteria causes depletion of the electron acceptors (EAs) (i.e. oxygen, nitrate, and sulphate), and a relative increase in the dissolved ferrous iron.

The TPH concentrations are only detectable at a relatively small distance from the source. This rapid removal of the contaminants from the aqueous phase is due to biodegradation. The trapping mechanism (see below) is an important reason that the contaminant does not displace much and together with a high rate of the degradation and dilution process has caused a reduced horizontal spreading of the dissolved contaminant plume. The hydraulic properties of the aquifer seems to be affected by the dissolution/precipitation processes. These processes are related to intense microbial activity, which produces organic acid and carbonic acid, responsible for the mineral dissolution. Effect of pore clogging due to the presence of trapped hydrocarbon and mineralisation seems to justify a decrease of hydraulic conductivity in the smear zone with respect to the lower part of the saturated zone.

The dissolution leads to an increase in the total dissolved solids (TDS) in the pore-fluid. As the dissolved plume core gradually re-encounters aerobic conditions far down-gradient, minerals (such as of Fe and Mn) begin to precipitate in the form of grain coatings or cement between the grains. This process depends on the different ion species as well as the local Eh–pH conditions. In steady state conditions, the mineral precipitation is responsible for zones of reduced porosity, and a decrease of the hydraulic conductivity of the medium has been locally observed by slug tests.
2.4 Modeling (Generation of predictions from conceptual model)

This step is not necessarily numerical or computer modeling. Sometimes it is simple, such as groundwater is flowing towards the east at 2 m/day so a nonreactive plume will travel to the east 750 m in a year. However, in the later stages and when dealing with complex interacting flow, transport and geochemical reactions it often required complicated numerical modelling.

2.4.1 Gardermoen site:

First step in modeling should be to define the question to which the modeling should give an answer. For the Gardermoen site, the modeling should support management decisions that prevent significant losses of de-icing chemical into saturated groundwater. Translated into operational results, this means that the modeling should identify under which conditions, significant losses occur.

Main factors to be considered are:

- The rate of supply (i(t)), and its cumulative value (V(t)) over time and the spatial distribution of the water available for infiltration starting from the time of melting and an estimation of typical early spring water content profiles, and field capacity water content.
- An estimate of the ‘field capacity’ hydraulic conductivity, giving an impression of how the front of melting water moves towards groundwater level as a function of cumulative infiltration. Special emphasis should be put on the quantification of the preferential flow component, because this is the one process which may result in direct discharge of de-icing chemical into groundwater.
- An estimation of the temperature profile in soil and its change after melting.
- If the available water is able to push de-icing chemical (first melting water fractions) beyond 2 m depth, computer modeling may be necessary as the integration of complexity may point towards hazards or no hazards for groundwater. The calculation of the depth where chemical may arrive at is given by $Z_{PG} = V(t)/(\theta_f - \theta_i)$, if the field saturated and initial water contents $\theta$ are about constant with depth. If this depth is smaller than 2 m, it depends on the default degradation rate and the temperature increase, whether the PG (generic id for de-icing chemical) degrades fast enough. By default, this is likely, except if $V(t)$ rapidly increases in a very wet and cold spring and summer. If the spring/summer is warm and dry, PG is unlikely to leach, however.
- If water with PG passes 2m depth regularly through the years, this may point to a typical situation with poor PG degradation conditions (cold, wet, poor oxygen), few opportunities that PG containing water is displaced by capillary action back to the soil surface, and may result in gradual stripping of soil from electron acceptors. Detailed interpretation of SoilCAM results, and additional monitoring and modeling may then be necessary to assess the risk of leaching of PG. In view of uncertainties, it is then advised to take previously mentioned measures, in particular removal of large amounts of contaminated snow, which are concentrated at single spots.
- Will Fe and Mn deplete? A first impression involves comparing drainage rates with readily available, e.g. oxalate extractable metal oxide. The potential of nitrate as an electron acceptor so far is not clear.
2.4.2 Trecate site:
At Trecate site, the modelling should supply the stakeholders in order to answer at three main questions:

- To predict the behaviour of the dissolved phase considering the transport of hydrocarbons and electron acceptors, and the relationships with adsorption, retardation and attenuation phenomena in groundwater;
- To estimate the potentiality of the residual phase on the smear zone to act as a continuous source of leakage;
- To analyse the seasonal variation of the degradation phenomena.

The key factors (details in deliverable D5.4) needing further investigation are:

- availability, typology, activity, vertical and lateral distribution of the bio-mass in the smear zone;
- impact of the groundwater level seasonal fluctuations on the variability of the aerobic and anaerobic condition of degradation;
- uncertainties in the estimate of kinetic of degradation and relevance of mass transfer issues;
- availability of electron acceptor and donor and their sensitivity on the local recharge condition of the aquifer system; particularly the contribution of infiltration water from rice paddy field in the warm season should be carefully evaluated, because such water is already depleted of electron acceptors;
- Part of the rice fields have recently been replaced by maize cultures over the area of residual groundwater contamination (wells B-S): an additional supply of electron acceptors from infiltrating water is expected in this case. Progressive replacement of rice with maize could explain the reducing groundwater levels in the last years as maize fields are not flooded. Is it possible that less reducing conditions found in the last years are the result of a progressive increase of well-drained aerated subsoil under maize fields? In which case, replacement of rice with maize could be a possible method for enhancement of natural attenuation.

2.5 Experimental design

Integrated laboratory, “invasive” and geophysical (non-invasive) measurement strategies to maximize site characterization and hypotheses testing.

Where should you measure: mainly in z or mainly in x,y? How often? How broad is the c(z) band. How fast does it move? How fast does it degrade? How much ‘early warning’ is feasible?

Considering Gardermoen site, an unsaturated zone monitoring additional to the currently performed groundwater monitoring is recommended. This appears a feasible way to detect a breakthrough of the contaminants through the natural barrier ahead of time. Special emphasis should be put on long term trends in the annual centre of mass vertical travel distance of target contaminants and seepage water quality (pore water electrical conductivity, pH, Fe2+ and Mn2+) at hot spots of de-icing chemical infiltration. Mind that fine and coarse textured geological strata observed at the airport site will react differently to the contaminant input. Of particular concern are coarse textured profiles, because they exhibit less buffer capacity, less evapotranspiration and larger flow velocities. Unsaturated zone monitoring centres should be established oriented on the number of hot spot locations in relation to their distinction into coarse and fine textured profiles and distance to the groundwater.

As an early warning- unsaturated zone monitoring centre, we suggest a combination of invasive sampling methods and non-invasive methods. Seepage water sampling will be particularly difficult for
depths >2m. Because so far contaminants were not discovered in depths deeper than 1.5m, installation of seepage water sampling systems (suction cups or better suction plates, see e.g. French, 1999) down to a depths of 2m so far seem to be sufficient. Water content and salinity changes should be observed spotwise in such a system with automated measuring devices (HYDRA-Probe or similar). The invasive sampling should be supported by a cross borehole electrical resistivity array, which needs to cover the whole vadose zone from top to bottom. It can resolve critical changes of subsurface electrical conductivity, which hint on adverse trends of the propagation depth and extent of the contaminant plume. Unless suction devices are numerous and closely spaced, this is not possible with invasive methods. With respect to remediation scenarios, further field scale trials are required. It is recommend to use closed system lysimeters for this type of investigation to be able to derive mass balances for the contaminants. Also this way, possible adverse effects of the remediation to surrounding media is avoided.

As far as Trecate site is concerned, laboratory experiments in a oedometer instrumented for 3D ERT capabilities have been used for the electrical and hydrological characterizations of the material in saturated and partially saturated conditions. Small-scale column experiments have been conducted to study the transport phenomena of hydrocarbon and hydrocarbon–water emulsions in the soil. Similar experiments have been conducted for transport and degradation of de-icing chemicals in Gardermoen soil. Small laboratory systems are a valuable tool to study specific processes under exclusion of unwanted degrees of freedom.

On Trecate site a monitoring program has been implemented by using surface and borehole geophysics, integrated by geochemical surveys, (standard borehole logs, groundwater sampling in Multilevel piezometers...) to characterize the hydrological properties of the aquifer (heterogeneity, porosity, and water content) and monitor the natural degradation of the residual hydrocarbons. The monitoring strategies of the SoilCAM project at Trecate site focused on a small scale (two boreholes, with an interdistance of 5 meters) in order to detect the seasonal effect of ground-water. The time-lapse monitoring with geophysical and geochemical surveys in two boreholes confirmed the sensitivity of the induced polarisation to detect the degradation effect of the residual hydrocarbons.

Integration of invasive and non-invasive methods for monitoring purposes on NAPL contaminated sites with microbial degradation seems to require further research. Although geophysical methods like georadar, electrical resistivity and induced polarisation are sensitive to the microbial processes, unambiguous interpretation of the geophysical results is in particular difficult at such sites. As explained below, one example is the counterbalancing effect of an increase of pore water electrical conductivity by microbial activity versus clogging of pore space and presence of a NAPL phase, which rather increase electrical resistivity. Encouraging results were received for larger scale geological site characterisation using the EM technique.

2.6 Analyse results and update conceptual model.

The upgraded conceptual model of the Trecate site consider the site as typical NAPL-contaminated site that in past has been subjected to several remediation activity (bio-pile, air sparging...). Mobility of the residual free-phase aged petroleum floating on the water table is limited by the high viscosity, low solubility and low volatility of recalcitrant high molecular weight hydrocarbons. According to this assumption, there is no reason to provide any active clean-up strategy; the site requires only a combined strategy for the monitoring of the natural attenuation and groundwater quality. The monitoring program could be limited to the analysis of the physical and geo-chemical indicators of the degradation phenomena in the two extreme condition of groundwater level: one in spring when the aquifer recharge is at maximum, and one in autumn when the groundwater level is depleted.
The seasonal water table fluctuations cause the free phase of hydrocarbons to move up and down with the water table, causing the NAPL to be trapped in isolated pores in the saturated zone and to form a smear zone where hydrocarbon residual saturation conditions are attained. This effect is in particular remarkable in view of the coarse grained media at the site, which should allow for rapid transport of the contaminants. Also the abundant colloidal size NAPL droplets are obviously not mobile enough to result in a significant movement of the source. The droplets seem to be retained by the lack of a significant horizontal flow component in the smear zone (probably caused by clogging) in combination with a high affinity for the solid phase and the residual NAPL.

Low electrical resistivity values may be associated to the presence of hydrocarbons in the smear zone and in the capillary fringe above water table. Partly, a high polarisability effect was observed in the smear zone. During the biodegradation process, the water phase in the smear zone develops a lower electrical resistivity than the surrounding non-impacted zone because of the presence of ions produced during degradation of hydrocarbons. The extent of resistivity should be governed by the production of ionic by-products during degradation, such as carbonic acid and organic acids. Polarizability might be enhanced by the development of biofilms and surface precipitates such as iron sulfite. The availability or abundance of leachable mineral species, the time required for the leachate to migrate down to the aquifer, and the amount of retention of leachate by silt/clay zones within the vadose zone are other relevant factors in this process. Effects increasing the resistivity are clogging of pore throats and tortuosity increase due to the development of biofilms and precipitation of minerals. Also, the presence of free phase NAPL increases the resistivity.

We assume that the fresh water infiltrated from the surface might be enriched in dissolved ions by passing through the smear zone; the biological activity is mainly enhanced in autumn because of the supply of new oxygenated water from the surface; moreover the biomass activity provides the formation of metabolites that could be responsible of the increase of the electrical conductivity and the polarisability of the active zone.
3. General meta model for employing the three instruments

EU wants to know whether the data needed for the subsoil can be accommodated with geophysical methods. What can we measure, how does it translate into model properties, what signals have to be separated from each other in the geophysical picture, and is that possible, or when is it possible, what are the uncertainties involved.

The following general aspects need to be addressed at contaminated sites to be able to develop and test conceptual site models:

1. Stratigraphy
2. Environmental conditions
3. Transport
4. Contaminant fate
5. Biogeochemical interactions

We want to address the methodological requirements of these topics based on the experiences of the SOILCAM project. Thus, our recommendations are based on a limited point of view and probably not valid for all types of contaminants, sites and methods. In particular, the project concentrated on electrical resistivity, induced polarization, radio magnetic telluric and ground penetrating radar in surface and cross-borehole configurations, so we will not extensively comment on other geophysical methods. Also, inorganic, volatile and halogenated organic contaminants and sites in hard rock environments or sediments with pronounced "extraordinary" geochemical and geophysical properties (e.g. organic sediments and metallic or magnetic precipitates) may require different approaches. In the next two section we describe a tiered approach with reference to reports describing our experience in the SoilCAM project (the deliverables referred to as D1.1 etc), as well as reference to relevant literature and websites. In the second part we show how this approach can be included in a decision tree which could be presented as a report, but is more suitable for presentation on a website.

3.1 Tiered approach

Each of the topics 1 to 5 above has certain data requirements, depending on the level of detail and objective of investigation. Thus, the benefits of different methods may vary, depending on the question addressed and on the level of detail. In most European countries a tiered approach of contaminated site assessment is followed [EEA, 2000]:

I. Preliminary survey
II. Preliminary site investigation
III. Main site investigation including long term monitoring

a fourth tier might be added:

IV. Remediation

The required level of knowledge, expenses and combination of methods is likely to be very different for the 4 tiers. The preliminary survey ("historical survey") is mainly based on existing data and will rarely employ technical investigations. The preliminary site investigation aims "to verify the presence of contaminated soil, including the identification of polluting substances" [EEA, 2000]. The site is poorly characterized at this tier and little background information is available for a conceptual model. The number and extent of technical investigations is very limited. One objective is to decide, which type, quantity and spatial distribution of further investigations are of benefit. The main site investigation is aiming for a thorough characterization of the topics 1-5 to be able to set a basis for a decision on the final treatment of the site. It requires the knowledge of the processes, which determine the fate of the pollutants and involves the largest technical effort. The final tier will either end the
investigation, with or without removal of the contamination (probably accompanied by monitoring), will result in a continuous monitoring.

Subsequently, we want to suggest some alternative investigation methodologies for each of the tiers I. to IV. An overview is provided in Table 1.

Table 1: summary of potential advanced monitoring methods.

<table>
<thead>
<tr>
<th>Tier</th>
<th>Standard methods</th>
<th>Advanced methods</th>
<th>Information gain</th>
<th>Advantage/Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary survey</td>
<td>Historical documents, maps, aerial photos, interviews</td>
<td>Remote sensing data</td>
<td>Potential area of influence of a contamination</td>
<td>Additional costs at early tier of investigation</td>
</tr>
<tr>
<td>Preliminary site investigation</td>
<td>Drillings, soil sampling, limited number of trace analytical samples</td>
<td>Surface geophysical survey</td>
<td>Stratification and anomalies (geological or contaminants) of subsurface. Improved drilling and sampling strategy</td>
<td>Additional costs at early tier of investigation; better data basis for subsequent investigation, can potentially reduce need for costly drillings and give a better spatial coverage.</td>
</tr>
<tr>
<td>Main site investigation including long term monitoring</td>
<td>Grid of piezometers and soil sampling. Point measurements of changes in soil temperature, water content and electrical conductivity.</td>
<td>Grid of piezometers based on surface geophysical survey</td>
<td>Multilevel piezometer + Surface and borehole geophysical methods Lysimeters and suction devices</td>
<td>Reduced costs for piezometers Additional costs but higher probability of success of remediation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time- lapse geophysical methods, Surface or borehole depending on special needs. Automatic sampling</td>
<td>Increase spatial coverage between point measurements, early warning system. Can help determine best time for sampling of subsurface water. Additional costs, but may also save cost if reduced manual sampling can be implemented. Better spatial coverage, better control of situation and contaminant development.</td>
</tr>
</tbody>
</table>
Tier I:

Pre-existing site knowledge from maps, historical documents and aerial photos, interviews with affected persons and prior investigations from installations like wells is usually evaluated for this type of survey. Additional knowledge could be gained from pre-existing remote sensing information from systems like ENVISAT and IKONOS. This is because vegetation cover shows significant changes in its reflectance spectrum under environmental stress situations, as can develop on contaminated sites [Ferrier, et al., 2009; Silvestri and Omri, 2008].

Tier II:

At this tier little new technical information will be produced. The spatial extent and character of the contamination is in the focus of the investigation. Decisions are most likely based on organoleptic analysis, on-site analytical methods and a limited number of trace analytical samples. The number of trace analytical samples may be reduced by surrogate methods. For example, IR-spectroscopy or total organic carbon content analysis can identify the presence of an organic contamination. The latter is a good surrogate for TPH in organic poor environments. The use of direct push techniques, for example in combination with online hydrocarbon analysis with IR and electrical resistivity for the detection of a plume should be considered.

In contrast to the first tier, now the addition of surface geophysical methods can add valuable information for the initial conceptual site model and the planning of further investigations. In particular, the stratification of the subsurface could be investigated by a single surface survey using electrical resistivity, induced polarization, ground penetrating radar, self-potential or radio magnetic tellumetry. Anomalies in the subsurface will be discovered by the geophysical methods and ease the decision on the layout of the future sampling mesh. Also, a first guess on the location of water table and the location of a plume could be supported by the geophysical data.

Geophysical methods are in particular recommendable for sites with pronounced geological contrasts - e.g. clay layers embedded in sands or unconsolidated deposits over bedrock. Each of the methods has its limitations - high frequency GPR has a good resolution but low penetration depth in water saturated media, for example (D1.1, D1.2). Thus, any geophysical investigation requires the unbiased evaluation of the site conditions by an expert a priori.

It is recommended to use at least two methods simultaneously to ease the interpretation of the results. For example, reflection boundaries of GPR can be used in inversion of ERT data to limit the degrees of freedom and to derive a more reliable distribution of layers. Also, the use of induced polarization in combination with ERT will provide information on changes in rock properties additional to water contents and quality (D 1.4).

Preliminary numerical case studies based on the initial conceptual model with parameter values derived largely from assumptions can help to develop hypotheses on the contaminant fate, define future points of interest and required parameters to be measured in hydrogeochemical- and hydrogeological field campaigns (D3.1-D3.3).

Tier III:

Building on the information from tiers 1) and 2), additional investigations are required aiming for a more detailed conceptual model. In particular, the processes determining the fate of contaminants and their influence on the subsurface are in the focus of the investigation. Unsaturated zone and saturated zone investigations require different approaches for investigations.

In the saturated zone, investigations usually rely on a grid of piezometers to characterize the plume. The number of piezometers can be reduced, when the layout of the grid is based on a surface geophysical survey (see @2), which helps to define anomalies and stratification. NAPL contaminated sites show opposing effects on electrical and electromagnetic properties, which may counterbalance
each other. For example, a high volumetric content of NAPL in the pore space reduces the bulk electrical conductivity, but the degradation of the contaminant increases pore water conductivity, which should result in an increase of bulk electrical conductivity. The plume characterization based exclusively on geo-electrical and electromagnetic methods is thus unreliable and definitely needs validation with piezometer sampling. More reliability would be achieved when the contaminant and its interaction with the subsurface environment creates the same geophysical signal. Also during long term monitoring, the use of time lapse geophysical data provides more reliable data on the plume development than a single campaign on its own, also in NAPL contaminated environments.

Multilevel piezometers provide a great level of detail for the depth resolution of the contaminant plume and would add information on the vertical extent. This great level of detail aids to interpret surface and cross-borehole geophysical data and provides information on the level of heterogeneity. Areal investigations with multilevel piezometers are likely to be incapable due to the large amount of samples per spot and the relatively large sampling effort. Yet, geo-electrical and electromagnetic methods in turn can be carried out with less effort in standard wells and on the ground surface. This way, an aerial and depth resolved characterization of the contaminant plume can be received by combining both approaches. Such a procedure will most likely be more costly than monitoring a grid of standard piezometers. Its gain is the better knowledge of the extent of the plume, local scale heterogeneities and the localization of hot spots. The use of such information in turn would produce more reliable numerical models and better predictability of plume development and the effect of in situ remediation methods.

Characterization of the unsaturated zone is most commonly connected with more difficulties than the saturated zone. Due to the presence of a gas phase and the time variability of aqueous phase properties, geophysical methods incorporate a great deal of ambiguity (see also Lambot et al., 2004, Vadose Zone Journal). Promising appears in particular the application of time lapse resistivity and polarisability data in silty media. The change of water content over time is fairly limited in such media, in particular in deep unsaturated zones in temperate latitudes. A propagating infiltration front with high ion concentration would produce an observable geoelectrical signal.

In the surface near unsaturated zone, field lysimeters and suction devices of various kinds are powerful methods to identify and quantify degradation and transport processes and their effect on the subsurface medium, though such investigations require more effort than groundwater sampling in wells. The simplest instrument is the suction cup, which can be installed where the contaminants are found (in situ) and with a set of multiple set of samplers provide information about spatial variability of the soil water chemistry. Confined lysimeters have the advantage to derive mass balances and enable quantification of field degradation rates with numerical models. Yet, so far existing models have limitations in this respect. Multicompartiment suction plates allow to evaluate the influence of preferential flow on contaminant transport and are suitable tools to parameterize fast and slow contaminant transport (http://www.hydrol-earth-syst-sci.net/16/2871/2012/hess-16-2871-2012.pdf). All these methods provide tools for understanding the processes better and validating the models required to extrapolate this understanding to other parts of the contaminant area. The sampling of soil solutions may prove impossible in deep unsaturated zones. Geophysical methods, probably assisted by coring analysis, may be the only way to get hold on the processes at such sites.

Hydrochemical data provide the signature of microbial processes in the subsurface. Due to interpretation ambiguities microbial investigations are recommended (see D2.3, D5.1 and D5.4). Many highly contaminated subsurface sites are at least in parts anaerobic, which makes authentic sampling of microbial communities a challenging task. Thus, culture independent methods should be favoured.

In complex systems, numerical modeling is basically the only way to quantify processes. Unfortunately, the use of such models always comes with a large parameter uncertainty. In particular, modeling of organically contaminated sites is particularly challenging due to the large amount of processes and parameters acting on different scales. The hydrochemical data from suction devices and lysimeters in the unsaturated zone and from piezometers in the saturated zone can serve as validation
for numerical models of the site to be able to develop realistic scenarios of the interplay of hydrological, geochemical and biological processes. Yet, it must be assumed that a crowd of valid models is able to explain the experimental data equally well. Therefore, particular care has to be taken that worst- and best-case scenarios embrace the valid site models (http://www.hydrol-earth-syst-sci-discuss.net/9/13451/2012/hessd-9-13451-2012.pdf).

A direct consequence of the complexity of both processes and the models that may be necessary to capture this complexity, is that experimental observations as well as model output can be very complex in space and time also. To compare experiment and model results, as well as to communicate these, it may be necessary to simplify to major features: robust results, in another word. A readable account has been presented by French and Van der Zee (2012) (see in: http://www.intechopen.com/books/soil-contamination).

The incorporation of geophysical data into numerical models is still in its infancy. Most promising is the use of stratification data as input for the geometrical set up of the modeling domain. Valuable is the translation of model outputs (saturation level, contaminant concentrations as EC) into geophysical variables (D6.3). If such data is compared with geophysical measurements, these can serve as a validation tool for the model in subsurface regions where no hard hydrogeochemical data is available. Time lapse geophysical measurements can be compared to changes in saturation and EC values in flow and transport models (D3.3) to validate hydrogeological parameters such as permeability, and porosity used in the models.

**Tier IV:**

Building on information from previous tiers, a selection of remediation strategies can be tested in the lab and in the field. If process of degradation and transport are well known from tier 3) it is more likely implement a successful remediation strategy.

Testing remediation strategies generally involve various tiers on a progressively increasing scale. In a first tier, several techniques can be recommended for a rapid screening of a range of potential strategies as shown in Table 2. Subsequently, laboratory column experiments offer the opportunity to test a selection of strategies under more natural flow conditions, while a high level of control is still exerted. In pilot scale tests in the field obviously the most natural boundary conditions control the situation. The level of natural complexity is high due to inherent heterogeneity and lack of control of the boundary conditions. In this context, geophysical tools provide valuable support to interpret the response of the system to the remedy. Provided sufficient hydrogeochemical data is collected, the geophysical tools applied in the pilot study can be calibrated to monitor the areal remediation effect on a larger scale. This again will most likely result in soft data and requires additional bio-geochemical information collected with lysimeters and multilevel-piezometers.

![Table 2: Bioremediation scale-up](Image)

<table>
<thead>
<tr>
<th>Tiers</th>
<th>Scale</th>
<th>Scope</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lab</td>
<td>Evaluation of potential for biodegradation</td>
<td>Microbiological and molecular biology techniques</td>
</tr>
<tr>
<td>2</td>
<td>Lab</td>
<td>Evaluation of factors that limit biodegradation in soil</td>
<td>Microcosms, slurries, column reactors</td>
</tr>
<tr>
<td>3</td>
<td>Field</td>
<td>Evaluation of mass transfer issues, hydrodynamics and heterogeneity at 1-m scale</td>
<td>Lysimeters</td>
</tr>
<tr>
<td>4</td>
<td>Field</td>
<td>Evaluation of mass transfer issues, hydrodynamics and heterogeneity at field scale</td>
<td>Pilots</td>
</tr>
</tbody>
</table>
### 3.2 Decision tree for selecting appropriate methods

This section describes a framework to help decide which methods (invasive and non-invasive) are most appropriate for a given contaminated site. The framework outlines how for instance a web-site could be constructed and how it could be extended progressively as more knowledge and experience on characterisation and monitoring of contaminated sites by combining different technologies becomes available. On the opening page the contaminated site managers will choose a number of different factors concerning geological and contaminant setting (Page 1). In Page 2T and 2G, the appropriate choices made for Trecate and Gardermoen accordingly are shown as rectangles around the site specific characteristics.

#### CONTAMINATED

<table>
<thead>
<tr>
<th>Geological setting</th>
<th>Permeable geology (sand, gravel)</th>
<th>Impermeable geology (clay, silt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of geological unit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contaminant history</th>
<th>Existing/historical contamination</th>
<th>On-going/continuous contamination</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Contaminant distribution</th>
<th>Mapping of extents in x,y,z</th>
<th>Mapping of sources and extents of these, frequency</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Contaminant properties</th>
<th>Water soluble</th>
<th>Non-soluble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degradable</td>
<td>Conservative</td>
<td></td>
</tr>
<tr>
<td>Affects electrical conductivity of solution</td>
<td>Does not affect EC</td>
<td></td>
</tr>
<tr>
<td>Radioactive</td>
<td>Non-radioactive</td>
<td></td>
</tr>
<tr>
<td>Adsorbed</td>
<td>Not adsorbed</td>
<td></td>
</tr>
<tr>
<td>Other...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site limitations</th>
<th>No restrictions – access to all potentially contaminated soil/groundwater via the surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil limited access due to infrastructure (buildings, roads etc)</td>
</tr>
<tr>
<td></td>
<td>Safety limitations (never access, access at times)</td>
</tr>
</tbody>
</table>

Page 1, Opening page for decision support tree. More selection criteria could be added to such a framework.
**TRECATE**

**Geological setting**
- Permeable geology (sand, gravel)
- Impermeable geology (clay, silt)

**Extent of geological unit**

**Contaminant history**
- Existing/historical contamination
- On-going/continuous contamination

**Contaminant distribution**
- Mapping of extents in x,y,z
- Mapping of sources and extents of these, frequency

**Contaminant properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water soluble</td>
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<td>Non-radioactive</td>
</tr>
<tr>
<td>Adsorbing</td>
<td>Non-adsorbing</td>
</tr>
<tr>
<td>Other...</td>
<td></td>
</tr>
</tbody>
</table>

**Site limitations**
- No restrictions – access to all potentially contaminated soil/groundwater via the surface
- Soil limited access due to infrastructure (buildings, roads etc)
- Safety limitations (never access, access at times)

Page 2T. Decisions made for the Trecate site (NAPL contaminated).
Page 2G. Decisions made for the Gardermoen site, based on contamination with Propylene Glycol (PG).

The opening page (Page1) could easily be expanded to more detail concerning each characteristic of the site. For instance in Page 2G, PG does not by itself affect the EC, but degradation products or release of iron and manganese due to anaerobic conditions will influence the electrical conductivity (EC) of the water, hence the system will change in time due to on-going processes. Hence some more specifications will be required here.

In Page 3, only illustrated for the Gardermoen case, the non-invasive and invasive methods selected for this particular site are shown. Also the integration of these data through modelling, and which choices to be made for modelling at different levels of complexity is illustrated.
Deliverable 6.4

Which methods are applicable for which combination of situations, here illustrated for Gardermoen.

**INVASIVE METHODS**

- Ram drilling
- Soil samples

**GARDERMOEN**

- Geological setting
  - Permeable geology (sand, gravel)
  - Extent of geological unit

- Contaminant history
  - Existing/historical contamination

- Contaminant distribution
  - Mapping of extents in x,y, z
  - Mapping of sources and extents of these, frequency

- Contaminant properties
  - Water soluble
  - Degradable
  - Affects electrical conductivity of solution
  - Does not affect EC
  - Non-adsorbing
  - Other...

- Site limitations
  - Soil limited access due to infrastructure (buildings, roads etc)
  - Safety limitations (never access, access at times)

**NON-INVASIVE METHODS**

- Geophysical methods: GPR
  - Electrical resistivity

- Site managers

- Geophysical methods: GPR
  - Electrical resistivity (EM, IP)

- Geophysical methods (lab): Petro physical relations – EC-microbial activity-Saturation→electrical resistivity

**INTEGRATION METHODS**

- Conceptual model (Important /less important processes)
- Compilation of all available data in 3D process based numerical model
- Compilation of all available information on boundary conditions (spatial and temporal distribution)
- Numerical limitations – data distribution/quality limitations
Examples of how you can be directed to relevant reports, literature, tables and websites to explore certain options further is shown on Page 4.

Page 4, Links to relevant deliverables produced in the SoilCAM project, many other references could have been included.
4. Conclusive remarks

The work presented here illustrates a systematic way of tackling contaminated sites in a generalised way and also illustrated specifically for the two case study sites in the SoilCAM project. A number of EU projects, such as the collaborating project ModelPROBE and those presented together one the website: www.soiltechnologyresearch.eu

Structuring and linking up such projects or the outcome of these projects, since the lifetime of their web-sites might be limited, could be a great benefit on a pan-European level. Unfortunately much information and gained experience might be lost since projects have limited lifetime. Some of the information and experience gained through EU projects reported in Deliverables may be of more practical use for site managers, stakeholders and policy makers than knowledge that is “conserved” through peer reviewed publications, hence an overarching structure on a European level is required. The outline illustrated in section 3.2 could be used for further development of such a pan-European web tool maintained by a European organisation, such as JRC or similar.
5. References


Ferrier, G., et al. (2009), Application of geophysical monitoring techniques as aids to probabilistic risk-based management of landfill sites, Geogr. J., 175, 301-314.
