Final Publishable Summary Report, SoilCAM

Executive Summary

The overall objective of the project was to determine necessary basis for designing an optimal combination of invasive and non-invasive methods for monitoring degradable contaminants in spatially variable soil systems. To achieve that, SoilCAM combined advanced conventional soil monitoring techniques with state-of-the-art geophysical approaches. These were interpreted individually and combined through pedotransfer functions and joint inversion. To integrate different pieces of information, i.e. the invasive and non-invasive field data and more detailed laboratory studies of microbial degradation processes and column experiments, numerical flow, transport and geo-chemical interaction models were used. The objective was the simulations were to explore effects on fate of contaminants of different boundary conditions (snowmelt, highly variable recharge and hence groundwater fluctuations), sensitivity to geological conditions and presence of membranes in the ground. Based on such simulations an optimised monitoring regime can be suggested.

Control of contaminant distribution and spreading is vital for acceptable bioremediation solutions. Hence, optimal design of monitoring and bioremediation strategies at field sites is crucial. Because of high costs and practical limitations of invasive sampling site managers are usually limited in their interpretation of the contaminant situation by too few data points. Interpolation techniques are required for obtaining a site comprehensive interpretation. Since interpolations are uncertain, so is the site-covering assessment. This may cause inability to design a sufficient action plan to reduce negative consequences for the surrounding environment.

SoilCAM activities were centred on two European field sites faced with contamination issues: Trecate in northern Italy (light oil) and Gardermoen (de-icing chemicals) in southern Norway. Geophysical time-lapse measurements were combined with point data collection methods. Single geophysical non-invasive approaches may give a site (or transect) covering interpretation of properties, but usually only at a relative scale. The point data provide absolute values of physical and chemical properties, hence act as ground truthing data for the relative scales. These methods enabled the determination of contaminant levels and spatial spreading of different contaminants in these heterogeneous and highly permeable environments.

The Gardermoen field sampling study was undertaken near one of the runways at Oslo airport in order to characterise sub-surface heterogeneities and distribution of area affected by de-icing chemicals. Using georadar and time-lapse electrical resistivity measurements and soil sampling, the soil's physical and bio-geochemical characteristics were parameterized for modelling of contaminant transport and changes in time could be used to validate the modelling results. In general the system can be described by fast vertical flow during the snowmelt followed by high evapotranspiration, stagnation of contaminants and high degradation in summer. The gravity dominated flow supports the one dimensional approach used for complex bio-geochemical modelling. Nitrate was tested as a method for remediation, but results were inconclusive with respect to whether it can be used to increase remediation without at the same time increasing risk of NO3 leakage to the groundwater.

Work at Trecate focussed on geophysical and hydrological characterisation of the mostly contaminated areas. Lysimeter experiments and sampling from multilevel samplers in the fluctuating zone of the groundwater were used to evaluate the geo-chemical composition, colloid interaction with oil components and degradation in the zone still affected by the oil blow out in 1994. The combination of invasive and non-invasive methods and modelling indicated that light oil is present in a poorly mobile form at the groundwater level, with both slow degradation and small losses to the broader environment. This provides a solid basis for sound contaminated soil management.

Integration of invasive and non-invasive methods combined with modelling as illustrated in the SoilCAM project provides a way forward on how to monitor and increase understanding of soil and groundwater contamination processes. 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.

Summary description of project context and objectives

Decision making concerning the need for remediation, and the optimal way of doing so in terms of environmental beneficial effect and cost effectiveness, involves problem owners, the authorities, and consultants. Each of these stakeholders has to deal with lack of knowledge and broad-bands of uncertainty regarding subsurface contaminant distribution and processes (transport, biodegradation). The primary cause is the spatiotemporal variability of both the subsurface and the pollution event (or on-going pollution), both of which affect contaminant transport and degradation in the subsurface. This variability leads to highly erratic patterns of contaminant concentrations, which cannot be captured experimentally with conventional techniques that provide point measurements (e.g. soil/water sampling).

The assessment problem propagates in the ability to correctly assess the situation, involved hazards and need for remediation, and in the optimal environmental and cost effective way to remediate. Once a decision for a particular bioremediation technique has been made, it is often completely unclear whether the remediation is working properly due to limited process understanding and rudimentary monitoring techniques, as process-understanding relies on similar techniques, causing up-scaling and predictions to be erroneous. The 'apparently increased problems' have caused decision challenges and law suits on consultancy firms.

An obvious solution to deal with the 'invisible subsoil' is to develop new ways of monitoring. To be a realistic alternative, such new monitoring techniques need to provide higher resolution, aerial and volume coverage, and more reliable and cost-effective information of the subsurface. These techniques are available in the field of geophysics that deals with similar problems. Whereas these techniques are very promising with regards to cost efficiency and the spatial versatility (three-dimensional instead of point measurements), they also have two distinct disadvantages:

1. for the decision makers, supervising authorities, and even consultants, they are unproven technology in this field of remediation

2. the techniques give quantitative information, but absolute levels often need to be fixed by ground truth (to fix levels by accepted methods of point measurements).

Soil contamination assessment and site characterization can only make progress if quasi field-scale, extensively instrumented tools, such as third-generation lysimeters, non-invasive (geophysical) and invasive (soil sampling, soil water sampling) methods are integrated. Such integration implies a better communication between the different disciplines involved. Traditional sampling techniques have the disadvantage that they only represent point measurements whereas geophysical methods can provide a continuous picture of the subsurface for large areas or volumes. However, geophysical measurements (akin to a snapshot at one point in time) are not easily interpreted due non-uniqueness (ambiguity), geological heterogeneity, non-linearity of system responses and ambient site noise. The introduction of continuous monitoring or time-lapse geophysical measurements in environmental studies (e.g. Daily et al., 1992) has reduced this drawback and resulted in the emergence of new techniques such as hydrogeophysics (e.g. Rubin and Hubbard, 2005; Vereecken et al., 2006) and biogeophysics (e.g. Atekwana et al., 2006) that are relevant for understanding contaminated land. New approaches to minimize ambiguity in contaminated site imaging (Gallardo and Meju 2003, 2004) resulted in novel methods of coupled imaging or joint data inversion (e.g. Linde et al., 2006; Gallardo and Meju, 2007) and holds great promise for non-invasive characterisation of contaminated soil. Hence, it is now feasible to integrate non-invasive physical and biochemical data taken from different measurement platforms at selected contaminated sites. Three approaches are combined in order to complement and support each other for a better basis for decision making at a contaminated site:

1. conventional invasive approaches provide data sets that reflect properties at different points in space and time, that require interpolation techniques for obtaining a site comprehensive interpretation. Since the interpolations are usually very uncertain, so is the site-covering assessment.

2. single geophysical non-invasive approaches may give a spatial interpretation of properties, but usually only at a relative scale and do not reveal the magnitude of the properties, only the spatial changes. Assuming geology and total porosity remains constant in time, time-lapse geophysical measurements reveal relative changes in geophysical properties, these reflect changes in the combination of saturation, electrical conductivity of the soil water and temperature over time.

3. the modelling is site covering, but is context specific, and if the values of properties from place to place and through time are not known, the modelling may weigh the various processes incorrectly.

The strategy of SoilCAM aims at an integrated site-characterisation and monitoring design, with a variety of methods and approaches. Thus, guidelines are aimed at for ‘full system’ characterisation integrating geophysical, pedological and biogeochemical data with a 3D numerical transport model for each contaminated site. Whereas the effort is aimed at, and illustrated for the two SoilCAM sites, it should be possible to more generally define an integrated strategy for monitoring and predicting future trends in shallowly contaminated field sites that contain aerobically biodegradable contaminants. The integrated strategy leads to recommendations for the decision making stakeholders. As the illustrative presentation for the two quite different sites reveal, the three main methodologies, i.e., invasive and non-invasive (geophysical) measuring and the modelling, are needed in the integrative approach, because each of these methodologies alone suffer from significant shortcomings. Hence, they serve as ground truth for each other, albeit on different aspects. Therefore, the integration as reported in this report has resulted in an appreciation of the contamination and its future development, for each of the sites, that is both more ambitious and better justified.

The aim was to investigate the water flow and solute transport in the unsaturated zone including the rhizosphere taking spatiotemporal variability of these processes as well as degradation kinetics of the (organic, aerobically biodegradable) contaminants into account. On the basis of this understanding, the primary aim is to investigate different techniques in their capability for detecting contaminants and the degradation of these contaminants. In particular, non-invasive techniques are applied, because these give a more detailed, 3D impression of contaminant distribution and much less expensive than conventional techniques. As the non-invasive techniques are new to contaminant research, conventional sampling technology to fix 'ground truth' is needed. Optimizing different techniques is expected to have higher cost efficiency and effectiveness. Secondary aim is to cast the observations into a consistent parameterisation of a flow and transport model, with which a process optimization is conducted after calibration of the model with experimental data. The calibrated model allows for numerical 'experiments' with which a broader range of situations can be mimicked after which it is possible to determine the optimal way of combining techniques for the assessment of contaminant distribution and degradation.

Rationale of these aims is the following. For the degradation of organic contaminants, the unsaturated zone is an important zone, in view of the large impact of both red-ox conditions and the present soil microflora on biodegradation. The rhizosphere has a particular importance due to the higher biological activity of the root zone and its chemical modification caused by exudation of various organic chemicals. These chemicals also have an important role in affecting the mobility and bioavailability of inorganic contaminants, which may be rendered either more or less mobile and bioavailable. For natural remediation as well as for leaching of contaminants, these effects are of high importance.

Important objectives of this project were to develop:
Improved monitoring strategies for contaminated sites with regard to site characterisation and remediation monitoring i.e. form a new basis for optimising monitoring at contaminated sites including the use of new technology especially geophysical techniques. Optimised use of combination and spatial resolution, meta-modelling. Improved monitoring technologies for mapping contaminants and quantifying degradation activity, i.e improve methods for geophysical and conventional measurements. Examine the accuracy of different techniques, and improve inversion techniques.

Description of main S & T results/foregrounds

Research activities to form the basis of the work towards the described objectives are described in the early deliverables of work packages 1-5. Although all partners worked in a highly collaborative manner throughout the project, increased interaction between the results from the different WPs is visible in the later deliverables. In WP6 results and conclusions are integrated in order to answer the overall objective. The objectives and main results of each work package are described in the following sections.

WP1) Geophysical monitoring and characterisation
WP2) Biogeochemical monitoring and characterisation
WP3) Flow and transport modelling
WP4) New technologies
WP5) Monitoring sustainable remediation
WP6) Integrated strategies.

For figures and list of abbreviations see attached files.

Geophysical monitoring and characterisation (WP1)

Objectives:

1) Conduct initial screening for first approximation of subsurface and contaminants variability.

2) Optimize non-invasive methods for site characterisation, taking into account the effect of geological heterogeneity and site (anthropogenic and measurement) noise on target resolution.

3) Develop and apply appropriately coupled geophysical methods for 3D characterisation of geological heterogeneity and time-lapse or continuous monitoring of contaminated land, and validate them using ground-truth (D2.1 of WP2) at two contrasting field sites.

Key results:

The initial screening and mapping of anomalous 'hot-spot' areas (contaminated zones) of the two test sites was conducted by integrating different geophysical methods: surface electrical resistivity (ER), ground penetration radar (GPR) and frequency domain electromagnetic induction (EM), radiomegneto ellurics (RMT) and Nuclear magnetic resonance (NMR). The general layering and areas affected by de-icing chemicals (low resistivity) at Gardermoen and NAPL (high resistivity) at Trecate could be identified and the correlation structure of the images were analysed as proxies for the hydrogeological features. These results are only indicative however. Both areas covered approximately 100 ×100 m2 and in addition more detailed time lapse studies were carried out along profiles and in between boreholes at both sites. NMR measurements at Trecate indicated the presence of two aquifers, one between 13 to 28 m depth and a deeper one starting at 45-50 m depth.

The time-lapse geophysical data were used to estimate hydrogeological structures and properties in combination with ground truthing data from invasive point sampling techniques at both contaminated sites. These were used for numerical flow and transport models for the area next to the runway at Oslo Airport (WP3). At Trecate these data were used in a more qualitative way for the modelling. Time-lapse resistivity measurements can be used for the validation of the spatiotemporal development of saturation and EC values in the unsaturated zone (integrated with D3.3 and D6.3). Detailed borehole ERT measurements were made at the Moreppen site simultaneously with the GPR measurements. During snowmelt a downward movement of a more conductive zone can be clearly seen on the resistivity models in qualitative agreement with the water content models from the radar experiments. Time-lapse georadar measurements in the depth range 1-3 m showed a marked increase followed by a slight decrease (Figure 1).

A useful method for reducing the ambiguity of interpretation of single geophysical datasets is to combine different non-invasive techniques. In that way the interpretation (inversion) of data from one method is constrained by the other. Joint inversion of Radio Magneto Telluric (RMT) and Electrical Resistivity Tomography (ERT) data were carried out for the Trecate test site to get an enhanced image of the variability in sedimentary structure above the ground water table as well the geometry of the underlying aquifer. Whereas ERT data are very sensitive to changes in the upper few meters the RMT data is more sensitive to deeper variations, especially variations in the geometry of conductive zones like aquifers. Joint inversion along profiles of the two datasets thus gives a more complete image than each individual inversion image. However, it is unclear whether the many small details observed in the images for the upper 10 meters can be trusted. Observations in boreholes can shed light on this question. In addition to the joint inversion along profiles, for the first time 3D inversion of the RMT data were attempted. Compared with the 2D models the 3D models show a more consistent and distinct image of the presumed water table at about 12 meters depth, but less details in the upper few meters than the joint inversion result. The inversion results were validated by comparing with cross-borehole results at a single pair of boreholes in the area. A remarkable coincidence between the resistivity in the 3D model distribution between the boreholes and the 3D image were found in the whole depth interval from the surface down to a depth of 16 meters. This might indicate that the 3D model is a better image than the more scattered image obtained from the joint inversion of RMT and VES data, because a 2D model approach is too simplified even for the relatively undisturbed sedimentary sequence found at Trecate.

Joint inversion of ERT and GPR data was performed on data collected at the Moreppen test site, next to Gardermoen airport with a view to get an enhanced image of the time evolution of tracer concentration in the vadose zone during snowmelt. The cross-gradient approach was used to search for models that possibly share a common geometry. The common time-evolution of the models can most easily be seen when visualizing the change of the estimated parameters. The resistivity models show many small scale anomalies, probably inversion artefacts due to bad data quality. However, on a course scale a simultaneous and collocated decrease of the respective model parameters can be observed, and the approximate location of the melt-water front can be located as a function of time in both images. The strongest dynamic changes occurred over a short time interval from April 3 to April 12 in the depth interval from 0 to 4 meters. Due to the poor quality of the ERT data collected on the same days as the cross borehole GPR at the Moreppen site, it was concluded that more advanced attempts to estimate hydrological parameters such as water saturation as a function of time would not be feasible. Instead synthetic data were constructed to test our new algorithm for estimating from time lapse measurements both static fields (parameters) such as porosity and dynamic fields (parameters) such as water saturation.

At the Trecate site, the datasets of the cross-hole radar surveys showed vertical changes of water content and were useful for analysing to what extent groundwater level fluctuations were responsible for the temporal changes of the water content in the vadose zone. The resistivity data and their interpretation using different strategies in time lapse data processing were not sufficiently accurate to apply petrophysical relationships to convert them to changes in water content over time. They were more useful for understanding how the oil-water emulsion is affecting the smear zone (the zone of groundwater fluctuation). In addition to high quality cross-hole radar measurements, cross ERT measurements were also performed. Because of the electrode array used (pole-dipole) for the ERT measurements we were not yet able to conduct a joint inversion with the present version of the program.

A new theoretical approach has been presented for the joint inversion of seismic P-wave velocities and surface wave dispersion curves for improved reliability of site characterization and for estimating the porosity in the saturated zone in shallow aquifers.

Bio-geochemical characterization and monitoring (WP2)

<u>Objectives:</u>

The aim was to determine the interplay of environmental conditions in field (in particular red-ox conditions) and biodegradation and transport of the contaminants in soils and aquifers, for ground truth for geophysical methods (WP1) and parameterisation and validation of models (WP 3).

1) Spatial and depth oriented sampling & soil material characterization after initial screening process (provide ground truth for geophysical methods, WP 1.)

2) Monitoring and characterisation of flow and transport by lysimeter- and column experiments for evaluation of flow, transport and degradation of contaminants and colloids. Provide ground truth of soil water movement for geophysical methods (WP 1) and parameterisation and validation of models (WP 3). Determine the influence of environmental conditions in field (in particular red-ox conditions) on biodegradation and transport of the contaminants in soil.

3) Microbial investigations. The role of the most well-known beneficial microbes (i.e. the microsymbiont fungi and bacteria, other rhizobacteria, etc.) in the various soil-plant-microbe systems, grown at the polluted sites is quantified and the temporal and spatial variability and functioning of those beneficial microbes in the rhizosphere of host-plants is assessed.

<u>Key results:</u>

At the Moreppen field site in Gardermoen, the fate and transport of de-icing chemicals in the vadose zone was investigated by multiple methods. We applied closed system lysimeters, an open system lysimeter trench and a multicompartment sampler to investigate infiltration events of solutions of bromide, propylene glycol (PG) and potassium formate. The results from the field site show that microbial degradation of de-icing compounds occurred was very efficient. Yet, during snowmelt in spring, high flow velocities along with low temperatures cause the transfer of considerable amounts

PG below the soil horizon. This may lead to potentially significant impact on deeper soil layers and groundwater. This is in particular critical because the predominant fraction of annual seepage water occurred during the snowmelt period from April to May. On the other hand, formate is usually rapidly degraded and seemed to be the preferred carbon source compared to PG. Our observations in the column experiments confirmed that the joint application of PG and formate retards PG degradation. Also large concentrations of PG result in long lag phases. In the columns, the extension of the retention time had a positive effect on PG degradation, as long as electron acceptors are not limiting. The results emphasize that an adapted microbial community is required for an efficient degradation. Based on experiments in the lysimeter trench, all PG was removed prior to leaving the depth monitored by suction cups in the lysimeter trench (approx. 3 m below the surface).

Pedological and geological description of soils and vadose zone at the sites was based on liner samples. From the airfield at Gardermoen, 13 ram drillings to a depth of 5m were conducted and the cores lithologically described. 120 selected horizons from these ram drillings were analysed for pH, total carbon, total organic carbon and total inorganic carbon, dithionite and oxalate extractable Fe, Mn and Al, propylene glycol content, grain size distribution and magnetic susceptibility. From the lysimeter extraction site 6 liners to a depth of 1m were characterized and analysed in the same way for detailed information on the lysimeters. Also unsaturated hydraulic characteristics were analysed for the lysimeters. From the Trecate site, 66 samples from 6 drilling cores were analysed for the same parameters plus total petroleum hydrocarbons. All collected data concerning soil characteristics were made available to the partners on the SoilCAM webpage. The unsaturated zone at the investigated area at Gardermoen airfield consists mainly of glacial deposits with predominantly silt and fine sand grain sizes in heterogeneous layering. Occasionally, finer grained sediments occur, which may act as hydraulic barrier. Whether these are not so extensive that they may prevent infiltration of de-icing chemical affected seepage water into the groundwater is difficult to say since they are based on point measurements. The horizons exhibit different grey and yellow/orange colours, indicating on-going redoximorphic processes (Figure 2). Soil extracts didn't show any evidence of de-icing chemicals present in the vadose zone in October 2008, which indicates that degradation of de-icing chemical input by natural attenuation processes, is still efficient.

Data describing flow, transport and degradation monitoring data in the field (lysimeters) and in the laboratory (column experiments & lysimeters) was acquired on several field campaigns and in the laboratory. In summary, at the Moreppen research station several experiments were carried out to investigate the fate of de-icing chemicals in the unsaturated zone applying multiple methods. Field studies were conducted in a lysimeter trench, which also contained a multicompartment suction sampler. On the same site 8 small scale lysimeters, which were extracted at the Gardermoen airfield were used for experiments. Concurrently, several column experiments were carried out to investigate the degradation of de-icing chemicals in more detail. At the Trecate site, a multilevel piezometer and laboratory lysimeters with Trecate material were studied. Aqueous samples from these experiments were analysed hydrochemically for parameters like pH, electrical coductivity, redox potential, contaminant content, DOC/TOC, anions and cations. Lysimeter studies at Oslo airport, Gardermoen were performed in 2010 and 2011 to quantify the transport of the de-icing chemicals (DIC) PG and formate during snowmelt, and to study the effects of DIC degradation on the hydrogeochemistry of the unsaturated zone. The annual monitoring revealed remarkable differences in solute and water transport. High cumulative infiltration and marginal degradation of PG during the snowmelt period allowed up to 50 % of the PG to leave the upper, microbially most active, region of the soil. Only marginal concentrations of formate were analysed in all lysimeters, indicating fast degradation and favoured metabolism by soil bacteria compared to PG. This was also confirmed in column experiments. Low contents of metabolites and the concurrent breakthrough of PG and Br in the seepage water even imply that PG was not significantly degraded before June. Redox values down to 200 mV in April, the detection of propionate and manganese, as well as a rise in pH, suggest partially anaerobic localities in the soil during high soil water saturation in April and May. The biodegradation of remaining PG in the upper soil layer during summer resulted in almost complete depletion of dissolved oxygen and the partially vast discharge of up to 6 mg/L manganese in autumn. In the long term, the intense depletion of secondary electron acceptors such as manganese oxides lowers the potential of the unsaturated zone to degrade high loads of DIC.

In the column system, redox potentials drop very rapidly to strictly anaerobic conditions, indicating that the microbial community can adapt quickly to the high carbon load. When added alone, more PG was degraded, but the microbial community required longer adaption. If PG is added alone in large concentrations, the lag phase is much longer, but the community can adapt to these conditions. When the community is already adapted, i.e. at the second treatment, the inhibitory effect of formate on PG degradation is strongly reduced. The extension of the retention time showed a positive effect on PG degradation, particularly during the first treatment of DIC application. In the subsequent treatment, this effect could not be repeated. This may be due to the worse availability of potential electron acceptors, such as Mn and Fe oxides, which are depleted during the experiment. The rapid degradation of the de-icing chemicals and the detection of pyruvate and lactate in the lysimeter effluent indicate that PG and formate degradation was largely aerobic. However, the appearance of both propionate, as an end product of anaerobic metabolism, and manganese, as a product of reductive dissolution of Mn(IV)(hydr)oxides, indicate partially anaerobic localities in the soil. This may occur due to during locally high soil water saturation in April and May. In the long run, the depletion of iron and manganese oxides, which act as soil inherent electron acceptors, would lead to deterioration of soil properties.

Water flow and reactive transport of both PG and bromide varied strongly between different lysimeters. Effects of soil heterogeneity were not only visible between different lysimeter cores but also on the sub-core scale. For example, the infiltration of melt water exhibited distinct structures of preferential infiltration in the multicompartment sampler. Likely, degradation is influenced by such flow behaviour. The preferential flow paths were stable between seasons. It must be assumed that the soil heterogeneity is mainly caused by local differences in the soil hydraulic properties, and not by macropores. Soil heterogeneity is the main reason for the heterogeneous water flow and solute transport in this soil. Heterogeneous melting of snow does not influence the heterogeneous flow in the soil much at this scale. These results underline the importance of a characterization of the heterogeneity of the unsaturated zone, preferably assisted by non-invasive methods.

Remediation strategies require thorough testing. In the lysimeters a bioaugmentation strategy does not seem to be successful. In particular, the addition of nitrate, which was added as electron acceptor, resulted rather in adverse effects on seepage water quality. PG degradation strongly depends on the retention time in the upper soil layers and soil temperature, which are the most crucial parameters and are therefore important parameters to influence remediation activities positively.

At the Trecate site a multilevel sampling piezometer (Figure 3) was installed to investigate the effect of the raw oil spill on the local aquifer. Free phase oil in the groundwater is located in large amounts in depths of around 8.5 m to 10m on each of the three campaigns – temporally constant, despite the large seasonal fluctuation of the groundwater level (Figure 3). It seems, however, that the layer of oil contamination in the solid phase is spread over a larger area than 8.5m to 10m. It may be that the groundwater concentrations reflect rather the presence of free phase oil, while from the solid phase concentrations alone it is not possible to distinguish trapped NAPL and free phase. The oil in the aquifer appears relatively immobile despite the large groundwater fluctuations in the area. Large concentrations adhered to aquifer material are spread over the whole groundwater fluctuation zone. Yet, free phase in the groundwater samples, where most TPH is present as colloidal drops > 0.45µm, occurs only between 8.5 m and 10 m, independent of the sampling date. Also, the groundwater level at the date of the oil spill still seems to affect the distribution of NAPL. Degradation of hydrocarbons result in anaerobic, ferrogenic and sulfidogenic, conditions in the aquifer. The microbial activity leaves a clear signature in the hydrochemistry of the aquifer with distinct zones of high iron- and manganese II production. Upstream depletion of sulfate and nitrate and most likely also oxygen affect the whole water column at the MLS. Reactive transport and mixing processes lead to a redox zonation, which contradicts the conventional expectation of a geometry, where the sulfate reduction zone is surrounded by an iron- and manganese oxide reduction zone.

Microbiological activity results in most pronounced changes of the geochemistry, which can be seen in redox sensitive species and also in the redox potential. Concomitantly to the production of TIC, the redox sensitive species iron and manganese show their most pronounced increases in the depths from 8.5m to 11m. In this area, the microbial activity leads to a change of conductivity of the pore water, which may be observable by ERT. Nitrate and nitrite are mostly below detection limit and sulfate concentrations are greatly reduced compared to the background concentration. Consequently, the conditions can be characterized as ferrogenic on the limit to sulfidogenic.

Microbiological characterisation of surface (horizontal) soil samples obtained as an increasing distance (0-150 m) from the runways at OSL. Further vertical belowground soil-samples were obtained from the lysimeters up till the 0-110 cm soil layers. The abundance of microbes, as total culturable aerobic and anaerobic bacteria and the microfungi was estimated. The CFU (colony-forming units/g soil) was counted by using selective plates, such as the Nutrient and/or the Rose-Bengal (RB) for the aerobic/anaerobic bacteria and/or the micromycetes, respectively. The total catabolic microbial activity was estimated by fluorescein diacetate enzymatic (FDA) hydrolysis. Ratio of pollutant-decomposing microbial components were assessed by the most probable number (MPN) method as a function of the increasing distance from the runway, as the pollution source and or the soil samples with an increasing depths. Isolated strains capable of degrading the PG in de-icing fluids were obtained by plating out on nutrient- and/or cetrimide agar plates (designated as selective mainly for the pseudomonads). Taxonomic characterization of dominant isolates was performed by molecular PCR techniques. Culturable aerobic bacteria were ≥ 2 orders of magnitude more abundant in the examined surface soil samples than anaerobic bacteria and microfungi. There was also 2 order of magnitude drop found in the soils in the microbial counts (CFU/g soil) below the 20 cm plough layers in the lysimeter samples. Further experiments using the MPN method demonstrated that a key limiting factor in the biodegradation of DF during snowmelt infiltration is low soil temperatures (about 0.2-9 °C). However, bacterial strains biodegrading DFs at 4 °C could be cultured and isolated from the soil samples. Molecular identification revealed that the isolated strains belonged to Pseudomonas spp., which is known as the most efficient soilbacteria in the biodegradation of PG containing de-icing fluids. Minimal inhibitory concentrations (MICs) of de-icing-fluid (DF) for these Pseudomonas strains proved ≥ 10-fold higher compared to other cultured soil bacteria from OSL. The isolates did not prove to be resistant to any of the 5 tested clinically useful anti-pseudomonas antibiotics, which show their abilities in using them as potential inoculums for enhancing the biodegradation potential of PG contaminated soils.

Modelling (WP3)

Objectives:

1) To describe the transient flow conditions and water availability in lysimeters and field sites.

2) To relate water flow to transport and biogeochemical interactions that is involved in biodegradation.

3) To A) fully quantify the transient flow conditions upon remedial actions such as air sparging, application of electron acceptors. B) Simplify advanced process based modelling to meta-level modelling.

Key results:

For the fully integrated modelling of the various physical, chemical and biological processes, a host of models has been used, and where necessary, developed. These software packages are available for interested EU partners. In addition, other software has been used (e.g. STOMP), but not linked to the major models used in this project, because it was only of limited importance for the present SoilCAM project and its purposes.

The modelling of these processes does not provide a 1:1 prediction of what is observed in reality and this is also not reasonable to expect. Reality is always so much more complex, that real productions cannot be the aim of modelling in these branches of earth sciences. However, the modelling has supported the interpretation of observations both in Trecate and in Gardermoen conditions. This is the true role of modelling and the results are cause of satisfaction.

Significant advances have been made with regard to the integration of software. Broadly accepted software, such as the EU pesticide screening model PEARL, has been linked to the multicomponent chemistry model ORCHESTRA. Likewise, the already quite complex SUTRA-3D-DENS code has become equipped with routines to enable the evaluation of complex heterogeneous strata in the subsoil, using state-of-the-art approaches. Water flow, degradation kinetics and redox chemistry are coupled in a transient model. This model is highly innovating (and freeware!) as it is based on a modular approach (object oriented), that ascertains very high process flexibility.

This model is used to simulate contaminant degradation in the unsaturated zone at Gardermoen to perform a sensitivity analysis on several hydraulic and degradation parameters. Furthermore, the model will be used to determine which remediation technique will be most effective.

From the 1D transport modelling was concluded that if the soil layers differ with respect to adsorption, the depth of the centre of mass of a solute plume depends not only on the adsorption constant and precipitation surplus, but also on the degradation rate and dispersion. The variability of the precipitation and evaporation in the transient weather causes variability in the leached fraction. If degradation occurs only in the aqueous phase, the variability in the leached fraction is less sensitive to the transient weather than if degradation occurs in both the adsorbed and the aqueous phase. When the adsorption constant increases, the weather dependent variability in the leached fraction decreases.

For Gardermoen, the contaminant of interest (de-icing chemical such as propylen glycol PG) is easily biodegradable, and it is recognized that the actual biodegradation in the case of a temporarily (snow melt) poorly aerated soil involves electron acceptors that are intrinsic to soils. However, if this potential is actually used, the long term impact is that the unsaturated soil zone will be stripped of these types of compounds. For soil's capability to degrade compounds such as de-icing chemicals, as well as for soil as an ecological niche, such a stripping is unfavourable.

The results of these experiments suggest that the application of nitrate as an (oxygen-) alternative electron acceptor is not a good approach. Basically, it is extremely difficult to ascertain both that all contaminant is nitrate-mediated degraded, and that also no nitrate is leached instead.

Simulations of vertical profiles with input on layering from the GPR data indicate that as long as the recharge is homogeneously distributed, the vertical displacement of the contaminants in the natural soils next to the runway is gravity dominated. This is consistent with the assumption made for the complex geochemical modelling of propylene glycol. The layered system with randomly distributed permeability and reduced infiltration rate, show exactly the same average vertical behaviour as the homogeneous non-layered system – it is however not possible to draw any generalised conclusion concerning the importance of the small scale variability based on results so far since only one random field was simulated.

The simulations also indicate that the layering structure has larger influence on the vertical spreading of the plume than on the vertical centre of mass, which is fairly similar for hydraulic permeability fields in the same order of magnitude. Simulations of the same profile but with a sloping to horizontal membrane along the runway, shows that this has large effect on the redistribution of water and gives focused infiltration along the edge of this membrane (at approx. 2.5 m depth, 7 m from the runway). This is only present along some lengths of the runways.

An interesting feature with these simulations results is that saturated conditions occur in certain layers of the profile during the snowmelt infiltration period. These saturation levels are consistent with measurements of water contents along a vertical profile along the two cables monitoring changes in electrical conductivity along the runway. And also observations of iron oxidation in narrow layers observed in the field (Figure 2). The saturation levels were observed to be in the range of 0.05 to 1, and especially one depth, was more prone to these high saturation levels than the other, which is also consistent with the simulation results here showing rather narrow layers with high water saturation. The non-continuous pattern of saturations in the heterogeneous permeability fields in contrast to the homogeneous layers simulations, illustrates the risk of missing some of these points in sparsely distributed monitoring setups. In the Gardermoen example there is only one vertical profile monitoring water contents, electrical conductivity of the soil water and the temperatures, which is too little both for control of the situation at the site, and also for validating simulations and time-lapse electrical resistivity measurement interpretation.

With multiphase flow modelling, it was established that light oil at Trecate is capillary entrapped during the draining season, causing its small mobility and degradation rates. This is crucial for the conceptual and Meta-models, as it indicates that time lapse monitoring of 'disappearance rates' may be impossible due to extremely slow changes, despite that this does not adversely affect environmental hazards. For slightly layered coarse strata multiphase flow modelling showed that the flow of air in the water-saturated subsoil is extremely sensitive for contrasts in hydraulic properties. Therefore, in practice, it is almost impossible to ascertain that injected air (for oil stripping and aeration) will actually reach the contaminated (mostly the finer textured) patches of soil.

Consequently, for Trecate, it is not advised to employ air sparging as an important active remediation tool. The persistence of the oil pollution over decades has been explained and made very plausible as being the consequence of capillary entrapment. This insight is useful for several reasons. First, it is clear why so much oil is still present at this site, and second, it is clear that local dissolution rates of oil into water that is bypassing will continue for longer times. As the emission rates of dissolved oil into the broader environment are quite limited, as is clear from experimental observations and supported by modelling, environmental risks appear to be modest. Options for enhanced biodegradation (remediation) are at the same time limited, as it is far from trivial to ascertain that electron acceptors can be made to be transported to the oil pockets. Our management control in this respect is limited. Both steady state and transient modeling of contaminant and degradation product transport at Trecate evidenced that transport is slow, and environmentally not very hazardous. This has immediate consequences for the feasibility to monitor degradation at Trecate non-invasively.

Using models as used and shallowly described, it is possible to make an assessment of sustainability of current management, and more importantly, to dimension such management. For instance, it becomes feasible to develop guidelines for estimating how much PG contaminated snow and ice can be allowed to infiltrate locally, without polluting saturated groundwater. To fully conduct such a management dimensioning analysis appeared to be a bit too ambitious for this project. One of the main reasons was that the parameterisation of biodegradation kinetics for soils appears to be a very challenging issue, while it was not a focus point of this project.

New technologies (WP4)

Objectives:

The main goal of this work package was to develop innovative tools for laboratory and in situ monitoring of soil properties, for the site assessment, for improvement of multiphase transport investigation and for monitoring remediation activity.

The integration of geophysical and biochemical new technologies will be tested at Trecate and Gardermoen sites to verify under well controlled conditions the improvements with respect to the standard approaches. The WP will be focused on:

- The development of ultra-fast complex resistivity device;

- The development of strategies to integrate bio-geo-chemical observation into the data processing of geophysical monitoring
- Development of simple site tailored measurement device for time-lapse measurements of electrical resistivity measurement and self-potential.

Key results:
Instrument development and upgrades:
The following developments of new technology and upgrades were developed in collaboration between scientific and SME/Enterprise partners: Development of the 3rd generation lysimeters; development of the acquisition device for automatic time lapse measurements of electrical resistivity amplitude and phase collected at different frequencies, Polares, as well as software for interpretation of collected resistivity data. And a new generation of resistivity equipment for fast data acquisition, remote control of acquisition and the development of useful instrument for time-lapse measurements of ER and SP.

Upgrades and development of the 3rd generation lysimeters allows for a greater control of water balance and redox conditions, limited soil sampling and injection of gases and liquids in remediation experiments. Drip irrigation systems and insulation caps allow to dose water and liquid inflow and to prevent unwanted rain or transpiration. Small soil samples can be gathered without disturbing the soil texture. A porous lance allows the injection of air or nitrogen to control oxygen concentration. Redox sensors continuously check aerobic/anaerobic conditions at several soil depths. The liquid injection system can be used to introduce pollutants or remediation agents in depth. Such additions extend the range of applications of lysimeters to the study of degradation and transport of contaminants in soil. The previous versions of these lysimeters were limited to the applications of natural attenuation in the unsaturated upper layer of soil in substantially aerobic conditions. The present design allows the realisation of anaerobic conditions and/or the implementation of active remediation techniques.

An acquisition device for automatic time lapse measurements of electrical resistivity amplitude and phase collected at different frequencies, called Polares, was developed. The instrument is useful for monitoring both the geophysical response due to flow and transport phenomena and to establish relationships between the geophysical signature and the presence of some contaminants. The instrument incorporates lower frequency in view of the special needs of contaminated site survey where the geophysical signature of hydrocarbon contaminant is enhanced at low frequency. The aim was to achieve a flexible instrument with the capability of automatic time-lapse measurements monitoring about 120 electrodes over a broad range of frequencies (0.1 – 100 Hz). The new instrument was tested on the Trecate site, by comparing the results with conventional time domain instruments.

A software code for the analysis of multifrequency resistivity data (complex resistivity data), with an accurate approach to model the borehole and electrodes' effect was developed; the new code allow us 2D and 3D modelling and inversion of complex resistivity data, with algorithm for including a-priori information and for taking into account the minimization of the L1-norm in the inversion process.

New strategies for resistivity data processing both of single data acquisition both in time lapse fashion have been considered: the automatic staggered grid method is used to increase the image resolution, preserving the conditioning of the inversion scheme; the method achieves multiple solutions of the inversion process as function of the grid node distribution and yields a more robust solution together with estimate of the uncertainties associated to the solution at the grid node. The new hardware and software permits collection of data and interpret time-lapse electrical complex resistivity data in tomographic fashion (cross-hole).

A site-taylored instrument for time-lapse measurements of ER and SP was developed in order to meet the potential needs of contaminated site managers employing the combined method approached outlined in SoilCAM. The instrument was developed in view of the special needs of contaminated site owners or consultants working at such sites. The aim was to achieve a less expensive and flexible instrument, but still with the capability of automatic time-lapse measurements. A propotype of a modified Syscal-Pro instrument that can be controlled remotely is now available for resistivity/chargeability and self-potential measurements.

Data integration

We worked on the development of strategies to interpret resistivity, polarisability and georadar data in terms of water contents and to estimate the effect of hydrocarbon contaminants in the test sites. Petrophysical models (mixing rules) have been adapted to interpret the full waveform georadar trace collected in cross-hole configuration in the contaminated area; the cluster of best fitting model parameters (such as porosity, water content, oil free phase) can be estimated. On the other hand the analysis is useful to fix a initial model for the tomographic processing of travel time georadar data. Particularly the models allowed us to analyse the sensitivity of electrical permittivity (from radar measurements) to the water content and trapped free phase of NAPL in the smear zone.

Laboratory tests have been performed for the characterization of soils from Trecate sites using conventional and advanced technique. In particular a novel approach for a fast estimation of the water retention curve of soils has also been proposed and applied.

Experimental tests were performed on sand and silt specimens, characterized by different retention curves. As preliminary step the materials were characterized in terms of water retention properties and the relationship between electrical conductivity and degree of saturation. Experiments of water inflow in unsaturated soil samples have been performed in a novel oedometer equipped with 42 electrodes for a 3D time-lapse imaging of the electrical conductivity. A finite element simulation permitted to infer the water retention curve and the unsaturated hydraulic conductivity from the tomographic imaging.

Integration of laboratory and field measurements was used to investigate the influence of evolution of the water table on the contaminant hydrocarbon at Trecate site. The effects of the dissolved phase due to the degradation of hydrocarbon on the pore water conductivity have been integrated in a model for computing the soil bulk conductivity. The sensitivity of the change of cation exchange capacity (CEC) related to the effect of biomass on the solid matrix is considered: we verified that the pore water conductivity and the CEC changes have been related to the smear zone where the phenomena of degradation are occurring. Moreover we pointed out how IP (chargeability and phase) data can be reasonably related to the seasonal variations of biomass degradation activity.

The integration between soil physical properties and bio-geochemical behaviour and the geophysical signature, focusing on the small scale of the Trecate test site is based on the result of electrical resistivity and induced polarisation and georadar in cross-hole modality. The integration between reactive transport modelling results and geophysical data is promising for a better constrains of geophysical data processing and interpretation. This has a relevant impact of the small scale modelling of the flow and transport at Trecate site (see for instance Deliverable 5.3). Modelling of petrophysical relationships and a priori information in the interpretation of geophysical data acquired in time lapse fashion is also a relevant strategy in general for analyzing the reliability of the integrated strategies in monitoring the time-evolving condition of contaminated sites.

Monitoring sustainable remediation (WP5)

Objectives:

1) Provide new and improved monitoring techniques at lysimeter scale for describing pollutant removal as a function of the specific remediation techniques adopted

2) Monitoring crude oil and de-icing fluid pollution within fully instrumented lysimeters backfilled with Trecate and Gardermoen soil, respectively.

3) Provide new and improved monitoring techniques at field scale for describing pollutant removal as a function of the specific remediation techniques adopted;

4) Suggest methods for potential optimisation and intervention strategies for increased remediation (including fertilizer application or enhanced nutrient availability through the microbial activities, supply of electron-acceptors, increasing unsaturated zone by pumping ground water)

Key results:

The improved monitoring and control techniques developed for the 3rd generation lysimeters (see WP4) allowed for a better control of water balance and red-ox conditions, soil sampling and injection of gases and liquids in remediation experiments. The new additions to the original design of lysimeters allowed for a greater control on water balance and redox conditions, limited soil sampling and injection of gases and liquids in remediation experiments. This implied monitoring effect of environmental stressors on biodegradation rate: fluctuations of temperature, soil water content, pH, etc. bound to real or simulated meteorological changes. Hence, soil and water remediation techniques were tested in a controlled environment with full control of mass balances. These capabilities allowed for up-scaled lab-experiments to deal with optimisation of remediation methods for different saturation levels. In addition laboratory slurry reactors, microcosms and enrichment cultures helped to determine which reaction types and pathways are involved in degradation activities. More extensive laboratory studies provided data for estimating kinetic parameters useful for modelling the biotransformations in the field (such as concentration dependence of kinetics, inhibition, nutrient requirements, and intermediate formation). Lab-scale degradation tests with soil samples from the site were also suitable for the validation of biostimulation protocols. Change in the kinetics of biodegradation in the presence of nutrients can be used as diagnostic tools for the effective stimulation of the growth of degrading microorganisms.

Main contaminants at Gardermoen, propylene glycol (PG) and potassium formate, are easily biodegradable. The hazard is bound to high solubility in water and to the huge amounts of chemicals seasonally discharged in the sandy soil. Chemicals could occasionally contaminate groundwater and exhaust the autoremediation capacity of the site. The scope of a remediation treatment is to enhance and sustain the on-going natural attenuation process.

Kinetics of aerobic PG and formate degradation was zero order in slurry systems in the absence of nutrients. PG degradation rates was of order of 1.4 g PG/(kg soil d) at 15 °C with surface soil samples with a prior exposition to the contaminants. The kinetics of aerobic PG degradation in slurry and microcosm systems in the presence of added ammonia (an easily assimilable nitrogen source) was accelerated due to growth of degrading microorganisms. Nitrate could be used as an alternate electron acceptor in PG and formate anaerobic degradation. Formate was not degraded anaerobically in the absence of alternate electron acceptors.

Tests of complex amendants to stimulate PG degradation were also successfully performed in soil microcosms at different water saturation levels. Selection of cultures of microorganism able to degrade PG by enrichment from soil samples taken at Gardermoen site also proved the potential for bioremediation. Identification of main genera, with a predominance of Pseudomonas sp., showed that the ability of PG degradation is widespread in soil. Functional gene probes qgdA and par for secondary alcohol dehydrogenase and phenylacetaldehyde reductase, respectively, were designed and tested on bacterial isolates able to use PG as sole carbon and energy source. qdgA genes was validated as functional biomarkers and a calibration curve for qPCR has been constructed to quantitatively track the active PG-degrading bacterial populations. Specific functional probes can aid the quantification of competent microorganisms in soil without culturing and potentially override microcosms and soil slurries to evaluate the soil activity. Selected PG-degraders allowed the characterization of stoichiometry and kinetics of aerobic degradation of PG in the absence of nutrient or electron acceptor limitations. Maximum specific growth rate in the absence of nutrient limitation was appreciable at 4°C (near 0.014 h^{-1}), allowing PG degradation at low temperatures. Stoichiometry of aerobic PG degradation (needed for nitrogen, phosphorous and oxygen requirements for biostimulation) was calculated from observed biomass yields in enrichment cultures. The calculated C:N:P molar ratios were very near to the values suggested in literature for nutrient additions on the basis of previous field experience. The use of enrichment cultures allowed also verifying the feasibility of co-metabolism of formate and PG.

Lysimeter experiments underline the role of the high permeability, preferential paths and immobile regions of the sandy soil in regulating the residence times of contaminants. PG degradation in the field is not limited by the availability of electron acceptors, but by the insufficient microbial activity at low temperatures and by scarcity of nutrients. The experiments showed that during snowmelt in spring high flow velocities along with low temperatures cause the transfer of considerable amounts of PG to deeper soil horizons.

Lab and lysimeter experiments suggest the use of biostimulation by addition of ammonium salts to increase microbial population and to overcome the effect of low temperatures. Nitrate addition is not expected to be as effective as ammonium in aerobic conditions. Reduction of infiltration rate by puddling (but avoiding water ponding) should be attempted in order to increase the average residence time of PG in surface soil layers.

In contrast with the previous site, Trecate is a classical NAPL-contaminated site, already object to several active remediation techniques. Mobility of 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. The scope of time-lapse monitoring is the assessment of effective remediation by natural attenuation.

At the Trecate site, lab-scale biodegradation experiments (soil microcosms with aquifer material) could not be performed at all due to the late availability of soil samples. Simulation of pollution and remediation events in lysimeters was limited to demonstrative and preliminary experiments, due to the initial delay in the availability of soil and oil samples and subsequently to the failure of equipment in the lysimeter station for flooding and damages by mice in the last part of the project. The discussion of scale-up of biodegradation data for the Trecate site has been somewhat impaired by the above failures. Due to the huge amount of literature data on hydrocarbon biodegradation and to the prior evidence of biodegradation activity at the site, the impact on modelling was not so relevant, as contaminant and electron acceptor transport are likely to be limiting the overall process rate.

The presence of an oil-in-water emulsion has been detected in monitoring wells. This is in favour of remediation because oil adhering to soil particles and oil dispersed as small droplets in water are subjected to mass-transfer limitations. It has to be investigated if the presence of an oil-in-water emulsion could be attributed to biosurfactant production (therefore a consequence of microbial activity). Even though the redox signature of the site was originally typical of a sulphate-reducing environment, later monitoring reports by ENI-Agip shows progressively less reducing conditions. In the last SoilCAM May 2011 survey, high concentration of nitrate (5.2±1.6 mg/L) and positive redox values (129±15 mV) were measured in monitoring wells near the most contaminated zone. A more detailed water and solute balance should be obtained, since the rate of advection of electron acceptors are likely to limit the degradation rate. The contribution of infiltration water from rice paddy fields in the warm season should be carefully evaluated, because such water is already depleted of electron acceptors. Apparently, part of rice fields were recently replaced by maize cultures just over the area of residual groundwater contamination: an additional supply of electron acceptors from infiltration water is expected in this case. The possible beneficial effect of a change in favour of cultivations that do not require submerged fields should be investigated. Time lapse monitoring of the aquifer redox state provides essential parameters for site modelling.

Integrated strategies (WP6)

Objectives:

1) Develop a conceptual meta-model that significantly assists with the current way of decision making for the field sites.

2) To define an integrated strategy for monitoring and predicting future trends in shallowly contaminated field sites that contain biodegradable contaminants (exemplified by Trecate and Gardermoen field sites).

3) To provide an example for translating the integrated monitoring strategy into recommendations for the decision making stakeholders and disseminate this to potential stakeholders and policy makers.

The aim of WP6 was to interact with stakeholders, to get to know how they would embark on this combined approach, which has resulted in an integration that advances non-invasive, invasive, and modelling approaches for contaminated sites.

Key results:

A meta-model has been developed throughout the project according to the 'description of work' to reveal how the different approaches may be combined, and what limitations are. The meta-model comprises of a number of steps to systematize knowledge about contaminant situation, geological setting and how various forcing conditions may affect the future situation of a particular site. 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. The meta-model has not been supplied as a CD. Primary reason is, during the discussions at the last two annual SoilCAM meetings, that such a digital 'prefab' tool would suggest certainty and accuracy, which the SoilCAM project cannot justify. Reason for the latter is that site specific aspects of both Trecate and Gardermoen (see above: significant results) limit the potential of non-invasive, geophysical technology. This limitation could not have been foreseen prior to the project, and is therefore a major, significant result.

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 (Trecate and Gardermoen). 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 with the use of large amounts of de-icing chemicals for winter maintenance and Case site 2) Trecate, with an accidental crude oil blow out and leakage down to the groundwater.

The Meta Models for the two case studies can be summarised in the following way: For the Gardermoen site, it was shown that flow and transport in the unsaturated zone is mainly vertical despite layering and heterogeneities. The local amount of infiltration determines the penetration depth. The geophysical time-lapse measurements are able to capture these changes. The application of nitrate as an (oxygen-) alternative electron acceptor is a challenging approach. Simulations have revealed that is extremely difficult to ascertain both that all contaminant is nitrate-mediated degraded, and that no nitrate is leached, the efficiency of such a remediation process is also difficult to monitor with geophysical methods. At the Trecate site the integrated approach showed that the rapid removal of the contaminants from the aqueous phase is due to biodegradation. Pore clogging due to the presence of trapped hydrocarbon and mineralisation, and Fe and Mn precipitation, seems to justify a decrease of hydraulic conductivity in the smear zone compared to the lower part of the saturated zone. This 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.

Whereas our work has been crucial for the conceptual and Meta-models of Trecate and Gardermoen, the ensuing understanding is pertinent for the optimal integration of invasive, non-invasive, geophysical methods and modelling approaches. This work explained why time-lapse monitoring at

Trecate can at best have modest results, in view of the specific (and explained) persistence of the pollution. It also explained that at Gardermoen, the flow in the coarse textured soil is vertical due to gravity, that more complex structure that becomes apparent from non-invasive, geophysical methods has a limited impact on flow and transport.

A decision tree was suggested that shows 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. In Figure 6 the decision tree for Gardermoen is presented as an example of how characteristic features of the site (combination of geological setting and contamination) determine applicability of different methods, invasive, non-invasive and modelling and how it in this case can be linked to Deliverables produced in this and other projects. This framework or web tool has the potential of disseminating outcome of similar projects in Europe. A further development of such a pan-European web tool could be maintained by a European organisation, such as JRC or similar. 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.

Potential impact and main dissemination activities and exploitation results

Soil and groundwater contamination represent major environmental problems worldwide. Control, monitoring and remediation is costly and complex. Hence these problems are demanding on understanding of the systems, and unpopular due to reported in-effectiveness. Besides process understanding, our limited possibilities to look into the subsoil are a major reason why management decisions are often frustrating. To enable improved process understanding and monitoring of contaminant fate and transport, many different disciplines were involved, such as biogeochemistry, hydrology, and geophysics. Such disciplines not only differ with respect to technical language, but also with respect to scale (from nanometer up to hundreds of meters), technology, and complexity. There are several compelling reasons, to raise this issue to the EU level, such as the limited availability in sufficient scientific knowledge on each of the important aspects of soil contamination monitoring and characterisation within each country, the broad range of ambient conditions from Nordic to Mediterranean climate zones, and the historical background of the various EU nations with regard to their capabilities to address such contamination. The soil types which are most vulnerable to contaminant transport are sandy soils which dominate throughout Europe. National pollution authorities have different strategies for acceptable levels of monitoring and methods for remediation.

There is often a long delay between when applicable methods for monitoring contaminant dispersion and degradation activities are identified within the scientific community and when the knowledge is made applicable for managers at a specific field location. To help reduce this time lag, SoilCAM incorporated end users such as Oslo Airport, BMI on behalf of Eni SpA (the oil company at Trecate) and pollution control authorities in both countries as an integral part of SoilCAM, it has however been a challenge to engage the contamination authorities to get involved in the project despite repeated invitations. Individual research scientists involved in the project are and will in the future be active in several local contamination problems and their experiences in the SoilCAM project therefore ensures a better geographical distribution of SoilCAM knowledge and combination of methods. In addition the Advisory Board (AB) members consisting of scientific experts from, representatives of national pollution authorities and stake-holders from countries of selected field sites. Through their involvement in the project they know about the work that has been done and can link others to the project groups via their activities. This experience was also active the opposite way, the AB members could provide links relevant to the SoilCAM researcher and hence increase knowledge of similar activities elsewhere. The personal contact is a very important since it can give access to unpublished experience. The involvement in the SoilCAM project has improved the competitiveness and has facilitated expansion of markets for the SMEs and Enterprise working with monitoring technologies. According to the UMS representative, the SoilCAM involvement was a contributing factor to their involvement and supply of lysimeter technology to the large German network on Terrestrial environmental observatories (TERENO). The involvement of scientists from two new member states of the EU, Hungary and Romania, is important because these countries represent a different history with respect to Soil Thematic Strategy contaminant issues, and the SoilCAM experience and network can be advertised in these countries. Hence the involvement in this project will promote further collaboration and the use of new technologies in these countries.

The research conducted addressed innovative, as well as proven technology, regarding non-invasive methods, which are completely integrated with the biogeochemical assessment of other partners, and, in the modelling components, with both geostatistical and forward/inverse modelling at different scales. Spatiotemporal heterogeneity was addressed through the use of geo-statistics and stochastic modelling of biogeochemical interaction and transport processes, measured at different scales with the geophysical, soil physical, chemical, and biological measurements. For the above reasons, recent advances are further developed, that can have a significant role in the European research platform of the near future. The challenge of conducting a full combination of methods as illustrated here is that some of the methods still require significant knowledge to interpret the results, as is the case for the geophysical data. To translate the observed geophysical data to meaningful information such as water saturation, contaminant concentration is still a topic for research, but it can already be used in a qualitative way without much additional data. This was clearly illustrated at Oslo airport, which consider continuation of the monitoring programme established during the SoilCAM project. Further experience at this site will also help distribute these monitoring strategies through the airport manager networks in Norway (AVINOR) and internationally.

The use and dissemination of foreground

Four-levels of dissemination was followed: i) direct dissemination of R&D results into the international scientific community, ii) exploitation of new potential applications through interested parties, iii) communication with government and stakeholder members of the Advisory Board, and iv) integration of results into popular layman version of Meta-Model of integrated prognosis/monitoring of contaminated sites. A web-page was created soon after the project had started and the site served as a library for communication of results among project partners, and for the general public. All partners were presented together with links to their institution's web-site. A common template for the report series for consistent style of document layout was made available early in the project. The management also provided guidelines for external presentations (Powerpoint files) and publications (Acknowledgement statement to SoilCAM and EU project number). The web-page consisted of an open part for the general audience as well as an internal page for project partners only (required login and password, the Advisory Board also had access to these pages). An email circulation list will be used to alert potential users in the internet networks whenever new information or products become available.

In the first year of the project, SoilCAM was presented at the ConSoil conference in Milan in 2008. This conference reaches a large number of stakeholders and consultants dealing with contaminated sites, hence it was a very appropriate arena to be presented.

Two sessions focusing on SoilCAM methodologies were organised in collaboration with ModelPROBE at the European Geosciences Union (EGU) general assembly (2011 and 2012). Many of the partners in both projects attended and contributed with oral and poster presentations. Both times the sessions were well attended by people not part of the project, hence reaching out to a larger scientific community.

All partners were also actively presenting SoilCAM results at a number of other international and national meetings and conferences. Through the involvement in SoilCAM some partners were also invited to take part in advisory boards of other research projects, ensuring links to related research and activities outside SoilCAM.

The experience and knowledge obtained through the project can provide useful input in the development and implementation of the guidelines for implementation of the Soil Thematic Strategy, concerning the soil contamination threat and is also highly relevant for EU Water Framework Directive (as both ground waters and surface waters may be strongly affected by pollutants from contaminated sites). On a world wide scale the following organisations may have relevant use of project disseminations: UNDP, UNEP, World Bank, UNESCO HELP Programme, and HELCOM.

All the involved Universities of the project are using the results and experiences (approaches and methods) from the SoilCAM project in their teaching curricula. A number of Master students and PhDs have completed their theses through the SoilCAM project.

Address of project public website and relevant contact details

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