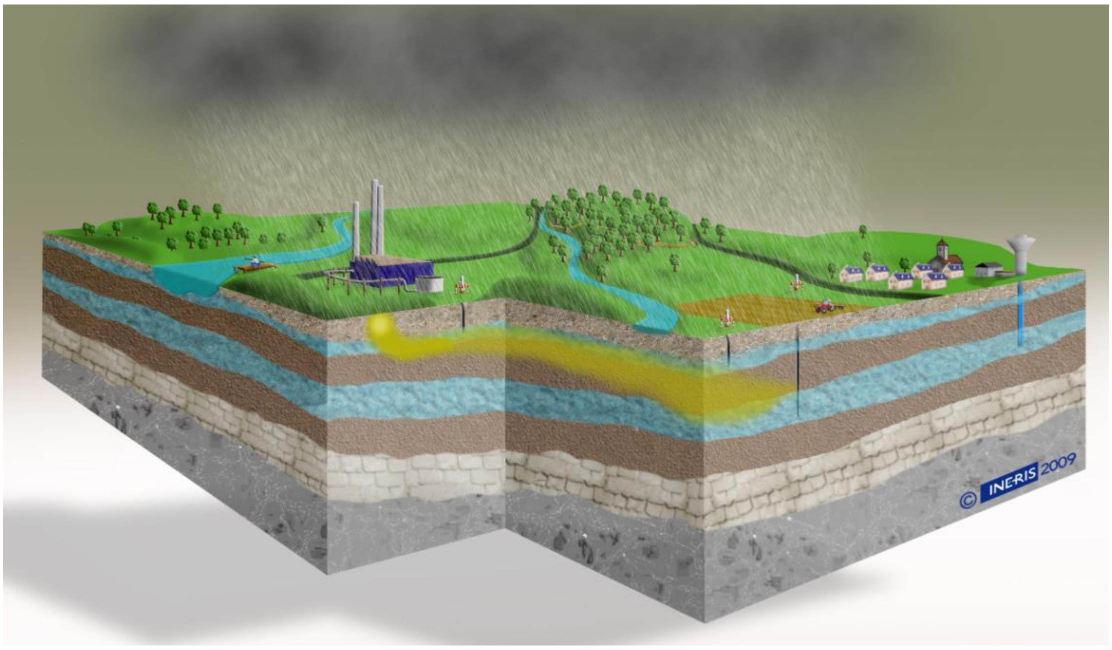
Long Term Monitoring Optimization (LTMO)

Concepts and tools



Investing in Opportunities

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INTERREG IVB

Summary

According to a previous literature review carried out by INERIS in 2009, evolution of a long-term monitoring (increase/decrease or stop of the monitoring) is performed usually on a "case by case" approach in many countries. Mainly because of the uniqueness of a site, the evolutions are usually based on different arguments that may affect the consistency of the approach. In order to harmonize practices and assist site managers and regulators, it seems necessary to develop a code of best practices.

The works carried out since 2009 by INERIS indicate the existence of two methods for the development and the optimization of groundwater monitoring on polluted site: the verification (UK-EA) and the Long Term Monitoring Optimization (US-EPA). The best professional judgment and the quantification approach are similar concepts to these two methods but the LTMO seems more complete (more detailed) and many applications are available today.

Optimization techniques have been applied in the USA to the design of monitoring networks for site characterization, detection monitoring, and compliance monitoring. In practice, however, optimization techniques are most often applied to Long-term monitoring (LTM) programs, as these programs typically provide well-defined spatial coverage of the monitored area, and have been implemented for a sufficient period of time to generate a relatively comprehensive monitoring history.

LTMO offers an opportunity to improve the effectiveness of the LTM in place by assuring that monitoring achieves its objectives with an appropriate level of effort. These methods are mostly used in the USA on large polluted sites, with very important network. INERIS analyzed the main methods and carried out tests on French polluted sites to evaluate and adapt the method to smaller sites, similar to those involved in CityChlor.

The results acquired on four real sites on which the process was carried out until the end by INERIS show that recommendations for changes in monitoring networks may differ depending on the method used, in particular with the quantitative approach. A qualitative approach is always necessary to analyze the data and to judge the relevance of the proposals of the quantitative analysis.

The qualitative approach is of interest to frame the process and provide guidance on the elements for reflection.

This report presents the first things to consider in the context of the evolution of monitoring: the minimum size of the network, the prerequisites and some adaptations proposed in the qualitative approach at this stage.

Indeed, work is continuing to draft a national methodology for specifying the issues in the context of an assessment of a monitoring (monitoring points and frequency, substances to be considered in particular).

Whatever the approach it turns out to be a tool for decision support, such as analytical or numerical modeling, the final stakeholders must make a choice, based on the results but also the uncertainties associated (must be clearly identified and presented).

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1 Introduction

1.1 CityChlor and the integrated approach

Space is scarce in Europe. Even in the subsurface it is getting busier. Large-scale soil and groundwater contamination with chlorinated solvents are often an obstruction for urban developments. The traditional way of dealing with polluted soil and groundwater does not work in all cases and is not economically and sustainable feasible. In urban environments multiple contaminations with chlorinated solvents are often mixed with each other and spread underneath buildings. This not only leads to technical problems for remediation, but also to liability and financial discussions and hence has an impact on society. An integrated approach and area-oriented approach is needed to tackle the problems. The CityChlor project has demonstrated that remediation and sustainable development can evolve on a parallel timescale.

An integrated approach combines all aspects that are relevant to tackle the problems that pollution with VOC in urban environment causes. Depending on area, site and context different aspects together or parallel to each other can be used. Not only technical solutions are included, but also socio-economical aspects as urban development, communication, financial and legal aspects, time, space, environment and actors (active & passive) have to be handled.

CityChlor did not remain at single case remediation, but looked at the area as a whole in a bigger context: the area-oriented approach. A technical approach that makes it possible to remediate, monitor and control multiple groundwater sources and plumes within a fixed area.

1.2 CityChlor and technical innovations

The managing of knowledge and technical innovations are one of the key to achieve a sustainable city development. A development project has to cope with loads of information coming from different disciplines in different (technical) languages and with different uncertainties. With chlorinated solvents, the knowledge about the pollution will always have a certain uncertainty that can have an impact on the course and the costs of the remediation. An efficient 'managing of knowledge' will try to decrease this degree of uncertainty.

CityChlor therefore also worked on the technical aspects of characterization and remediation. The conventional techniques that are applied for investigation and remediation have their limitations dealing with chlorinated solvents. Promising innovative techniques exist, but do not easily find their way to current application. This barrier is often caused by lack of knowledge on different levels. Experts and contractors do not always have the means to invest in experiments with new techniques, authorities are reluctant to accept techniques of which the results may be uncertain and clients aren't eager to pay for experimental techniques.

Dissemination of knowledge can break this deadlock. CityChlor therefore collected experiences from field application of innovative techniques and implemented itself a number of techniques in pilot projects. For the detailed outcomes, the reader is referred to the specific reports.

2 Context and aim of this guideline

Depending on management options, groundwater quality monitoring aims to inform about the presence of pollution, to understand its evolution, or guide and verify the effectiveness of management actions.
In the framework of the CityChlor project (polluted sites with chlorinated hydrocarbons in urban areas), long-term monitoring can be necessary. The present document deal with “how this long-term groundwater monitoring can evolve?”
According to a previous literature review carried out by INERIS in 2009, evolution of a long-term monitoring (increase/decrease the sampling frequency or the number of substances and monitoring wells, completely stop the monitoring) is performed usually on a "case by case" approach in many countries (INERIS, 2009). Mainly because of the uniqueness of a site, the evolutions are usually based on different arguments that may affect the consistency of the approach. In order to harmonize practices in France and in Europe and assist site managers and regulators, it seems necessary to develop a code of best practices.
The state of the art about long-term monitoring optimization has not identified a specific methodological tool in Europe (INERIS, 2009). But a recent approach for verification of remediation efficiency is available in the UK (for short-term, medium-term and long-term monitoring). In the USA, it appears that concept is underway for several years and feedback is important on Long-Term Monitoring Optimization (LTMO) (EPA, 2005).
Optimization techniques have been applied in the USA to the design of monitoring networks for site characterization, detection monitoring, and compliance monitoring (Loaiciga et al., 1992). In practice, however, optimization techniques are most often applied to Long-term monitoring (LTM) programs, as these programs typically provide well-defined spatial coverage of the monitored area, and have been implemented for a sufficient period of time to generate a relatively comprehensive monitoring history.
LTM is defined in the USA as a monitoring conducted after some active, passive, or containment remediation has been selected and put in place. It’s also used to evaluate the efficiency of the remediation as regard to its objectives (e.g., removal of groundwater contaminants, restoration of groundwater quality, etc.). After a site enters the LTM phase, site characterization is essentially complete, and the existing monitoring network can be adapted, as necessary, to achieve the objectives of the LTM program (Reed et al., 2000). However, site characterization networks often are not perfectly suited for LTM, because they were installed with a different purpose, to define the nature and extent of the problem when the site was not very well known. Sometimes, the money spent on LTM program provides incomplete information but in other situations the monitoring yields procures much more information than necessary.
LTMO offers an opportunity to improve the effectiveness of the LTM in place (during cycles: between 2 and 5 years,) by assuring that monitoring achieves its objectives with an appropriate level of effort. The optimization may identify inadequacies in the monitoring program, and recommend changes to achieve remediation objectives and limit potential impacts to the public and the environment. LTMO may also reduce monitoring costs.
These methods are mostly used in the USA on large polluted sites, with very important network. INERIS analyzed the main methods and carried out tests on French polluted sites to evaluate and adapt the method to smaller sites, similar to those involved in CityChlor.

3 Literature review, feedback in Europe and the USA

The state of the art regarding the optimization of monitoring programs for groundwater was carried out over Europe and the USA. In addition to the consultation of scientific publications and Internet sites, various people involved in the field of groundwater pollution have been contacted. Our request was for current practices in their respective countries and the existence of specific methodological tools on groundwater monitoring evolution (especially in the context of a polluted site).

As shown in Figure 1 about 81 people were initially contacted. 29 answers were received, for 27 countries (mainly in Europe).

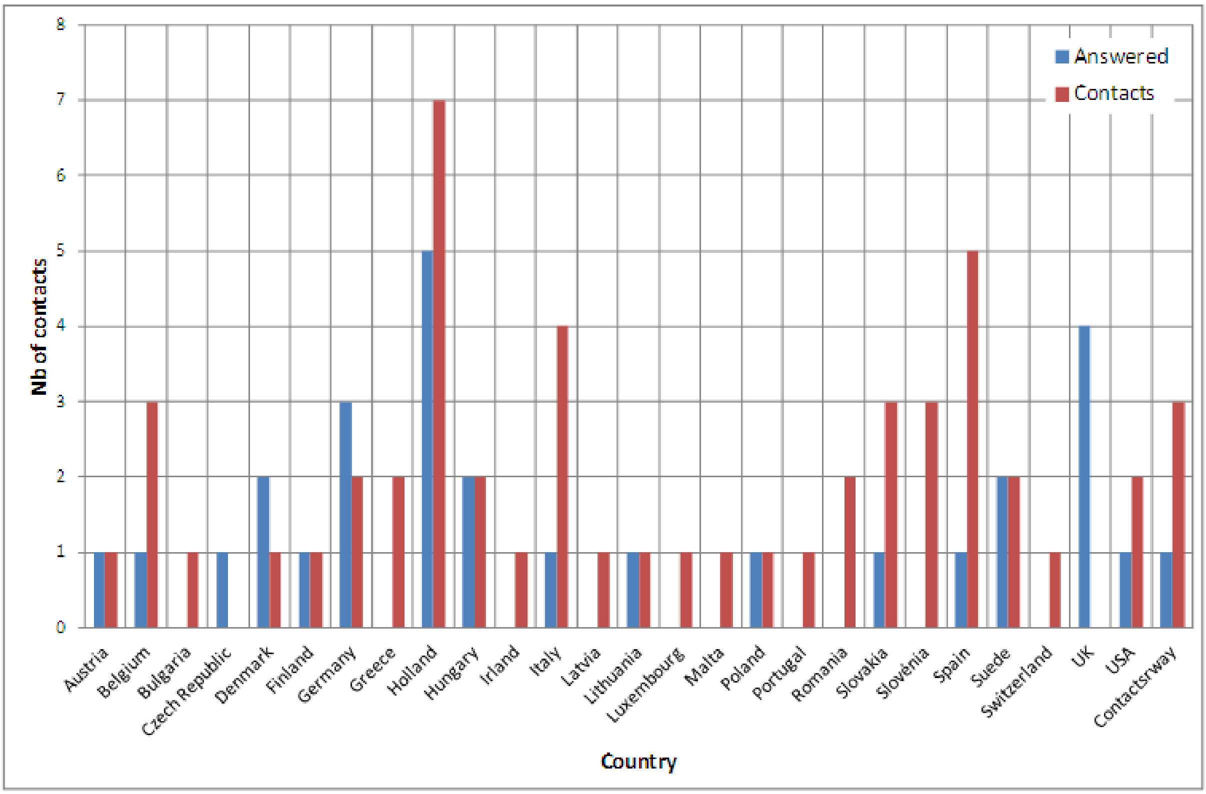


Figure 1 : Contacts and number of answers (modified from INERIS, 2009)

Although the number of answers collected thanks to this survey does not guarantee the completeness of the information shown, they nevertheless provide an indication. Thus, it appears that many studies on groundwater monitoring are ongoing in relation with the implementation of WFD (Water Framework Directive).

Works on verification of the effectiveness of remediation are in progress in the UK and works on long term monitoring and optimization are underway in the U.S.A for several years (LTMO).

The following sections introduce the concepts developed in the UK and in the USA.

3.1 Concept developed in the UK: verification (with short-term, medium-term and long-term monitoring)

This document provides guidance on designing and implementing verification activities to demonstrate the effectiveness and to increase confidence in the outcome of a remediation strategy.

Verification is defined by Environmental Agency (EA) as the process of demonstrating that the risk has been reduced to meet remediation criteria and objectives based on a quantitative assessment of remediation performance (Figure 2). The fundamental objective of a verification program is to proof that identified risks are successfully managed over pre-defined timescales and to stop monitoring.

> **Verification plan**
> A document that sets out the requirements for gathering data/evidence to demonstrate that remediation meets the remediation objectives and remediation criteria. It includes monitoring, sampling and testing criteria, and identifies all those records that should be retained to demonstrate compliance within the specification (e.g., field monitoring data, laboratory data, level surveys above and below capping layers).
>
> **Verification report**
> A document that provides a complete record of all remediation activities on site and the data collected as identified in the verification plan to support compliance with agreed remediation objectives and criteria. It also includes a description of the work (as-built drawings) and details of any unexpected conditions (e.g. contamination) found during remediation and how they were dealt with.

Figure 2 : Verification definitions (EA, 2010)

In many cases the duration of post-remediation monitoring is short enough to enable verification leading to project closure, with no need for further monitoring or maintenance. However, groundwater monitoring may need to be extended over a period of years, possibly decades, to demonstrate that long-term remediation objectives are achieved (Figure 3).

The verification report may be interim in nature. Indeed, monitoring and verification activities may need to continue until all objectives are achieved.

A list of lines of evidence related to the verification of remediation is proposed. This list includes in particular the achievement of field measurements to complement and correlate laboratory analysis, data acquisition for the immobilization of pollutants (sorption), the analysis of concentrations of intermediates and final (bio)degradation products (Figure 4).

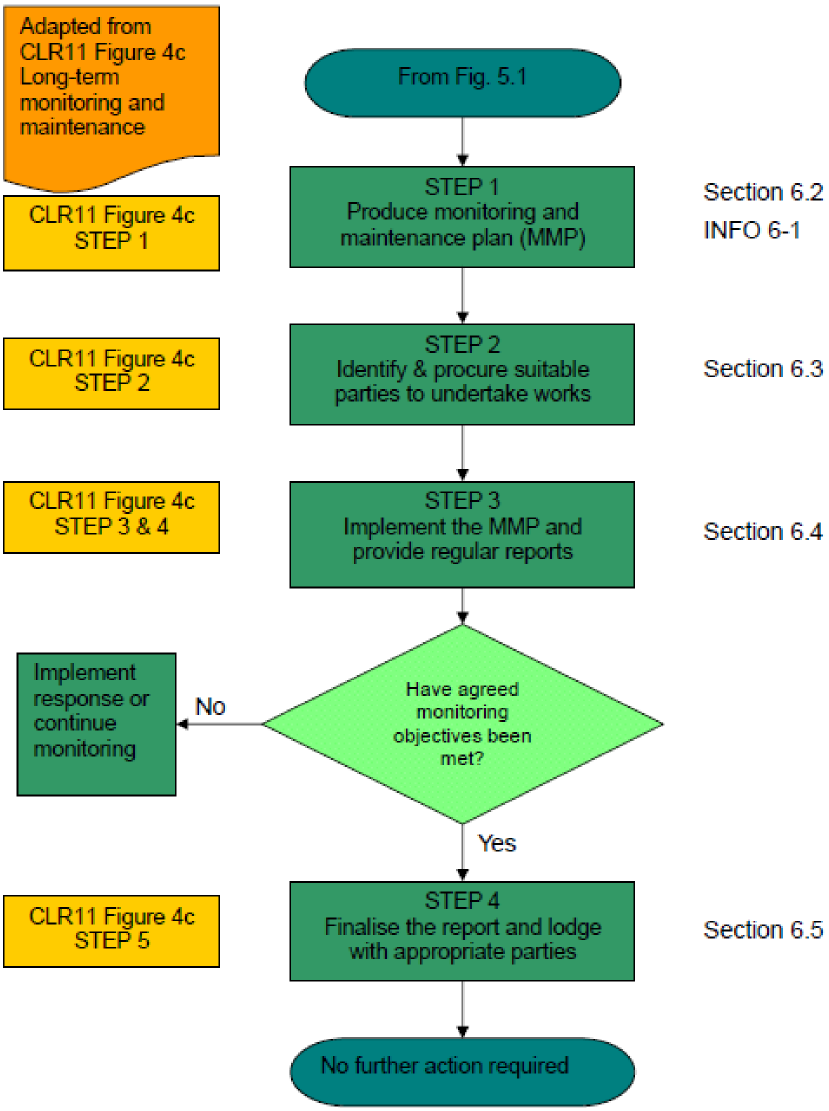


Figure 3 : Flowchart for long-term monitoring (EA, 2010)

Box 3.3 Examples of lines of evidence.

Field measurements to support laboratory analysis.

Field measurements to test model predictions.

Data on the physical properties of barrier systems.

Data to show that contaminants have been immobilised.

Data on intermediate and final breakdown products, such as evolution of carbon dioxide during biodegradation.

Concentration of conservative components and/or internal markers.

Process parameters, e.g. pH, temperature, moisture content.

Bioassays to indicate a reduction in toxicity of soil.

Data to show the location and volume of treated materials.

Additional sampling outside the remediation area to quantify any spread of contaminants beyond the remediation area.

Geophysical survey data to delineate a contaminant plume.

Data on nutrients and/or electron acceptor/donor concentrations that are required to drive a biological process.

Inspection of infrastructure (for example fencing, signage) where land access or water-use restrictions are in place.

Figure 4 : Examples of lines of evidence (EA, 2010)

To interpret "lines of evidences" EA presents "weight of evidence" approaches that are taken to assess multiple information sources used for risk assessment. The approaches are reproduced below with comment on their applicability to remediation. This is an evolving area of environmental decision-making, and the aim should be to apply as objective a method as possible to integrate individual lines of evidence. In many cases this will rely on sound, and defensible, professional judgement. A key to integration will be to maximise the use of information collected before or in preparation of the remediation strategy to understand how best individual lines of evidence can be linked.

As we shall see, best professional judgment and quantification are similar concepts to these which are developed in the USA. But LTMO seems more complete (more detailed) and many applications are available today (see annex 1).

Table 1: "Weight of evidence" approaches (EA, 2010 from Linkov et al. 2009)

Approach	Description	Applicability to remediation
Listing evidence	Presentation of individual lines of evidence without attempt at integration	Adds little benefit to remediation decision-making.
Best professional judgement	Qualitative integration of multiple lines of evidence	Subjective integration – may be defensible on a case-by-case basis.
Causal criteria	A criteria-based method for determining cause and effect relationships	An example is correlating operating conditions with remediation performance or correlating hydraulic conductivity with moisture content-dry density curves for engineered containment.
Logic	Standardised evaluation of individual lines of evidence based on qualitative logic methods	Uses a previously outlined method, for example the guidance on monitored natural attenuation (Environment Agency 2000).
Scoring	Quantitative integration of multiple lines of evidence using simple weighting or ranking	Not likely to be used, although statistical methods such as double sampling or ranked set sampling (Gilbert, 1987; USEPA, 1995) may be used to integrate large (field observations) and small (laboratory data) data sets.
Indexing	Integration of lines of evidence into a single measure based on empirical models	An example is integration of assays to produce an index of the biological quality of a treated soil, for example Dawson *et al.* (2007).
Quantification	Integrated assessment using formal decision analysis and statistical methods	This is the ultimate level of "weight of evidence" and, for remediation, is currently aspirational and in many cases unnecessary.

3.2 Approach developed in the USA: Long Term Monitoring Optimization

Concerning the evolution of groundwater monitoring, the United States are working on optimizing of long-term monitoring for several years. The Long-Term Monitoring (LTM) is defined in the U.S. EPA report of 2005 entitled "Roadmap to Long-Term Monitoring Optimization (LTMO)" as a follow-up process after treatment of the source of pollution

(assets, liabilities or confinement) and used to assess to what extent the objectives of remediation are achieved over time (EPA, 2005).
Optimization techniques have been applied to the design of monitoring networks for site characterization, detection monitoring and compliance monitoring (Figure 5) but they are most often applied to LTM programs after remediation (if they provide well-defined spatial coverage of the area they are monitoring and have been implemented for a period of time sufficient to generate a relatively comprehensive monitoring history).

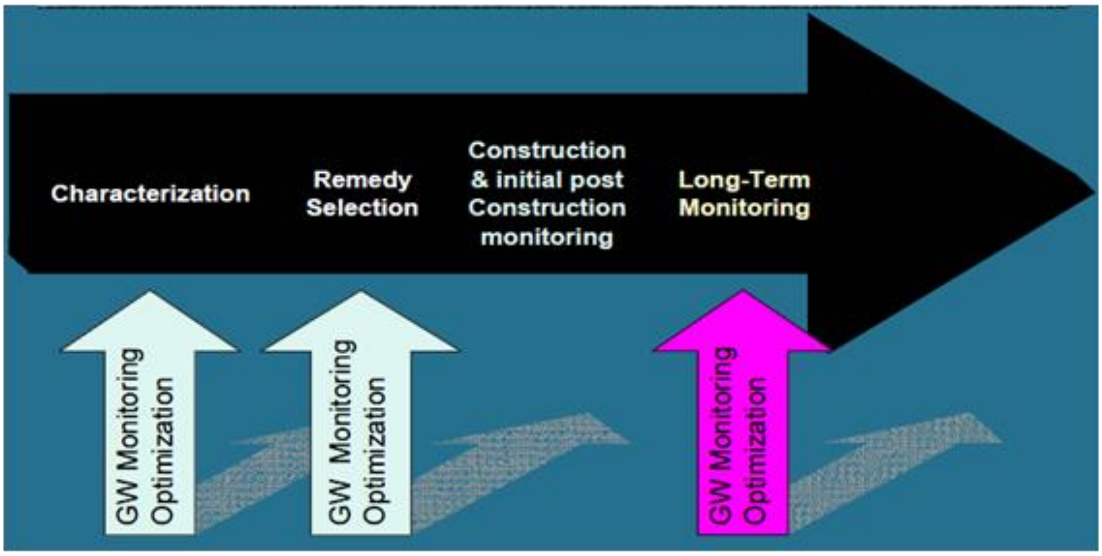
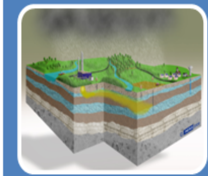


Figure 5: Applications of an optimization approach (LTMO) in USA

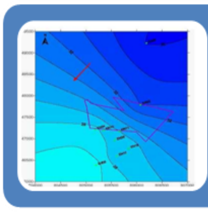
Work is still on-going but according to the U.S. EPA there are many ways to complete this process and various guides, documents, tools are available and have been successfully applied on sites.
Many references are given including case studies. (annex 1).

7 Steps to optimize a long-term groundwater monitoring are defined as follows (EPA, 2005; Figure 6). We will detail LTMO in the next section.



Clearly define and document the current monitoring program

- Define monitoring objectives, parameters/constituents measured, sampling and analytical methods, frequency and location of sampling, and monitoring program costs. In addition, ensure that the monitoring program meets criteria. This information is used to establish the baseline conditions of the monitoring evaluation to be completed during the LTMO



Examine existing data

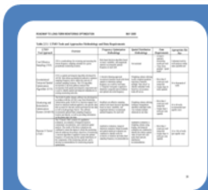
- Determine the amount, types and quality of data available to discover data gaps and decide what types of analyses will be feasible. Ensure that the data are defensible, come from reputable sources, and meet the purpose for which they were collected

Determine if the site is a candidate for a detailed LTMO

- Establish whether the site meets minimum threshold criteria for LTMO. The potential success of implementing LTMO recommendations can be greatly enhanced by introducing and discussing the idea of optimization with site managers and stakeholders early in the LTMO process

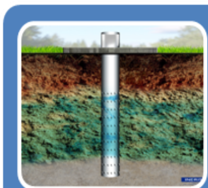
Determine the type of evaluation

- Evaluate whether a stand-alone qualitative evaluation or a qualitative evaluation, with supporting quantitative temporal and/or spatial statistical analysis, is appropriate for the site



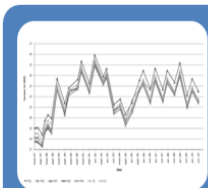
Select the LTMO methods/tools

- Assess and select the LTMO methods and tools available to optimize the monitoring program



Perform the optimization

- Apply the selected tools and methods to develop recommendations for the monitoring program's optimal well distribution and sampling frequency



Assess and implement the results

- Check the reasonableness of the LTMO results, confirm stakeholder buy-in, and implement the recommendations

The time interval between periodic LTMO evaluations will vary depending upon site conditions; typically, programs should be evaluated at least every 2 to 5 years

Figure 6 : 7 Steps to optimize a long-term monitoring (EPA, 2005)

4 Summary of LTMO concepts and tools

LTMO offers an opportunity to improve effectiveness of the LTM by assuring that monitoring achieves its objectives with an appropriate level of effort (eliminate redundancy, reduce sampling frequency, change sampling method…).
What does LTMO includes?

- data management;
- evaluation of sampling locations;
- evaluation of sampling frequency;
- evaluation of sampling methods;
- evaluation of analytical program.

This approach can result in increase or decrease in effort, depending on site conditions and objectives. This should involve site manager, all stakeholders and population depending on the issues.
Two types of evaluation can be used:

- qualitative evaluation: using technical expertise, professional judgment;
- quantitative evaluation: temporal and spatial analysis, using statistical, numerical analysis.

According to the previous works there is no definitively right way to conduct a LTMO, because various guidance documents, tools, standardized methods and approaches exists and have been applied successfully (annex 1).

4.1 Qualitative evaluation – Best professional judgment

Qualitative aspects include especially a review of the site conceptual model, hydrogeology and contaminant distribution, sampling and analytical methods, data management and regulatory framework.

Table 2 presents priority and useful information, potential data sources and the associated purpose of the data required to conduct a LTMO.

Typical factors considered in developing recommendations are given in Table 3.

Remark and recommendation (section 6):
In order to carry out a first test concerning a possible evolution of the monitoring program, the following requirements should be met (in porous media):

- the monitoring network should be composed of at least 5 wells;
- at least 2 sampling campaigns should be carried out per year;
- at least 4 years of monitoring should be available.

Table 2: Data needed checklist (EPA, 2005)

Data Needed	Potential Data Source(s)	Purpose
Current monitoring program description	– Monitoring program plan – Recent monitoring report	Establish baseline conditions, purpose of monitoring program, rationale for monitoring wells, and sampling and analytical methods
Well locations and coordinates	– Database – Well construction information – – Site maps	Determine spatial distribution of monitoring points
Analytical data and COC sampling results	– Database – Monitoring reports – Site investigation reports	Define concentrations of COCs in space and time, Confirm primary COCs, Verify data quality
Potentiometric surface configuration – groundwater flow direction, velocity, and gradient	– Recent monitoring report – Document providing facility and site information (e.g., CSM, remedial investigation [RI] or RCRA facility investigation [RFI] report, or similar) – Database	Evaluate direction and rate of groundwater movement and contaminant migration
Hydrogeologic conditions	– Document providing facility and site information (e.g., RI/RFI or similar document) – CSM – Hydrogeologic testing results	Identify geologic or other controls on occurrence and movement of groundwater and dissolved COCs
Well completion intervals and hydrogeologic zone	– Database – Well construction diagrams – Drilling logs	Determine depth of sample collection in groundwater system and potential hydrogeologic and stratigraphic zones
Cleanup goals and regulatory limits	– ROD – Decision document – RI/RFI	Establish cleanup limits and areas of concern requiring monitoring
Potential receptor and compliance point locations	– RI/RFI – ROD – Site map – Site visit	Identify areas and/or migration directions of concern, e.g., nearby public supply wells

RCRA: Resource Conservation and Recovery Act
ROD: Record of Decision
CSM: Conceptual Site Model

Table 3: Qualitative evaluation (EPA, 2005)

Qualitative Monitoring Network Optimization Decision Logic

Reasons for Retaining or Adding a Well in a Monitoring Network	***Reasons for Removing a Well From a Monitoring Network***
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time.	Well provides spatially redundant information with a neighboring well (e.g., same constituents, and/or short distance between wells).
Well is important for defining the lateral or vertical extent of contaminants.	Well has been dry for more than two years, and there is no expectation for the water levels to recover in the foreseeable future.
Well is needed to monitor water quality at a compliance point or receptor exposure point (e.g., sentinel well for municipal wells).	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals.
Well is important for defining background water quality.	

Qualitative Monitoring Frequency Decision Logic

Reasons for Increasing Sampling Frequency	***Reasons for Decreasing Sampling Frequency***
Groundwater velocity is high.	Groundwater velocity is low.
Change in concentration would significantly alter a decision or course of action.	Change in concentration would not significantly alter a decision or course of action.
Well is close to source area or operating remedy.	Well is far from source area or operating remedy.
Whether concentrations will change significantly over time cannot be predicted, or there is no ready explanation for recent irregular or contradictory data.	Concentrations are not expected to change significantly over time, or contaminant levels have been below cleanup objectives for some period of time.

4.2 Quantitative evaluation

Newer quantitative methods are proposed to evaluate sampling locations and frequencies, see Table 4.

Statistics and geostatistics are employed to evaluate redundancies or deficiencies in monitoring network. Some information about data requirements and appropriate site size are given in Table 4.

A quantitative evaluation is based on:

- temporal statistical evaluation (frequency optimization methodology): contaminant concentrations measured at different times (temporal data) can be examined graphically or using statistical tests to evaluate dissolved-contaminant plume stability (trends, annex 2);
- spatial statistical evaluation (spatial distribution methodology): repeated application of geostatistical estimation techniques, using tentatively identified sampling locations, then could be used to generate a sampling program that would provide an acceptable level of uncertainty regarding to the distribution of pollutants with the minimum possible number of samples collected.

Table 4: Quantitative evaluation - LTMO tools and approaches methodology and data requirements (EPA, 2005)

LTMO Tool/Approach	*Overview*	*Frequency Optimization Methodology*	*Spatial Distribution Methodology*	*Data Requirements*	*Appropriate Site Size*
Cost Effective Sampling (CES)	CES is a methodology for reviewing and assessing the lowest-frequency sampling schedule for a given groundwater monitoring location.	Rule-based decision algorithm based on trend, variability, and magnitude statistics recommends optimal frequency at each well.	Not included	– At least 6 quarterly monitoring results per well – Clean down-gradient "guard wells"	Unlimited (well-by well analysis) within same operable unit
Geostatistical Temporal/Spatial Optimization Algorithm (GTS)	GTS is a spatial and temporal algorithm developed by AFCEE that utilizes geostatistical methods to optimize sampling frequency and to define the network of essential sampling locations. The GTS algorithm incorporates a decision pathway analysis that incorporates both spatial and temporal components and is used to identify spatial and temporal redundancies in existing monitoring networks.	1) Iterative thinning approach reconstructs baseline trends with fewer samples to determine optimal frequency on a well-by-well basis. 2) Temporal variogram is applied to determine composite autocorrelation and optimal site-wide frequency.	Weighting scheme utilizing locally weighted quadratic regression examines multiple "time slices" to identify redundant wells based on cost-accuracy trade-off curves.	– More than 8 events per well (temporal) – Greater than 30 wells (spatial)	30 to thousands of wells
Monitoring and Remediation Optimization System (MAROS)	The MAROS public domain software was developed in accordance with the AFCEE Long-Term Monitoring Optimization guide. MAROS is a decision support tool based on statistical methods applied to site-specific data that accounts for relevant current and historical site data as well as hydrogeologic factors. The software recommends optimal future sampling frequency, location and density, as well as providing information on the plume state over time.	Modified cost-effective sampling method (rule-based decision algorithm based on trend, variability, and magnitude statistics) recommends optimal frequency for each well.	Weighting scheme utilizing Delaunay triangulation identifies redundant wells. Can evaluate multiple chemicals at one time.	– More than 4 events per well (temporal) – Greater than 6 wells per zone (spatial)	40 to 80 wells recommended (per aquifer zone)
Parsons 3-Tiered LTMO	The 3-Tiered LTMO consists of a qualitative evaluation, an evaluation of temporal trends in contaminant concentrations, and a statistical spatial analysis. The results of the three evaluations are combined to assess the degree to which the monitoring network addresses the primary objectives of monitoring. A decision algorithm is applied to assess the optimal frequency of monitoring and the spatial distribution of the components of the monitoring network, and to develop recommendations for monitoring program optimization.	Qualitative evaluation, temporal statistical evaluation (Mann-Kendall), and spatial statistical evaluation are combined to identify wells for exclusion or retention and make final sampling frequency recommendations.	Qualitative evaluation, a weighting scheme using kriging, and temporal evaluation are combined to identify the relative spatial value of each well And make final network distribution recommendations.	– More than 4 events per well (temporal) – Greater than 10 wells per zone (spatial)	10 to 100s of wells (per aquifer zone)
Adaptive Environmental Monitoring System (AEMS)	AEMS performs sample redundancy analyses and enables smart online data assessment and adaptive monitoring of environmental systems. The sample redundancy analyses use multi-objective optimization to remove spatial, temporal, or simultaneous spatial and temporal redundancies, including an option to explicitly account for uncertainty in the historical data. A suite of spatial and/or temporal models can be built from historical data and used within the redundancy analyses to find the optimal set of samples that meet user-specified performance objectives. The models can also be used to automatically assess new data in online systems, sending alerts when data indicate significant deviations from recent spatial and/or temporal trends. The adaptive optimization system can also recommend optimal locations and times for additional sampling to respond to any observed anomalies.	Genetic algorithms are used to search for optimal designs given a temporal interpolation model or multiple spatial interpolation models built from historical data.	Genetic algorithms are used to search for optimal designs given a spatial or spatiotemporal interpolation model built from historical data using geostatistical, statistical, or analytical approaches. AEMS is currently the only optimization software to perform simultaneous spatial and temporal optimization, as well as allowing optimal tradeoffs to be identified among user-specified performance objectives and allowing explicit consideration of uncertainty.	– More than 8 events per well (temporal) – More than 15 events per well (spatial) – More than 30 events per well (combined spatial and temporal optimization)	Unlimited

LTMO approaches offer an opportunity to improve the effectiveness of the LTM in place and may also reduce costs of monitoring (Table 5).

Table 5: Costs of monitoring / optimized sites

Site	Original sample frequency (events/yr)	Optimized sampling frequency (percent reduction) (cost reduction/yr)
Fort Lewis	180	113 – 110 (37 – 39 %) ($ 34 600 – $ 36 500)
Mc Clellan	34	31.5 – 17 (7 – 50 %) ($ 300 – $ 2 550)
Long Prairie	51	36 – 24 (30 – 53 %) ($ 4 000 – $ 6 700)

5 Methods tests

Following the study previously carried out by INERIS in 2009, data was collected on 8 French sites (Figure 7), with groundwater pollution by organic and inorganic substances and a monitoring network. All sites were monitored for about 10 years at the beginning of our study and the aquifers were of sedimentary rock (porous media). Several LTMO methods were tested on 4 sites particularly in different conditions in order to provide feedback and recommendations.

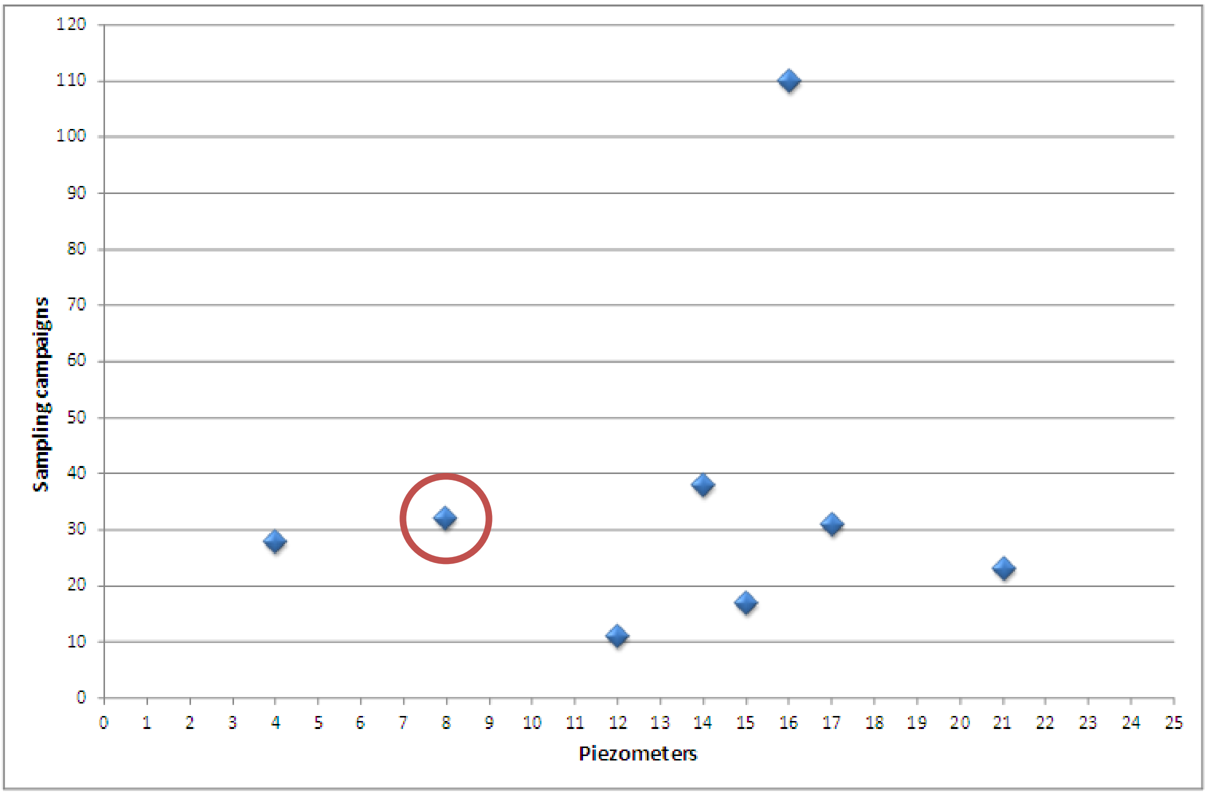


Figure 7 : Illustration of the range of networks (piezometers and sampling campaigns) for 8 sites used for tests

All results are not presented here but the site circled in red in Figure 7 is presented below because it corresponds to a typical configuration in urban area, with less than ten monitoring wells and few substances sampled twice a year (hydrocarbon pollution with monitoring of tracers or global settings). This example does not cover chlorinated hydrocarbons but it is the most representative to highlight the qualitative and quantitative approaches and to provide feedback in order to give recommendations on LTMO.

As shown in the figure below two tests were conducted on this site and the main information are presented.

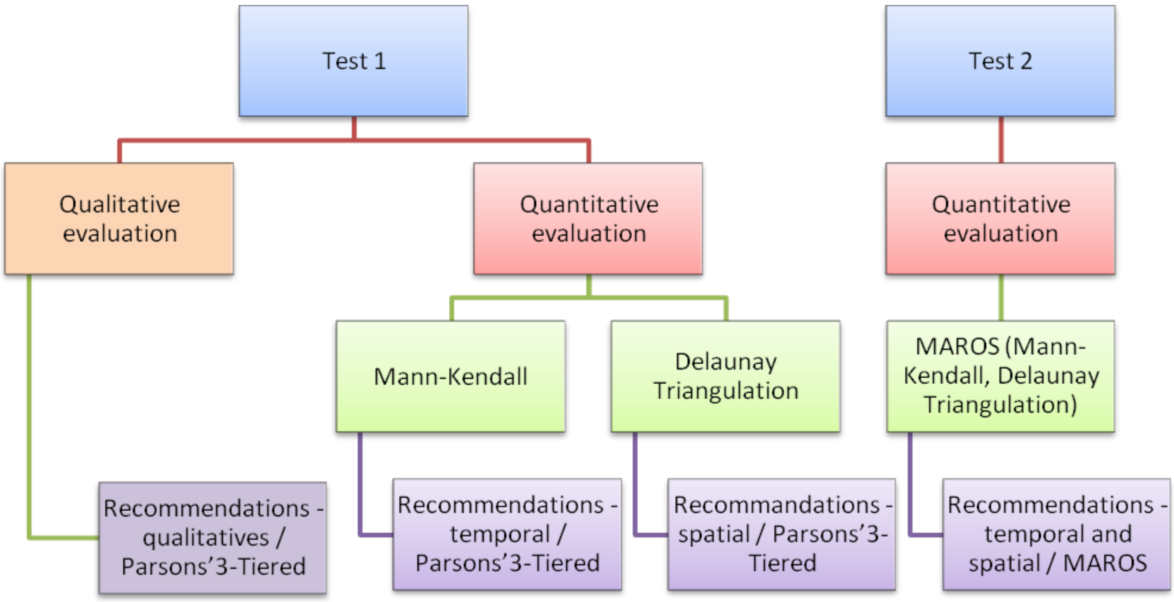


Figure 8 : Tests conducted by INERIS on this site

A first test was performed by coupling the results of the qualitative assessment with those of the statistical and geostatitical tools (Mann-Kendall and Delaunay triangulation).
Concerning Mann-Kendall the recommendations are made via a decision tree used with the tool Parsons 3-Tiered.
A second test consisted in using the tool MAROS and following its recommendations without conducting a qualitative evaluation before (the software provides the final recommendations to be made to the network).
Test 1 is detailed below, results are compared with test 2.

5.1 Brief overview of the data available and evaluations

5.1.1 Site background information

The site was an in-service industry producing lubricants. These activities started in the 80s.
The hydrogeological context is mainly sedimentary with chalk groundwater.
Groundwater quality monitoring began in 1997 and the last measurement campaign considered in this work was conducted in the first semester of 2012.
8 wells (Figure 9) are or have been part of the groundwater quality monitoring network (chemical and piezometric measurements). Pz 4, Pz 5 and Pz 6 are not used for sampling (piezometric measures).

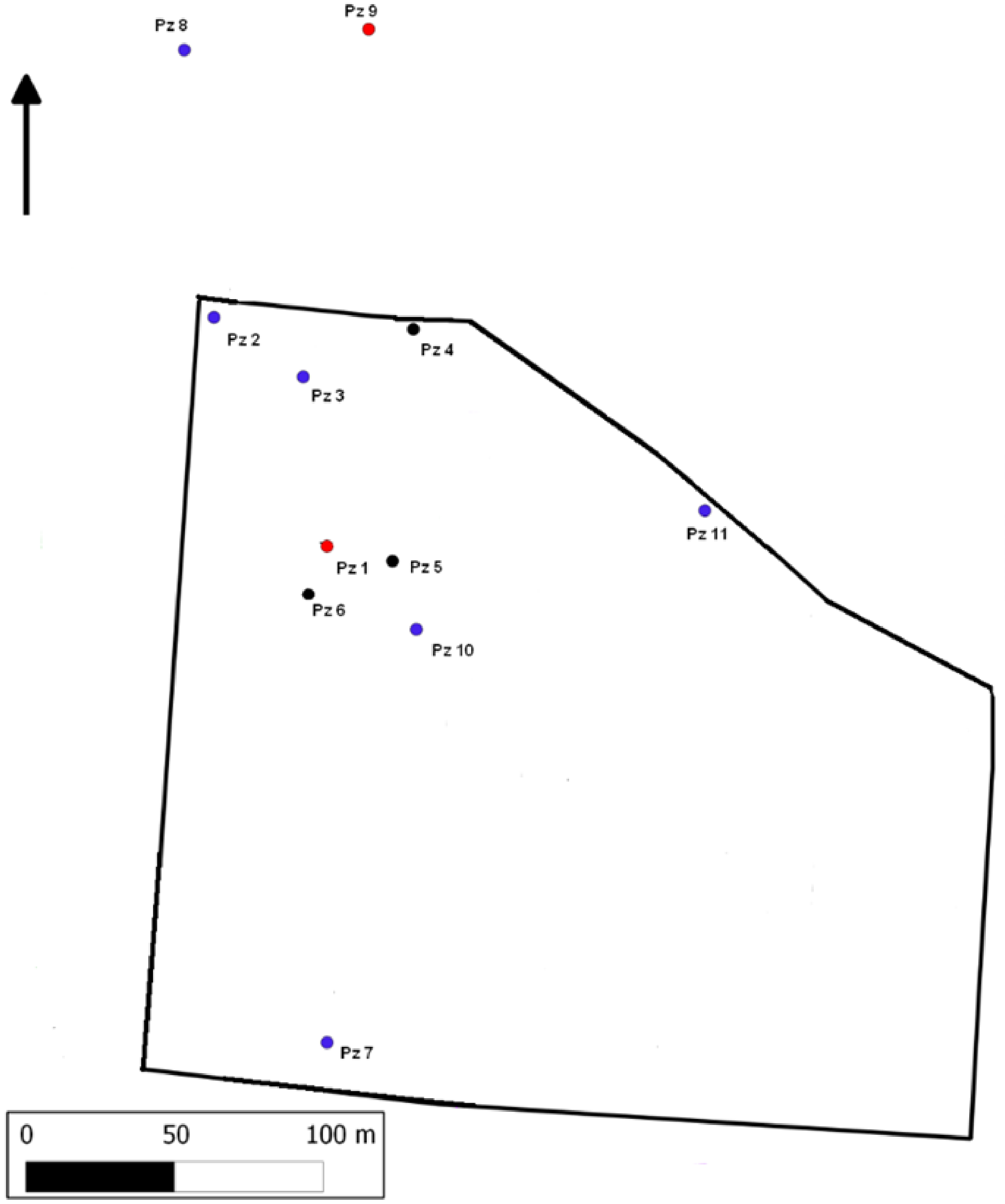


Figure 9 : Pilot site (8 wells for sampling)

The piezometric level varied from 6 to 9 meters deep depending on the season. The direction of flow not varies.
Substances measured are Benzene (Figure 10), Toluene, Xylenes (BTX), naphthalene and total petroleum hydrocarbons (TPH).

Table 6 summarizes evolutions of the monitoring program of groundwater quality. Table 7 give information about quality data for substances studied (number of samples, detection intervals...).

It appears that the xylenes and naphthalene are substances that are regularly observed at concentrations above the threshold values (40.9 and 46.8% respectively). Total hydrocarbons are below the detection limit in almost 71% of the samples analyzed since 1997 and all wells in the network but detected in two piezometers (Pz 2 and Pz 3) only (plume). Overall the site only Pz 2 and Pz 3 detect pollution, the rest of the piezometer network detect only very rarely concentrations above the detection limits of substances.

Screen intervals are depicted graphically on Figure 11; the portions that are monitored by wells are not consistent across the site.

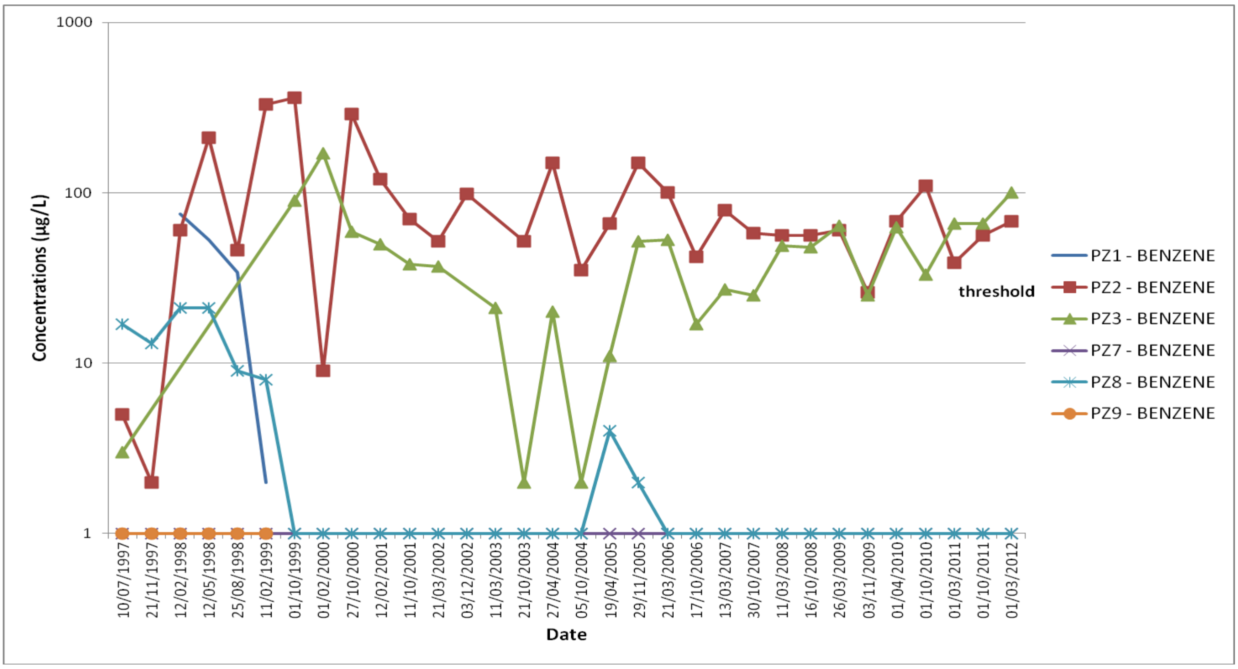


Figure 10 : Benzene results (1997-2012)

Table 6: Monitoring evolution

<table>
<tr><th>wells</th><th>wells screen (deep m)</th><th></th><th>First program 1997</th><th>Change 1998</th><th>Change 1999</th><th>Change 2000</th><th>Change 2002</th><th>Change / current program (since 2009)</th></tr>
<tr><td>Pz 10</td><td>5,5-12,5</td><td rowspan="8">1994 contamined soil treatment</td><td colspan="6">TPH</td></tr>
<tr><td>Pz 11</td><td>4,3-12</td><td colspan="4">drilled in 2000</td><td colspan="2">TPH</td></tr>
<tr><td>Pz 1</td><td>4,5-15</td><td rowspan="2">BTX – TPH – PAH with Naphtalène – metals</td><td rowspan="2">BTX – TPH – PAH with Naphtalène</td><td>BTX</td><td colspan="3">remote</td></tr>
<tr><td>Pz 2</td><td>4,5-15</td><td colspan="4">BTX – TPH - Naphtalène</td></tr>
<tr><td>Pz 3</td><td>4,5-12,2</td><td colspan="6">BTX – TPH – Naphtalène</td></tr>
<tr><td>Pz 7</td><td>5-12</td><td rowspan="3">BTX – TPH – PAH with Naphtalène – metals</td><td rowspan="3">BTX – TPH – PAH with Naphtalène</td><td colspan="4" rowspan="2">BTX – TPH - Naphtalène</td></tr>
<tr><td>Pz 8</td><td>6,5-12</td></tr>
<tr><td>Pz 9</td><td>6,5-12</td><td>BTX – TPH</td><td colspan="2">TPH</td><td>remote</td></tr>
</table>

Table 7: Summary of occurrence of groundwater contaminants of concern

Parameters	Samples	Concentrations - Interval detecting	Concentration < LOQ* (%)	Concentration > water thresholds limits (%)	Number of wells that exceeded
Benzène	135	1-360 (µg/l)	48,8	30,1	3
Toluène	136	1-5000 (µg/l)	55,8	5,9	2
Xylènes	137	2-2300 (µg/l)	52,5	40,9	3
Naphtalène	126	0.1-500 (µg/l)	48,4	46,8	4
TPH	227	50-76000 (µg/l)	70,9	22,9	2

**LOQ : Limit Of Quantification*

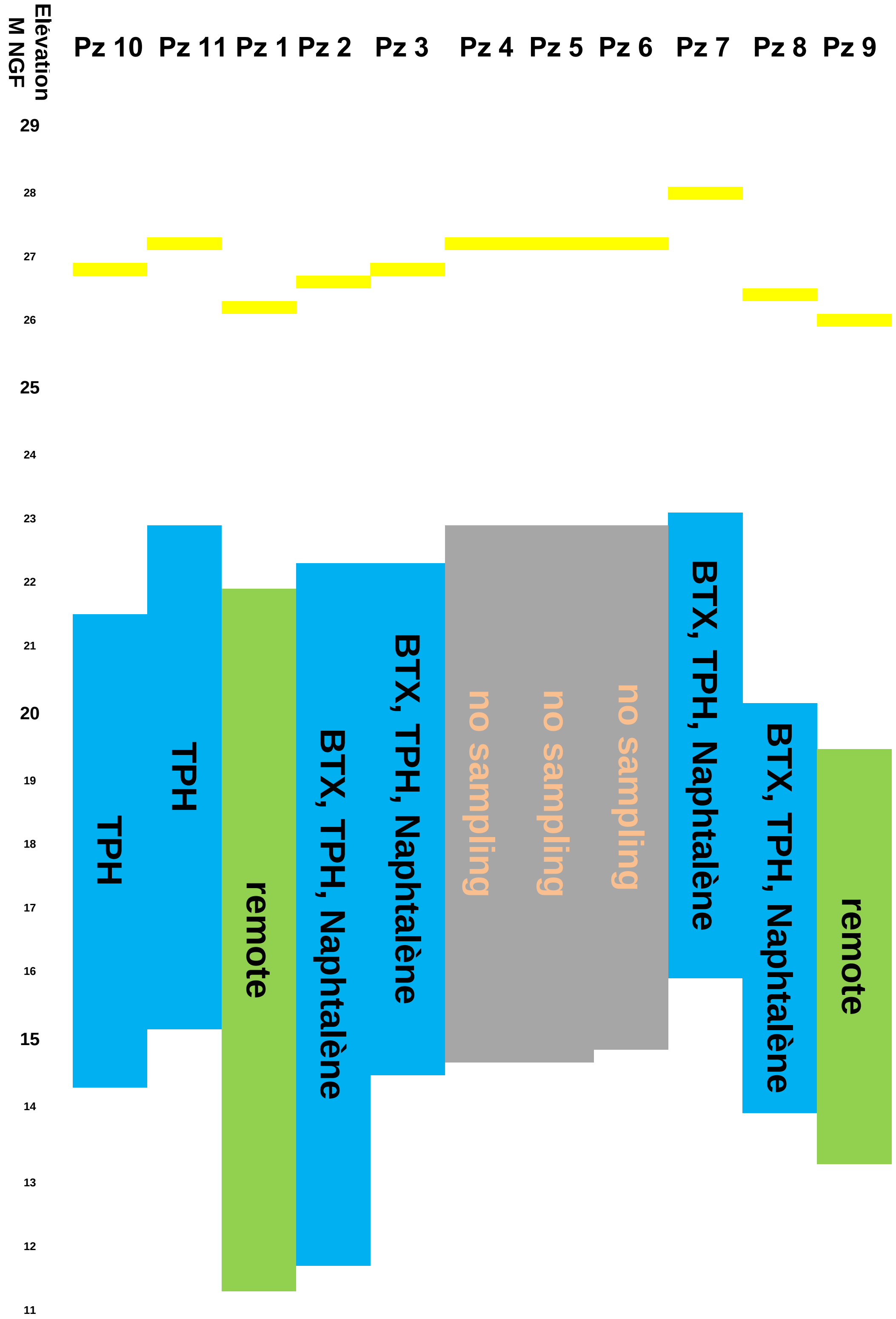


Figure 11: Wells screen elevations (in NGF meters, topography in yellow)

5.1.2 Qualitative evaluation

Typical factors considered in developing recommendations for example to retain a well in, or remove a well from, or all others changes are summarized in Table 3.
Based on the data presented above and others not presented here, the main conclusions of this evaluation are:

- hydrodynamic conditions of the site have not changed over time (flow direction and gradient similar, no occurrence around the site seems to have changed the conditions);
- wells are suitable for monitoring LNAPL (screen levels);
- monitoring TPH on Pz 10 and Pz 11 can be stopped (the results do not show concentrations above the LOQ TPH since monitoring began), replaced by naphtalene, BTX;
- monitoring on Pz 2, Pz 3 and Pz 8 can’t be modified (measured concentrations for benzene notably are still above the concentrations in upstream Pz 7 and water thresholds limits);
- Pz 4 can be sampling to get more information on the site (lateral);
- monitoring electron acceptors and electron donors may give information on biodegradation process (natural attenuation).

This recommendations are based on available data regarding current (and assumed future) site conditions. Changing site conditions (e.g., periods of drought or excessive rainfall or changes in hydraulic stresses) could affect contaminant fate and transport. Therefore, the LTM program should be reviewed if hydraulic conditions change significantly (with new pumping well for example), and revised as necessary to adequately track changes in the magnitude and extent of pollution in environmental media over time.

5.1.3 Quantitative evaluation

<u>Temporal analysis</u>
Visual identification of trends in plotted data may be a subjective approach, particularly if the concentration data do not exhibit a uniform trend, but are variable through time (annex 2).
The possibility of arriving at incorrect conclusions can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including regression analyses and the Mann-Kendall test for trends.
The Mann-Kendall nonparametric test is well-suited for evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data.
The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a statistically significant temporal trend is exhibited by contaminant concentrations detected through time in samples from an individual well. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually from plotted data. In this analysis, a 90% confidence level is used to define a statistically significant trend.

This statistical tool can be useful for example in the following cases:

- a trend of increasing contaminant concentrations in groundwater at a location between a contaminant source and a potential receptor exposure point may represent information critical in evaluating whether contaminants are migrating to the exposure point, thereby completing an exposure pathway.
- a trend of decreasing contaminant concentrations at the same location may be useful in evaluating decreases in the area extent of dissolved contaminants, but does not represent information that is critical to the protection of a potential receptor.
- a trend of decreasing contaminant concentrations in groundwater near a contaminant source may represent important information regarding the progress of remediation near, and downgradient from, the source.

By contrast, the absence of a statistically significant (as defined by the Mann-Kendall test with a 90% confidence level) temporal trend in contaminant concentrations at a particular location within or downgradient from a plume indicates that virtually no additional information can be obtained by frequent monitoring of groundwater at that location, in that the results of continued monitoring through time are likely to fall within the historic range of concentrations that have already been detected. Continued monitoring at locations where no temporal trend in contaminant concentrations is present serves merely to confirm the results of previous monitoring activities at that location.

The temporal trends and relative location of wells can be weighed to determine if a well should be retained, excluded, or continued in the program with reduced sampling. Figure 12 presents a flowchart demonstrating the method for using trend results to draw these conclusions.

Table 8 give results of this analysis. These results confirm qualitative evaluation. Abandoning Pz 9 is also validated by this approach. However, Pz 1 should be monitoring, this conclusion is due to the small amount of data available for this well (3 years of monitoring).

Statistical results must be read taking into account other factors that may affect the recommendations.

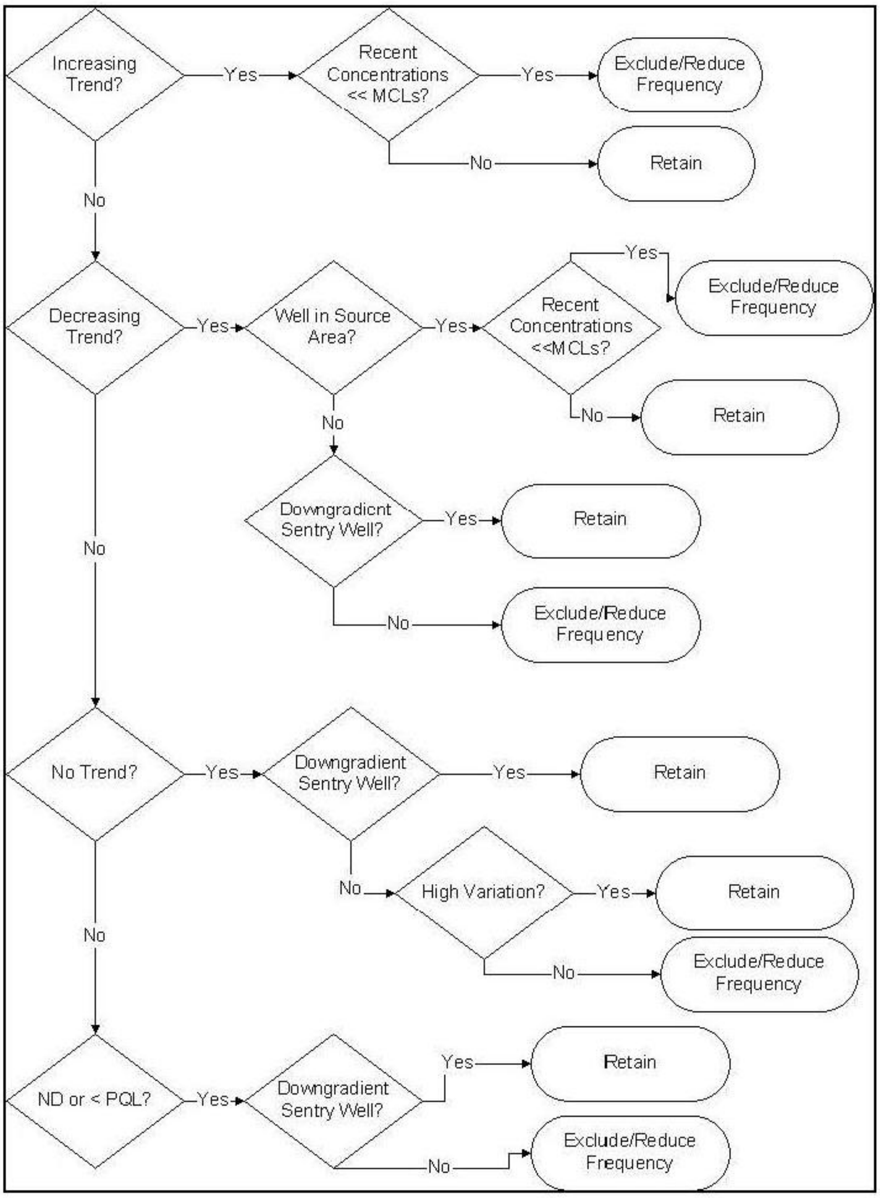


Figure 12 : Temporal trend decision - Flowchart for long-term monitoring (Wash King Laundry Superfund Site, annex 1)

Table 8: Temporal analysis results (quantitative evaluation)

wells	In current program?	Situation / plume	Contaminants					Results	
			Benzène	Toluène	Xylènes	Naphtalène	TPH	Retain	Remove
Pz 1	no	upstream	D	NT	NT	NT	NT	X	
Pz 2	yes	plume area	S	D	S	I	D	X	
Pz 3	yes	plume area	NT	S	NT	NT	D	X	
Pz 7	yes	upstream	S	D	D	S	S	X	
Pz 8	yes	downstream	D	D	D	D	NT	X	
Pz 9	no	downstream	S	S	S	NT	S		X
Pz 10	yes	upstream	-	-	-	-	S		X
Pz 11	yes	upstream (lateral)	-	-	-	-	S		X

D: Decreasing, NT: No Trend, S: Stable, I: Increasing

Spatial analysis

Spatial statistical techniques can also be applied to the design and evaluation of groundwater monitoring programs to assess the quality of information generated during monitoring and to evaluate monitoring networks. This analysis may eliminate “redundant” wells or add wells in areas with high concentration uncertainty.

The Delaunay method is developed based on Delaunay triangulation, which is the triangulation of a point set with the property that no point in the point set falls in the interior of the circumcircle of any triangle in the triangulation. All nodes (potential well locations) are joined by the blue lines, which form the edges of Delaunay triangles. The yellow lines form many polygons called Thiessen polygons or Voronoi diagrams, which are the dual parts of Delaunay triangles.

This method is presented in detail in the annexes of the manual software MAROS (http://www.gsi-net.com/en/software/free-software/maros.html).

The application of this method gives the following results for benzene and TPH.

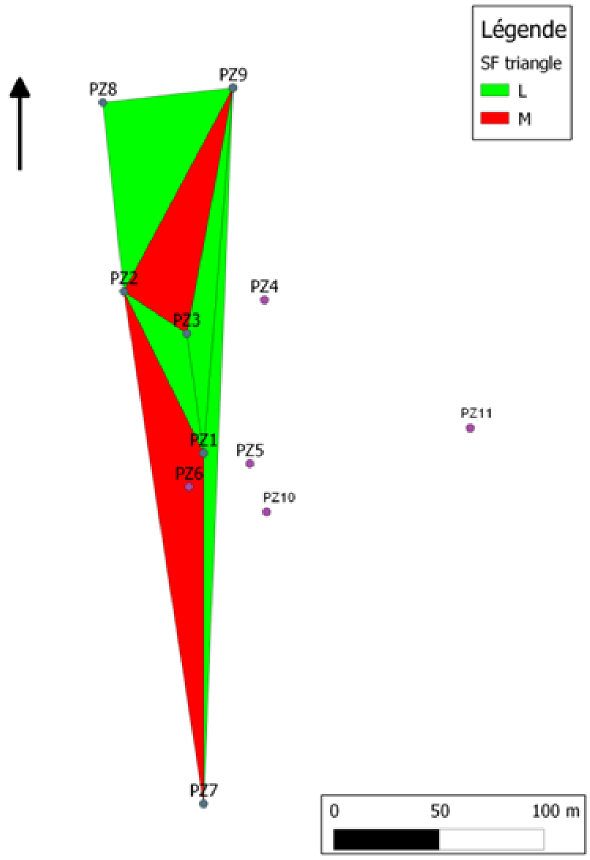


Figure 13 : Spatial analysis results Benzene (quantitative evaluation)

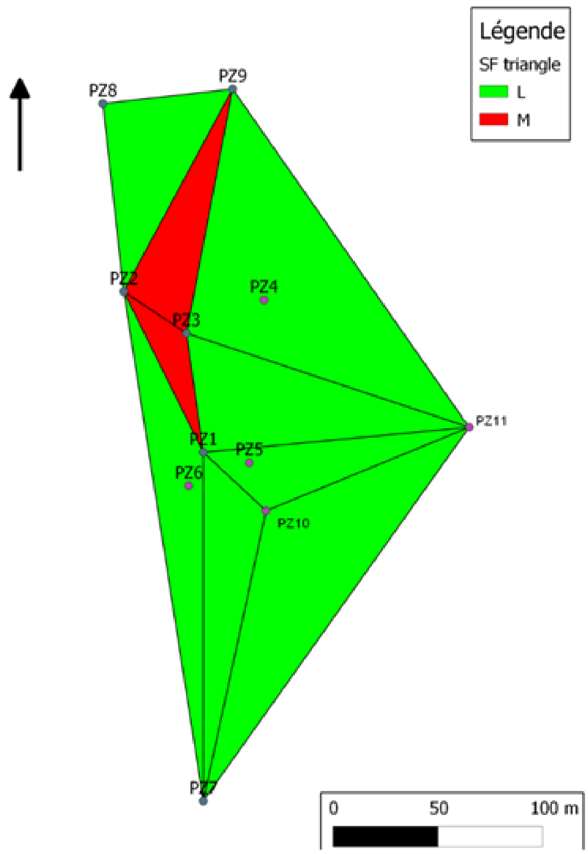


Figure 14 : Spatial analysis results TPH (quantitative evaluation)

The proposed areas of operations to implement new piezometers are shown in green.
The main conclusions of this analysis are:

- adding Pz 4 could significantly increase the accuracy of the plume delineation;
- Pz 5 and Pz 6 are also found in areas of potential additions wells;

One of the biases inherent to this method of interpolation is that it puts more weight to point limits. For example Pz 8 is estimated only through Pz 2 and Pz 9 and its estimation error will be larger than Pz 3 (estimated by Pz 1, Pz 2, Pz 9 and Pz 11).
This technique, like kriging, must be used on a dense network with wells close to limit bias by giving too much weight to sink away.
Network density used here does not seem suited for the approach.

5.2 Synthesis qualitative and quantitative evaluation (test 1)

The results of the qualitative, temporal, and spatial evaluations for the groundwater monitoring are presented below (Table 9 and Table 10).

They were combined and summarized in accordance with the decision logic shown on Figure 12 and these recommendations:

- each well retained in the monitoring network on the basis of the qualitative hydrogeologic evaluation was recommended to be retained in the refined monitoring program;
- those wells recommended for exclusion from the monitoring program on the basis of all three evaluations, or on the basis of the qualitative and temporal evaluations (with no recommendation resulting from the spatial evaluation) were recommended for removal from the monitoring program;
- if a well was recommended for removal based on the qualitative evaluation and recommended for retention based on the temporal or spatial evaluation, the final recommendation was based on a case-by-case review of well information;
- if a well was recommended for retention based on the qualitative evaluation and recommended for removal based on the temporal and spatial evaluation, the well was recommended to be retained, but the possibility of reducing the sampling frequency was evaluated based on a case-by-case review of well information

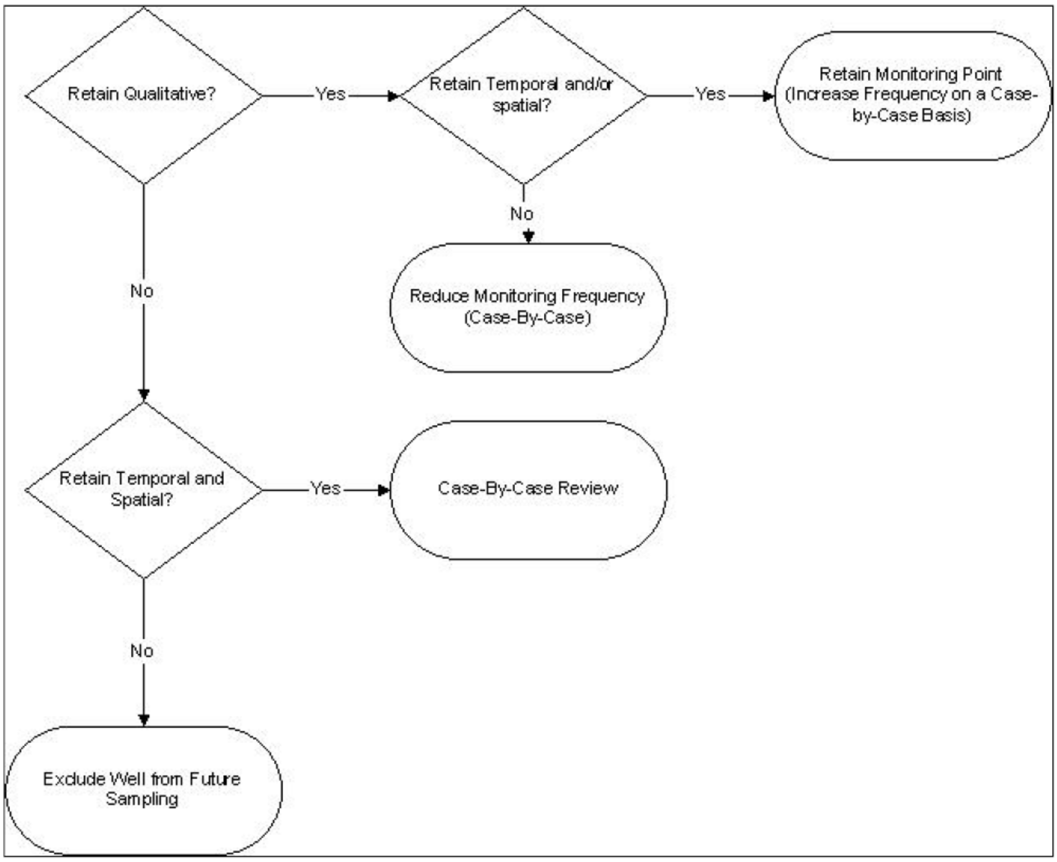


Figure 15 : Combined temporal and spatial analysis - quantitative evaluation (Wash King Laundry Superfund Site, annex 1)

Table 9: Evaluations results – test 1 (qualitative and quantitative)

wells	Situation / plume	Frequency	Qualitative evaluation				Evaluation quantitative				Recommendations (see Figure 15)		
							Temporal		Spatial				
			Remove	Retain	Substances	Frequency	Excluded / reduced	Retain	Remove	Retain	Remove	Retain	Frequency
Pz 10	upstream	Every 6 months		X	replace by naphtalene, BTX	No change	X			X		X	Every 6 months
Pz 11	upstream (lateral)	Every 6 months		X		No change	X			X		X	Every 6 months
Pz 1	downstream	No sampling	-	-	-	-		X	-	-	-	-	-
Pz 2	plume area	Every 6 months		X	No change	No change		X		X		X	Every 6 months
Pz 3	plume area	Every 6 months		X	No change	No change		X		X		X	Every 6 months
Pz 4	near plume area	No sampling		X	add naphtalene, BTX	Every 6 months	-	-	-	-		X	Every 6 months
Pz 5	upstream	No sampling	-	-	-	-	-	-	-	-	-	-	-
Pz 6	upstream	No sampling	-	-	-	-	-	-	-	-	-	-	-
Pz 7	upstream	Every 6 months		X	No change	No change		X		X		X	Every 6 months
Pz 8	downstream	Every 6 months		X	No change	No change		X		X		X	Every 6 months
Pz 9	downstream	No sampling	-	-	-	-	X		-	-	-	-	-

Table 10: Evaluations results – test 1 – Recommendations comments

wells	Recommendations comments
Pz 10	Monitoring naphtalene, BTX
Pz 11	
Pz 1	-
Pz 2	Plume monitoring – no evolution
Pz 3	
Pz 4	add Pz 4 with naphtalene, BTX
Pz 5	-
Pz 6	
Pz 7	upstream monitoring – no evolution
Pz 8	downstream monitoring – no evolution
Pz 9	-

5.3 Comparison between tests results (test 1 and test 2)

Test 1 presented above showeds that under an optimization approach, the qualitative assessment may be sufficient. Indeed, the qualitative study recommended an increase in monitoring of BTX and naphthalene parameters (Pz 10 and Pz 11) instead of the parameter TPH and the addition of Pz 4 to the monitoring network too.

The spatial and temporal analyzes (quantitative approach) dido not provide additional recommendations to the qualitative assessment: they confirmed those made previously. Thus, the analyses allowed firstly to validate the hypothesis formulated in terms of trends in the qualitative evaluation with the use of Mann-Kendall, then it also validated the changes previously made to the monitoring program including the removal of Pz 9 (stable trends, without going over the threshold value). Spatial analysis using the Delaunay triangulation did not provide additional information, but it allowed identifying an area to improve the existing network (near Pz 4).

The recommendations of test 2, obtained using the software MAROS seemed partially different. On the one hand, the frequency of monitoring could be reduced to a campaign per year according to these results. On the other hand, the analysis did not find monitoring points to remove, even taking into account Pz 1 and Pz 9, the decision to remove these wells was not justified according MAROS.

The difference between the recommendations made by test 1 and test 2 came from the decision matrix used in the case of test 2 by MAROS, which is different from decision trees used for test 1 (from the Parsons 3 – Tiered method).

However, test 2 considered the network as not sufficient for the proper characterization of the pollution plume. This was consistent with the conclusion of the spatial analysis conducted via the Delaunay triangulation in test 1 at the end of which an area to add a tracking point is proposed (near Pz 4).

The advantages of the qualitative assessment are that it considers the specific context of the site and includes multiple factors, though it depends on the experience of the hydrologist in charge of the study which can lead to biases in data interpretations. The quantitative evaluation identifies data gaps and is less likely to be biased. However, to be effective, this quantitative evaluation requires a certain rigor to acquire and format data, test different tools and be able to judge the relevance of the results (based on uncertainties).

The results acquired on this site as well as on the others on which the process was carried out until the end, therefore show that recommendations for changes in monitoring networks may differ depending on the method used, in particular for the quantitative approach. In both cases, a qualitative analysis is necessary to analyze the data and to judge the relevance of the proposals of the quantitative analysis. The financial aspects were not taken into account in this study.

Recommendations are given thereafter to carry out such an evolution process.

6 Recommendations in the context of « Citychlor » (COHV, Urban zone)

Following the tests, the following recommendations can be made. In order to carry out a first test concerning a possible evolution of the monitoring program, the following requirements should be met (in porous media):

- the monitoring network should be composed of at least 5 wells;
- at least 2 sampling campaigns should be carried out per year;
- at least 4 years of monitoring should be available.

6.1 Remarks / prerequisites

Notes on prerequisites to any change in monitoring:

- the control of the source (or sources) is essential for any decrease and therefore to stop monitoring. Moreover, the presence of secondary sources initially untreated can be especially highlighted during the monitoring by observing peak pollution due to unusual rainfall events (flushing effect or remobilization of pollutants); these sources should also be controlled;
- the objectives and criteria must be defined (in relation to regulatory thresholds, geochemical background / local environmental control, and other criteria for acceptability on the basis of a cost / benefit analysis).

Notes on data and information necessary to consider the development of monitoring

- the quantity but also the quality of the monitoring data is essential especially when it comes to change and stop monitoring;
- enough data on concentrations allow the use of a statistical tool to identify trends. Trend analysis should be conducted over several seasonal cycles and focused on "normal" conditions or reflect "abnormal"events (eg heavy rainfall may cause remobilization of pollutants);
- the hydrogeological context (porous media, fractured / fissured, karst) must be sufficiently known in particular to evaluate the transfer time of a source area to an observation point, a stake;
- the behavior of pollutants is very variable depending on the substance considered, mobility (dissolved, particulate, gas), the retention of substances (eg PAHs sorption on organic matter) or (bio) degradation in other substances more toxic (ex. trichlorethylene with the appearance of vinyl chloride). These phenomena are studied;
- in the case of pollutants that (bio) degrade the byproducts must be followed as well as the pollutants identified in the source zone.

Notes relating to the sustainability of the situation:

- the control of the site use and memory are important to sustain the situation observed over several years and avoid any modification of hydrogeological conditions and geochemical due to anthropic action. Indeed, a change in flow (rate, direction) may occur due to the establishment of a pumping whose radius of influence disturbs the studied area and affects the transfer of pollutants;

- hydrogeological and geochemical conditions must be stable and sustainable over time before considering stopping monitoring.

6.2 Adaptation of the qualitative approach

As indicated, the qualitative approach seems at first most relevant to have a framed and reproducible method. Compared to information obtained from the method, INERIS has made adaptations and especially regarding the questions to be asked to consider various aspects, such as natural attenuation with monitoring the introduction of donor and acceptor electron, or the taking into account of the tides.
The following tables summarize this information.

Table 11 : Evolution related to monitoring points

Retain	Groundwater well is used to monitor and improve the understanding of changes in concentrations observed over time Groundwater well is important to define the extent of the plume Groundwater well is necessary to monitor the water quality at a potential stake Groundwater well can monitoring groundwater underlying to see its quality Groundwater well allows us to characterize relations between groundwater / river and / or tidal Groundwater well is necessary to define the quality of groundwater upstream of polluted zone. Upstream point should be integrated into all campaigns as the first criterion for assessing an impact
Remove	Groundwater well provides redundant information with another one near this one for several campaigns (minimum 4 years) Groundwater well is dry and the situation is unlikely to change in the coming years. Rely on regional piezometric or constructive conditions (drawdown, civil engineering) to assess the sustainability of the situation The concentrations of monitored parameters arebelow the predefined threshold values or detection limits of the laboratory for several campaigns (minimum 4 years). Rely on regional piezometric or constructive conditions (drawdown, civil engineering) to assess the sustainability of the situation Groundwater well is not adapted to the requirements of the monitoring. Not deep enough, screened interval is not positioned to monitor NAPL ...
Creation	Hydrodynamic conditions and flow direction changed due to natural or anthropogenic reason Result analysis on several campaigns shows that pollution will spread outside the area covered by the network Malfunction is observed. Vandalism, clogged srceened interval, unintentional destruction ... One or more control points are not suitable for monitoring requirements.Not deep enough, screened interval is not positioned to monitor NAPL ...

Table 12 : Evolution related to number of monitoring parameters / substances

Increase	A secondary pollution is highlighted and further diagnosis is carried out Monitoring of degradation products was not considered when defining initial network In the case of in situ remediation by injection, monitoring of injected product is carried out Monitoring of electron acceptors and donors is relevant in assessing natural attenuation
Decrease	The concentrations did not change significantly, or the concentrations are below the predefined threshold values for several years (minimum 4 years). Rely on regional piezometric or constructive conditions (drawdown, civil engineering) to assess the sustainability of the situation The remediation of a source may cause the disappearance, not appearance or stabilization of some compounds. Rely on regional piezometric or constructive conditions (drawdown, civil engineering) to assess the sustainability of the situation Redundancy between information. Behavior of similar pollutants families , analysis of specific substances, semi-volatile screening ...

Table 13 : Evolution related to monitoring frequency

Increase	Hydrodynamic conditions and flow direction changed due to natural or anthropogenic reason. Increase sustainable over time of flow velocity associated with the activation of an industrial pumping A change of uses within the area of influence of the site. A new stake is to be considered: catchment that provide drinking water or residential with private wells downstream Groundwater well is located near the source area where rehabilitation works will be undertaken Significant changes or contradictory (concentrations and / or piezometric measures) are observed and can not be explained
Decrease	Hydrodynamic conditions and flow direction changed due to natural or anthropogenic reason. Decrease sustainable over time of flow velocity associated with the activation of an industrial pumping A change of uses within the area of influence of the site. An existing stake is no longer to be considered: catchment that provide drinking water is abandoned in a sustainable way Piezometer is far from the source area or upstream, source has been treated, treatment whose efficiency is followed by other wells Concentrations did not change significantly, or they are below the predefined threshold values for several years (minimum 4 years). Rely on regional piezometric or constructive conditions (drawdown, civil engineering) to assess the sustainability of the situation

7 Conclusion and further work

The works carried out since 2009 by INERIS and pursued here indicate the existence of two methods for the development and the optimization of groundwater monitoring on polluted site: the verification (UK-EA) and the Long Term Monitoring Optimization (US-EPA). The best professional judgment and the quantification approach are similar concepts to these two methods but the LTMO seems more complete (more detailed) and many applications are available today.

The LTMO consists of two evaluations: a qualitative and a quantitative approach. Qualitative aspects include especially a review of the site conceptual model, hydrogeology and contaminant distribution, sampling and analytical methods, data management and regulatory framework. Typical factors considered in developing recommendations are notably some questions to ask itself. Quantitative analyses include statistics and geostatistics and are employed to evaluate redundancies or deficiencies in monitoring network.

The advantages of the qualitative assessment are that it consideres the specific context of the site and includes multiple factors, though it depends on the experience of the hydrologist in charge of the study and that can lead to biases in the interpretations of data. The quantitative evaluation identifies data gaps and is less likely to be biased However, to be effective, this quantitative evaluation requires a certain rigor to acquire and format data, test different tools and be able to judge the relevance of the results (based on uncertainties).

The results acquired on four sites on which the process was carried out until the end by INERIS, one example is presented here, show that recommendations for changes in surveillance networks may differ depending on the method used, in particular with the quantitative approach. A qualitative approach is always necessary to analyze the data and to judge the relevance of the proposals of the quantitative analysis.

The qualitative approach is of interest to frame the process and provide guidance on the elements for reflection.

This report presents the first things to consider in the context of the evolution of monitoring: the minimum size of the network, the prerequisites and some adaptations proposed in the qualitative approach at this stage.

Indeed, work is continuing to draft a national methodology for specifying the issues in the context of an assessment of a monitoring (monitoring points and frequency, substances to be considered in particular).

Whatever the approach it turns out to be a tool for decision support, such as analytical or numerical modeling, the final stakeholders must make a choice, based on the results but also the uncertainties associated (must be clearly identified and presented).

8 References

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9 Annexes

Annex 1

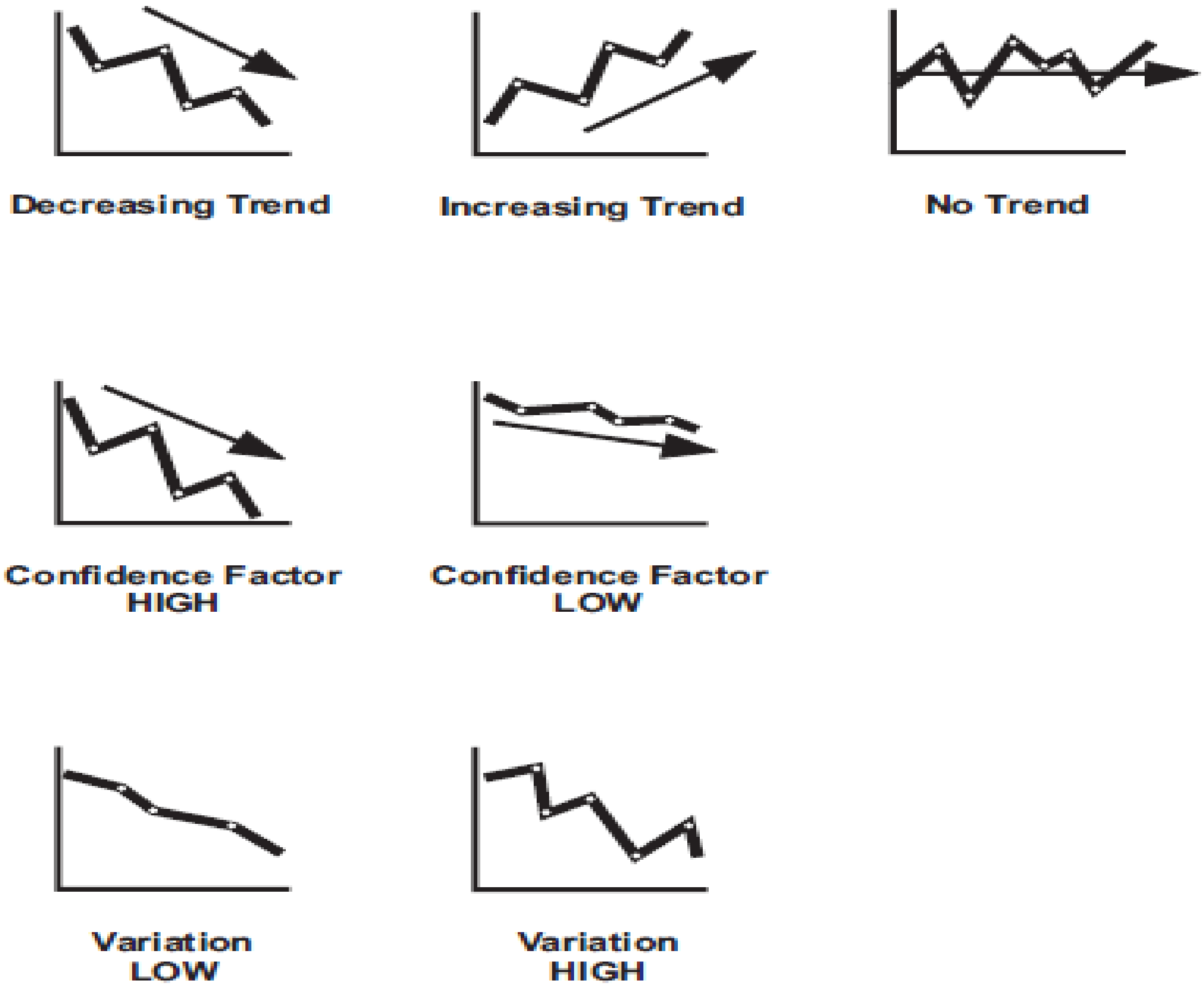
LTMO references and case studies

(http://clu-in.org/)

Study (http://clu-in.org)
Roadmap to Long-Term Monitoring Optimization
Demonstration of Two Long-Term Groundwater Monitoring Optimization Approaches
Final Report: Applied Materials Building 1: Long-Term Monitoring Strategy
Final Report: Pilot Region-Based Optimization Program for Fund-Lead Sites, EPA Region III
Final Report: Technical Assistance for the Gilson Road Superfund Site, Nashua, New Hampshire, EPA Region 1
Final Report: Technical Assistance for the Kearsarge Metallurgical Corporation Superfund Site, Conway, New Hampshire, EPA Region 1
Final Report: Technical Assistance for the Somersworth Sanitary Landfill Superfund Site, Somersworth, New Hampshire, EPA Region 1
Groundwater Monitoring Network Optimization, Delatte Metals Superfund Site, Ponchatoula, Louisiana, Region 6
Groundwater Monitoring Network Optimization, Frontier Hard Chrome Superfund Site, Vancouver, Washington
Long-Term Groundwater Monitoring Optimization, Clare Water Supply Superfund Site, Permeable Reactive Barrier and Soil Remedy Areas, Clare, Michigan
Long-Term Groundwater Monitoring Optimization, Clare Water Supply Superfund Site, StageRight Area, Clare, Michigan
Long-Term Monitoring Network Optimization Evaluation for Operable Unit 2, Bunker Hill Mining and Metallurgical Complex Superfund Site, Idaho
Long-Term Monitoring Network Optimization Evaluation for Wash King Laundry Superfund Site, Lake County, Michigan
Long-Term Groundwater Monitoring Optimization, Newark, Muscoy, and Source Operable Units, Newmark Superfund Sites, San Bernardino, California
Long-Term Groundwater Monitoring Optimization, Taylor Road Landfill Superfund Site, Seffner, Hillsborough County, Florida

Annex 2

Conceptual representation of temporal trends and temporal variations in concentrations


Decreasing Trend
Increasing Trend
No Trend
Confidence Factor HIGH
Confidence Factor LOW
Variation LOW
Variation HIGH

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