FINAL VERSION OF THE GUIDELINES

WP T1, Deliverable D.T1.4.3

Delivery month
12.2018

Table of content

LIST OF ABBREVIATION

BMT:	Biological Molecular Tool
BTEX:	benzene, toluene, ethylbenzeneandxylene
CE:	chlorinated ethene
CHC:	Chlorinated Hydrocarbon
cis-DCE:	cis-Dichloroethylene
CSIA:	Compound Specific Isotope Analysis
DSS:	decision support system
FUA:	Functional Urban Area
GIS:	Geographical Information System
GW:	groundwater
MPS:	Multiple Point Sources
NGS:	next-generation sequencing
NPS:	Non-Point Sources
PCE:	Perchloroethene
PCR:	polymerase chain reaction
PS:	Point Sources
qPCR:	real-time polymerase chain reaction
TCE:	Trichloroethene
VC:	vinyl chloride

1. Introduction

The continuous development of the urban areas (including built up areas, suburbs and industrial districts) has an ever-growing relationship with the presence of wide areas with contaminated groundwater, where it is difficult to identify contamination sources.

AMIIGA tools are suitable for **Functional Urban Areas** (FUA after OECD, 2012[1]) that consists of a urban core and its commuting zone whose labour market, urban development and environmental issues are highly integrated with the city. Before to continue it is important define the different types of contaminations and their scale.

<u>Type of contamination</u>

In general the causes of groundwater contamination can be roughly classified in three different classes: a) **Point Sources** (**PS**), contamination hot spots corresponding to areas releasing plumes of high concentrations; b) **Multiple Point Sources** (**MPS**), where the contaminant load comes from a series of point sources that release a low contaminant mass and consequently are difficult to identify, and they are responsible of diffuse groundwater contamination that can be also defined as an anthropogenic background contamination level; c) **Non-Point Sources** (**NPS**), where the contaminant load comes from the development of anthropogenic activities on large areas (for example pesticides from agricultural practices).

<u>Scale of the contamination</u>

Frequently PS are located inside a Contaminated Site that represents an active industrial or an abandoned industrial area (i.e. a brownfield). The contamination can involve only the industrial area or can spread outside its boundaries involving some sector of the FUA (**local scale or contaminated site scale**). MPS are often clustered within a relatively large area (e.g. industrial district) and the related contamination has a dimension concerning the entire FUA (**medium scale or FUA scale)**. Finally, NPS involve very large areas and the related contamination must be managed at a **water body scale** which is bigger than the FUA scale and include it.

Monitoring network and remediation actions have to be planned in order to guarantee water quality objectives required by the EU Groundwater Directive, 2006. Failure to remediate and plan accordingly, has a substantial impact on society due to the management and action costs and the related soil use conflicts. AMIIGA project focuses on FUAs scale because MPS groundwater contamination requires intervention at a medium scale (the FUA scale) neglected in the existing legislation and is in the loophole between EU-regulation concerning Non-Point sources and national legislation concerning Point Sources. Frequently the problem in FUAs is that many areas prone to diffuse contamination cannot be managed with the usual remediation techniques used for small contaminated sites, mainly for two reasons: a) the difficulty to identify specific point sources in reason of the low mass released and b) the wide extension of the contaminated areas. Both aspects require alternative approaches, because standard remediation procedures are not effective and economically sustainable for diffuse contamination. The above-mentioned conditions are mainly related with the urban and industrial historical development of the areas, where the possible contamination sources (both PS and MPS) are often very old and have been subjected to many changes (concentration released, areas redevelopment, partial remediation, etc). Last but not least, Public Authorities need to evaluate the level of MPS contamination in FUA to introduce sustainable threshold limits for local remediation actions.

[1]OECD, 2012. Redefining "Urban": A New Way to Measure Metropolitan Areas. OECD Publ., pp. 1-9 https://doi.org/10.1787/9789264174108-en

AMIIGA project is building upon previous Central Europe project **FOKS** (2008-2012). The FOKS project general objective was to focus the remediation efforts in degraded areas on the key sources of contamination.

Specific objectives of FOKS project were:

- demonstration and application of innovative tools for integral groundwater risk management on degraded areas such as contaminated sites and brownfields

- prioritization of mitigation measures on key sources of groundwater and soil contamination

- performing of pilot applications and feasibility studies for source remediation activities

- downscaling the cornerstones of EU Groundwater Directive for the scale of contaminated sites and brownfields.

FOKS project have achieved to demonstrate and to apply innovative tools for integral groundwater risk management on degraded areas and mainly focused at **local scale**. Tools such as: integral groundwater investigation approach, passive sampling, fingerprinting, modeling & backtracking, risk-based approach and robust data treatment have been demonstrated in a series of training workshops and successfully applied on FOKS test sites.

Differently AMIIGA project works at a scale larger than FOKS, and it focuses on FUAs, because groundwater contamination is an issue that goes beyond administrative boundaries of a local public authority. AMIIGA main objective is to strengthen the planning, management and decision making capacity of the public sector related to groundwater management in FUAs. The tools and DSS prepared and implemented by FOKS for urban brownfield sites have been further developed and upscaled in AMIIGA in order to make them suitable for FUAs.

Therefore, the specific tasks of AMIIGA project are:

1) providing Public Administrations with tools and procedures for comprehensive characterization of groundwater contamination in FUAs
2) providing the public decision makers with innovative biological technologies to improve groundwater quality in FUAs
3) establishing of the groundwater Management Plan as a strategic tool for regional groundwater bodies.

The present document wants to be a practical guideline that summarize the tools developed in AMIIGA and considers the synergies with FOKS tools, helping the user in selecting the most appropriated ones for the contamination issue that he has to face. In this aim is here reported a Decision Tree (Figure 1), where all the tools are showed in a glance subdividing them in FUA and contaminated site scale. Following the tree and answering to the questions, the user can verify the available information and select the tools useful to increase, step by step, the knowledge about the contamination that is necessary to adopt an appropriated Management Plan.

Both at FUA and contaminated site scale (respectively at medium and local scale) the first step is data collection, that involves all the activities needed to collect all the available information useful to assess the contamination status (e.g. monitoring network characteristics, concentration values, groundwater elevation, aquifer characteristics, historical data concerning contaminated sites former productions, etc.).

Previously, within the FOKS framework, the mathematical ***gnostics*** tool was indicated as an efficient method to improve the data analysis at contaminated site scale. In AMIIGA, at FUA scale, data come from private, municipal and regional networks and the concentration values dataset is very large and complex to be analysed. Data collected over many years of monitoring campaigns have a key role for contaminant plumes and source identification. For this reason, the ordinary statistics were added to the FOKS Gnostic tool in order to study more in detail the large FUA dataset: the ***exploratory data analysis*** can be applied to setup the database structure, detect outliers, errors and missing values and to identify PS and MPS monitoring wells (see D.T1.1.2).

To support the groundwater **conceptual model implementation** , AMIIGA introduces ***Biological Molecular Tool (BMT)*** (see D.T1.3.4) to evaluate the capability of natural (i.e. indigenous) microbial consortia to degrade certain contaminants in situ. Moreover, BMT provides evidence about the progress of supported biological degradation or describe impact of particular remediation methods on indigenous microorganisms over different remediation phases.

Furthermore, to understand **source-plume relationships and contaminant transport conceptual model**, AMIIGA adds the new following tools:

Compound Specific Isotope Analysis (CSIA) (see D.T1.2.4), to distinguish between contaminant's sources, thus representing a valuable approach in identifying the PS responsible for the contamination at a local and medium scale and/or to demonstrate degradation processes, being of great interest for remediation purposes;

Inverse Transport Model (see D.T1.1.3), to spatially delimit the boundary of the plumes, to separate PS and MPS groundwater contamination, to identify the area most likely to contain MPS responsible of the diffuse contamination and to support the implementation of groundwater resource management plans.

Last but not least, ***Multivariate and Geostatistical Analysis*** and ***WebGIS*** are the AMIIGA tools to be implemented with the main goal to support the **selection of measures and compiling the management plan**, by improving the decision support-process (for more detail on management plan see D.T3.3.7). Multivariate and geostatistical analysis allow to define the FUA areas affected by MPS contamination and estimate the background concentration values of diffuse contamination over large areas, (see D.T1.1.2). WebGIS represents an innovative approach to share data and information among institution and technical offices, improving internal and external communications, supporting and facilitating decisions, advancing data analysis and conceptual model interpretation (see D.T1.1.1).

In this document, the analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT analysis) of AMIIGA tools support the users to evaluate the added value to process data, determine the extent of groundwater contamination, clarify the origin of contamination (source-plume relationships), improve the conceptual model, evaluate the anthropogenic background contamination level, assess the natural attenuation processes, plan and select measures and remediation actions.

The general key questions that drive for AMIIGA tools selection are:

- Is a big dataset available at FUA scale? ***Exploratory data analysis*** can improve FUA **groundwater data analysis**, that includes **dataset cleaning** and **PS/MPS monitoring wells identification**
- Are additional groundwater characterization data needed? ***BMT*** can improve the **conceptual model implementation**
- Are there still contaminants sources unknown? ***CSIA*** and ***Inverse Transport Model*** can clarify **source-plume relationships** and improve the **contaminant transport conceptual model** knowledge
- Is a decision support-process required? ***Multivariate, Geostatistical Analysis*** and **WebGIS** can support the decision making process for **selection of measures** and **compiling the management plan.**

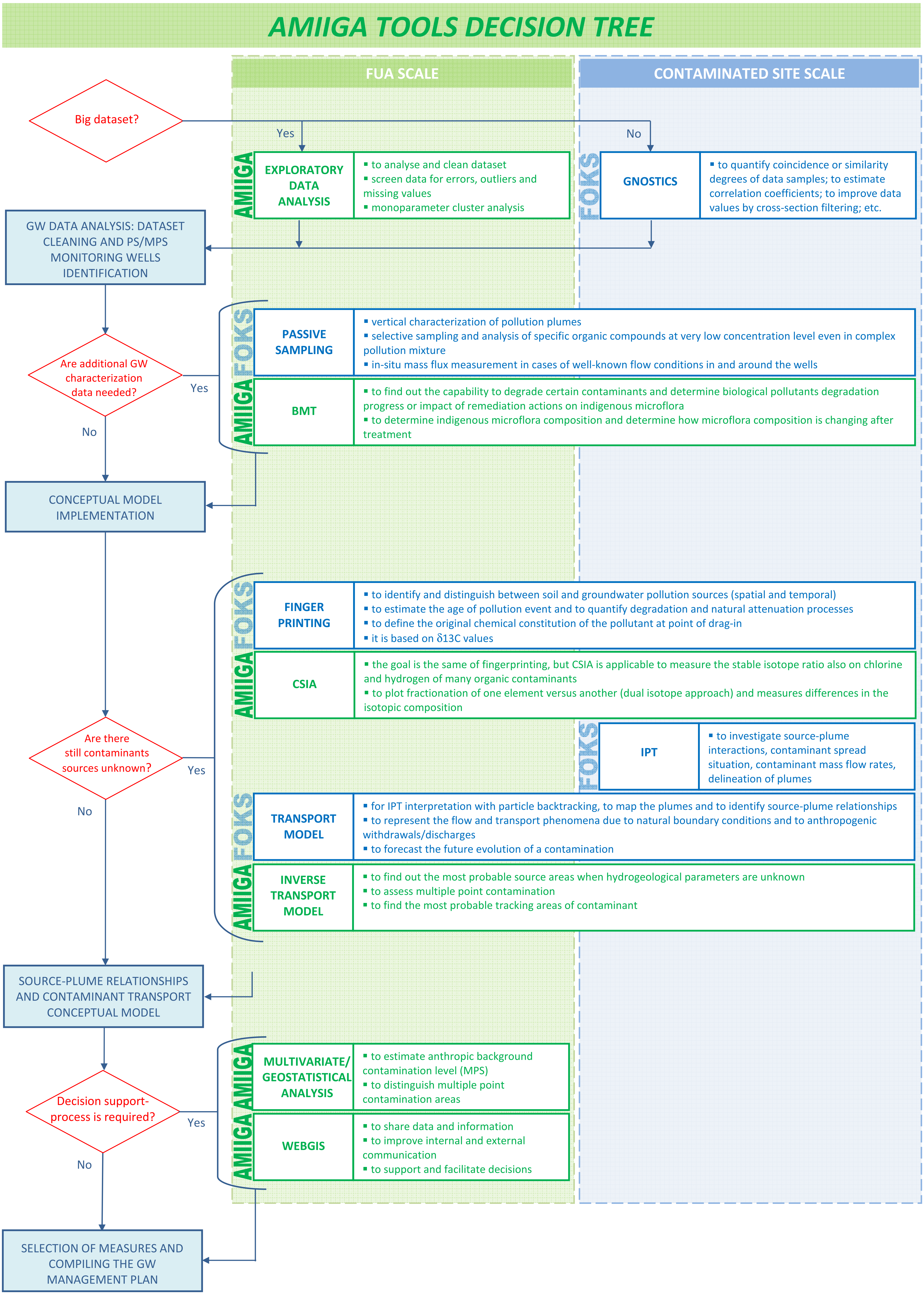

Figure 1: AMIIGA tools decision tree

2. AMIIGA groundawater tools

In this chapter, the guiding questions in the box below were answered for the analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT) of each AMIIGA tool. Furthermore the application examples in AMIIGA project pilot areas were described to help the reader to understand the applicability of the tool in different frameworks.

STRENGTHS	What are the strengths and advantages of this tool or this tool in combination with others to reach the selected objectives? Which kind of data does the tool provide for each objective? For which types of objective does it work better? Why? Other strengths?
WEAKNESSES	What are the weaknesses and disadvantages of the tool? What are the weaknesses as regards to the selected objectives? Which aspects are not covered? For which type of objective the tool is less suitable? Why? Other weakness?
OPPORTUNITIES	Which are the additional advantages for the user in the applying the tool? Is there potential for enhancing the effectiveness of the tool?
THREATS	Which are the threats in developing this tool into a good practice tool for the selected objective? Could there be problems in effectiveness? Could there be problems of acceptance?

<table>
<tr><th colspan="3">EXPLORATORY DATA ANALYSIS (D.T1.1.2)</th></tr>
<tr><td colspan="3">Description: Exploratory Data analysis includes the statistical analysis methods (data cleaning, missing value, descriptive analysis, monoparameter cluster analysis) used at FUA scale to analyse big (temporal and spatial) and multiparametric groundwater datasets (for example monitoring data of contaminants concentration values). It involves all the activities needed to detect outliers, errors and missing values, to identify the hot spots and to separate the point sources (PS) from the diffuse pollution (MPS) monitoring wells.

Applicability: big dataset at FUA scale, for example of contaminant concentration values or groundwater head elevations, collected from different networks (private, municipal and regional).

Combination with other tools: the monoparameter cluster analysis method can distinguish between hot spots (PS) and diffuse (MPS) contamination monitoring wells, the deterministic and inverse transport model give information about the distribution of the plume in the area. Combined together these information may improve the comprehension of contaminant transport conceptual model and of diffuse contamination spatial distribution, so to support the decision making process for groundwater management for what concerns for example the selection of monitoring network.</td></tr>
<tr><td rowspan="4">OBJECTIVES</td><td>GW data analysis: dataset cleaning and PS/MPS monitoring wells identification</td><td>X</td></tr>
<tr><td>conceptual model implementation</td><td></td></tr>
<tr><td>source-plume relationships and contaminant transport conceptual model</td><td></td></tr>
<tr><td>selection of measures and writing of GW management plan</td><td>X</td></tr>
<tr><td>STRENGTHS</td><td colspan="2">Data exploration works at FUA scale, analyses large and complex datasets and data collected in many years.

Data exploration methods detect outliers, errors and missing values of large datasets.

The monoparameter cluster analysis groups the observations into cluster and each cluster is dissimilar to each other.

It identifies the hot spots and allows to distinguish monitoring wells contaminated by point sources (PS) from those contaminated by a diffuse contamination linked to multiple point sources (MPS).</td></tr>
<tr><td>WEAKNESSES</td><td colspan="2">A complex data collection and dataset preparation is necessary before the statistical methods application. This phase require big efforts both due to the lack of homogeneity of data collected from different institutions and the necessity to involve the institutions itself to appropriately deliver the information.

The different procedures for data cleaning (error detection, consistency checks, and treatment of missing responses) may yield different results and therefore utmost care should be taken during data cleaning process.

The data cleaning should be kept at a minimum if possible.

Missing values (for example when in a well it is not available the concentration value for one of the considered parameter) may strongly affect the results of certain techniques. If the missing values are more than 30%, it generally poses some problem and a decision on how to treat missing values has to be adopted.</td></tr>
<tr><td>OPPORTUNITIES</td><td colspan="2">The tool highlights lack in groundwater monitoring network and may identify new potential contaminant source areas. This tool may be implemented by public authorities for the selection of the monitoring network and of the analytical set, to improve results robustness and optimise the efficiency and efficacy of measures.</td></tr>
<tr><td>THREATS</td><td colspan="2">The results need to be consistent with the conceptual model (hydrogeological structure, groundwater flow, pollution fate and transport). The threat is that the statistical methods are applied without considering the characteristics of the monitoring points.</td></tr>
</table>

APPLICATION EXAMPLE IN AMIIGA PROJECT

Milan pilot area (IT)

Exploratory data analysis was applied in Milan FUA where the two main aquifers were considered (shallow and deep aquifer). Dataset was composed by a monitoring network of about 2.000 points with available hydrochemical data.

Cluster Analysis, applied to more than 45 000 records of PCE groundwater concentration values, enabled to detect outliers, to separate monitoring wells contaminated by PS from those contaminated by a diffuse (MPS) contamination. A numerical transport model was implemented thanks to the identified hot spots (PS monitoring wells) and taking into account the identified MPS monitoring wells.

Moreover, the results supported the decision making process for groundwater management, in particular to highlight lacks in monitoring network and to identify areas where new monitoring wells are needed.

BMT - Biological Molecular Tool (D.T1.3.4)

Description: BMT is a bio-molecular tool used for characterization of autochthonous bacterial consortia by advanced genetic methods (real-time PCR and next generation sequencing). Specific bacterial strains or enzymes could be analysed using the real-time PCR, while complex bacterial consortia could be described using the NGS. A typical task for BMT would be to verify presence and estimate abundance of bacterial species or groups able to metabolize specific contaminants present in soil or groundwater. Furthermore, through BMT is possible to identify explicit biodegradation pathways and link them to biodegradation products or by-products. When biodegradation is chosen as the key remediation method in situ, it is then necessary to characterise the ability of indigenous bacterial consortia to metabolize contaminants, specific bacterial strains or enzymes using BMT.

Applicability: BMT is applicable for diagnosis of ongoing biodegradation processes in groundwater and soil from contaminated environment. Based on presence and abundance of specific biological markers, it can be more precisely decided about accurate treatment of the contaminated plume. For example, if the abundance of bacteria capable of biodegradation is too low, it can be simply increased by addition of suitable substrate; or well-established biodegrading consortia can be transferred to wells with poor biodegradation ability. It is also possible to analyse microbial consortia established on biomass carriers submerged in contaminated aquifer.

Combination with other tools: the BMT analysis together with chemical analysis, CSIA, physical parameters and geological information is a strong tool for the assessment of natural attenuation and/or enhanced bioremediation activities in contaminated areas.

OBJECTIVES	GW data analysis: dataset cleaning and PS/MPS monitoring wells identification	
	conceptual model implementation	X
	source-plume relationships and contaminant transport conceptual model	
	selection of measures and writing of GW management plan	X
STRENGTHS	BMT includes very precise analysis of wide spectrum of bacterial species or enzymes in complex environmental samples. In combination with other tools (CSIA, chemical analysis) it provides a strong apparatus for description of contaminated locality and evaluation of its biological activity. BMT delivers relative values based on the specific bacterial abundance for groundwater characterization. Then it is possible to predict metabolic capability of microflora in the sample, and most importantly, ability to degrade contaminants in anaerobic/aerobic way. Last but not least, it is possible to predict if the underground environment has conditions suitable for biodegradation (for example presence of sulfate reducing or denitrification bacteria). The qPCR analysis is targeted, fast and cost effective, while NGS tool gives more complex image about the microbial community in situ. Therefore, the combination of these two methods would lead to the best diagnosis of the locality.	
WEAKNESSES	The main BMT weakness is the difficulty of extraction of genetic material (DNA). Some samples can contain high concentration of chemical compounds interfering with DNA isolation. This can influence the yield and quality of isolated DNA and thus BMT results. It is only possible to measure relative level of the markers (specific genes) within sampling period and evaluate how the remediation procedure influences autochthonous bacteria. Expert knowledge of local conditions (CSIA and chemical analyses) are necessary to interpret the results. The qPCR markers have not been developed for biodegradation of all possible pollutants in the environment yet. There are still many unknown specific bacteria or enzymes, which could be important in biodegradation processes. Accurate NGS data processing is dependent on careful work of a bioinformatician, which may be a problem, because there is generally lack of good bioinformaticians.	

OPPORTUNITIES	BMT results allow us for better understanding of the microbial activities on the contaminated locality. BMT data show the biodegradation potential of the remediated locality, it can also predict the usability of chosen procedure as well as correct the number of applications of chemical treatment. There is also potential to extend the spectrum of specific markers as the knowledge of bacterial metabolism is rapidly increasing. The effectiveness of BMT could be enhanced by a combination with other methods (CSIA, chemical and physical analysis, geological information).
THREATS	The biggest threat is low quality of DNA from sample and too low level of tested markers. Both of them strongly influence BMT results and have to be interpreted very carefully.

APPLICATION EXAMPLE IN AMIIGA PROJECT

Parma pilot area (IT)

BMT analysis was applied in Parma FUA where groundwater pollution (BTEX, CEs) was caused by improper operation of a gas station. Two sampling campaigns were realized in December 2017 and May 2018.

During sampling campaign, physical parameters (e.g. pH, oxidation-reduction potential and conductivity) were measured.

BMT results showed an increasing trend in total bacterial biomass in the 2nd sampling (thousands time higher levels). This could be explained by higher groundwater level and also by the seasonality. We were able to detect denitrifying (nirK gene) and sulfate-reducing (dsrA gene) bacteria that confirm reducing conditions. Low levels of BTEX degraders for anaerobic pathway (bssA gene) with slightly higher level for aerobic degradation pathway (DEF/G gene) in both sampling round confirmed ongoing BTEX degradation. Presence of organohalide-respiring bacteria (bvcA, vcrA genes, *Dehalococcoides* sp., *Desulfitobacterium* sp., *Dehalobacter* sp.) was not observed (on enzyme as well as on bacterial genus level). As the concentrations of CEs were low, probably only slightly active organohalide respiration was detected, but no VC reductases were found. Demonstrable reductive dehalogenation was not detected in this locality, so we can speculate that it occurred through aerobic and cometabolic pathways that could not be detected using our primers.

The tables below show the six wells in two sampling rounds (December 2017 – left, May 2018 – right) and specific degradation detection. Total bacterial biomass (U16SRT), vinyl chloride enzymes (bvcA, vcrA), *Dehalococcoides* sp. (DHC-RT), *Desulfitobacterium* sp. (Dsb), *Dehalobacter* sp. (Dre), sulfate-reducing bacteria (dsrA), denitrifying bacteria (nirK), HCH degrader (linA) and BTEX (DEF/G, bssA).

Primer	PM3	PM5	PZ3	PZ4	PZ5	PZ8
U16SRT						
bvcA						
vcrA						
DHC-RT						
Dsb						
Dre						
dsrA2						
nirK						
linA						
DEF/G						
bssA						

Primer	PM3	PM5	PZ3	PZ4	PZ5	PZ8
U16SRT						
bvcA						
vcrA						
DHC-RT						
Dsb						
Dre						
dsrA2						
nirK						
linA						
DEF/G						
bssA						

The benefit of BMT in this example is the best overview of the locality. These analyses were meant as an additional monitoring which helped chemical analysis and CSIA to understand biological processes on the locality. Based on the BMT analysis, a recommendation was made for next remediation step. Substrate application for microbial community enhancement was suggested for the Parma locality.

CSIA - Compound Specific Isotope Analysis (D.T1.2.4)		
Description: Successful application of CSIA can be applied to distinguish between contaminants sources and to improve the knowledge about source-plume relationships. Thus it represents a valuable approach in identifying the contaminated site responsible for the pollution at a target area (FUA or contaminated site scale). Consequently, thanks to CSIA results is possible to improve the contaminant transport conceptual model and to help in distinguish plumes (PS) from diffuse (MPS) contamination. Furthermore CSIA allows to determine if natural attenuation processes are occurring and are able to degrade the contaminants, which is of great interest for remediation purposes. ***Applicability:*** Nowadays by mean of CSIA, it is possible to measure the stable isotope ratio on carbon, chlorine and hydrogen of many organic contaminants. A minimum concentration value of the contaminant around 5/100 µg/l is required depending on lab instruments, selected isotopes and compounds analyzed. ***Combination with other tools:*** CSIA can be applied coupled with other tools such biological molecular tools (BMTs), particularly for monitored natural attenuation (MNA) applications and for the design and monitoring of enhanced bio-remediation strategies. In this way it supports the decision making process for groundwater management for what concerns for example the selection of remediation actions to be adopted at FUA or contaminated site scale.		
OBJECTIVES	GW data analysis: dataset cleaning and PS/MPS monitoring wells identification	
	conceptual model implementation	
	source-plume relationships and contaminant transport conceptual model	X
	selection of measures and writing of GW management plan	X
STRENGTHS	The changes in relationship between stable isotope (Isotope fractionation) can unambiguously demonstrate the presence of degradation of contaminants in groundwater and can provide information to quantify the biodegradation . The use of the isotope tools allow to have a better understanding of contaminants behavior in groundwater, as well as the significance of physical (i.e. dilution or abiotic process) and biological-transformations. CSIA quantifies the isotopic composition of a specific contaminant and hence provides additional and often unique means to allocate and distinguish sources of organic compounds. Furthermore CSIA helps in identify transformation reactions and quantify the percentage contaminant mass degraded allowing to forecast the future contamination evolution.	
WEAKNESSES	CSIA sampling procedure and preservation must follow the best practice in order to prevent biodegradation or abiotic transformation of contaminants. Otherwise, the results can be compromised. A minimum concentration value of the contaminant around 5/100 µg/l is required depending on the lab instruments, the selected isotopes and compounds analyzed. The analytical uncertainty of CSIA can represent an issue, since a significant variability exists depending on the internal protocols and the analytical methods applied in laboratories. It is the responsibility of the user to determine whether the uncertainty is acceptable or not for their specific application. In order to make this tool more efficient and results comparable among different laboratories, European analytical protocols should be developed. Several limitations apply to the use of CSIA for biodegradation evaluation, such for example uncertainties related to the presence of multiple sources, complex contaminated sites but also minor effects such sorption/desorption. Another important limitation is represented by the correct measurement of the isotopic signature for the source, as sources usually may have been removed or may have not been identified yet.	

OPPORTUNITIES	By routinely using CSIA for contaminated sites and FUAs characterization more data will be made available allowing more appropriate assessment of the Natural Attenuation processes and/or of remediation action progress. Furthermore, it would be possible to confirm or improve the contamination conceptual model strengthening the forecast made about the contamination time evolution.
THREATS	It is best practice to purge the well before sampling. If the well is not purged prior sampling, then the pumped groundwater may not be representative, leading to a misinterpretation of analytical results. It is recommended to minimize the volatile contaminant loss, by limiting the exposure of groundwater sample to atmospheric oxygen. As a common knowledge, oxygen can easily lead aerobic degradation in dissolved organic compounds. It is also recommended to stabilize the sample adding a bactericidial to avoid any degradation during the sample preservation. In sampling strategies, it is mandatory to have a comprehensive and appropriate understanding of the hydrogeological conceptual model and of the monitoring network. This mainly in order to: correctly choose the points where to take samples and correctly know the depth where groundwater is collected. Frequently the use of monitoring wells having different length of screens or a different depth can determine a bad data interpretation, mixing information coming from different geological units.

APPLICATION EXAMPLE IN AMIIGA PROJECT

Milano pilot area (IT)

CSIA were applied to the Milano pilot area (IT) with the objective to better differentiate plumes boundaries with respect to the diffuse pollution. Different stable isotope compositions for PCE (both for Carbon [^{13}C] and Chlorine and/or [^{37}Cl]) mainly were used to distinguish if a contamination was part of a specific plume or represented the diffuse background contamination. CSIA data were used to elaborate more precise conceptual models with regards several areas within the pilot area helping in locating, whenever possible, the source areas or the potential responsible for the contaminations.

A secondary objective was to assess the biodegradation processes and more in general the natural attenuation of the target contaminants as for example PCE. The isotopic composition of TCE and cis-DCE were used to gain insights into the degradation pathways and extent of PCE and to understand when TCE was a degradation product or a primary contaminant at selected locations.

INVERSE TRANSPORT MODEL (D.T1.1.3)		
Description: Inverse Transport Model can be applied in order to evaluate the influence of aquifer parameters uncertainty on transport simulation. Considering different possible distribution of those parameters (e.g. hydraulic conductivity, porosity etc.) it is possible to find the most probable ones and consequently the most probable pathways followed by the contaminants. The technique can be used starting from the source (if known) and following the most probable flow direction (named forward tracking) or starting from some contaminated monitoring wells and moving backward along the flow direction (i.e. backward tracking) in order to find the most probable sources (if unknown). The inverse transport modeling allowsto improve the knowledge about source-plume relationships and to strength the transport conceptual model evaluating its uncertainties. Finally it represents a powerful tool able to support decision makers in monitoring, investigation and management activities related to groundwater contamination. . ***Applicability***: The inverse modeling approach developed in AMIIGA should be applied at medium scale areas (FUA), where many sources can be responsible of the contamination detected in groundwater. The inverse modeling technique can be applied both for PS and MPS localization. In the AMIIGA project, it is applied to find the most probable source contamination area upgradient respect to the monitoring points (for PS and MPS) or to delimit the contaminant advective transport downstream of some suspected sources (for PS). In AMIIGA the numerical codes applied were MODFLOW for the flow model, MODPATH for the particle tracking and PEST for the K-field generation and inverse modeling, MT3DMS for the advective-dispersive modeling. Nevertheless, the methodology can be applied with any other numerical codes for groundwater flow and transport modeling. A classic (i.e. deterministic) calibrated flow model is necessary to apply the tool. ***Combination with other tools:*** If applied in combination with statistical tools, it improves the capacity to localize contaminant sources. Moreover, in combination with a full transport model (advection+dispersion), it improves the capacity to assess suspected sources and the extension of plumes in a probability framework, that means it is possible to evaluate the probability that a plume has a determined extension.		
OBJECTIVES	GW data analysis: dataset cleaning and PS/MPS monitoring wells identification	
	conceptual model implementation	
	source-plume relationships and contaminant transport conceptual model	X
	selection of measures and writing of GW management plan	X
STRENGTHS	The presence of multiple point sources (MPS) that determine groundwater diffuse contamination in FUAs must be addressed through non-conventional management and remediation activities. MPS are by definition unknown sources and classic transport models are unable to represent the diffuse contamination determined by these sources. Differently inverse transport models are able to simulate this kind of contamination. For this reason they are essential tools to assess and forecast the development of contamination and effectively plan its management. Furthermore inverse transport model can also be applied to find out the most probable PS responsible of a single plume, allowing to determine the most probable tracking areas of contamination by implementing backward particle tracking. There are no limitations to the application of any chemicals occurring in groundwater.	
WEAKNESSES	In order to explore deeply the uncertainty linked to the hydrogeological properties it would be useful to consider a higher number of parameters for each inverse model.. Unfortunately at present the parameters should range between 1 and 4 to avoid model instability or uncalibrated model results. It's expected that the inverse modeling capacities will increase in future in parallel with computer power. Output data are often bigdata (i.e. number of particles passing through a cell, in different layers for each simulation) and are quite difficult to analyse with GIS environment (i.e. a home-made software is preferable to analyse frequency and spatial probability).	

	Currently, only few modelers have the required experience to implement inverse models.
OPPORTUNITIES	The uncertainty predictive analysis will help Public Authorities to optimize public economic resources by planning investigations preferentially in those areas that are likely responsible for the diffuse contamination. Furthermore, the results of the inverse transport modeling highlight areas where the FUA monitoring network should be improved to better survey the fate of diffuse contamination. Finally, the management of pumping for public use can also be improved, if the upgradient presence of MPS clusters is accounted for.
THREATS	The results should be carefully analysed and need to be consistent with the conceptual model (hydrogeological structure, groundwater flow, pollution fate and transport). The threat is that the inverse model results depend on the calibrated numerical/deterministic model, which is the basis for its application i.e. initial condition for inverse iteration.

APPLICATION EXAMPLE IN AMIIGA PROJECT

<u>Milano pilot area (IT)</u>

Inverse transport modeling was applied in a sector of Milano FUA in order to identify the areas with the highest likelihood to host potential MPS. Starting from a calibrated model (deterministic) it was necessary to generate 400 different distribution of hydraulic conductivity values (i.e. K-fields). Among these distribution 11 were excluded because unable to satisfy the calibration targets, that is adopting these K-fields the model was unable to correctly represent the piezometry.

The remaining 389 calibrated models showed slight differences in K values and being all able to correctly represent the piezometry, they was considered equally probable (i.e. equally true). Then each one of them was used to backtrack particles from monitoring wells that, thanks to the exploratory data analysis phase, were already recognized to be contaminated by a diffuse contamination. In the present case among those wells showing a diffuse contamination, only the points presenting a median PCE value higher than 10 µg/l were selected for the back-tracking phase (PCE limit under the Italian drinking water standard is 10 µg/l). As particle back-tracking analysis is sensitive to the starting depths of the particles, the assignment of their starting locations was based on the actual screen position. For each well, a particle was added at the center of the screened depth for each layer crossed by the screen length. Then in each model particles were tracked backward based on the simulated piezometry. The different paths followed by the same particle in the 389 simulations area result of the different piezometries due to the different K-fields generated following the procedure above described. By computing the number of particles crossing each model cell in all the 389 simulations, it has been possible to obtain maps of occurrence frequency of the particle traveling in each aquifer layer: in the model cells where the number of particles passage is highest, the probability that diffuse contamination sources are present is higher than in the other cells (i.e. MPS). This result is then considered to be representative for the FUA areas with the highest likelihood to contain MPS responsible for the diffuse contamination observed in the monitoring wells used for the particle.

Furthermore, the inverse transport modelling was used to identify the areas with the highest likelihood to contain potential PS. The procedure in producing K-fields and equally probable models was the same above described. But in this case particles were added only in those wells showing high PCE concentration and not belonging to the points involved by the diffuse contamination (resulted from exploratory data analysis application), that means considering now only points suspected to be hit by a plume.

Thereafter, the MODPATH code was applied to generate back-traced advective flowpaths for each of the models built by using the conductivity field realizations. Maps were then created displaying the number of backtracked particles that crossed each model cell in each calibrated model. The result was considered to be representative of the FUA areas with the highest likelihood to contain PS responsible for contamination. The results were compared with the deterministic transport model (i.e. plumes in FUA) and with hydrochemical results obtained in the AMIIGA sampling campaigns.

MULTIVARIATE AND GEOSTATISTICAL ANALYSIS (D.T1.1.2)		
Description: Multivariate analysis (principal component analysis, factor analysis, multiparameter cluster analysis, regression analysis) and geostatistical analysis are statistical methods, different form the ones used for exploratory data analysis, that support data analysis and decision making process for groundwater management (i.e. supporting the prioritization, selection of measures) at a medium scale (FUA scale) to estimate anthropogenic background contamination level (MPS) and to distinguish areas with different strength of diffuse contamination in the same FUA. In particular: *Multivariate analysis*: to evaluate dataset principal components (that means for examples the main contaminants) and the patterns of diffuse contamination which might be present in the FUA *Geostatistical analysis*: to evaluate spatial distribution of diffuse contamination. ***Applicability:*** Multivariate Analysis consists of a collection of statistic methods that can be used when several measurements are made on each monitoring well. The Multivariate Analysis can be applied to different kind of parameter measurements (e.g. pollutant concentrations, water characteristics etc.) taking in consideration the spatial variable of each monitoring well. Indicatively the analysis can be applied when 2 monitoring wells every 100 ha are available in FUA. Multivariate Analysis methods can be applied across all site conditions, such as pollution release detection, site characterization, remediation, monitoring and closure. Geostatistical methods can be used in conjunction with Multivariate Analysis results to better address environmental data that are often biased, clustered and spatially correlated. ***Combination with other tools:*** Multivariate and Geostatistical analysis results, in combination with deterministic and inverse numerical transport model results, distinguish PS and MPS areas, giving information about the diffuse contamination strength. These information support the decision making process for groundwater management to estimate the background concentration values of diffuse contamination.		
OBJECTIVES	GW data analysis: dataset cleaning and PS/MPS monitoring wells identification	
	conceptual model implementation	
	source-plume relationships and contaminant transport conceptual model	
	selection of measures and writing of GW management plan	X
STRENGTHS	Typically in contaminated areas, more than one variable are measured simultaneously on each monitoring well and may be potentially correlated. The need is to untangle the overlapping information provided by correlated variables to see the underlying structure. Thus, the goal of many multivariate approaches is simplification, trying to express what is going on in terms of a reduced set of dimensions (that means for example to group the contaminants that have the same pattern). Multivariate Analysis methods study temporal evolution of parameters and the relationships between different parameters. Multivariate Analysis allows to evaluate dataset principal components (that means for examples the main contaminants) and the patterns of diffuse contamination, which might be present in the FUA, estimating the background levels of diffuse contamination over large areas. Spatial interpolation (geostatistical analysis) estimates the unknown data values at specific locations using the known data values for other points. Geostatistical analysis evaluates spatial distribution of diffuse contamination. Multivariate and geostatistical analysis results support decision making process for groundwater management at a medium scale (FUA scale).	
WEAKNESSES	Once the data is collected, even when the research project has been organized and carried out correctly, the final dataset need to be checked, validated and prepared prior to proceed with analysis. There are several steps, which are required to prepare the data for analysis: data editing and coding (e.g. check for errors or omissions) and	

	data cleaning (see exploratory data analysis tool). Homogeneous spatial and temporal distribution of data facilitates the analysis. The increase of spatial and temporal data density improves results solidity.
OPPORTUNITIES	The results of multivariate and geostatistical analysis may be applied to monitor the evolution of contamination, if applied always at the same monitoring networks.
THREATS	The results need to be consistent with the conceptual model (hydrogeological aspects, groundwater flow, pollution fate and transport). The threat is that the statistical methods are applied without considering the characteristics of the monitoring wells (for example depth and length of the screen). Currently, in geostatistical analysis, it is difficult to select the best spatial interpolation method for a wide range of georeferenced data. Therefore, the selection of an adequate method with appropriate parameters for a particular application is crucial. Different methods can produce quite different spatial representations and "in-depth" knowledge of the phenomenon is needed to evaluate which one is the closest to reality. The use of an unsuitable method or inappropriate parameters can result in a distorted model of spatial distribution, leading to potentially wrong decisions based on misleading spatial information.

APPLICATION EXAMPLE IN AMIIGA PROJECT

Milan pilot area (IT)

Multivariate and geostatistical analysis was applied in Milan FUA where two aquifers exist (shallow and deep aquifer). Dataset was composed by a monitoring network of about 2.000 points with available hydrochemical data.

The multiparameter cluster analysis could correlate concentrations profiles of different contaminants. 5 clusters were identified as representative of PCE diffuse contamination, they represented the large group of the background value measurements. The characteristics and the mean PCE temporal trends of the five clusters, that represented the diffuse contamination, were studied more in detail.

Moreover, geostatistical method analysed the spatial distribution of the 5 clusters in the study area and the most representative cluster for each zone was identified by multivariate analysis results. Therefore, it was highlighted that a unique value of diffuse pollution throughout the study area was not representative of the inhomogeneity of the true diffuse contamination distribution, but more than one background concentration value had to be assigned in the FUA.

Statistical and geostatistical analysis, combined with numerical and inverse transport model results, distinguish PS and MPS areas and supplied the most representative concentration values of diffuse contamination in Milan FUA.

The results supported the decision making process for groundwater management, to plan the measures and to identify new potential contaminant source areas to be monitored.

<table>
<tr><td colspan="3">WEBGIS (D.T1.1.1)</td></tr>
<tr><td colspan="3">SHORT DESCRIPTION OF THE TOOL
Description: WebGIS is a tool that can be used to display and process data on the Internet. It offers a means to access and share information online. It improves the efficiency of data analysis and conceptual model interpretation, enables data and information sharing among institution and technical offices. The main goal is to display data in a map, to enable the discussion about project data/results and to support and facilitate the decision making process for groundwater management.
Applicability: FUA scale. The availability and performance of the internet band have to be efficient.
Combination with other tools: The results of exploratory data analysis, chemical analysis, groundwater levels, BMT, CSIA, inverse and deterministic transport model, multivariate and geostatistical analysis can be represented simultaneously or in different combinations to improve the comprehension of the study area conceptual model.</td></tr>
<tr><td rowspan="4">OBJECTIVES</td><td>GW data analysis: dataset cleaning and PS/MPS monitoring wells identification</td><td></td></tr>
<tr><td>conceptual model implementation</td><td></td></tr>
<tr><td>source-plume relationships and contaminant transport conceptual model</td><td></td></tr>
<tr><td>selection of measures and writing of GW management plan</td><td>X</td></tr>
<tr><td>STRENGTHS</td><td colspan="2">The WebGIS is an open-access tool for data consultation.
WebGIS can be accessed everywhere from different platforms, keeping the authorization defined by the access levels (with username and password). This means that it is possible to control the permissions for certain users or certain groups to allow them accessing specific subset of data or maps.
It is the way to publish and share multi-layer features on a single web map.
It improves the efficiency of data analysis and conceptual model interpretation.
It is a good way to share data and information among institution and technical offices, to improve internal and external communications and cross-collaboration, to support and facilitate decisions.
Periodically the information can be updated, consequently, all the WebGIS users simultaneously and any time can access the most recent information.
It empowers organisations to become more efficient, productive and reactive to their spatial data.
Many features like panning, zooming, printing, the possibility of uploading data and overlapping it to existing map, searching data by address, processing data may be implemented.
It allows everybody, not only expert, to access and understand geospatial data easily and with less effort. Users, even if not expert in geoinformatics, can use GIS tools focusing on the data of their specific domain.
No need of very performing PCs to manage the data.
No need to keep data on a computer, since all the data are cloud based.</td></tr>
<tr><td>WEAKNESSES</td><td colspan="2">The availability and performance of the internet band is already an issue, but it is probably improving in the future.
Professionals specifically dedicated to the development and maintenance of environmental datasets and WebGIS functionality are needed to implement the tool and update information.</td></tr>
</table>

OPPORTUNITIES	Thanks to the potentiality of the Internet and of the tool itself, it should be possible to perform even complex analysis and processing of vector and raster data on the web, collaborating with other users any time.
THREATS	Sharing data is not an easy process. GIS users tend to develop their own data sets. This imply, for example, that they may not know other available existing datasets, errors corrected by some other users. Generally the access to a complete and reliable data sets is difficult. Each GIS user is not used to sharing data sets with other sectors and organizations. Some of the difficulties about sharing data are caused by a common suspicion about the quality of third party data, by a presumption that data may be "wrongly" used if shared with a third party and their ownership can be lost or by a fear that other users could discover the poor quality of their data by sharing them. Professionals specifically dedicated to the development and maintenance of environmental datasets are not always available in the working team structure; environmental analysts often work also in the phase of preparing datasets for specific tasks they are dealing with. This can imply that datasets are not ready to be shared for general use.

APPLICATION EXAMPLE IN AMIIGA PROJECT

The AMIIGA WebGIS is available at the following link http://131.175.56.100/lm/. Seven WebGIS projects, one for each pilot area, were performed and only AMIIGA partners can access the projects using a personal login and password. The WebGIS is accessible from a simple web browser on any device.

All the software are installed on a server machine, running on an Ubuntu 14.04 Installation, and all the components in the architecture are Free and Open Source Software (FOSS).The architecture starts from the main component which is QGIS, a Free and Open Source Software for Geospatial (FOSS4G). QGIS enables to perform the data processing and store all the layers in a local database. The database chosen is PostgreSQL, with a PostGIS extension, which is specific for handling geospatial data. Another component of the architecture is QGIS Server, a component that serves the layers in a QGIS project, thus from the database, over the web using OGC standards such as a Web Map Service (WMS). To show all the layers in a web browser, the architecture implements a dynamic component called Lizmap that generates a WebGIS based on users needs.

All partners were involved in data collection activities (monitoring network characteristics, concentration values, aquifer characteristics, etc.). Data displayed in the AMIIGA WebGIS are: pilot area and FUA extension; monitoring network characteristics; top and bottom of the aquifers; zone of significant changes in the hydrogeological layout; hydraulic conductivity test results; piezometric head contours and piezometric head punctual data; contaminant concentrations; industrial and productive sites; diffuse contamination maps.

For each partner, the AMIIGA WebGIS improves the efficiency of data analysis and conceptual model interpretation, simplifies data and information sharing among institution and technical offices with the main goal to support and facilitate the decision making process for groundwater management.

3. Conclusion

AMIIGA project tools can be summarized according to their objectives. The following tables provide an overview on the tools described in the previous chapter.

AMIIGA tools objectives

The table shows the objectives of each tool, according to the description in the previous chapter.

		OBJECTIVES			
		GW data analysis: dataset cleaning and PS/MPS monitoring wells identification	conceptual model implementation	source-plume relationships and contaminant transport conceptual model	selection of measures and writing of management plan
AMIGA TOOLS	EXPLORATORY DATA ANALYSIS	X			X
	BMT		X		X
	CSIA			X	X
	INVERSE TRANSPORT MODEL			X	X
	MULTIVARIATE AND GEOSTATISTICAL ANALYSIS				X
	WEBGIS				X

AMIGA tools in the Pilot Areas

The table shows an overview of the AMIIGA tools adopted in the project and the goals achieved in the pilot areas.

	Pilot Area (PA)	PA1 (HR)	PA2 (SL)	PA3 (IT)	PA4 (IT)	PA5 (CZ)	PA6 (PL)	PA7 (DE)
	size of working area [ha]	6 500	7 000	15 740	600	3,1	2 475	530
	size of FUA [ha]	26 000	25 100	52 100	58 594	3 750	20 190	4 810
	type of contaminants	Bacteria, nitrates	Cr VI, NO3, B, desethyl-atrazine, new emerging pollutant	PCE, TCE	PCE	CHC	Pesticides, organic solvents	CHC
OBJECTIVES	GW data analysis: dataset cleaning and PS/MPS monitoring wells identification			X	X		X	X
OBJECTIVES	conceptual model implementation	X		X			X	X
OBJECTIVES	source-plume relationships and contaminant transport conceptual model	X	X	X	X		X	X
OBJECTIVES	selection of measures and writing of management plan	X	X	X	X	X	X	X
AMIIGA TOOLS	EXPLORATORY DATA ANALYSIS		X	X				
AMIIGA TOOLS	BMT		X		X	X	X	X
AMIIGA TOOLS	CSIA		X	X	X	X	X	X
AMIIGA TOOLS	INVERSE TRANSPORT MODEL	X		X				
AMIIGA TOOLS	MULTIVARIATE AND GEOSTATISTICAL ANALYSIS	X		X				
AMIIGA TOOLS	WEBGIS	X	X	X	X	X	X	X

LITERATURE

- 2011 - *FOKS Handbook for Integral Groundwater Investigation – Toolbox for the identification of key sources of groundwater contamination*
- D.T1.1.1, *WebGIS tool development for groundwater database management and open-access consultation*
- D.T1.1.2, *Guideline for statistical method and geostatistical analysis for GW quality studies at FUA*
- D.T1.1.3, *GW contamination modeling at FUA: "inverse iterative modeling" guideline for implementation and use*
- D.T1.1.4, *Technical protocol for statistical analysis coupled with transport modeling for GW pollution assessment*
- D.T1.2.4, Final version of the CSIA technical protocol for GW pollution assessment and remedial evaluation
- D.T1.3.4, Final version of the BMTs technical protocol for remedial implementation and performance evaluation
- D.T3.3.7 *Management Strategy on groundwater contamination in Functional Urban Areas of Central Europe*