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Planning for Groundwater Protection: monitoring Systems & Data Requirements

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Abstract

Contemporary IC Technologies and the development of advanced sensor systems provide the means to monitor groundwater resources and to provide early warning, in line to the respective EU principles and existing research.

Groundwater monitoring effectiveness depends on the operational characteristics/specs of the groundwater monitoring system (GMS), as these are related to the actual risks groundwater faces over the monitored area. Groundwater aquifer systems are themselves very complex and moreover, they are affected by numerous natural and anthropogenic factors; so, defining the types, the magnitude, the spatial location and/or extend of such threats for any area, in relation to the respective groundwater regime, is a demanding task.

Unfortunately, there's a limited, indirect access to the subsurface domain where changes to groundwater quantitative and qualitative characteristics take place. Thus, there has to be an integration of information related to numerous parameters affecting groundwater, which can lead to a consistent interpretation of the hydrogeologic regime over the study area and to building a respective conceptual hydrologic model. In this way, groundwater monitoring can be tailored to the specific local conditions, threats and risks and thus, it can become most efficient. There's of course a level of uncertainty in any conceptual model due to justifiable assumptions and/or generalizations which can be reduced during the GMS calibration phase, where actual measurements are used to calibrate the conceptual model and adapt/tailor it to local hydrogeologic conditions thus optimizing it.

An example of the required parameters necessary for building a conceptual hydrogeologic model for monitoring, managing and protecting groundwater in an area, is presented and discussed. It includes information regarding the groundwater recharge zones and hydrogeologic basins, vulnerability assessment from surface pollution, land use and pressures from non point and point sources of potential contamination. Remote Sensing and geomatics technologies have been used to integrate this information and to visualize the outputs.
Keywords: groundwater monitoring, groundwater vulnerability, hydrogeologic conceptual models.

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Introduction

Environmental resources are under a gradually growing pressure due to climate change and to the continuously increasing demand with overexploitation and pollution among the main hazards [1].

One of the most important environmental resources is groundwater (GW) which is a key component for sustainable development. Deterioration of groundwater quantity and/or quality, has also an additional impact on related surface water and terrestrial ecosystems [2]. For those reasons, the preservation of this natural resource through protection and management is absolutely essential.

Contemporary IC Technologies and the development of advanced sensor systems provide the means to monitor groundwater resources and to provide early warning, in line to the respective EU principles and existing research [3]. Sensor development, installation, and maintenance costs impose decisive restrictions in installing, operating and maintaining monitoring systems [4]. The reduction of these costs can therefore play an important role in promoting the use of such systems thus improving the operational capacity of societies to protect and manage groundwater resources [5].

Pressures and Risks on groundwater are related to the dynamic balance between consumption and resource availability which is also affected by climate change, and contamination/pollution from either natural or anthropogenic sources. Having said that, it is important to note that Climate Change negatively affects both sides of this balance by imposing conditions for an increased demand for consumption while at the same time it causes a significant reduction of resource availability.

As it is therefore evident, an understanding of the nature of the impact that may result from a pressure, and the identification of methods to monitor or assess the relationship between pressure and the respective impact, is absolutely necessary. The assessment of whether a pressure on a groundwater body is significant, must be based on good scientific knowledge of the pressures within the *hydrogeological* basin [6], together with understanding the parameters and interactions defining the groundwater regime (water flow, chemical transfer, and biological functioning of the water body within the hydrogeological basin).

In any case, for a “Pressure” to cause an impact there has to be Vulnerability of groundwater resources coupled with *insufficient Capacity* to reduce the Risk. So, the question/challenge that emerges is “how can we improve our capacity to reduce the risk or how can we reduce Vulnerability and/or Exposure in order to reduce the risks groundwater faces.

Monitoring systems can greatly help towards achieving these goals but their efficiency strongly dependents on knowing “what”, “where”, “when” and “how” any parameter is going to be monitored. Since groundwater related properties and pressures are highly location dependent, the sound scientific knowledge of the impact which may result from a pressure, taking into consideration the existing geological and hydrogeological conditions, is absolutely essential to develop a conceptual model representing the groundwater regime in the area and to understand the respective uncertainties. In this way, a cost efficient groundwater monitoring system can be developed and maintained, leading in turn, to the efficient management and protection of the resource [7], [8], [9].

EU Groundwater Protection & Management Policies & Environmental Data Management

EU current policies and standing regulations define at large the necessary steps to be taken towards sustainable groundwater management both from a scientific and from a technical aspect.

Problems identified regarding the up-to-date implementation of the respective EU policies, include the

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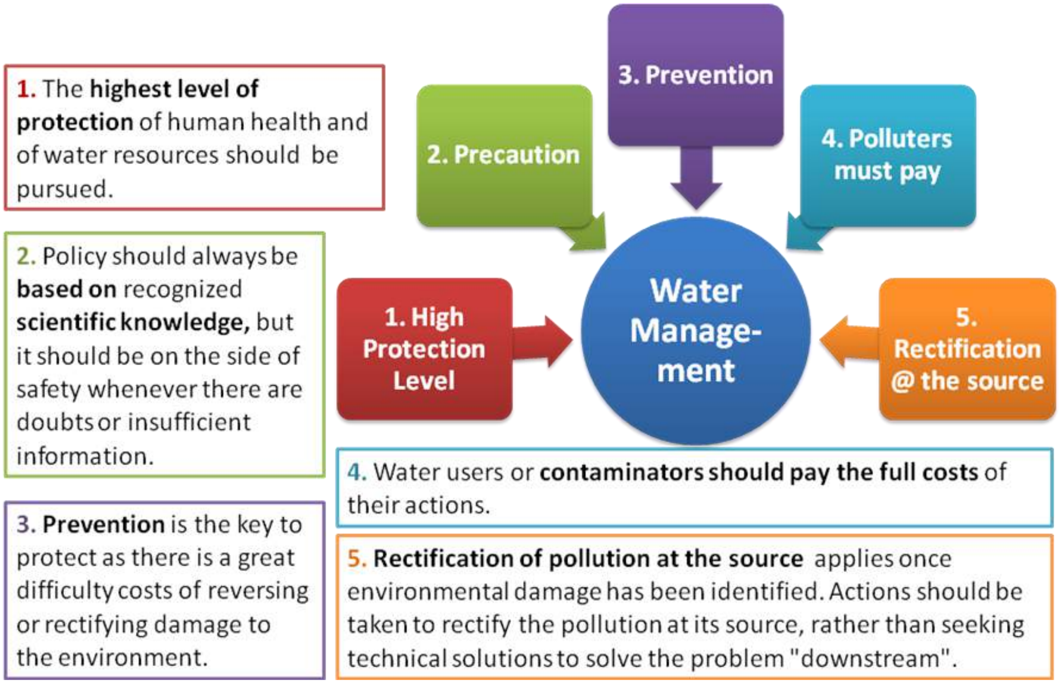
lack of Harmonization, lack of sufficient data at “decision making scales” and the lack of spatially registered information [3]. Harmonization of methodologies is a key issue and a consensus among scientists activated in this scientific field is necessary in line with standing EU regulations.

The EU policies regarding Water Protection and Management are based on a set of Principles:



1. The **highest level of protection** of human health and of water resources should be pursued.

2. Policy should always be **based on** recognized **scientific knowledge,** but it should be on the side of safety whenever there are doubts or insufficient information.

3. Prevention is the key to protect as there is a great difficulty costs of reversing or rectifying damage to the environment.

4. Water users or **contaminators should pay the full costs** of their actions.

5. Rectification of pollution at the source applies once environmental damage has been identified. Actions should be taken to rectify the pollution at its source, rather than seeking technical solutions to solve the problem "downstream".

Fig. 1. EU Principles regarding (Ground) Water protection and Management.

Based on those Principles, the EU Commission has issued numerous Directives, a list of which is shown below (Table 1), covering a number of essential issues related to groundwater (GW) protection and management.

Most if not all of the Directives have already been incorporated into the National Law of the EU Member States. GW related issues, have been consolidated into the Water Framework Directive –WFD which covers a number of different steps for achieving sustainability of the resource.

Table 1. EU policies related to GW, classified as “Legislative” and Supplementary measures.

	EU Legislative Measures (Directives)										
Bathing Water Directive 76/160/EEC	Birds Directive 79/409/EEC	Drinking Water Directive 98/83/EEC	Major Accidents (Seveso) Directive 96/82/EC	Environment Impact Assessment 85/337/EEC	Sewage Sludge Directive 86/278/EEC	Environmental Liability Directive 2004/35/CE	Urban Wastewater Treatment Directive 91/271/EEC	Plant Protection Products Directive 91/414/EEC	Nitrates Directive 91/676/EEC	Habitats Directive 92/43/EEC	Integrated Pollution Prevention Control 96/61/EEC

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EU Supplementary Measures (Controls, Codes of good Practices, funding research etc)										
Legislative, administrative or fiscal instruments	Negotiated environmental programmes	Emission controls, abstraction controls	Major Accidents (Seveso) Directive 96/82/EC	Codes of good practice, demand management	Recreation and restoration of wetland areas	Efficiency and reuse measures	Desalination plants	Construction projects, rehabilitation projects	Artificial recharge of aquifers	Educational projects, research, demonstration

Based on the above, Member States should, by the end of 2006, establish monitoring networks aiming at providing an overview of the chemical and quantitative status of GW; River basin management plans completed by 2009. These aim at investigating the pressures and impact of human activities on GW, economic analyses of water use, protection programmes, monitoring of remediation measures where applicable.

European Environment Agency (EEA) identified and examined the most important adverse effects of human intervention on the quality and the availability of GW [10], a number of factors imposing pressures on groundwater quality and quantity. According to this report ("Groundwater quality and quantity in Europe"), physical and chemical parameters defined as indicators to assess the pressures on GW, include nitrates, pesticides, chloride, pH-value, alkalinity, electrical conductivity, GW abstraction and human interventions in the hydrologic cycle.

As was shown in the same report [10], many of the problems affecting GW quality and quantity are common across Europe so these can better be addressed at a European level. A serious problem towards that end, more intense in Cross Border Areas (CBA), is the heterogeneity of data acquired and used. This problem blocks cooperation, restricts competence sharing and slows down overall progress. An additional problem identified was related to the monitoring strategies and methods adopted or adapted to "domestic" needs. Various countries had applied different monitoring systems and more importantly, different methods; a fact which led to investigating different aspects and to acquiring different types of data, incompatible between different countries even in respect to the same environmental parameters, thus making comparison among data from different locations, extremely difficult.

Another reported issue, related to the data provided, was their low level of reliability since in most cases, no additional information (type of the sampling sites, their status, hydro-geological regime, exact location etc) was available.

Having said that, efficient environmental resource management, attempts to balance between needs and resource availability so it must be based on well documented decisions. Environmental problems usually present a high spatial variability so, effectiveness of actions towards a sustainable resource management & protection strongly depends on spatial information availability, reliability and accuracy [11].

The EU has responded to this challenge by developing policies which aim at developed Policies aiming at ensuring: "that data is handled in a consistent and transparent manner and; that data providers having agreed to share, are assured that their data are properly handled, disseminated and acknowledged following pre-defined similar rules and principles in all countries and stakeholders" (EEA Data Policy, 2013).

An important step towards achieving this goal is the existing Infrastructure for Spatial Information in the European Community (INSPIRE) Directive (Directive 2007/2/EC). For the implementation of the INSPIRE Directive, the European Commission (EC) has also released the (EC) No 1205/2008 Regulation of the 3rd of December 2008 and its supportive documents (INSPIRE Metadata

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Implementing Rules: Technical Guidelines based on EN ISO 19115 and EN ISO 19119 - 06.11.2013). The European Environment Agency (EEA) also supports the operation of Environmental Data Centres which can host data, provided that these follow certain criteria concerning data structures and formats.

As it therefore seems, the necessary respective Legislation exists and sets the legal framework for water protection and management including data management, sharing and dissemination.

One of the remaining issues towards the efficient resource protection and management is the law enforcement. Among other targets, law enforcement aims at removing "profit" as a parameters of misuse of the resource or threatening its status by poorly applying methods and technologies to protect it [12]. Interpreting the "polluter pays" principle for instance, indicates that it has a twofold role: i) to remove the motivation created by "profit" (since the polluter will have to pay for the damage) and ii) to lift the burden from the rest of the tax payers (who are not responsible for the damage) and remediate the resource at the expense of the polluter. In order to indicate the polluter beyond reasonable doubt, a very efficient monitoring network, based on sound knowledge of the groundwater regime, is needed.

Land Use Legislation, especially regarding the installation of various activities can play a very important PREVENTIVE role and the same stands for legislation regarding the exploration, exploitation and management of the resource which may even be more important.

Groundwater Monitoring for Protection & Management

Efficient ground (and surface) water protection within the framework set by EU policies can be achieved through the development and use of Ground Water Information Systems (GWIS), which are capable of providing real time information regarding water physical, chemical and dynamic parameters.

Taking into consideration the EU Commission set principles regarding Water Management & Protection as set out in numerous Directives and "Communication by the Commission" documents, an indicative list of GWIS actions would include:

- Continuously monitor groundwater quantity and quality related parameters.
- Determine (near "real time") current status and estimate future trends.
- Provide Early warning in case of exceeding set thresholds of measured or forecasted parameters.
- Provide Early Detection of pollution/contamination, indicate pollution source, take remediation measures at the source.
- Monitor remediation measure performance and calibrate them.
- Provide support to regulate demand and balance consumption to availability.
- Support decisions for legislation and law enforcement (i.e. "polluter pays" principle, etc).
- Support decisions regarding groundwater protection & management, Land Development and Land Use.

Various approaches have been proposed and used to design and develop such systems taking always into consideration the existing geological conditions, the monitoring targets and the costs for system development, operation and maintenance [11], [13a], [13b], [14], [15], [16], [17].

As far as the "Informatics" part is concerned, available technologies provide low cost or even for free solutions, when using Open Source tools. For instance, such a system (fig. 2) can be based exclusively on Interoperable Platforms of the Open Source Geospatial Foundation and on Open Standards of the Open Geospatial Consortium (OGC). The web interface can be based on Javascript and its OpenLayers using GeoExt geospatial libraries. This kind of structure ensures that the outputs comply to Open Standards which fully meet the dissemination requirements of the water quality assessment parameters for policy implementation, decision making, enforcement, communication and public awareness.

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Data acquisition can be benefited by using new technologies (Cloud GIS) for Collaborative Mapping and the free access to Remote Sensing data from “Landsat 8” and “Sentinel” satellites (fig. 2), in order to compress and minimize time needed to collect reliable data from large areas.

Surface and groundwater data can be combined through Geographical Information Systems in order to assess surface/groundwater interactions and to control the impact of surface water quality to GW quality [18]. As is therefore evident, such a Ground Water Information System (GWIS) can provide outputs which can support decisions and law enforcement, communication/dissemination to raise awareness.

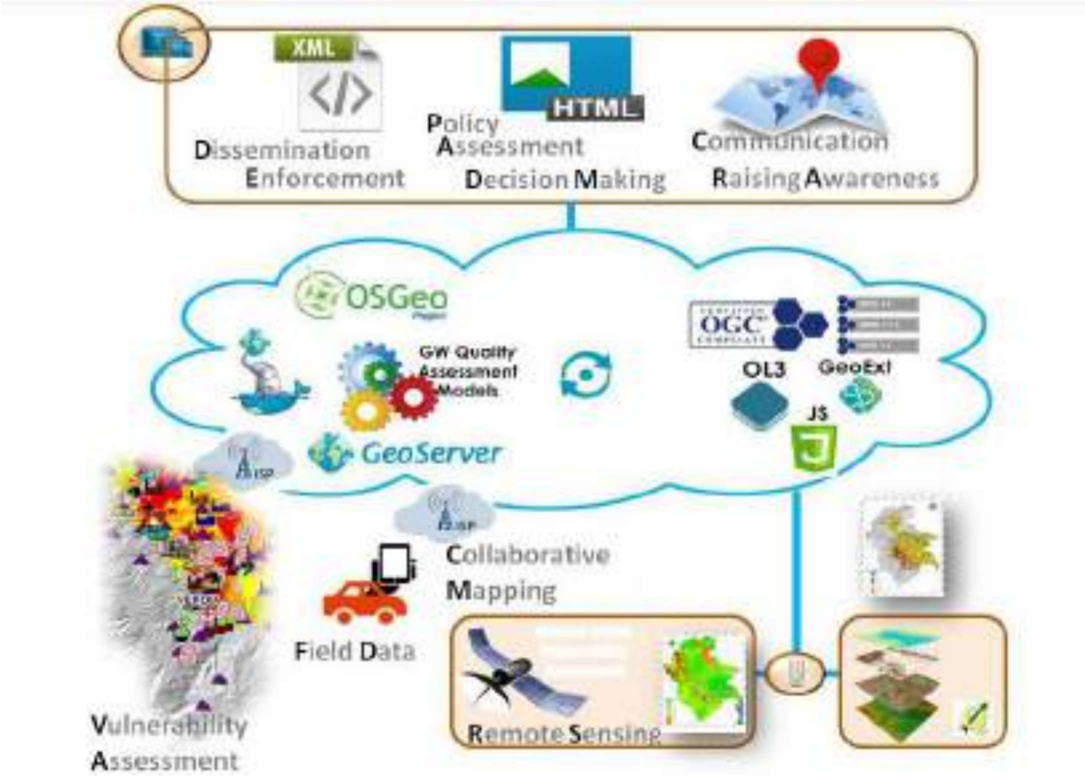

Fig. 2. Schematic representation of a Ground Water Information/Monitoring System based on interoperable platforms of the Open Source Geospatial Foundation and on Open Standards of the Open Geospatial Consortium (OGC). The GWIS incorporates Geo-informatics Technologies to manage Geospatial information and Cloud based services to support collaborative mapping and information sharing.

Efficient development of a GWIS requires a multi-disciplinary approach, which covers the development of the Conceptual Model (provision of sound scientific knowledge), the development of (custom if necessary) sensors, and the development of the Information & the Communication Systems (infrastructure). Since in the long term, the main costs of these systems are related to sensor purchase, installation and maintenance, the number of sensors installed and their specifications define at large the total costs and the feasibility to develop, install and maintain such a system.

At present, groundwater monitoring is being done using one of two main directions: i) in-situ measurements using stand-alone equipment and ii) real-time monitoring.

The first option is costly, time consuming and labor since it involves a lot of field work. There’s also a high potential of equipment being damaged because of their use in difficult conditions (inside boreholes, pipes etc).

Real-Time monitoring on the other hand can provide the information needed (provided that it measures the correct parameters in the right location) but it is inflexible (one the sensors are install they remain in place for their entire operational period and very costly due to the cost of sensors, the sensor

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maintenance costs and their low life-span [19]. For these reasons, many attempts to install and maintain such a system have failed and these systems, after an operational period, have been abandoned due to the lack of funding maintenance and/or sensor replacement.

The solution to this problem is the development of a new sensor generation which will incorporate a number of properties: low purchase cost (affordability), minimal dimensions (to fit in narrow spaces); modular design (to be expandable in measuring at the same location additional parameters); flexible installation (to be transferred in another location if necessary); uninterruptible communication; longevity; and of course these sensors must provide at least the expected level of sensitivity, accuracy, precision, repeatability, selectivity, durability and have minimal maintenance requirements. Obviously, these requirements pose a challenge to the sensor development Research and Industry.

Early warnings for contamination depend on triggering alarms when specified threshold of monitored parameters are exceeded. Taking into consideration that triggering an alarm for water contamination has a great impact on social life and on any anthropogenic activity, such a decision must be based on absolutely reliable information and should not rely on measured values of the monitored parameters only.

Information leading to decisions must take into consideration the interaction of the values of more parameters related to a potential contamination or pollution because monitoring upper and lower thresholds of specific parameters is not enough to trigger an early warning. For instance, an increase in Cloride ion concentrations and Conductivity values could indicate sea water intrusion but these changes could also be attributed to different causes. This information combined with a respective increase in Na and sulfates (SO_4) with a HCO_3 decrease at the same time, is signaling a sea water intrusion and can be used to trigger and alarm [20], [21]. It is therefore obvious that an in depth knowledge of all aspects related to groundwater hydrology, hydrochemistry and hydraulics for the area under investigation must be consider and incorporated into the monitoring system, in order to support decision making.

This task can only be implemented through the development of a conceptual model that will identify all involved parameters as well as their interactions, which define the groundwater status, the potential threats and their impacts.

Conceptual Modeling for Groundwater Protection & Management

In general, the number of sensors installed and their specifications define the main costs and thus the feasibility to develop, install and maintain a GroundWater Monitoring System (GWIS). In order to minimize the cost of such a GWIS the least possible number of sensors should be used but at the same time, a number of questions arise. Answering those questions, defines the system’s operational specifications, including sensor specifications, their location and spatial coverage, and at large, the GWIS potential to protect groundwater and support management related decisions:

- Which are the Ground Water monitoring targets?
- Which is the required “resolution” and the one provided by the GWIS? (ie. does it allow for detecting/monitoring a specific point source? …a plume, etc).
- Are the appropriate aquifers being monitored at the appropriate locations n order to detect at an early stage any potential problem?
- Are the appropriate parameters being measured to an adequate degree of accuracy, consistency and reliability?
- Does the monitoring network provide a coherent and comprehensive overview of the groundwater status within a river basin/ hydrogeological basin / groundwater body?
- Does the system collect sufficient data to indicate seasonal and mid-term variations and to estimate trends?
- Does the system permit for trend analysis (does it include groundwater flow/hydraulic models?)

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Based on the answers, some basic considerations [22], [23] regarding the requirements for setting up such a program are related to:

- Compliance of the GWIS operational specs and outputs to the existing legislation.
- GWIS efficiency, which in turn requires to take into consideration:
    - the aquifer (flow) system characteristics (recharge, flow conditions, available reserves, boundary conditions, spatial extend and other parameters related to understanding all the processes/interactions between surface and groundwater.
    - Groundwater physical, chemical and dynamic Properties; because an understanding of the connection between the aquifer material and the physico-chemical parameters of groundwater as well as the relationship between groundwater hydraulic heads, is necessary.
    - The groundwater Vulnerability against any potential Hazard, in order to identify the kind/type and level of potential threats and Risks.
    - The Pressures which exist including the kind and magnitude of problems they may cause. In respect to anthropogenic hazards, this means that for any activity the information needed includes any kind of used substances and any kind of products, by-products and wastes produced by any activity or installation.
    - the Risks groundwater faces to identify the type and level of potential damage.

Only the well documented knowledge of all this information can lead to justified decisions regarding “why”, “what”, “where” and “when” to monitor and in turn lead to planning “how to” set-up an efficient monitoring system with all its components.

Understanding all these parameters which are related to the groundwater flow system, its dynamic, physical and chemical parameters as well as their potential temporal variations and their interaction with aquifer media, with surface water bodies and terrestrial eco-systems, constitutes the groundwater Conceptual Model of the area, which is essential for developing an efficient GWIS. A Conceptual Model is always dynamic, evolving and improving with time as new data are obtained; and the model is continuously refined in an iterative way.

The Conceptual Model must also include water quality information and pressure assessment. In essence, the model should include the nature of the aquifer system, both in terms of quantity and quality, and the potential consequences of pressures taking always into consideration the existing legislation regarding any of its components (Fig. 3).

Groundwater conditions are actually related to a balance between availability (groundwater recharge), consumption (groundwater exploitation) and potential threats against it quality (vulnerability and pollution/contamination risks). Any of the three components (recharge-exploitation-vulnerability), require a list of data and information related to various parameters, a non-exhaustive list of which includes [22], [23]:

- Recharge
    - Geologic and Hydro-geologic maps
    - Tectonic maps (to investigate recharge through rock formations)
    - Remote Sensing analysis for tectonic mapping,
    - Stratigraphy from bore-logs (aquifer media, aquifer potential, flow conditions, strata thickness, aquicludes etc)
- Extraction/Exploitation
    - Borings/water wells: location; data regarding the physical-chemical-dynamic properties of groundwater in each location;
    - Demand & Consumption (including temporal variations)
- Vulnerability & Risk Assessment (Potentially Hazardous to GW installations/activities:
    - Vulnerability:
        - Litho-Stratigraphy/Geological structure (lithological cross sections from borings; type of formations; thickness; sequence, permeability etc)
        - Aquifer systems: Hydrogeological parameters (hydraulic conductivity, permeability,

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groundwater levels, groundwater flow direction etc)

    - Recharge conditions (recharge status including recharge zones, direct percolation from surface etc)
- Risk:
    - Point sources: land use/activities (location, type, chemicals used for processing, products, by-products, wastes, type of produced potential contaminants, protection measures taken, demand for groundwater consumption etc). All required information is per activity and (if) any temporal variations should also be considered.
    - Non point sources: types of activities (ie. agriculture, rivers, lakes); Demand each source (ie. agriculture: cultivated area, types of crops, crop demand for agro-chemicals throughout the year, crop demand for consumption etc; rivers: permeability of surface formations along the stream bed in the entire watershed and especially downstream from various point sources; lakes: the same etc).

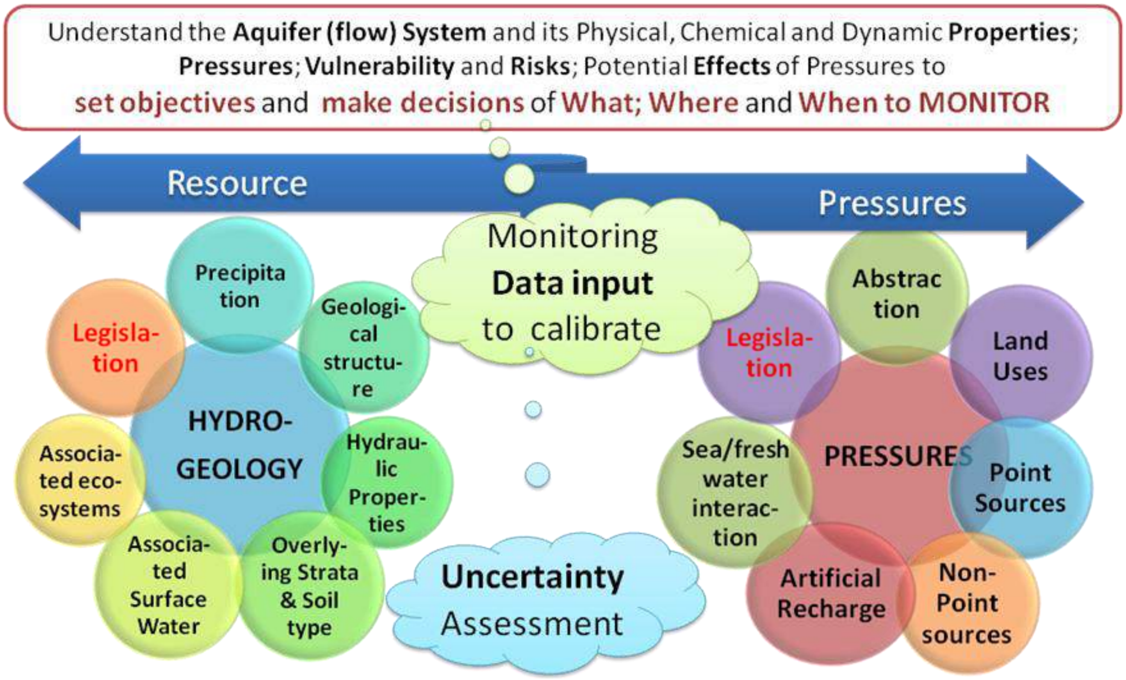

Fig. 3. A schematic representation of the required parameters to develop a Groundwater Conceptual Model (GCM). Scope of the GSM is to help understand the linkage between the existing hydro-geological conditions and the existing threats for groundwater quantity and quality, in order to balance the preservation of the resource with its uses in a sustainable way.

The multitude of parameters needed is indicative of the difficulty to collect the respective data, since there are specific constrains set by location and time (fig. 4). For instance, water level data can be compared if they have been collected during the same hydrologic year; chemical analyses data can be compared only when collected from the same sampling point or in the case of different sampling points, during the same period. As is evident, there may be various resources of data, and this fact imposes a series of concerns regarding data quality (accuracy, reliability, completeness, currency/timeliness and since they may be coming from different sources, consistency).

To overcome this issue and in order to gradually increase the number of scientists following harmonized approaches, a strategy including the development of technical guidance based on best practice cases leading to a common understanding of the entire spectrum of actions towards groundwater protection and management, and the development of open standards for ground water monitoring are essential.

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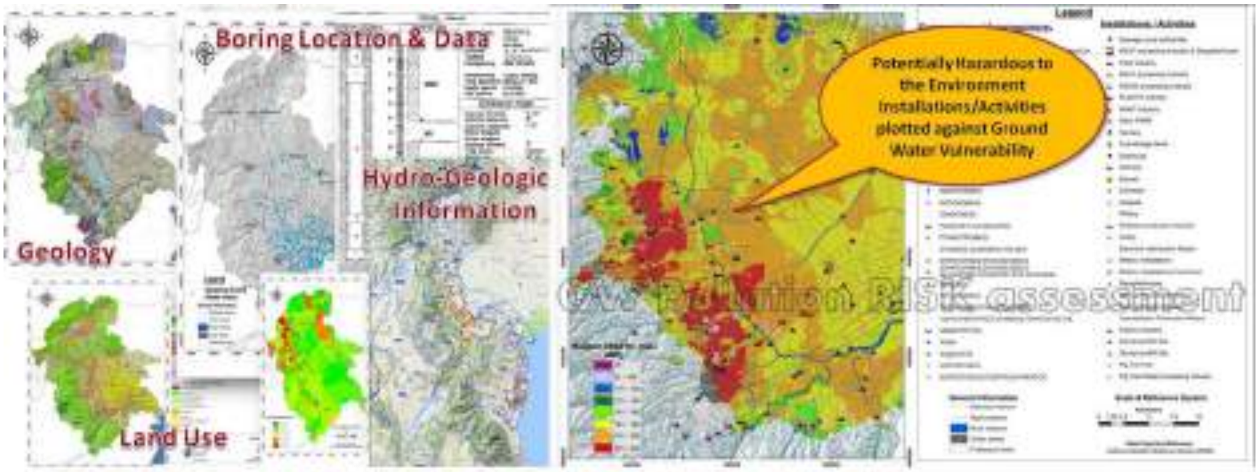

Fig. 4. A indicative «list» of required data for building a Groundwater Conceptual Model (GCM).

Conclusions

A review of the conditions required to develop an efficient groundwater monitoring system have been presented and discussed.

The development of a groundwater monitoring program requires a multi-disciplinary approach, which covers the development of the Conceptual Model, the development of (custom if necessary) sensors, and the development of the Information & the Communication Systems (infrastructure).

Groundwater Conceptual Model (GCM) development, is a decisive stage in compiling a groundwater monitoring program since it justifies the reasons for monitoring, it defines “what”, “where” and “when” to monitor and moreover, it sets the operational requirements for “how” any parameter should be monitored. It also requires a multi-disciplinary approach which may involve geologists, hydro-geologists, hydro-chemists, chemical engineers, geo-informatics (remote sensing and GIS) experts, hydraulic engineers and more. The respective geo-database must contain all parameters related to groundwater/aquifer physical, chemical and dynamic parameters as well as their inter-relations.

Accurate, precise, consistent, timely and as complete as possible information is precious in all stages of the monitoring system development because it can greatly improve the conceptual model accuracy and overall, the monitoring program efficiency.

Sharing information and data can greatly improve the capacity to develop efficient systems but harmonization of both methodologies and data is absolutely necessary. The existing framework set by the INSPIRE Directive can greatly help towards that scope but consensus among the scientific community is also required.

A Strategy to achieve these goals, should include:

- Harmonization of approaches/methods used.
- Competencies sharing to build capacity of researchers. Exchanging experiences, broadens the ideas, offers more potential solutions and saves time and effort. Harmonization of methodological approaches is the key to sharing competencies. It requires a common understanding of the problem and great efforts for achieving consensus.
- Develop technical guidance based on best practice cases, so that gradually, the “user” base following harmonized approaches will grow;
- Develop open standards for ground water monitoring;

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- Develop efficient and more affordable monitoring systems;
- Systematically assess Vulnerability and pollution Risk. This is an essential step. Planning for protection absolutely requires a sound knowledge of vulnerability and Risk.
- Develop a common understanding of the entire spectrum of actions towards groundwater protection and management. This common understanding should apply to the monitoring programme development team and to the stakeholders including the Administration and the rest of the "stakeholders", who include the Industry, Water Companies, farming companies and farmers and of course the rest of the public;
- Raising awareness is another, very effective preventive measure. Creating aware and conscious citizens is like transporting them from the side of the problem to the side of the solution; they become a part of the solution. Web based technologies (portals with near real-time information about the status of the resource, the problems, solutions applied etc) can greatly help towards this scope.

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