PROTECTING AND PRESERVING GROUND WATER WITH MONITORING SYSTEMS AND VULNERABILITY MAPS

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ABSTRACT

As Ground Water (GW) is a natural resource of vital importance, it's protection against all types of threats can be considered as an absolute necessity. GW as a natural source can be effectively protected and managed using GW monitoring systems provided that, when developing such a system for a specific area of implementation, certain conditions are met and parameters are taken into account including GW recharge conditions, hydrogeological regime, land uses and GW vulnerability from surface pollution (as GW is often hydraulically connected to surface and surface water).

To assess those parameters, reliable and accurate data are needed. The acquisition of such required data, regarding their economic cost and time needed, poses obstacles sometimes difficult to overcome.

At this point, contemporary technologies as Geographic Information Systems (GIS) and Remote Sensing (RS) can provide solutions. In the present paper, a combination of case studies including the identification and delineation of GW recharge areas using RS, the GW vulnerability assessment using GIS and the development of a Web based GW monitoring system that can also be used as an early warning system for GW protection, is presented. The methodologies proposed have been tested in various areas of Northern Greece providing reliable results at minimal costs. Their combined application can provide the tools to constantly monitor GW quality, to detect GW pollution at a very early stage, to select and apply remediation measures and to continuously rate them, to detect pollution sources, to support decision making regarding land uses, to help raise public awareness and overall, to ensure GW protection and sustainability.

Keywords: groundwater vulnerability, groundwater monitoring

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1. Introduction

Ground water is a natural resource of vital importance as it is usually the main source of potable water. Conservation and enhancement of groundwater resources through land care, management, recharge preservation and protection of quality is therefore essential. Within this context, recharge area delineation, groundwater vulnerability assessment and groundwater management are key issues.

Groundwater recharge areas feed with water the rest of the aquifer towards the water abstraction facilities and have therefore to be identified and protected in order to preserve groundwater quality. Groundwater recharge can take place through inflow along aquifer boundaries among different aquifers; especially where aquifers developed in mountainous areas come in contact with permeable sediments along valley edges, thus forming primary groundwater recharge zones.

As groundwater recharge can also take place via direct rain water percolation through permeable geologic formations, groundwater vulnerability from surface pollution is in many cases, high and has to be assessed in the most possible accurate and reliable way. Provided that they are based on reliable and accurate data and tested and approved methodologies, vulnerability maps can then be used to help make decisions about land use planning thus preserving groundwater's integrity.

During the last decades, the continuously increasing demand in groundwater created the necessity for groundwater resources management in order to protect the quantity of groundwater and ensure a dependable and affordable supply of this resource. A management system that provides groundwater monitoring on a constant basis is therefore required. Such a System can help manage groundwater resources, fine tune exploitation parameters, indicate pollutants from a very early stage, evaluate measure effectiveness, project to future needs and over all, help make decisions about the sustainable use of this natural resource. Designing such a system is not an easy task as it is a dynamic procedure that changes both spatially and temporarily in parallel with the continuously changing demand, production and consumption conditions. Additional problems for groundwater sustainable management include the lack of a systematic source protection, not always imposed legal frameworks, the lack of reliable information and lack of public awareness.

As data availability, accuracy, reliability and costs are among the key issues in all three aforementioned problems, the use of contemporary technologies as Remote Sensing (RS) and Geographic Information Systems (GIS) to tackle these issues is demonstrated. Within this context, methodologies used and results from case studies are presented and discussed.

2. Groundwater protection and management. Methodologies applied

GROUNDWATER RECHARGE AREA DELINEATION

Area of implementation is the plain of Trikala, Greece (Figure.1) where due to groundwater over-exploitation during the past decades, groundwater degradation problems emerged. As groundwater demands in the area continuously increase due to population growth and climate change, prevention and management of groundwater resources is essential for reassuring sustainable development.

There are two main aquifer systems developed in the area; one is developed in the carbonate formations of Koziakas mountain and another, within the alluvial sediments that fill the basin of Trikala plain. Previous investigations on the groundwater regime of the area (Kallergis, 1970 & 1972; Payne et.al., 1976) suggest that there is very small or not at all hydraulic connection between the two aquifer systems due to the presence of an ophiolitic complex that separates them and acts as an impervious barrier (Figure.1-geologic cross section).

Groundwater recharge in the aquifers developed in Trikala basin is therefore suggested to take place directly from surface water percolation through the permeable surface formations. Based on this assumption, a number of potentially hazardous to groundwater land uses could be selected for the area where the ophiolitic formations outcrop as they are considered to be impermeable.

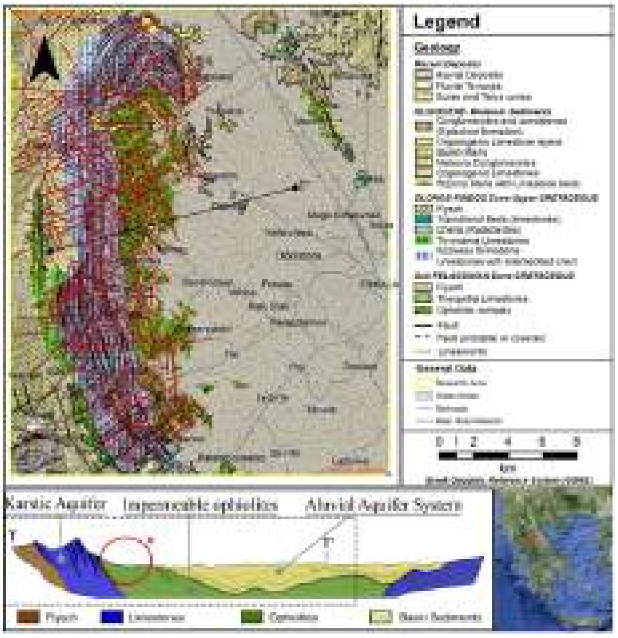

Figure 1: Geologic Map and geologic cross section of the area under investigation (red circle).

The integration of a sequence of remote sensing techniques with geologic and hydrochemical data for geological and hydrogeological assessment was used (fig. 2) to trace groundwater flow paths through the theoretically impermeable ophiolitic formations and to delineate recharge areas. Landsat TM (http://glcf.umiacs.umd.edu/) image visual interpretation was based on remote sensing techniques including band ratio-ing, Principal Component Analysis (PCA), and False Color Composite creation. Lineament statistical analysis, lineament density maps, geologic maps and hydro-chemical data were additionally used in order to verify remote sensing results and to indicate potential groundwater flow paths through the ophiolitic formations that outcrop in the area.

As resulted the investigation, there is a far greater number of faults than the ones already mapped in the area. Landsat TM Band Ratios (BR) and False Color Composites (FCCs) as the (R-G-B) (PC2-BR4/7-BR4/3), (BR4/7-BR4/3-TM4), (Papatheodorou, 2010) as well as the [(BR4/3)x(BR7/4)] image (Papatheodorou et.al., 2012) are suggested to be appropriate for mapping these features.

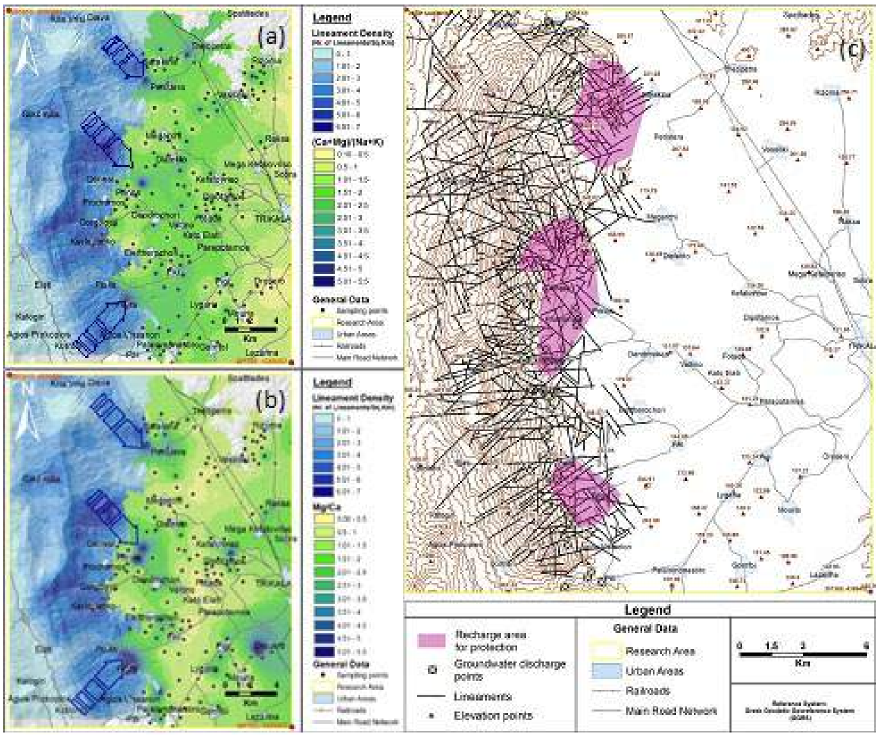

Figure 2: Ion Ratio spatial distribution in the research area as compared to lineament density maps. (2a): [(Ca+Mg)/(Na+K)] indicating groundwater residence time in the aquifer, (2b): [Mg/Ca] indicating groundwater origin and 2c: Recharge areas delineated.

To verify groundwater flow through the ophiolitic complex, groundwater chemical analyses data in the form of ion concentrations and their ratios were used as they can help indicate water origin and residence time in geologic formations (Hounslow, 1995). Ion ratio [Mg/Ca], was used to indicate groundwater flow through limestones ([Mg/Ca]<0.7), dolomites (0.7-0.9) or ophiolitic formations ([Mg/Ca]>1.0). Ratio values in the area range from 0.1 to 5.39 and ion ratio [Mg/Ca] spatial distribution indicates groundwater inflow from the ophiolitic formations towards the plain sediments (fig. 2a). Ion ratio [(Ca+Mg)/(Na+K)] provides information about groundwater's residence time in the aquifer and indicates if a part of the aquifer is under continuous groundwater flow. Ratio values range from 0.5 towards the center of the basin, a value indicative of high residence time, to 5.0 at the edge of the basin, a value that corresponds to continuous groundwater flow (Figure.2b). Concluding, ion ratios as compared to the lineament and the lineament density maps, provide strong indications of groundwater inflow towards the basin sediments so principal recharge areas that must be protected can be delineated (Figure.2c).

GROUNDWATER VULNERABILITY ASSESSMENT

Groundwater is subjected to contamination from various natural and anthropogenic sources so groundwater vulnerability against pollution from ground surface must be carefully considered when planning land use on a long term. The area of implementation is located in Northern Greece and covers a large part of Emathia and Pella plains (Figure.3), forming one of the most important agricultural areas in northern Greece. In the same area, the presence of numerous industrial and other potentially hazardous installations, pose a significant hazard against groundwater preservation.

The DRASTIC method (Aller et.al. 1987) and it's variations were applied to assess groundwater vulnerability in the area. DRASTIC method is considered among various groundwater vulnerability assessment methods as the one that takes into consideration most of the hydro-geological parameters. DRASTIC is in fact, the acronym of D(epth to groundwater), R(echarge rate), A(quifer media), S(oil media), T(opography), I(mpact of vadose zone) and C(onductivity of the aquifer). The method involves the calculation of DRASTIC Index (DI):

$$\text{DRASTIC Index (DI)} = Dr \times Dw + Rr \times Rw + Ar \times Aw + Sr \times Sw + Tr \times Tw + Ir \times Iw + Cr \times Cw$$

where r is the rating for each of the parameters and w the respective weighting factor which is standardized and given by respective tables (table I).

The "Pesticide DRASTIC" method incorporates a modification that takes an additional consideration on the nature of the soil media which, due to organic matter and clay minerals present, affects the pollutant reduction/retention process. An additional approach is suggested by the “Modified DRASTIC” method (Secunda et.al., 1998; Thitumalaivasan et.al., 2003) which takes into consideration land use. The Modified Drastic Index (MDI) is calculated as MDI = DI + Lr × Lw, where DI is the typical DRASTIC Index (DI), Lr is the Land Use parameter and Lw the weighting factor (both parameters are given by respective tables provided by the methodology).

TABLE I. DRASTIC and Pesticide DRASTIC weighting factors

DRASTIC parameter	Weighting Factors	
	DRASTIC	Pesticide DRASTIC
D	5	5
R	4	4
A	3	3
S	2	5
T	1	3
I	5	4
C	3	2

In order to assess groundwater vulnerability, a Geographic Information System (GIS) was developed. To calculate the individual DRASTIC parameters, soil maps, digitized topographic maps of 1:5000 scale and data from more than 250 sampling points were used including bore logs, water level measurements, pumping test results and water chemical analyses results (Tzimourtas, 2001; Veranis, 2008 & 2009). Data available were updated with in situ measurements.

DRASTIC and Pesticide DRASTIC (Engel et.al., 1996) parameters were calculated as described by the respective methodologies. Weighting factors were taken from TABLE.1 and all other parameters were classified according to the DRASTIC methodology provisions.

i. Depth to groundwater (D): Was calculated by classifying water level measurements according to the methodology’s provisions.

ii. Recharge rate: Calculation was based on rainfall and on the infiltration rate of each of the geologic formations that outcrop in the area.

iii. Aquifer media (A): Characterization was based on bore log data.

iv. Soil media (S): Soil media was evaluated by available soil maps, soil analyses data (Tzimourtas, 2001) and in situ observations/sampling and analyses.

v. Topography (T): Considering the low topography of the area, topographic maps at a 1:5000 scale were digitized and used to create a Digital Terrain Model which was in turn used to create a slope map of the area

vi. Impact of vadose zone (I): Calculation was based on bore log data.

vii. Hydraulic conductivity of the aquifer (C): The parameter was assessed from pumping tests carried out in the water wells of the area.

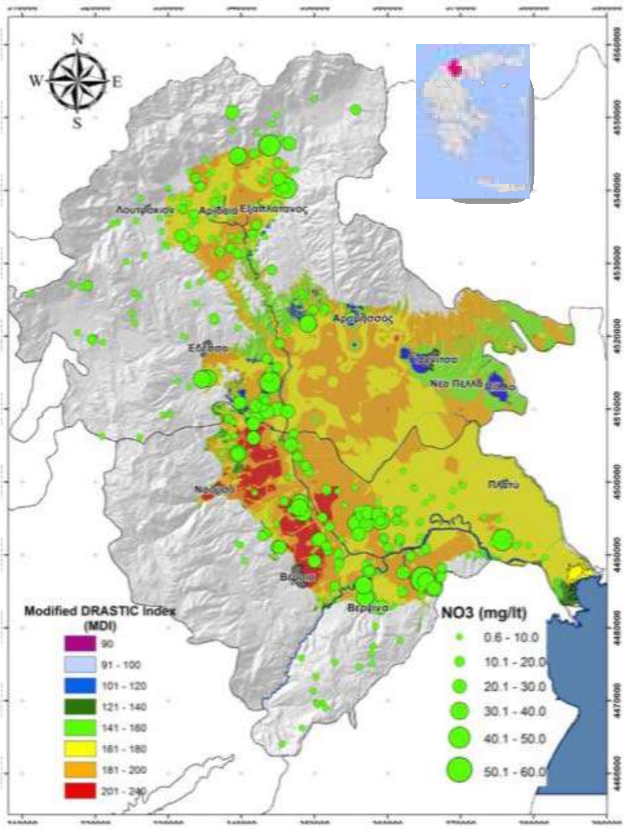

Figure 3: Nitrogen ion concentration plotted against the vulnerability map. Increased NO_3 concentrations in “High” and “Very High” vulnerability areas indicate groundwater’s high vulnerability and the used method’s results reliability.

As resulted, DI values for the entire area range from 77 to 217. These values indicate, according to the methodology, “very low” (81-100) to “Very High” (greater than 200) groundwater vulnerability.

The DRASTIC method does not take into consideration land use despite the fact that the main causes of groundwater pollution are anthropogenic so the “Modified DRASTIC” method which considers land use in assessing vulnerability was used. Modified Drastic Index (MDI) was calculated using Corine Land Cover 2000 (European Environment Agency) data and maps. As resulted, MDI values range from 81, which is considered as “Low” to 256 which is considered as “Very High”, groundwater vulnerability. As is shown (Figure.3), the western part of the plain exhibits a “High” to “Very High” vulnerability whereas the eastern part a “Low” to “High” one with a part showing a “Moderate” vulnerability (green area).

To evaluate groundwater vulnerability assessment results, groundwater chemical analyses data from 114 water wells in the area were used. Nitrate concentration has been suggested as an anthropogenic pollution index and has been used to evaluate the results of groundwater vulnerability assessment methods (Rupert, M.G., 1999). Nitrate concentrations (as NO_3_N mg/l) in groundwater as compared to the vulnerability map created show a considerable agreement. Nitrate concentration is greater in the western part of the implementation area which exhibits “high” to “very high” vulnerability. Moreover, nitrate concentration in a number of water wells has been found to be very high indicating that pollution has advanced, especially considering the fact that water samples were pumped from the well and not taken from the shallow phreatic aquifer alone. As it therefore appears, the DRASTIC methodology based on relatively high resolution data, can provide reliable results regarding the assessment of groundwater vulnerability to contamination from ground surface. Vulnerability maps can in turn, provide reliable information and assistance to decision making regarding legislation and landscape sustainable planning.

GROUNDWATER PROTECTION AND MANAGEMENT

A monitoring and early warning system for groundwater level fluctuations due to climatic condition changes or human activities as well as for water quality changes, can greatly help in decision-making on water-takings, drought management and land use planning thus providing support for groundwater sustainable management. Designing groundwater monitoring systems and networks is not a simple task because such a system strongly depends on site specific conditions and on the continuously changing demand, production and consumption conditions. Various approaches have been proposed and adopted for that matter (Environmental Agency UK, 2001; Dutta D. et al, 2007) and any approach, in order to be effective, must depend on the objectives of the groundwater monitoring system as well as on the parameters affecting groundwater quantity and quality over the entire study area.

The presented GroundWater System’s (GWIS) development was based on those concepts so it is designed in a way that selected parameters regarding groundwater quantity and/or quality can be constantly or selectively measured and data can be instantly transferred and stored in a server (Papatheodorou et.al. 2009). This is achieved either by direct input or by using telecommunication technology (i.e. commercial GPRS network).

Sampling point’s selection in an area is based on the conceptual site model, the data quality objectives, the existing regulatory framework and the performance monitoring requirements.

The conceptual model itself focuses in understanding the existing problems for the specific site. Factors that must be known include the scope of the monitoring procedure, the geologic and the hydro geologic regime of the area, the biological and geochemical conditions, potential pollutant transport pathways of (potential) contamination as well as historical data. GWIS implementation includes performance monitoring which aims at the progress verification towards the overall monitoring program goals; the most important being to make informed decisions regarding environmental issues as well as possible groundwater monitoring system enhancements (fig.4).

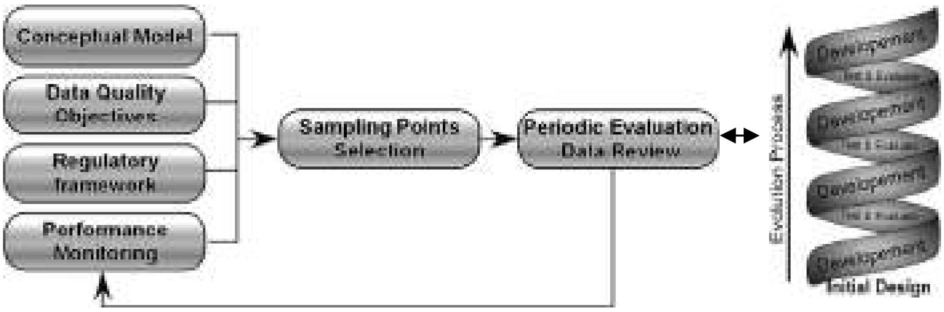

Figure 4: GroundWater Information System's (GWIS) conceptual model.

The adopted System Architecture is a typical multi-tier architecture customized to meet the proposed system requirements and is introduced through three major tiers (layers):

A. The Data Collection Layer which comprises any kind of field equipment device that is used to perform measurements related to groundwater critical factors.
B. The Data / Services / Application Layer which groups the typical data and application (business logic) layers of the 3–tier architecture (Eckerson et al, 1995) along with a layer comprising the required services provided by standard software components (Web Server, Map Server and Database Sever). It also includes a number of sub-layers as:
   - Database and Assisting Services.
   - Application and Data access code that contain Web-GIS applications and groundwater simulation models.
   - User access control and content management, that ensures authorized user access built on user profiles.
C. The Presentation layer which aims at providing custom browser based applications to satisfy user interaction.

GWIS, made use of commercial software products including ESRI's Internet Map Server (v.9.3) which cooperates with specific combinations of Web Server and Servlet Engine versions of the Apache products. The test area selected for the implementation was a part of Thessaly plain (Figure 1) where data from a total number of 303 sampling points were available. Data included bore logs, water levels measured periodically as well as data regarding the physical and chemical parameters of groundwater in the area. As the data used in the pilot implementation were already available, they were imported in GWIS as standard tabular data files (Excel worksheets, comma and/or tab delimited etc) and were used to create various types of spatial information including groundwater level maps as well as spatial distribution maps of physical properties and ion concentrations. Data retrieval and processing is done through a Web application, so authorized users can have access to the system remotely, through a web browser service (Figure 5a).

Sustainability and improvement of the GWIS is through periodic evaluation on a regular basis. Evaluation includes a review of all the data and results generated and their comparison to historical data. Data reviews can help detect major changes in the hydro geologic regime of the area sometimes indicative of contamination. It can also help reveal contaminant trends and evaluate remedial measure performance in case measures have been taken. The designed system including the monitoring network can not only adapt to local conditions but it can also be optimized. The monitoring network optimization can be based on tracking measured parameters as groundwater levels or ion concentrations and evaluating their spatial distribution changes over time.

GWIS is capable of monitoring in real time, the status of critical groundwater parameters and of providing alarms and special information when a set threshold in one or more selected parameters is exceeded (Figure.5b). As all parameter values change over time, appropriate feature symbology facilitates sampling point performance control and “surveillance” capabilities.

Concluding, the basic characteristics of the GWI system developed and implemented, include adaptability to user needs that change according to demand, production and consumption conditions, conformity with National and EU Provisions and Directives regarding the use of Geographic Information Systems and Data, ease of use for non-expert users, remote access for data updating and evaluation, integration of various types of data and information. Moreover it can incorporate various models for data processing and interpretation and it can provide results in various forms (tables, charts, maps, reports). Map and data access over the internet provides accessibility to experts according to their access rights and can also be used to inform the public thus helping raise public awareness and promote groundwater protection, conservation and management strategies.

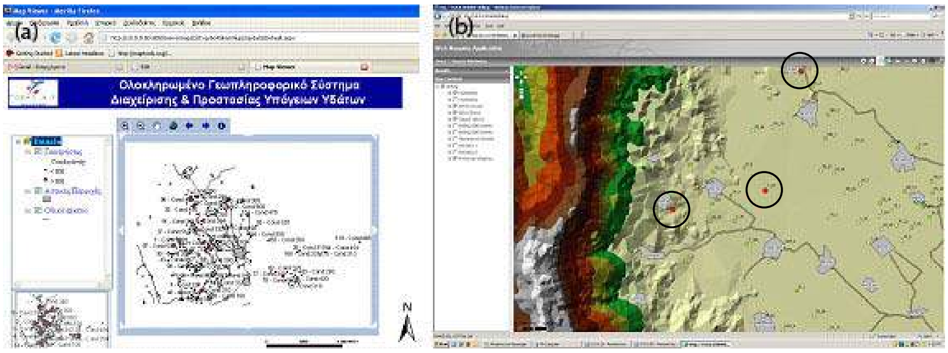

Figure 5: GWIS implementation. (a) Data input and management. (b) Alarms triggered (red dots) when set parameter thresholds are exceeded.

3. Conclusions

Contemporary technologies as Remote Sensing and Geographic Information Systems can provide reliable and accurate enough information to assess important parameters necessary to protect and preserve groundwater.

Vulnerability maps can be produced and used to support decisions regarding legislation and land use planning. In any case, data availability, reliability and accuracy are the main concerns.

Groundwater protection and management can be based on a GroundWater Information System as the one proposed. GWIS can adapt to local conditions and to user needs even as they change over time. By tracking measured parameters as groundwater levels or ion concentrations that are above a set threshold, it can be used as an early warning system helping identify hazards at a very early stage. In any case, contaminant trends can be identified and remedial measure performance can also be evaluated. Finally, as it is Web based it can provide information to the public, helping in this way to raise public awareness and promote groundwater conservation, protection and management strategies.

Overall, contemporary technologies as remote sensing and geographic information systems can add value to scientific knowledge and strongly support decision making regarding the establishment of regulatory frameworks for groundwater sustainable exploitation, management and protection.

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