REMOTE SENSING AND GEOMATICS TECHNOLOGIES TO SUPPORT GROUNDWATER SUSTAINABILITY

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ABSTRACT

Groundwater management and protection is widely considered as a key factor in sustainable development as it plays a dominant role in both economic and demographic growth. As groundwater quantity and quality are strongly related to land use, sustainable land use planning should take into account all parameters related to groundwater sustainability. In broad terms, groundwater sustainability can be considered as a three-fold issue comprising exploration, management and protection. All three aforementioned issues can be addressed both in local and regional scales with the assistance of contemporary technologies such as Remote Sensing and Geographic Information Systems (GIS) including Web-GIS platforms.

An evaluation of the role Remote Sensing and Geo-informatics technologies can play in all phases of groundwater resources development -exploitation, management and protection- is presented. Within this context, remote sensing and water chemical analyses data are used to trace groundwater flow through impermeable formations and to delineate recharge zones which should be protected. In addition, groundwater vulnerability in an intensely cultivated area is assessed and compared to nitrate concentrations showing the credibility of the method as well as the already imposed cultivation impact on groundwater. Maps created, provide valuable information about the land use interaction with groundwater and subsequently assist in specifying basic guidelines both for land use planning and cultivation practices applied. Finally, a Groundwater Information System developed to address management and protection issues and aiming to support decisions regarding a land use planning regulatory framework towards groundwater sustainability, is presented.

1. INTRODUCTION

Various known landscape planning models (Ahern, 1995 & 1999; Steiner, 2000) include among their specific goals, water resources planning. Groundwater in particular, plays an increasingly important role as it forms the basic potable water resource.

The main concerns about groundwater quantity and quality are primarily related to land-uses that require the quantity and are known to be adversely affecting groundwater quality or have the potential to do so. Conservation and enhancement of groundwater resources through land care, management, recharge preservation and urban design is therefore essential. Within this context, recharge area delineation, groundwater vulnerability assessment and groundwater management are key issues.

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

Groundwater recharge can also take place via direct rain water percolation through permeable geologic formations. In such a case, groundwater vulnerability from surface pollution is high and has to be assessed in an accurate and credible way so that vulnerability maps can be used to help make the right 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 is therefore required; a system that provides groundwater monitoring on a constant basis, thus helping manage groundwater resources, fine tune exploitation parameters, evaluate measure effectiveness, project to trends and future needs and over all, help make decisions about the sustainable use of this natural resource. On the down side, problems related to groundwater sustainable management include lack of systematic source protection, not imposed legal framework, lack of reliable information, lack of public awareness. An additional problem lays on the fact that designing for the optimal development of groundwater resources is a dynamic procedure that changes both spatially and temporarily in parallel with the continuously changing demand, production and consumption conditions.

As data availability, accuracy, reliability and cost are among the key parameters in all three aforementioned issues, 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. DATA & METHODS

2.1 FIRST CASE: PRINCIPAL RECHARGE AREA DELINEATION

Area of implementation is the plain of Trikala, Greece (fig. 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, 1971 & 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 (fig.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.

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 (Fig.1). 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.

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 (fig. 2b). Concluding, ion ratios as compared to the lineament and the lineament density maps created, provide strong indications of groundwater inflow towards the basin sediments so principal recharge areas that must be protected can be delineated (fig. 2c). As is therefore evident, remote sensing techniques combined with GIS can provide reliable and adequate information to delineate groundwater recharge zones and help make decisions regarding land use planning.

2.2. SECOND CASE: 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 under investigation is the plain of Emathia (fig. 3), 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):

$$\text{DRASTIC Index (DI)} = D_r \times D_w + R_r \times R_w + A_r \times A_w + S_r \times S_w + T_r \times T_w + I_r \times I_w + C_r \times C_w$$

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 1). 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 $MDI = DI + L_r \times L_w$, where DI is the typical DRASTIC Index (DI), L_r is the Land Use parameter and L_w the weighting factor (both parameters are given by respective tables provided by the methodology).

In order to assess groundwater vulnerability in the plain of Emathia, 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 115 water wells 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 respective tables (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.

As resulted, DI values for the entire area range from 77 to 217. These values indicate, according to the methodology, “very low” to “Very High” 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 (Fig.3a), the western part of the plain exhibits a “High” to “Very High” vulnerability whereas the eastern part a “Low” to “High” one with it’s main part showing a “Moderate” vulnerability (green area).
To evaluate groundwater vulnerability assessment results, groundwater chemical analyses data from 104 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 (fig. 3b). Nitrate concentration is greater in the western part of the plain 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 then provide reliable information and assistance to decision making regarding landscape sustainable planning.

2.3. THIRD CASE: GROUNDWATER MANAGEMENT AND PROTECTION

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 and various approaches have been proposed and adopted for that matter (Environmental Agency UK, 2001; Dutta D. et al, 2007). Each one of them proved not to be equally suitable and reliable for any particular region, as the design of such a system strongly depends on site specific conditions and on the continuously changing demand, production and consumption conditions. Any approach used in order to be effective, must therefore 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.
With those concepts in mind, the developed system 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. This is achieved either by direct input or by using telecommunication technology (i.e. commercial GPRS network). In this way, sampling costs can be significantly reduced.
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 and historical data. GWIS implementation includes performance monitoring which aims at providing the quantity and quality of data necessary to verify progress towards the overall monitoring program goals and to make informed decisions regarding environmental issues as well as possible groundwater monitoring system enhancements (fig.4).
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. Reviewing the temporal variations of collected data, can help detect major changes in the hydro geologic regime of the area and also can help to verify that the assumptions made are valid. A data review can also help to identify contaminant trends and to evaluate remedial measure performance in case measures have been taken. The designed system can not only adapt to local conditions but it can also be optimized. The monitoring network optimization is based on tracking measured parameters as groundwater levels or ion concentrations and evaluating their spatial distribution changes over time.
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):

- The Data Collection Layer which comprises any kind of field equipment device that is used to perform measurements related to groundwater critical factors.

- 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.
- The Presentation layer which aims at providing custom browser based applications to satisfy user interaction.

The pilot implementation presented, 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 300 sampling points were available. Data included bore logs, water levels measured periodically as well as hydro-chemical 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).

The system 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.

3. CONCLUSIONS

Groundwater protection and preservation is a key issue when planning for sustainable Landscape development. Within this context, remote sensing methods can provide in short time and at a low cost, accurate and reliable information which when incorporated in a GIS and combined with additional data can help identify groundwater flow paths and delineate groundwater recharge areas, helping in this way define regulations and make decisions about sustainable land use planning. A pilot implementation of the suggested procedure in the plain of Trikala, Greece, helped delineate recharge areas for protection.

DRASTIC groundwater vulnerability assessment methodology, when applied using high resolution data can provide reliable results. Groundwater vulnerability maps produced in the plain of Emathia, Greece, show a considerable agreement with Nitrate ion concentrations in the area, indicating a high credibility of the method's results. Vulnerability maps produced can help make decisions about land use planning in the area.

The Ground Water Information System (GWIS) developed to manage and protect groundwater resources, 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, contaminant trends can be identified and remedial measure performance can also be evaluated. Moreover, GWIS can be used as an early warning system, thus providing a valuable groundwater protection tool. Finally, as it is Web based it can provide information to the public, helping in this way to raise public awareness and promote 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 within the context of sustainable land use planning.

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LIST OF ATTACHMENTS

Figure_1.jpg
Figure 1: Geologic Map and geologic cross section of the area under investigation (in the red circle).

Figure_2.jpg
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.

Table_1.rtf
Table 1: DRASTIC and Pesticide DRASTIC parameter’s weighting factors.

Figure_3.jpg
Figure 3: DRASTIC method performance evaluation. (a) Modified DRASTIC vulnerability map of the Emathia plain and (b) Nitrate (NO_3 mg/l) concentration in groundwater.

Figure_4.jpg
Figure 4: Ground Water Information System (GWIS) concept design. Evaluation on a regular basis and performance monitoring ensure GWIS’s adaptability to local conditions and user needs.

Figure_5.jpg
Figure 5: Ground Water Information System implementation. (a) Data input and management. (b) Alarms triggered (red dots) when set parameter thresholds are exceeded.