An Agricultural Decision Support System for Optimal Land Use Regarding Groundwater Vulnerability

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ABSTRACT

The availability of good quality water is worldwide a basic condition to pursue the socioeconomic development. The agriculture water demand can be damaged by contamination of groundwater resources. This paper proposes a tool to preserve the groundwater quality by using groundwater vulnerability assessment methods and a decision support system (DSS). Vulnerability map could be used for planning, policy, management, and contamination assessment. The mapping of intrinsic groundwater vulnerability was based on reliable methods, i.e., the DRASTIC and the SINTACS methods. A vulnerability map could be used for planning, policy, management, and contamination assessment. A DSS was developed in order to assess the groundwater vulnerability and pollution risk due to agricultural activities and land use changes. The proposed DSS software package was designed using the Matlab language. The software is a friendly application for everyone ranging from the novice user, e.g., a student, to an operations research scientist. It quickly and efficiently performs the task that is scheduled to carry out, and it can incorporate new maps in order to cover new areas. The tool was tested using two study areas located in the Mediterranean area. The test sites are dominated by different prevalent hydrogeological features, i.e., the typical porous features of alluvial deposits in the Greek study area and the typical fissured and karstic features of limestones and dolostones in the Italian study area.

Keywords: Decision Support Systems, Environmental Management; Groundwater Pollution; Land Use; Matlab Toolbox; Vulnerability

INTRODUCTION

In many countries, including those in the Mediterranean region and numerous coastal areas with worldwide distribution, groundwater is the main source for drinking and irrigation use. The availability of good quality water is a key factor for social and economical development. For this reason, preserving its availability and quality is a crucial issue for the future (EU Council, 1998; UNESCO, 1998). The degradation of groundwater resources can be quantitative if the discharge exceeds the natural recharge and qualitative if the chemical, physical, and biological water quality is threatened. In the former case, if the aquifer is on the coast, overexploitation is also qualitative risk due to possible seawater intrusion, causing salt degradation in the groundwater quality (Polemio et al., 2009a). The definition of a suitable policy for water is important in the context of growing scarcity and competing uses (Bazzani, 2005). For this reason, the importance of integrated water resource management was emphasized in the recent EU Water Framework Directive (2000/60/EC).

If groundwater degradation risks are considered, planning decisions should be reached based on risk assessment procedures in which the effects of anthropogenic activities on natural resources and the environment are considered. Agricultural activities are surely some of the most

relevant endeavors. However, massive soil and continuous groundwater exploitation have a relevant negative impact on the environment.

In many farming areas, anthropogenic modifications are mainly caused by the following two types of activity: direct pollution from agricultural activities due to the use of agrochemicals, fertilizers, and pesticides and farming improvements, thereby provoking other negative impacts. Fires and the clearing of forests and stones with the advent of machinery have been widely used to make the land suitable for farming. Over-irrigation and salt-recycling due to overexploitation in the coastal areas also create problems (Voudouris et al., 2004). The effects on groundwater availability and quality are complex and generally negative.

The regional assessment of groundwater vulnerability is a useful tool for water resource management and protection. The results provide important information that can be used by local authorities and decision makers. A groundwater vulnerability assessment could be used to more effectively determine the choice of land use modifications, the location, the type of farming, and use of chemicals and irrigation in the farming endeavor.

The use of computer-based systems to support decision making regarding groundwater resource management has increased significantly over the last decade. In the case of land management, decision support systems (DSSs) are typically used to select an optimal or satisfactory solution from a set of feasible alternatives (Shim et al., 2002; Manos et al., 2004a). DSSs are defined as computerized systems that include models and databases used in decision-making (Uricchio et al., 2004). They are useful tools that help scientists and administrators in the decision-making process and in choosing the economically, socially, or environmentally best alternative solution (Hwang & Yoon, 1981; Manos et al., 2004b; Manos

et al., 2007; Leung, 1997; Zhu et al., 1998; Vacik & Lexer, 2001).

The implementation of geographic information systems (GIS) and DSSs in hydrogeology offers effective tools for groundwater resource management. GIS has been widely used to establish a database for collected data (Süzenm & Doyuran, 2003; Gemitzi et al., 2006). In hydrogeology, both GIS and DSS have been developed to support local authorities, decision makers, and stakeholders in terms of groundwater resource management, vulnerability and pollution risk assessment, and protective zoning.

From a theoretical point of view, the paper briefly describes the main methods for groundwater vulnerability assessment while considering typical porous aquifers on the alluvial or coastal plains and the peculiarities of rocky aquifers (i.e., typical karstic aquifers). Additionally, methods to assess groundwater risks and hazards in the case of agricultural activities are described. From an operational point of view, the paper also describes some case studies of relevant farming areas located in southern Italy and northern Greece.

STUDY AREAS

The Florina basin is located in the central part of the Florina prefecture territory in western Greece, and its surface is roughly 319 km2. The average altitude is around 620 m asl, and the average slope is 1.5% (Figure 1). The annual rainfall is 643 mm per year (Kazakis, 2008). Based on results from soil analyses, the predominant soil types are as follows: Clay, Silty-clay, Sandy-clay, Sandy-loam, Silty, Silty-loam, and Loamy. Aquifer systems are developed in alluvial and Neogene deposits in the basin. The depth to groundwater in the alluvial aquifer of the Florina basin ranges from 0 to more than 25 m below ground.

*Figure 1: Location of the Florina basin in northern Greece*
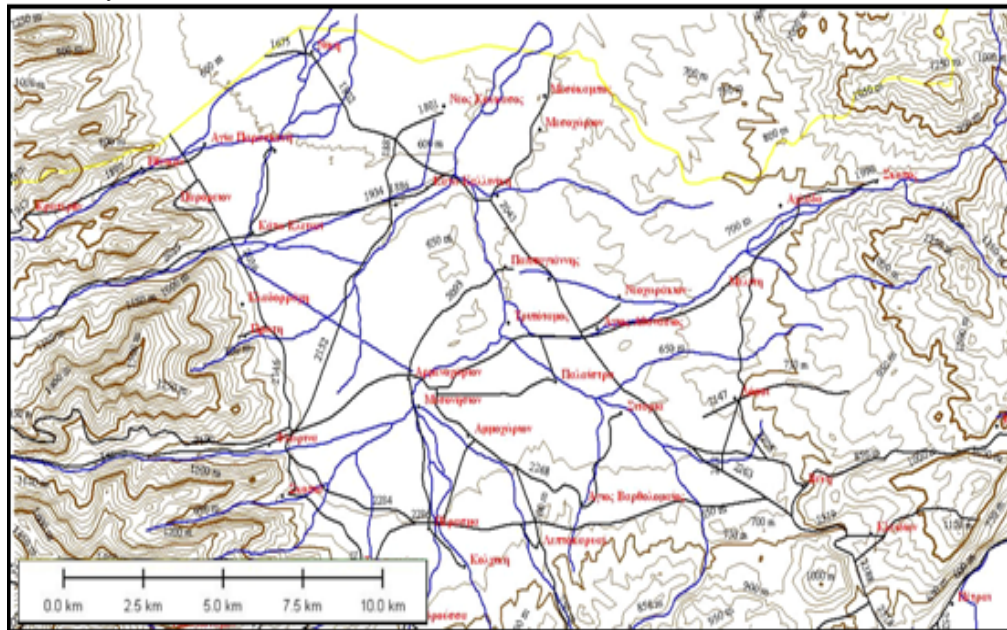
Economic development in the area largely depends on pumped groundwater, which has increased in amount since 1980. The land is predominantly used for agricultural purposes in the lowlands, and irrigated agriculture is predominant in the basin. Groundwater is abstracted for irrigation purposes during the dry season (i.e., May through September). In the wet period, groundwater extraction is limited to domestic use.

The Monopoli area or test site (Figure 2) is located in the low Murgia Plateau (i.e., the Apulia region) and is characterized by Mesozoic limestone and dolostone that is several thousand meters thick. The entire study area is characterized by developed karst landforms, i.e., karst formed in response to several morphogenetic phases that took place in different climatic and structural contexts. As a result, an underground network of cavities, caves, and conduits has been developed; some of these have large dimensions. The landscape is characterized by many dolines, valleys, and drainage lines that are not clearly defined, thereby creating a discontinuous network.

Figure 2: Location and geological map of the Monopoli area in Italy (Polemio et al., 2009b, modified)
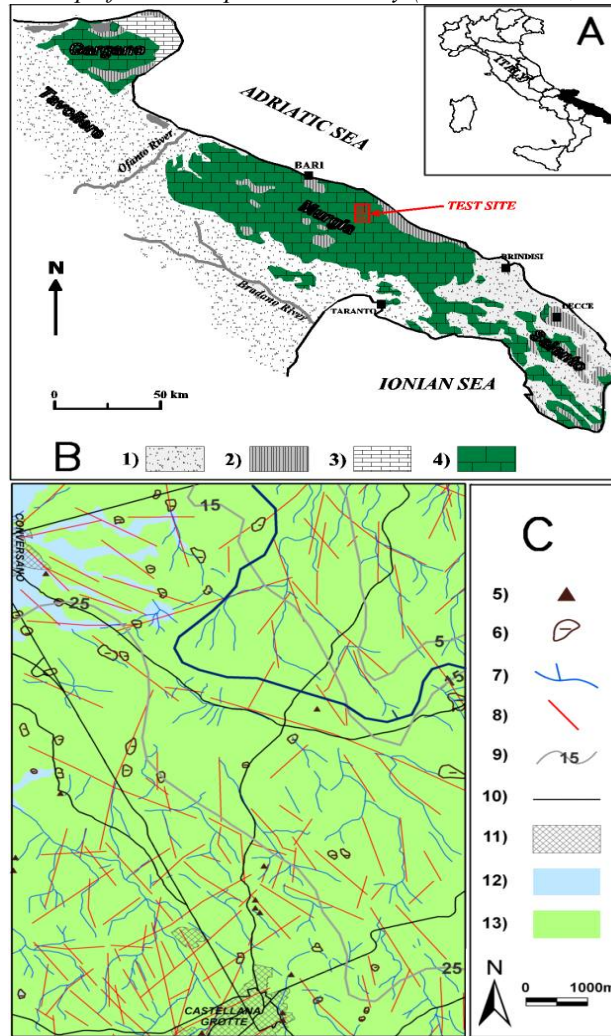
A: Apulian region and Italy.

B: Geological scheme of the Apulian region; 1) Recent clastic cover (Pliocene-Pleistocene), 2) Bioclastic carbonate rocks (Paleogene) and calcarenites (Miocene), 3) Scarp and basin chert-carbonate rocks (Upper Jurassic-Cretaceous), and 4) Carbonate platform rocks (Upper Jurassic-Cretaceous).

C: Schematic geological map of the study area; 5) Cave, 6) Doline/Sinkhole, 7) Drainage pattern, 8) Fault, 9) Piezometric contour line (m asl), 10) Road, 11) Urban area, 12) Alluvial deposits, and 13) Limestone.

A wide and thick aquifer resides in these carbonate rocks. The aquifer is divided into more permeable strata because of the variable distribution of fractured and karstified strata confined between impermeable levels of various extensions and thickness. This mainly occurred due to tectonic events that fractured the carbonate mass in a poor and discontinuous manner and variation in the base level of groundwater flow. It is generally confined except along a narrow coastal strip; faults govern the major preferential flow paths and seawater intrusion (Polemio, 2005). The groundwater in the study area has undergone a twofold pollution that is all due to human action. Saline pollution has progressively evolved as it affects increasingly large portions of land, and biological and chemical-physical pollution is mainly concentrated around urbanized areas.

GROUNDWATER VULNERABILITY ASSESSMENT

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection for groundwater

against human activities. In other words, vulnerability represents the degree of weakness of one aquifer system to pollution.

In this study, two methods were applied in order to evaluate vulnerability, i.e., DRASTIC and SINTACS. Both the DRASTIC and SINTACS method are representative of rating methods or Point Count System Models (PCSM) for assessing groundwater vulnerability.

The initials in the acronym DRASTIC (Aller et al., 1987; Secunda et al., 1998; Al-Zabet, 2002; Voudouris, 2009) correspond to the following seven (7) parameters measured in this system: Depth (to water), Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and hydraulic Conductivity of the aquifer.

Determination of the DRASTIC index involves multiplying each parameter weight by its site rating and summing the total. The equation for the DRASTIC Index (DI) is as follows:

$$DI = \sum_{j=1}^{7} r_j . w_j \qquad (1)$$

or

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

where r is the rating for the study area, and w is the importance weight for the parameter.

The SINTACS method was defined in an attempt to improve the DRASTIC method and uses almost the same parameters (Civita, 1994, 1995), which are as follows: depth to water, recharge or effective infiltration, attenuation capacity of unsaturated (or vadose) zone, soil attenuation capacity, hydrogeological characteristics of the aquifer, aquifer hydraulic conductivity, and slope. The vulnerability index $I_{SINTACS}$ can be computed as follows:

$$I_{SINTACS} = \sum_{J=1}^{7} r_j w_j \qquad (2)$$

where r is the rating of each of the seven parameters, and w is the correlated weight.

The SINTACS point-count system has a complex structure (Gogu & Dassargues, 2000) (Figure 3). The core of the method is the use of five set of weights or strings (i.e., normal impact, relevant impact, drainage, karst, and fissured aquifer) simultaneously in large areas and also if dominated by different prevalent conditions (e.g., in the case of zones that are deeply modified by anthropogenic activities as in urban areas) or due to the intensive use of agricultural chemicals and different types of aquifers, such as porous, fissured, or karstic aquifers (Polemio et al., 2009b).

Figure 3: SINTACS method (Adapted from Vrba & Zaporozec, 1994)
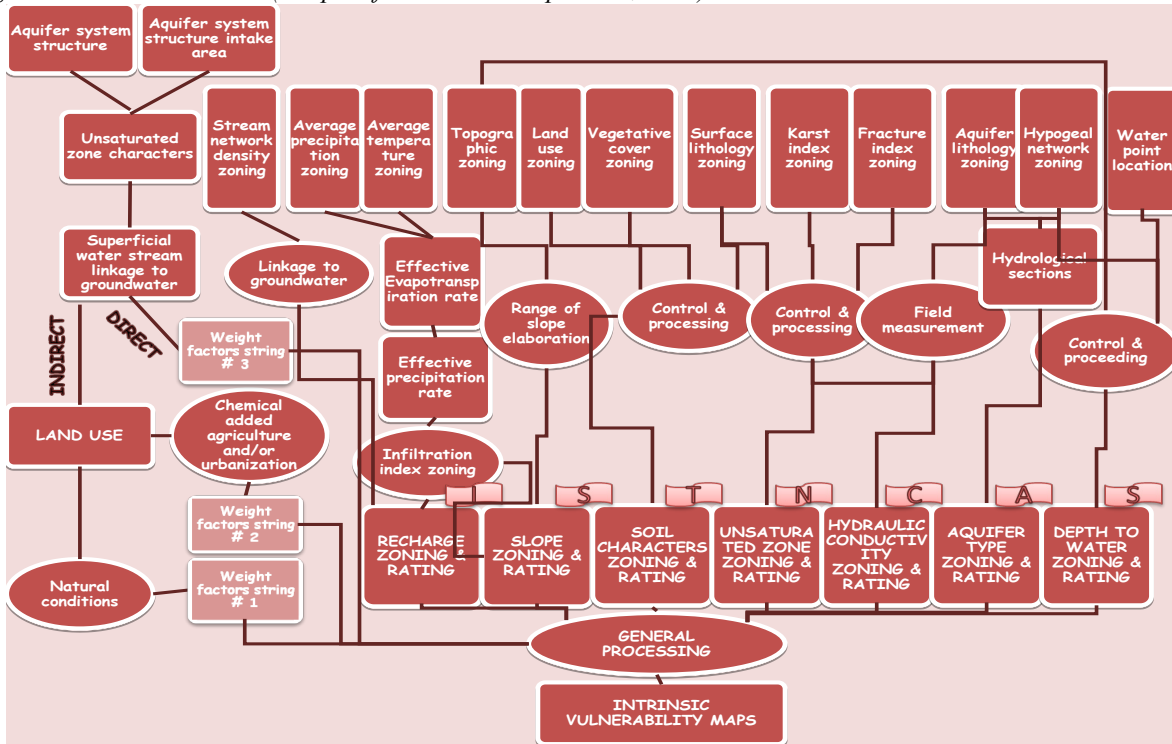
In both methods, each parameter included in the index must have an assigned numeric value between 1 and 10. A higher index value indicates greater groundwater pollution potential or greater aquifer vulnerability.

Parameters used in the aforementioned method are fundamentally derived from monitoring gauges, hydrogeological field surveys, including water level measurements, pumping tests, soil analyses, and aero-photo and remote sensing studies (Figure 4).

Figure 4: Vulnerability assessment: Worksheet of required data in Excel format

	X	Y	Z	Aquifer media	Vadose zone media	Thickness of the vadose zone	Depth to groundwater	K (m/day)	Recharge (mm)	Soil texture	Slope (%)
1	2705382	4527867	300	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	274	274,5	10,8	37,9	silty clay	1,7
2	2703213	4529043	285	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	252	252,1	6,9	38,0	silty clay	0,0
3	2707560	4526833	300	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	259	259,7	0,6		silty clay	0,0
4	2702771	4525790	335	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	302	302,8	19,8		silty clay	5,0
5	2700363	4527475	327	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	330	330,4	4,8		silty clay	5,8
6	2700805	4528625	304	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	308	308,2	8,7	38,2	silty clay	3,4
7	2715379	4527531	89	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks			4,2			
8	2709068	4535551	91	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		103,3	2377,0		negligeable or absent soil	3,2
9	2712013	4531314	95	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		132,3	46,6		negligeable or absent soil	4,3
10	2713084	4528549	127	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		165,2	0,8		negligeable or absent soil	3,0
11	2708714	4534736	147	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		129,2	390,6		negligeable or absent soil	3,2
13	2706601	4533904	215	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	295	295,3	0,2		silty clay	8,1
15	2706533	4531117	268	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	423	423,1	1,9		silty clay	4,9
16	2709838	4534071	98	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		103,9	95,5		negligeable or absent soil	4,2
17	2710429	4534024	83	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		98,9	119,2		negligeable or absent soil	2,8
18	2709633	4531868	155	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		172,0	5,9		negligeable or absent soil	0,0
19	2708427	4532974	175	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		186,0	0,2		negligeable or absent soil	12,2
20	2707627	4531161	245	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	262	262,1	4,8		silty clay	4,4
21	2706059	4535226	210	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	244	244,6	5,0		silty clay	16,3
22	2705077	4537812	147	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	251	251,0	183,5	28,6	silty clay	3,0
23	2707719	4538544	58	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		115,8	900,9		negligeable or absent soil	3,3
24	2703353	4533311	196	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	296	296,5	0,2	34,0	silty clay	0,0
25	2703703	4534569	211	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	203	203,5	1,2	33,6	silty clay	3,2
26	2703961	4536801	176	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	253	253,1	30,7	31,2	silty clay	2,3
27	2705479	4536224	185	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	214	214,3	71,2	30,8	silty clay	1,8
28	2702117	4537002	181	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	188	188,1	1,5	33,0	silty clay	0,0
29	2699197	4538530	183	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	162	162,9	194,0		silty clay	3,3
30	2705032	4536599	177	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	288	288,3	269,0	30,6	silty clay	2,1
31	2703460	4535034	209	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	214	214,2	7,0	33,4	silty clay	0,0
32	2706207	4536135	175	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	190	190,1	56,8		silty clay	7,4
33	2704355	4534913	207	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	205	206,0	4,3	33,0	silty clay	4,4
34	2702436	4537286	178	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	174	175,0	5,0	32,6	silty clay	1,9
35	2704951	4535509	195	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	206	206,5	45,8	32,0	silty clay	3,6
36	2705518	4535232	211	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	205	205,6	16,3	32,3	silty clay	0,1
37	2713416	4527438	181	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks		188,6	1,0		negligeable or absent soil	15,2
38	2701556	4538123	172	Mesozoic limestone and dolomite rocks	Mesozoic limestone and dolomite rocks	228	228,3	6,0	33,0	silty clay	1,9

RESULTS

The final vulnerability DRASTIC map of the Florina basin was produced using the values of the DRASTIC index (Figure 5). The highest vulnerability values in the Florina basin are associated with shallow aquifers that do not have great depth in the vadose zone. Low and very low values of vulnerability are observed in the centre of the basin where the aquifer has great depth in the vadose zone with layers of clay and silt and great depth to groundwater level.

*Figure 5: DRASTIC index (DI) worksheet in Excel format*

The SINTACS intrinsic vulnerability map (Figure 6) reveals the presence of the following four vulnerability classes in the study area: low, medium, high, and very high. Most of the area is classified as medium in terms of vulnerability. High or Very high risk is reported where karst features are present on the ground surface (i.e., dolines) and/or the top soil is negligible. The urban areas are generally classified as medium in terms of vulnerability.

Figure 6: SINTACS vulnerability map of the Monopoli study area 1) Road, 2) Urban area, 3) low, 4) medium or moderate, 5) high, and 6) very high vulnerability
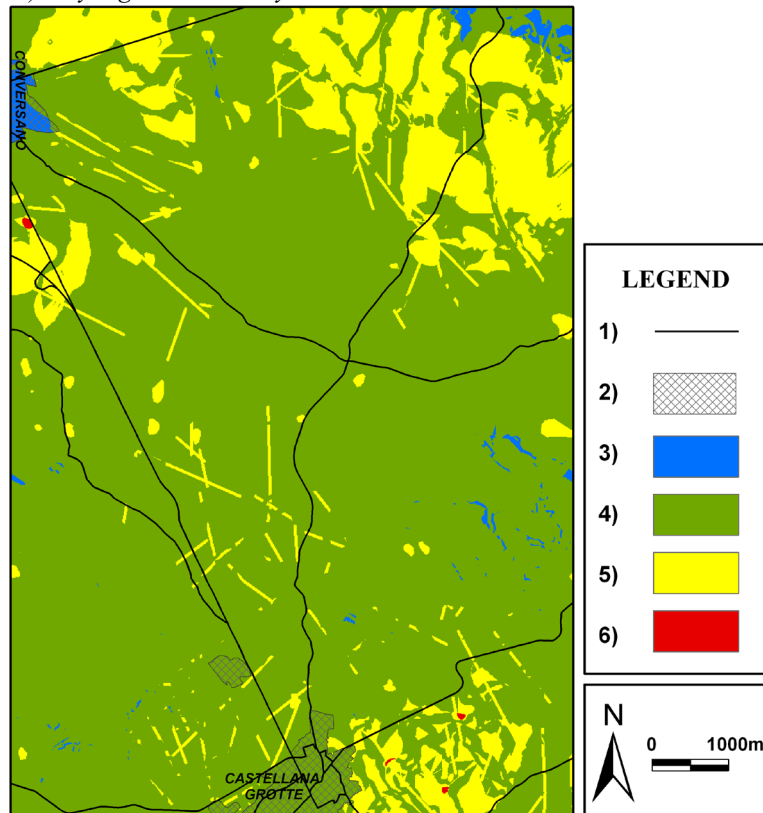
In general, the results of this study describe the relevant vulnerability of the groundwater in the Murgia aquifer. The intrinsic vulnerability map that was produced can provide useful information with sufficient spatial resolution and precision for the planning of local anthropogenic activities.

DSS ARCHITECTURE

Implementation & installation issues of the DSS software package

The proposed DSS software package has been designed using the MATLAB language. More precisely, the proposed DSS software package makes use of all the programming capabilities that are offered from MATLAB version R2009a.

Matlab toolboxes are widely used by many scientists. They are easily deployed while exploiting all the Matlab programming benefits; thus, they are frequently used for diverse types of computational tasks. For example, Dosios et al. (2002) presented the LinPro Matlab toolbox, which is an educational platform for Linear Optimization. Furthermore,

Dosios et al. (2003) developed the NetPro Matlab toolbox as an educational tool for the teaching of Network Optimization. Furthermore, Matlab combines animation and graphics (e.g., Marchand & Holland, 2002), thereby enabling the user to deploy complex graphical user interfaces (GUI).

All of the functions in the proposed DSS software package are separate m-files. The installation using Matlab is easy and can be accomplished using similar methods to the installation of any other function or toolbox. The current version of Matlab is quite sophisticated and provides the user with many built-in functions and useful tools (e.g., Hahn & Valentine, 2007).

All the necessary files must be copied to a folder, like Matlab/Work, and the user must consecutively select File → Set Path → Add with subfolders to add the directory of the proposed DSS software package into the current path for Matlab.
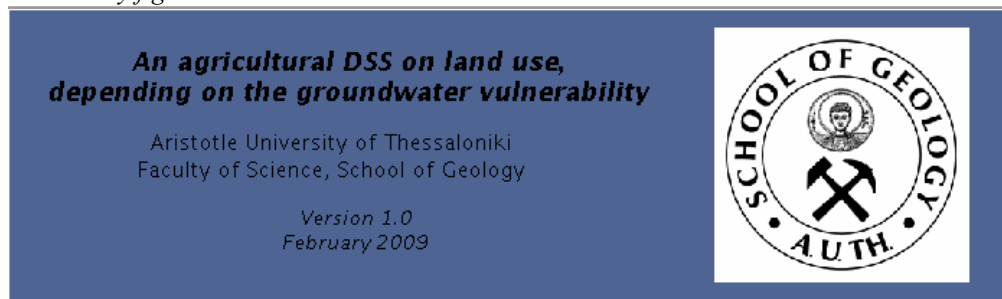
The Graphical User Interface (GUI) of the DSS software package

The user can start the proposed DSS software package easily by running the function *landuse.m*

through the Matlab environment. After the command execution, an introductory screen (Figure 7) is shown to the user for 3 seconds.

Figure 7: Introductory figure

The user has two choices depending on whether he has already made a decision on how to utilize the land or not. In the latter case, the user may previously know the ground water vulnerability within his land and wants advice from the DSS software. This user may submit his choice on the following screen (Figure 8).

Figure 8: Possible ways to use the DSS software
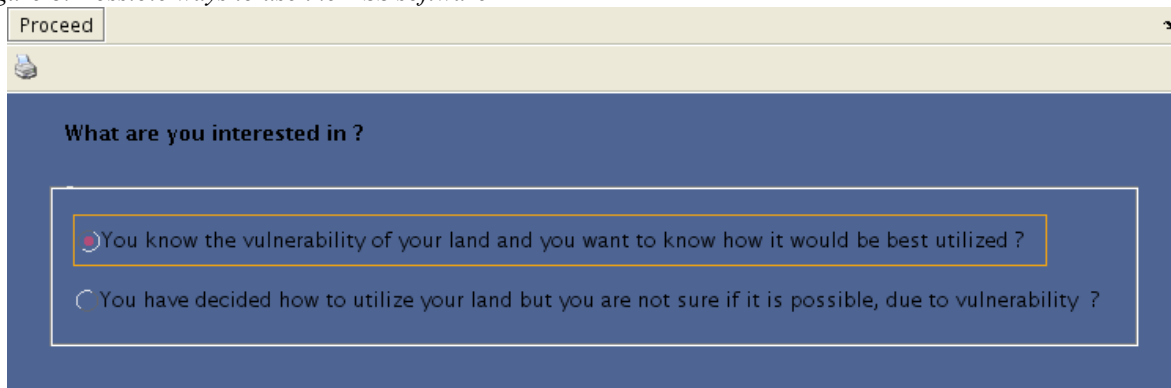
The GUI consists of a main menu bar and one toolbar, both of which may contain different buttons depending on the specific figure. In the above Figure 8, the user may either print this dialogue window or press the "Proceed" button in the menu bar. Assuming that the user already knows the ground water vulnerability of his land, he probably wants direction regarding what types of exploitation for which the land is suitable. In the following figure (Figure 9), the user can now submit the vulnerability of his land and press the "Proceed" button again.

Figure 9: Area identification (Monopoli area left, Florina basin right)
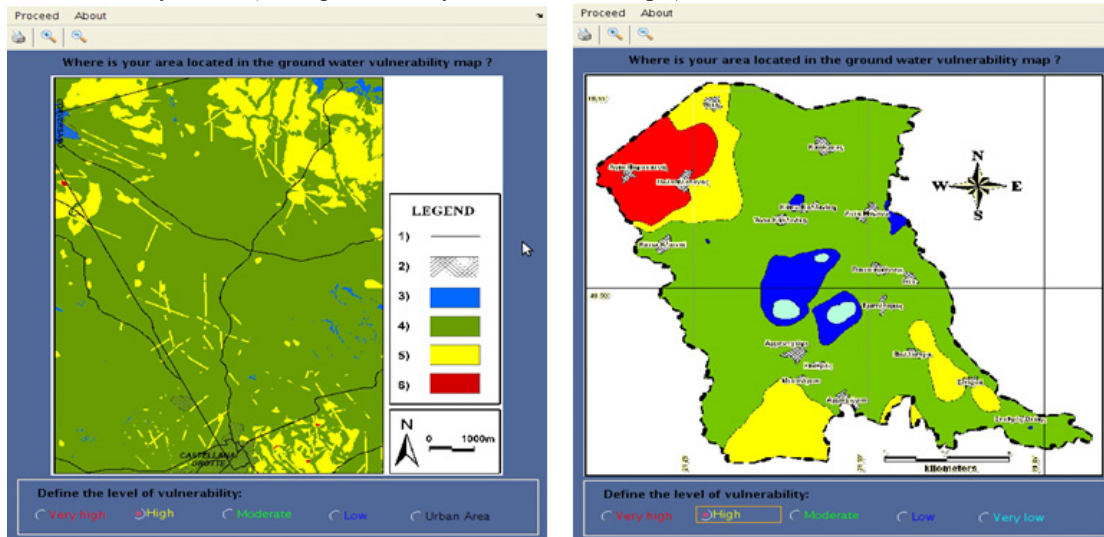
Notably, the menu bar and the toolbar now provide some more options. For example, the user is now able to either zoom in or zoom out on the map and even print the map provided in the software. For further explanation, assume again that the user presses the radio button in the lower part of Figure 9, which corresponds to High vulnerability. On the next screen (Figure 10), the DSS software asks the user if he/she has identified a desired use for his/her land. For example, if the user wants to cultivate the area with fertilizers, then he should select the appropriate radio button and press the "Recommendation" button.

Figure 10: Desired area usage

The recommendation by the DSS software would then appear in the bottom part of that window. Initially, Figure 10 does not contain any textual recommendation. The recommendation is made visible to the user only after he presses the previously mentioned button in the menu bar. Moreover, if the user wants to make a different decision, he can simply press a different radio button and then press the "Recommendation" button.

On the other hand, if the user selected the second choice in Figure 8, (i.e., he/she does not know his/her land vulnerability in advance), the following screen (Figure 11) would appear. For the sake of example, assume that the user wants to build up an area without using a sewerage system.

Figure 11: Desired area usage without having decided upon the location
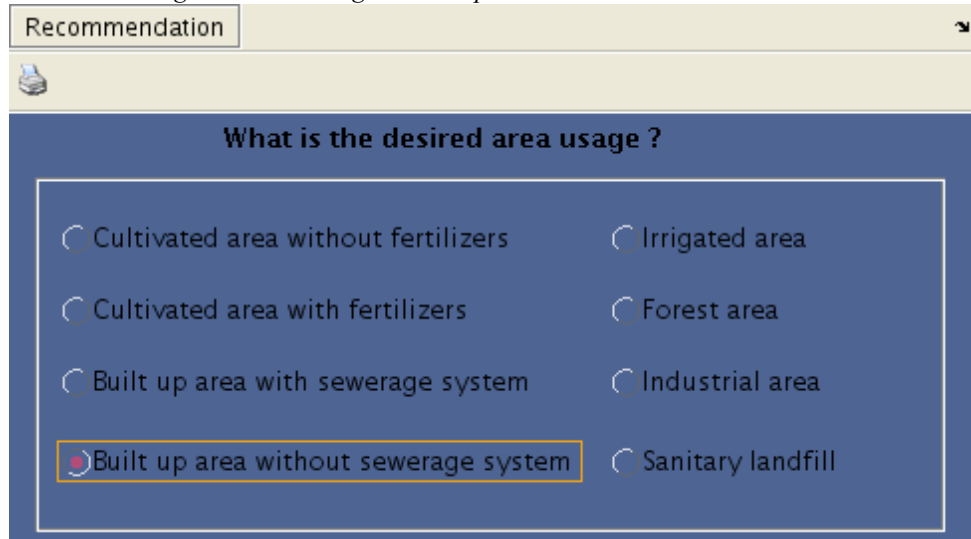

After pressing the "Recommendation" button, the following screen (Figure 12) will appear in order to inform the user about the possible acceptable locations for his/her plans. In our example, the DSS software advises the user that he should select an area with very low or low vulnerability on the map. Furthermore, the DSS software visually informs the user that potential, suitable areas are highlighted in blue or green respectively.

Figure 12: Land utilization (Monopoli area left, Florina basin right)
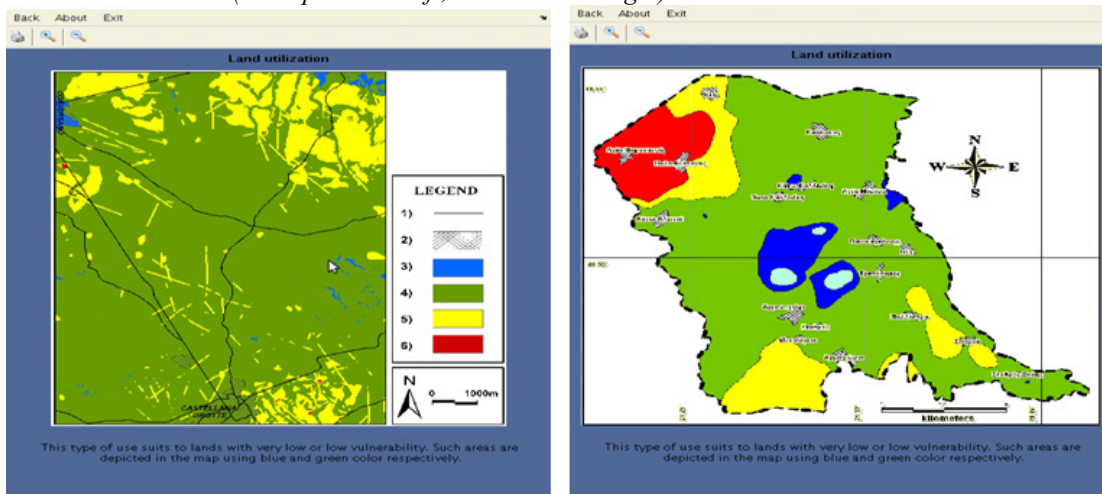
The proposed DSS software is a user friendly application for the novice user (e.g., a student) and an operations research scientist alike. It quickly and efficiently performs the task that is scheduled for completion, and it can incorporate new maps in order to cover new areas. More precisely, a file called "map.jpg" can be found among the files within the DSS application. If the user exchanges this file/map with a new one, then the DSS will advise him about the new areas. In this way, the user does not need to know anything about the groundwater vulnerability or the geological processes in general for the land in question.

CONCLUSIONS

Methods for groundwater vulnerability were applied to different hydrogeological and socio-economical situations. The assessment results are sufficiently clear and can thus be understood by any kind of stakeholder without specific expertise on hydrogeological or environmental matters. The groundwater vulnerability was relevant in all cases.

The proposed software was demonstrated as a reliable tool for managing the effects of agricultural or anthropogenic activities on groundwater quality while pursuing sustainable growth. In areas with a high degree of hazard, e.g., intensive irrigated areas, a set of measures can be defined in order to mitigate the groundwater quality impact using the DSS tools.

The proposed DSS could be easily joined to other packages, e.g., irrigation type, crop type, type of fertilizers, water consumption, to create a more comprehensive tool in order to define land allocation and protection zoning.

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