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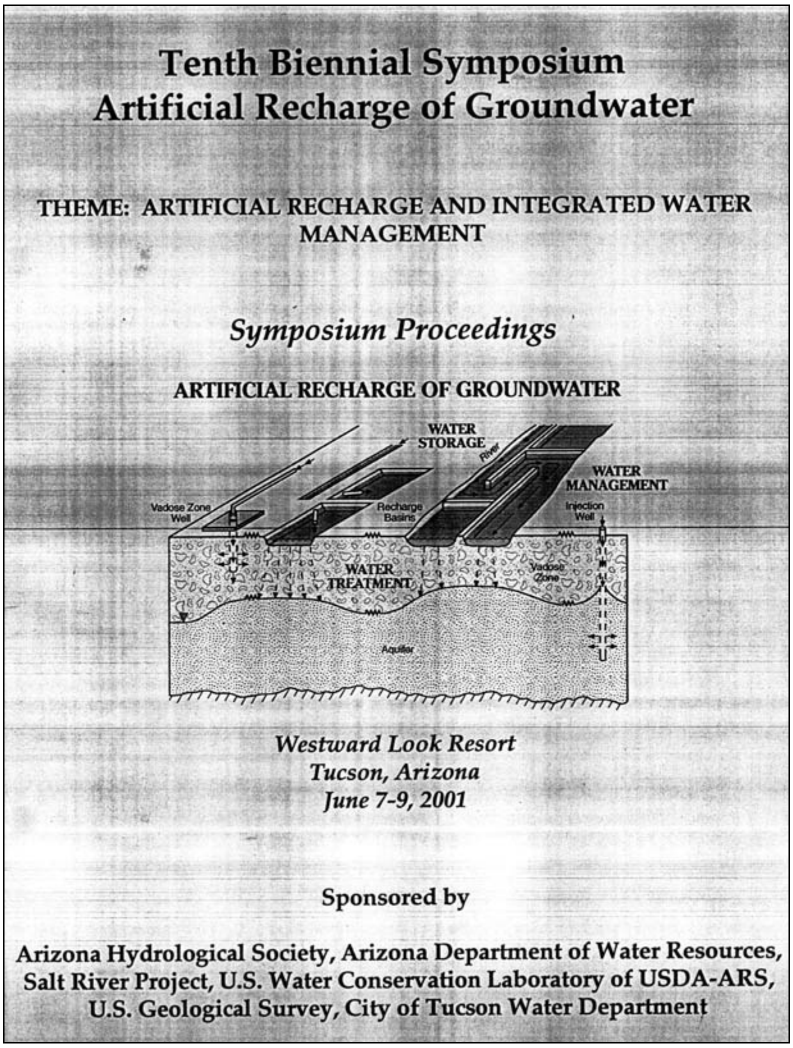

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# A HOLISTIC METHODOLOGY FOR SUSTAINABLE WATER MANAGEMENT IN KARSTIC CIRCUM-MEDITERRANEAN REGIONS[1]

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## ABSTRACT

Natural resources management requires thorough **understanding** of the **natural processes** controlling each resource and **human activities** affecting and being affected by it. In the case of fresh water, the hydrologic cycle and the geometrical and physical properties of the aquifers need to be investigated. It is very important to examine the interaction between surface water and groundwater, determining every system's biological health and ecological function, including urbanization and agriculture. The regional **social** and **financial infrastructure** are human induced factors which affect water demand and hence resource availability. The multidisciplinarity and interdisciplinarity of the methodology, responds to a **holistic approach of water management**. The interconnections between the minor allocated tasks of different work packages (modules) are many, but coherent to groups familiar to geosciences, environmental and economical sciences.

### Karst and Artificial Recharge in Tectonically Active Areas

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The primary factors causing karstification are: $H_2O$, atmospheric temperature ($T_{Atm}$ $^oC$), in accordance with climate and climatic changes, during the alpine and the post-alpine period, $CO_2$, related to biological factors (flora) and in association with the climatic conditions of a certain area, during a specific period of time, hydrostatic pressure (P), which is affected by tectonics and lithostratigraphy and porosity related to lithology, and/or tectonic deformation. The impact of natural water chemical composition during the karst formation period and the water flow rate should also be considered.

It is not the objective of this work to examine the way caves are formed, however, a few theories on the subject should be mentioned, to underline the difficulties on the study of karstic formations, especially in a country like Greece, which is characterized by complicated alpine and post-alpine tectonics. The most significant theories about cave and karst formation are (a) the theory of infiltration, according to which caves are formed along the ventilation zone as water flows downwards to the aquifer, (b) A.C.Swinnerton's (1932) theory, according to which maximum dissolution occurs on the aquifers' water surface or exactly beneath it and (c) the two cycles theory by W. Davis (1930), according to which caves can be formed in great depths even beneath the aquifer's water surface.

## Important features of Karst

Artificial recharge studies concerning karstic aquifers, require solid background knowledge of the following:

**The age of karstic formations:** Karstic formations can be created under suitable climatic conditions, where rock formations are soluble, (i.e. carbonates and/or evaporites), and tectonic conditions form discontinuities, which allows the water to flow along the sides. In the greater Hellenic area, karst has been formed during an older time period and therefore it is called "palaeokarst" (Richter D. & Mariolakos I. 1972, Riedl H., 1977). This type of karst developed during the alpine period, when great shallow water areas rose above the sea water level for significant periods of time and were subjected to erosional processes, such as karstification. Some of these periods are related to the formation of bauxites and others can be linked to the period that preceded the flysch deposition. On the other hand, recent karst formations have been created during the post-alpine period, more specifically in the neotectonic period. The "newest" karst formations in some places are still active, while elsewhere the process has ceased.

**The scale of the karstic formations occurrences:** It is very important to know the scale of the karstic formations and the relation between the minor and major karstic structures. More specifically, microscopic and mesoscopic karst must be studied in depth, (for example, narrow openings inside discontinuities and minor caves, etc).

**Karst depth:** Karstic formations may have been created beneath the earth's surface in various depths but they have been formed above the sea level. Nevertheless, they can be found in different levels relative to the present day sea surface (high, low and underwater karst respectively). In Parnassos Mountain, for example, high and lower karst formations occur (Marinos, P., 1993, Monopolis D., 1971).

### Statistics

Carbonates, such as limestone, dolomite and marble, that usually host karst formations, cover more than 30% of the Hellenic area whereas impermeable rocks, such as flysch and schists, cover nearly 40% (Papakis N., 1962). Neotectonic sediments consisting of clastics, such as pelite, marl, sandstone and conglomerates, cover a total of 30% of the area, half (15%) being of neogene age and the other half being of quaternary age.

Most of the neotectonic sediments have been deposited on the plains (neotectonic basins), whereas most of the alpine sediments occur on the surrounding margins and in mountainous areas, as well as on the basement of certain basins. A karstified basement can be used for artificial recharge of the overlying micro-permeable clastic sediments. If the alpine basement of the basins is taken into account, then the percentage of karstified carbonates suitable for artificial recharge is significantly greater than 30%.

### Neotectonic Evolution And Structures

The geological period from the Upper Miocene till today is described by the term "neotectonic period". It followed the tectonic period characterized by horizontal movements, during which the alpine thrusts and overthrusts were created. Many models describing the evolution of the Hellenic Arc during the Neotectonic Period have been proposed. In one of them (Mariolakos & Papanikolaou, 1981) the Hellenic area is divided into the following three morpho-neotectonic regions (MNR) (Fig 1a).

- The area between the Anatolian fault zone and the Axios fault zone (NE MNR).
- The area between the Axios fault zone, the Ionian Sea and the great Malliakos – Amvrakikos fault zone (NW MNR).
- The area between the great Anatolian fault zone, the Malliakos – Amvrakikos fault zone, the Hellenic trough (Ionian & Libyan Sea) and the troughs of Plini and Strabo (south of Kriti island), extensions of the Hellenic Trough to the east (S MNR).

Specifically, the Southern morpho-neotectonic region can be subdivided in three sectors (I, II, III) according to the general direction of the neotectonic major structures prevailing in the region. They consist of successive neotectonic multi-fractured horsts and troughs. Horsts form great mountains, e.g. Parnon and Taygetos Mts and others, horsts neotectonic multi-fractured troughs in between, e.g. Evrotas River (Fig 1b).

In an artificial recharge study, concerning the Hellenic Arc area the following characteristics should be taken into account:

- It is tectonically, seismically and volcanically active.
- Major fault zones and great individual faults created during the neotectonic and the alpine period, cross the whole area of the Hellenic Arc.
- The neotectonic faults have displaced, re-orientated and transformed older alpine tectonic structures, such as overthrusts, thrusts and other alpine faults.
- The neotectonic faults have been repeatedly reactivated.

- Reactivations characterized by non-alpine kinematics are reported for alpine faults.
- Major vertical movements tend either upwards or downwards. For certain periods of time, it is possible for vertical movements to tend upwards and then downwards.
- The movement rate is about 0,1 – 1 mm/year. It has been proven that average movement rates may vary through time, parts of a major geological structure may move independently whereas rotation around vertical and/or horizontal axis has been observed.

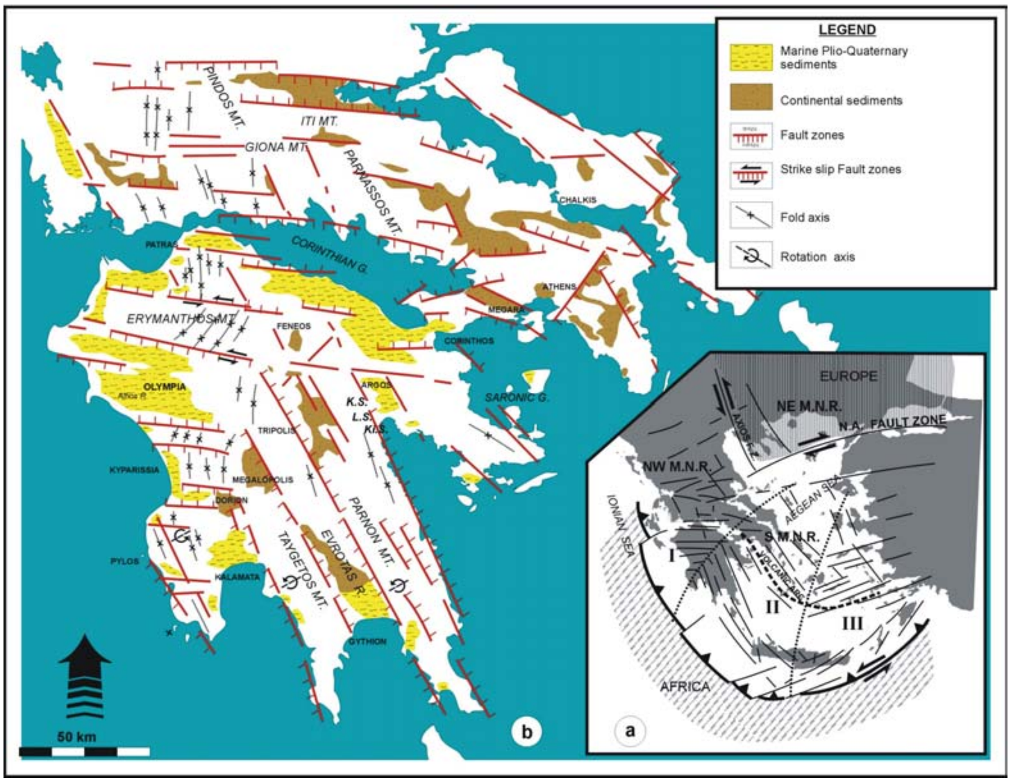


***Fig 2:*** *Distribution of the neotectonic basins in SW Greece and location map of the Hellenic Arc.*

The knowledge of the type of hydrogeological–physical-geographical system, in which the aquifer is located, is crucial for the study of groundwater flow and karstification. Areas of interest are usually located in composite neotectonic grabens surrounded partially or totally by mountains, where the alpine rocks outcrop. These grabens represent physico-grographical systems which are usually divided into closed and open. The neotectonic grabens-basins are complicated and they are divided into the following categories:

- Hydrologically and hydrogeologically closed systems, when there are neither surface nor underground water losses. In such cases the basin may theoretically turn into a lake.
- Hydrologically closed systems, with no water run-off outside the basin, but open hydrogeologically, when the ground water escapes through permeable formations of the basement. These usually form temporary lakes.

- Hydrologically and hydrogeologically open systems, when both surfacial and underground water may run off easily.
- Hydrologically open and hydrogeologically closed systems.

Undoubtedly, this theoretical classification cannot be strictly applied in practice, but we have to take it into account for certain conditions and for specific time periods of basin evolution, in cases we want to have a holistic approach of the artificial recharge.

## Karst and artificial recharge

It has been shown that karstified aquifers are appropriate for the application of artificial recharge, and specifically the karstified formations surrounding neotectonic grabens.

If there are no natural conductors on the surface, they have to be constructed in the form of drillholes and tunnels to the depth of the karstified bedrock (Artificial Recharge via wells: Aquifer Storage Recovery). A basic advantage of artificial recharge in karstic aquifers is that clogging is not likely, permitting the development of high hydraulic pressure and high velocity of flow. The basic disadvantage is that the water used for recharge is not naturally filtered and the risk of infection of the aquifer by pollutants is relatively high. Thus, the solutes should be deposited, and infiltration can follow to improve the water quality before the injection. Water has to be monitored and analysed constantly, before and after injection.

Detailed morphotectonic and hydrogeological study of the broader area are fundamental for the success of artificial recharge. They include detailed geological mapping focused on carbonate rocks, tectonic analysis of alpine deformation (faults, joints, thrusts), neotectonic analysis (neotectonic faults, kinematics analysis, vertical movements, rotation of tectonic blocks etc), mapping of the fault zones, focused on the transitional areas from the tectonic grabens to the horsts, quantitative geomorphological analysis, systematic study of karstification and karstification phases, relations between karst and tectonic discontinuities, karst basic level and type, construction of tectonic subsurface maps (strike contur maps) and maps of the contact surface between permeable and impermeable formations, location of aquifers, computer aided 3D simulation of the aquifer geometry, volumetric analysis, and definition of the type of basin (hydrologically and hydrogeologically closed or open).

## Basic elements and procedures of the holistic methodology

A simplified representation of the interactivity and relationships between the work packages is shown in Fig. 2. The product of the thorough examination of the hydrogeological regime of the study area and the hydrological data accumulated by the research activities of work package I, for the specification of the aquifer properties and the analogous simulation in CAD environment, is calibrated and verified by the results of the experimental work and monitoring data from work package II. This leads to the control point of the decision on the feasibility and applicability of artificial recharge (A.S.R.), within the framework set by the socio-economic analysis. An affirmative decision leads the project to the realisation of the A.S.R., and the monitoring network will be expanded to include the A.S.R. monitoring. The monitoring network will feedback a data base platform to support the GIS, along with the socio-economic data. Water management guidelines, will support the programming of the DSS software, where the aquifer properties and A.S.R. monitoring data along with the socio-economic data will be integrated, in an operational dynamic simulation. If conditions are not favourable for application, the procedure integrates the existing monitoring network with the socio-economic data, and the final target of formulation of the DSS, bypassing the A.S.R. work package.

**Work package I** includes **geological and hydrogeological** fieldwork, as well as the **specification of** the **geometry** and other **properties** of the **karstic aquifer system**. A 3D digital geometry model of the geological structure of the area will be set up, upgraded to a 3D property model of the karstic aquifer system, with the aid of tracer tests.

A main problem addressed in this project, is the heterogeneously distributed temporal precipitation on several island and coastal regions. The most promising technology to improve availability of water on these regions through the year is **Artificial Recharge via wells (A.S.R.)**. In many of them, there are complex karstic aquifer systems, above and below sea level, resulting in the loss of millions of cubic meters of fresh water in the sea. The whole effort aims at the **final selection of the appropriate method of artificial recharge** of the aquifer, so that the highest possible quantities of water are obtained for utilisation. A monitoring network for recording dynamic processes of storage and runoff in the karstic system, including the submarine springs and their catchment areas and the workout of the gathered data under consideration of the possibilities of artificial groundwater recharge during flood events, will aid the ensuring of environmental friendly policy of the method, and sustainable management of the resources.

A remote data transfer monitoring network will be set up (**w.p. II**) consisting of existing or customised wells, springs and submarine outlets, thus contributing to the knowledge of the properties and the potential of the aquifer(s). This monitoring network will be permanent, giving valuable feedback for the improvement of the simulation of the aquifer, and after the end of the project, it will be handed to the End User. Moreover, the monitoring network will be assigned the safeguarding of the procedure of A.R., in terms of protection from pollutants entering the karstic system. The work package consists of the following different parts:

- **Selection of monitoring locations**, based on a detailed geological and hydrogeological mapping, considering the possibilities of data transmission at the site. The transmission of data, from the field site to the headquarters, can be done either via GSM-cell-phone networks or via satellites. Representative terrestrial and submarine springs monitoring sites, that will be included in the monitoring network, will be selected along the basis of the existing precipitation monitoring network.
- **Installation of monitoring equipment at selected sites**, including tests of existing available data transmission possibilities, and selection of the most effective transmission platform. Recorded parameters and gathered samples will be selected

for the evaluation of the hydrologic cycle dynamic processes in representative regions.

- **Separation of flow dynamics,** based on two different kinds of methods: (a) hydraulic separation, and (b) separations based on mass transport models. At terrestrial springs, water quality and quantity parameters (i.e. salinity, discharge) will be measured. Special monitoring equipment will be set up at submarine springs, where beside conventional parameters (i.e. conductivity/salinity and temperature), other parameters will also be measured, such as the flow velocity at their outlet, which will be measured with ultrasonic Doppler instruments.

The **classification of potential artificial recharge areas** (**workpackage III**) as appropriate or non appropriate zones for artificial recharge will be based on (a) the natural processes related to the karstic aquifer system of the study area, (b) the evaluation of karstification distribution within the carbonate aquifer, (c) the accessibility of the potential sites, and (d) the properties of the potential sites.

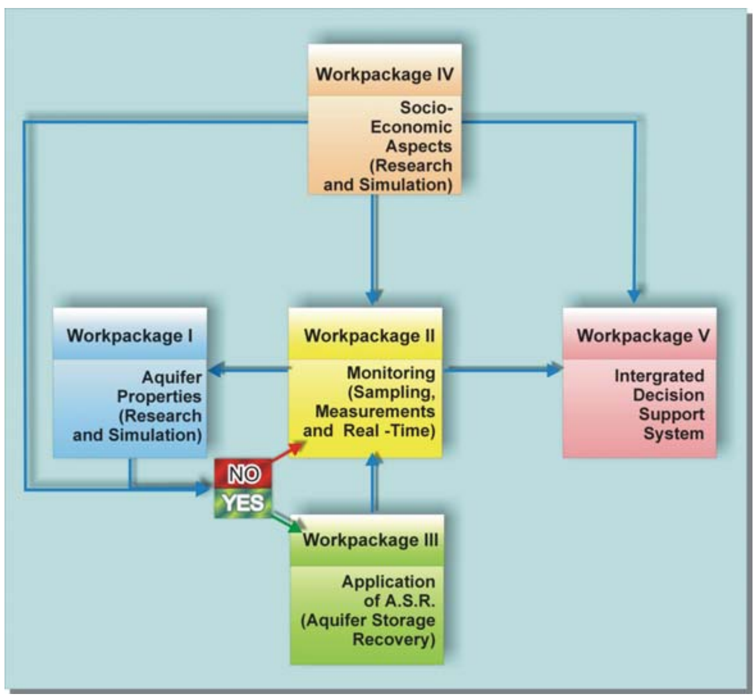


***Fig 2:***
*The proposed work packages for the accomplishment of rational water management related to artificial recharge.*

**Alternative methods of artificial recharge will be evaluated**, in terms of applicability for the selected "appropriate" area(s). Environmental Impact Assessment for artificial recharge comes next, taking into account all data gained to that point, in the shape of a multidisciplinary analysis. The final formulation of the methodology for artificial recharge to be applied will be based on the terms of **sustainability**.

After the selection of the artificial recharge method and the application area(s), the project proceeds to the construction of the artificial recharge facilities. The inflow data collected (a) on the site of the artificial recharge, and (b) at monitoring points located uphill from the artificial recharge site(s) will be transmitted to the workstation via the monitoring network. The application of artificial recharge will not commence, unless the artificial recharge monitoring points are included in the monitoring network.

**During application**, real time data transfer to the surveillance station established at the End User headquarters, will **secure the procedure**, and lead to re-calibration of the equipment of the infrastructure. At the same time, feedback to management database will be stored for the development of the Decision Support System (DSS) in w.p. V.

The overall objective and rationale of the socio-economic research (**work package IV**), is to **investigate the protection and provision of high quality water reserves in sufficient quantity at affordable costs, while maintaining its various functional roles in the ecosystem**. This objective is further specified in the elaboration of an integrated framework of hydrological and economic data and tools. The emphasis of the research will be the evaluation of alternative groundwater policies and management options on different spatial, institutional and time scales. The social scientific work will focus on stakeholders and processes of communication, understanding and participation in water decision-making, improving the effectiveness of existing institutions and incentive structures. The findings will contribute to the formulation of institutional arrangements, flexible enough to account for dynamic changes (e.g. multi-equilibria and threshold effects).

A second task is the investigation of preference formation processes in the region referring to groundwater protection. Understanding of stakeholders' perception on water quality and the functions of underground water reserves will contribute to an improved design of the non-market valuation surveys. Conflicts between uses and social groups will be explored with the help of focus groups and informal deliberating techniques.

The third task is the investigation of the institutional and the policy context process. The nature of the national environmental policy should be analysed and the institutional setting, supporting such a policy, should be studied in detail including the description of interactions and interrelationships of institutions with respect to decision making (pricing policies, investment decisions, arbitration processes, setting of standards, etc). Data will be spatially explicit with the help of thematic maps organized in a GIS database.

State of the art technology will support the effort in every phase of research and application, so that the final integration of monitoring data from both the aquifer and the application of the artificial recharge, with a customised decision support system (**work package V**), will provide the End User with a powerful and flexible tool, which will propose, **in time**, alternative solutions for every possible situation that would have to do with water management and protection of water resources of the area. An effective Decision Support System (DSS) for Water resources management is generally characterized by integration of computer technologies for the benefit of a decision maker. That means a support system, responsive to the needs of the decision maker, rather than the modeller and developer. Yet, this approach should not sacrifice modelling at the scale of physical processes for the sake of remaining useful for decision-making.

The proposed DSS is designed on an open architecture modular basis for the advantage of flexibility of implementation, portability to different platforms, ease of integration of advances in the underlying fields (e.g. simulations, G.I.S.). At every stage of the development of the DSS, local Decision Makers and operators will be involved.

Requirements to the DSS are: (1) providing additional information useful for decision making; (2) reducing the time and costs required for plan formulation and evaluation; and (3) increasing project benefits by identifying solutions which might not be otherwise identified. The main elements of the proposed DSS are presented in **Figure 4** and can be grouped in **user-interface, information manager, and set of analytical tools**, described below.

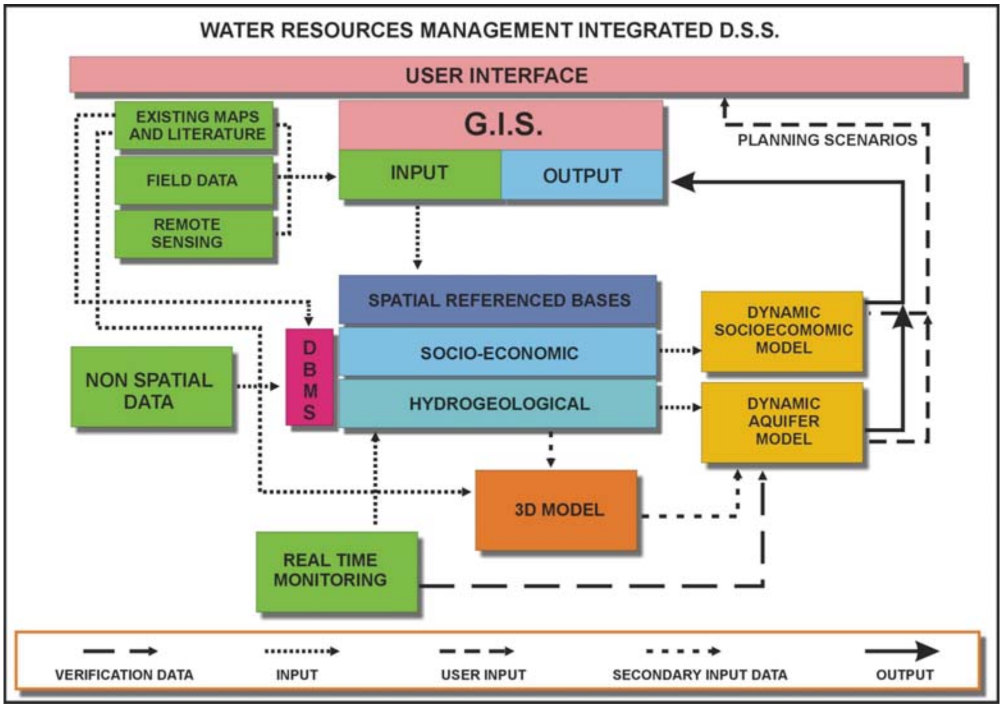


***Figure 3:** The elements of the proposed operational Integrated Decision Support System*

- **User Interface:** This module will be responsible for the user communication with the system. It will be based on a G.I.S., enabling the decision maker/planner to control the existing situation in water resources and test planning scenarios.
- **Information manager: G.I.S., DBMS:** can be used not only for information management but also for spatial analysis and the visualization of model output. In a sense, a GIS by itself could function as a DSS, provided that spatial analyses alone provide adequate support in the decision making process. Since many problems require more than the analysis of spatial data, the development of spatial decision support systems requires merging of geographic information systems and dynamic models. Open architecture facilitates integration of GIS and water resources and environmental models in an DSS. Data from maps, authorities databases, fieldwork and remote sensing will be incorporated in a spatial referenced database. Through the database Management System, data of non-spatial nature will be added to the database.
- **3D Model:** The digital 3D model of the karstified region consists of the geometry and the properties model. The geometry model will be set-up from the data from

remote sensing and geological mapping using 3D CAD techniques. Distribution of the properties affecting the water flow in the karstic aquifers will be estimated with geostatistics based on the results of the tectonic analysis. The 3D model will be the main input, together with the hydrogeological data, to the dynamic aquifer model.

- **Dynamic models:** Classical simulation and optimisation models build the heart of a water resources DSS. Two dynamic simulation systems, simulating the aquifer functions and the socio-economic processes, will take the input either from the databases or from the user interface and interacting on each other, predict the effects of water management decisions and natural systems variations.
- **Real time monitoring:** A more detailed description has already been given above. Data from the monitoring system will be used to verify the function of the dynamic model of the aquifer.

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