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Management of coastal hydrosystems through the application of free and open source software tool FREEWAT

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Abstract: FREEWAT is an open source and public domain GIS integrated modelling environment for the simulation of water quantity and quality in surface water and groundwater with an integrated water management and planning module. It involves the integration of: (i) Observation-Analysis Tool (OAT) that combines a number of time-series processing functionalities for statistical analysis of observations and help prepare model input data; (ii) AkvaGIS that involves hydrochemical and hydrogeological Analysis Tools and (iii) Groundwater Flow (MODFLOW-2005) and Transport modeling modules. FREEWAT platform will be applied in a typical Mediterranean environment that hosts a naturally occurring –and today degraded– coastal wetland with the characteristics of a distinct ecosystem linked to a typical coastal hydrogeological system of a semi-arid region; and therefore can serve as a model for similar systems world-wide. The geo-hydrological setting of the area involves a multi-layer aquifer system consisting of (i) an upper un-consolidated formation of depositional unit dominated mostly by fluvial sediments and (ii) the surrounding and underlying karstified marbles; both being linked to the investigated wetland and also subjected to seawater encroachment.

Key words: Groundwater modelling, Open source public domain GIS integrated GW modelling, Marathon coastal hydrosystem, water resources management

1. INTRODUCTION

Water framework directive as well as its daughter directives, consider integrated water resources management as a matter of ample priority for the European Union Member States. Water resources simulation is widely accepted as a crucial pillar in the management process, by means that it provides a sophisticated tool for stakeholders, decision and policy makers.

FREEWAT is an open source and public domain GIS integrated modelling environment for the simulation of water quantity and quality in surface water and groundwater with an integrated water management and planning module. FREEWAT aims at promoting water resource management by simplifying the application of the Water Framework Directive and other EU water related Directives.

It provides an integration of existing software modules for water management in a single environment into the GIS based FREEWAT platform and supports their application in an innovative participatory approach gathering technical staff and relevant stakeholders (in primis policy and decision makers) in designing scenarios for the proper application of water policies. The open source characteristics of the platform allow to consider this an initiative "ad includendum" (looking for inclusion of other entities), as further research institutions, private developers etc. may contribute to the platform development.

The core of the FREEWAT platform (Figure 1) is the SID&GRID (Rossetto et al., 2013) framework in its version ported to the QGIS desktop (Borsi et al., 2013). FREEWAT is conceived as a composite plugin for the well-known GIS open source desktop software QGIS. As composite plugin, it is designed as a modular ensemble of different tools: some of them can be used

independently, while some modules require the preliminary execution of other tools. In this framework, the following tool classifications can be defined:

- Tools for the analysis, interpretation and visualization of hydrogeological and hydrochemical data and quality issues, also focusing on advanced time series analysis, embedded in akvaGIS module.
- Simulation of models related to the hydrological cycle and water resources management: flow models, transport models, crop growth models, management and optimization models (also related to irrigation management and rural issues).
- Tools to perform model calibration, sensitivity analysis and uncertainty quantifications.
- Additional tools for general GIS operations to prepare input data, and post-processing functionalities (module OAT – Observation and Analysis Tool).

The modelling environment is based on the well-known codes of the MODFLOW family (USGS)– basically used for analysis of groundwater systems. The version integrated in FREEWAT is the MODFLOW One Water Hydrologic Model (MODFLOW-OWHM; Hanson et al., 2014), aiming at performing simulations of systems where conjunctive use of surface- and ground-water is of concern. It also includes a specific module to run management decisions and evaluate different irrigation scenarios, which is coupled to a crop growth module for simulating crop yield.

Along to this, simulation of solute transport in aquifers may be performed by means of the MT3DMS code (Zheng, 2010), including density dependent capabilities using the SEAWAT code (Langevin et al., 2007).

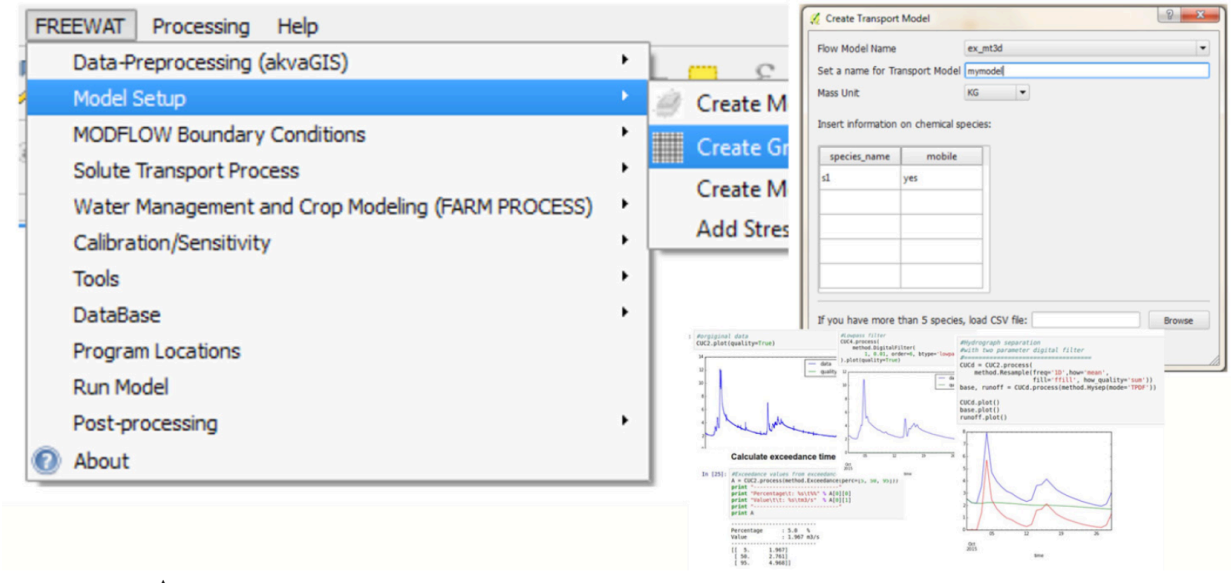

Figure 1. Example of the FREEWAT main menu with some graphs produced using the OAT module.

The modelling framework is completed by including GUIs (Figure 2) to run automated codes (Poeter et al., 2014) for assessing sensitivity analysis, calibration and uncertainty evaluation of hydrologic models (Foglia et al., 2007).

A set of tools to facilitate the management of a large number of physical and chemical parameters, to ensure compliance with standard regulatory guidelines (with a special focus on requirement deriving from the Groundwater Directive), is included via the akvaGIS module (developed by the IDAEA-CSIC).

Finally, the FREEWAT platform is improved by adding the following modules:

1. aquifer-lake interaction (integration of the MODFLOW – LAK7 package, USGS);
2. a tool for time-series analysis in data processing for model calibration (Observations Analysis Tool - OAT).

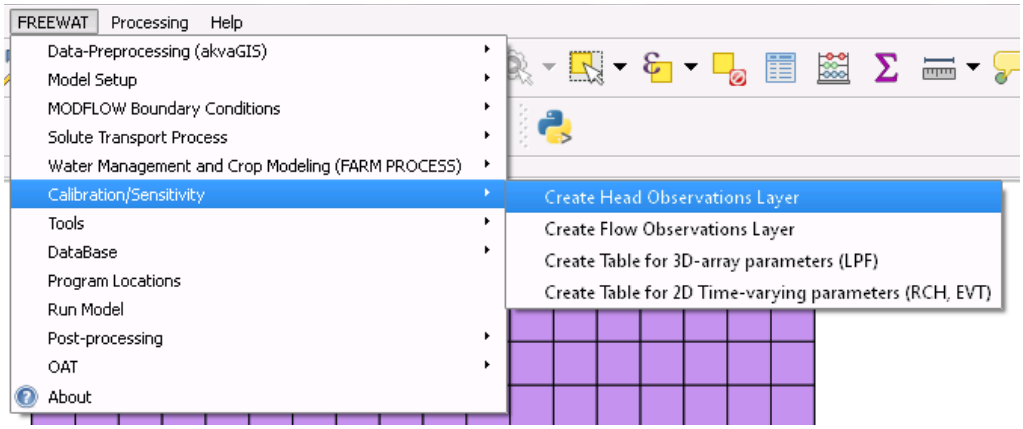

Figure 2. Example of the Model Data Object of observation heads.

This paper presents an application of the FREEWAT platform in a coastal unconsolidated aquifer that is hydraulically connected to the Mediterranean Sea. It provides the information used for the development of the conceptual model, based on a series of hydrogeological data, as well as the application of groundwater flow simulation under steady state conditions.

2. CASE STUDY DESCRIPTION

2.1 General setting and condition.

Marathon plain (40 km^2), located at the NE of Attica (Greece), is characterized as a typical Mediterranean environment that involves a naturally occurring –and presently degraded– coastal wetland with the characteristics of a distinct ecosystem linked to a typical coastal hydrogeological system of a semi-arid region. The area faces severe surface and groundwater degradation issues due to recent human activities.

2.2 Hydrogeological characteristics

The geo-hydrological setting of the area involves a multi-layer aquifer system that consists of (i) an upper unconsolidated formation dominated mostly by alluvial deposits and (ii) the surrounding and underlying karstified marble units (Figure 3). Both aquifers are subjected to intensive pumping conditions due to agricultural activities in the largest part of the plain. As a result, seawater intrusion affected the groundwater within both formations; however more it is more pronounced in the upper unconsolidated layer.

3. MODELING TOOL APPLICATION

The mathematical model of the unconsolidated aquifer of Marathon plain, was applied through the FREEWAT platform.

3.1 Conceptual model of Marathon plain

For the simulation of the unconsolidated aquifer, the conceptual model of Marathon plain took into consideration geological, hydrogeological, hydrological, geophysical data (existing and recently collected field data), as well as geographical information such as land cover, land use, DEM.

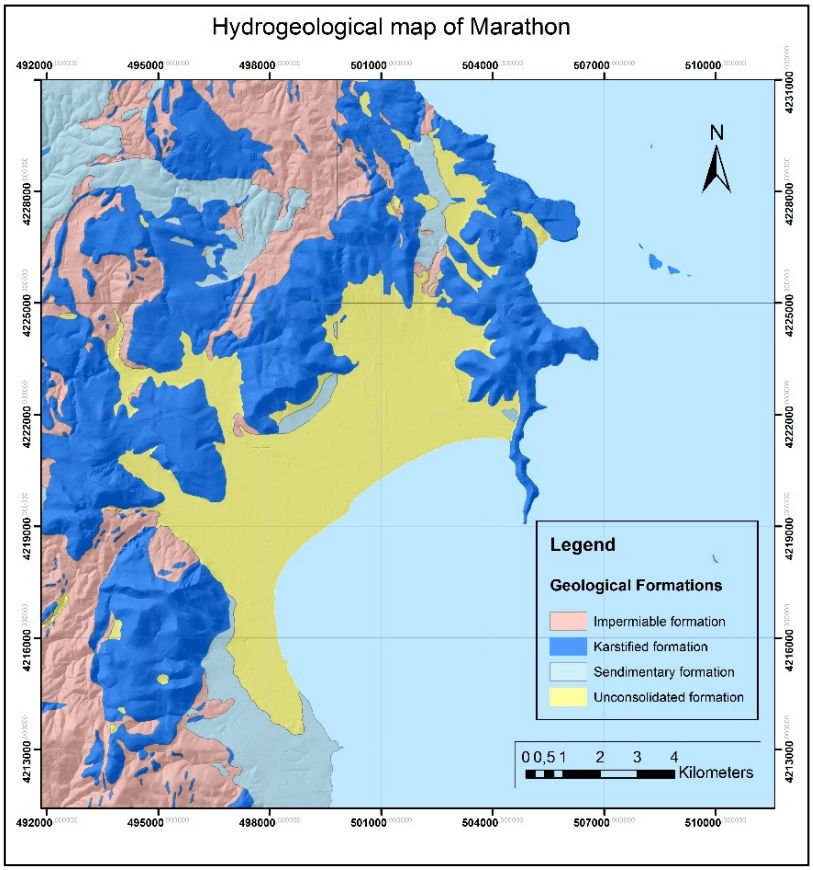

Figure 3. Hydrogeological map of study area.

The natural boundaries of the system are the karstified marbles at the northern and western part of the plain, the coastline at the southern part, while at the east the study area includes a coastal wetland that is hydraulically disconnected to the underlying alluvial aquifer layer. The system discharges into the Mediterranean Sea, while water that is pumped from a number of shallow and deeper groundwater wells -used for agricultural purposes- is considered another significant loss from the system. The unconsolidated formation is recharged mainly through: (i) direct infiltration from precipitation; (ii) the lateral inflows from the surrounding karstified marbles; (iii) by irrigation return inflows; and (iv) the karstic spring of *Makaria* which is a major discharge point of the local marble unit at the NE part of the area.

3.2 Simulation the granular aquifer through the FREEWAT platform

The granular system of Marathon plain was simulated using MODFLOW 2005 (Harbaugh, 2005) in the FREEWAT platform while the aquifer was simulated considering the available data of the year 1998. The model was run under steady state conditions for a stress periods of 5 months. The top and bottom parts of the aquifer were defined from a series of geophysical surveys that conducted in the study area during previous research by Melissaris and Stavropoulos (1999). The initial head was calculated from a piezometric map of May 1998 (Melissaris and Stavropoulos, 1999) and the model was calibrated using the piezometric map of October 1998 (Melissaris and Stavropoulos, 1999). For the temporal discretization of the simulated aquifer, a grid was created with cell size of 100×100 m^2; whereas the hydraulic conductivity of the unconsolidated formation ranges from 10^{-6} to 10^{-5} m/sec (Siemos, 2010). The aquifer was considered to be homogenous and isotropic so the hydraulic conductivity was used for the entire formation is 2 m/day (equals to 2.3×10^{-5} m/sec) and was estimated by “trial and error” methods.

The boundary conditions of the case study are presented in Table 1.

Table 1. Assigned boundary conditions

Boundary	Type of Boundary Condition	Quantity	Unit
Rainfall	Recharge(RCH)	$4.4x10^{-5}$	m/day
Nothern & Southern Marble	General Head (GHB)	2	m
Makaria spring	General Head (GHB)	2.5	m
Coast	Constant Head (CHD)	0	m
Swamp	Constant Head (CHD)	0	m
Wells	Well(WEL)	-100	m/day

The direct infiltration from precipitation was calculated from meteorological data of this period, while the total amount of rainfall from May to September 1998 was 34 mm and the direct infiltration from precipitation was considered as 20% of the precipitation. Finally this volume was equally assigned to the entire surface of the model (4.4×10^{-5} m/day).

The surrounding karstified marbles were represented as a general head boundary taking into consideration the piezometric level at the contact zone between the unconsolidated aquifer and the marbles in question. This boundary condition is considered a result of the diffuse flow that corresponds to the fractured porosity of the marble unit. Pumping volume has been estimated at 2×10^{6} m^3/year (Siemos, 2010), and refers to the irrigation needs of the area corresponding to the agricultural activities at the period of investigation.

The following figure shows a step of the procedure to construct the model in QGIS using the FREEWAT plugin.

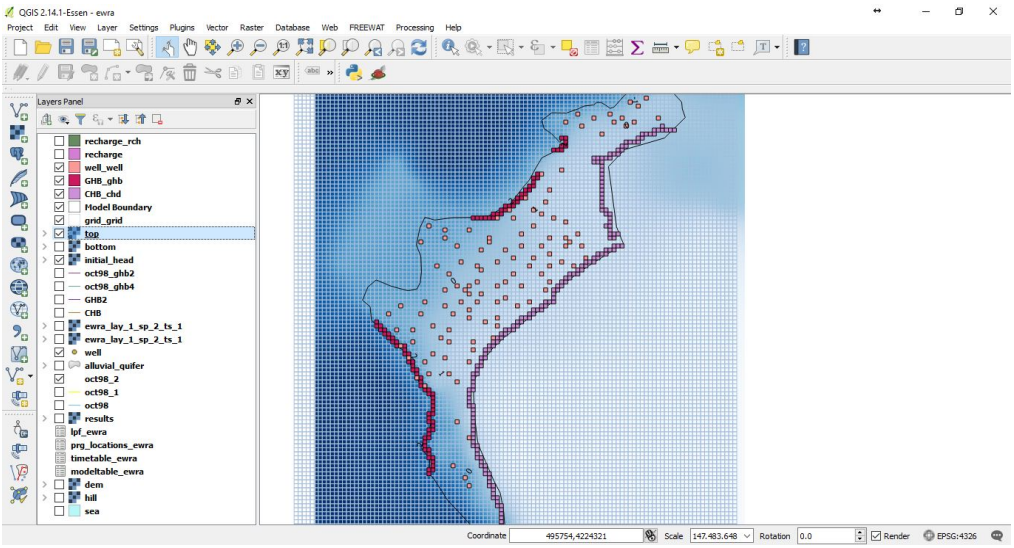

Figure 4. Construction of the mathematical model of Marathon plain using QGIS and FREEWAT.

The results of the simulation were visualized using the post-processing tool of FREEWAT and other tools of QGIS (Figure 5).

4. CONCLUSIONS

This study presents the application of FREEWAT platform in a coastal aquifer system in the Mediterranean region. FREEWAT is an open source and public domain GIS integrated modelling environment for groundwater simulation and data processing. The coastal area of Marathons was selected as a case study for the application of FREEWAT platform, to simulate the groundwater flow of the alluvial aquifer layer. The study area is a typical Mediterranean coastal site that is hydraulically connected to the sea, while the groundwater resources are exclusively used for irrigation purposes. The model calibration was based on a series of geological, hydrogeological, hydrologic and geographical data that were collected from previous studies as well as during this

present research. Freewat platform was proved an efficient and flexible tool for the realization of the groundwater simulation of the study area, while as being integrated within a GIS environment, it provided additional capabilities to this exercise.

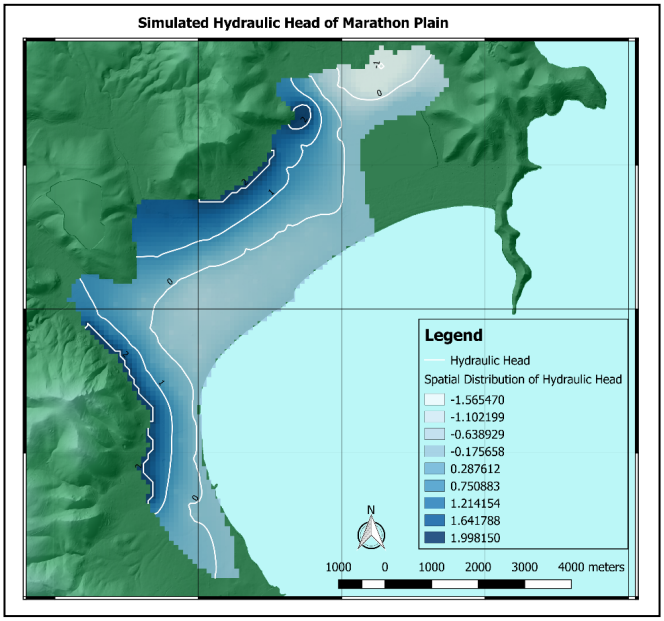

Figure 5. Results of simulation for the granular aquifer of Marathon.

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