INTEGRATING NUMERICAL MODELS IN RIVER BASIN MANAGEMENT PLANS: THE FREEWAT PROJECT

MANUEL SAPIANO[1], MICHAEL SCHEMBRI[1], HENRY DEBATTISTA[2] & NADIA THEUMA[3]
[1]Energy and Water Agency, Malta
[2]Malta College for Arts, Science and Technology, Malta
[3]Paragon Europe, Malta

ABSTRACT

The EU Water Framework Directive (WFD) requires the achievement of good status in the water environment through the implementation of River Basin Management Plans (RBMP). The long-term impact of these plans and their contribution to the achievement of good status is however generally difficult to predict and quantify, thus presenting an important constraint in this planning process. Numerical models are a tool which can enable water managers to predict the effective impact of measures on a water-body scale, and therefore enable a more reliable assessment of the effectiveness of the plan in achieving the set objectives. The FREEWAT Project aims at the development of an open source and public domain GIS integrated modelling environment for the simulation of water quantity and quality in surface water and groundwater bodies. One of the pilot initiatives under this project focuses on the island of Gozo (Malta) where the FREEWAT modelling environment is being used for the development of a numerical model of the mean sea-level groundwater body present in this island. This paper assesses the integration of this numerical model in the river basin management framework of the island, in support of the achievement of the good status objectives for this groundwater body. The paper focuses on the application of the FREEWAT based numerical model for the assessment of the impact of the groundwater management strategies envisaged under Malta's 2nd RBMP on the quantitative status of the groundwater body. Furthermore, it provides an outlook on the application of the model to assess the response of the groundwater body to changing natural conditions arising due to the projected impact of climate change. In so doing, the modelling framework provides water managers the opportunity to consider within the basin river management framework the necessary flexibilities to ensure the continued achievement of the WFD's objectives under future scenarios.
Keywords: water framework directive, FREEWAT, numerical model, groundwater status, river basin management plan.

1 INTRODUCTION

The purpose of the Water Framework Directive (2000/60/EC) (WFD) is the protection of all waters in the European Community. To achieve its objective the Directive establishes a regulatory structure/framework to support the:

- prevention of the deterioration in the quality of aquatic ecosystems, their protection and the improvement of the ecological condition of all waters;
- promotion of sustainable water use based on a long-term protection of available water resources;
- reduction and progressive removal of hazardous pollutants and priority substances into the aquatic environment;
- progressive reduction in pollution of groundwater and the prevention of further pollution; and
- mitigation of the effects of floods and droughts.
- in achieving these purposes, the implementation process of the Directive would therefore contribute to the:

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- provision of a sufficient supply of good quality surface water and groundwater to sustain the needs of the environment and the population;
- significant reduction in pollution of groundwater, inland surface waters, transitional and coastal waters;
- restoration and protection of territorial and marine waters; and
- achievement of objectives of other relevant international agreements, which aim to prevent and eliminate pollution of the marine environment.

In order to reach these objectives the WFD proposes a general planning process at the river basin level which focuses on the preparation of actions or measures needed to protect or improve the status of the water environment. The resulting 'programme of measures' needs to be implemented within the respective WFD planning cycle, which covers a period of 6 years. The programme of measures is revised during each subsequent planning cycle under the Directive.

The long-term impact of these plans and their contribution to the achievement of good status is however generally difficult to predict and quantify, thus presenting an important constraint in this planning process. Numerical models are a tool which can enable water managers to predict the effective impact of measures on a water-body scale, and therefore enable a more reliable assessment of the effectiveness of the plan in achieving the WFD's set objectives.

The main focus of this paper is that of presenting a numerical model of the mean sea level groundwater body in the island of Gozo (Malta) and its application to assess the impact of the water management measures under Malta's 2nd River Basin Management Plan towards the achievement of good quantitative status conditions in the body of groundwater.

2 CONCEPTUAL MODELS

Guidance Document No. 26 of the Common Implementation Strategy of the Water Framework Directive defines Conceptual Models as "*a means of describing and optionally quantifying systems, processes and their interactions. A hydrogeological conceptual model describes and quantifies the relevant geological characteristics, flow conditions, hydrogeochemical and hydrobiological processes, anthropogenic activities and their interactions.*"

The Guidance Document notes that Conceptual Models are required during the implementation process of the Directive to support the understanding of groundwater quantity (quantitative status) as well as groundwater quality (chemical status) in the development of monitoring programmes, implementation measures and the eventual assessment of the achievement of the good status conditions required by the Directive.

It also highlights that Conceptual Models for the purpose of the WFD implementation process can be developed to different degrees of complexity. These range from simple schematic descriptions of the hydrogeological conditions supporting the development of the groundwater body to complex numerical models providing a comprehensive qualitative and quantitative framework of the hydrogeological processes leading to the development of the groundwater body and enabling the assessment of impacts to the status of the groundwater body.

3 THE FREEWAT PROJECT

The FREEWAT Project focuses on the development of an open source and public domain GIS integrated modelling environment for the simulation of water quantity and quality in surface water and groundwater bodies. The FREEWAT modelling framework is being applied to the development of numerical groundwater models in fourteen different case-study areas. This paper focuses on the development and application of the numerical model of the mean sea-level groundwater body present in the island of Gozo. The integration of this numerical model in the river basin management framework of the island, is intended to support the achievement of the good status objectives for this groundwater body.

The numerical model represents an advanced conceptual understanding of the groundwater body and will thus permit the undertaking of the 'further characterisation' assessments under Annex II of the Directive. The application of the numerical model will also support the assessment of the achievement of good quantitative status by increasing the reliability in the assessment of key parameters under the water balance calculation for the groundwater body. The WFD recognizes water balance models (water accounts) as key tools to support the assessment of the achievement of good quantitative status in bodies of groundwater.

The application of the FREEWAT based numerical model will furthermore permit the assessment of the impact of the groundwater management strategies envisaged under Malta's 2nd River Basin Management Plan (RBMP) on the quantitative status of the groundwater body. Furthermore, it provides an outlook on the application of the model to assess the response of the groundwater body to changing natural conditions arising due to climate change related impacts. In so doing, the modelling framework will provide water managers the opportunity to include the necessary flexibilities, within the river basin management framework, to ensure the continued achievement of the WFD's objectives under future water management scenarios.

4 THE GOZO MEAN SEA-LEVEL AQUIFER

4.1 Conceptual understanding

The sea-level groundwater bodies in Malta and Gozo locally referred to as the Mean Sea Level Aquifers (MSLAs) originate by virtue of density difference between fresh and saline water. As such these two liquids are in lateral and vertical contact within the limestone aquifer matrix. In shape, these aquifers can be compared to a lens of fresh water which is dynamically afloat on more saline water, having a convex piezometric surface and conversely a concave interface, both tapering towards the coast where there is virtually no distinct definition between the two surfaces.

The freshwater lens sinks to a depth below sea level roughly 40 times its piezometric head at any point, following closely the Ghyben-Herzberg model, with freshwater slowly merging into seawater across a transition zone. The limits of the transition zone are commonly defined by the surfaces of 1% and 95% seawater content in groundwater based on total dissolved solids or chloride content. The lens structure entails the development of a high storage capacity compared to the mean annual recharge.

The geometrical configuration of the lens has serious implications on the physio-chemical characteristics of groundwater. It implies that all the outer surface of the lens, excluding the piezometric surface, is in physical contact with seawater whilst the bulk of its mass and storage lie below sea level. Under such conditions therefore, the slightest amount of abstraction will destabilise the sensitive hydrodynamic balance at the salt/freshwater interface resulting in upconing (upward intrusion) of seawater. This condition together with the slow recharge process is a major constrain to the abstraction of freshwater from the Mean Sea Level Aquifer systems.

The structure of the lens also entails an outflow gradient towards the sea, physically reflected in a significant loss of freshwater reserves. An aerial survey using infra-red imagery has been recently undertaken with the aim of identifying natural groundwater outflow points in coastal areas. The identification of such natural outflow points will also permit an assessment of the importance of fracture flow in the hydrogeolgical context, and thus guide the development of more reliable groundwater models of the aquifer system. Under natural conditions therefore, these lenses lose a substantial portion of the freshwater content derived through natural recharge, by way of scattered diffusion and also through submarine springs.

Also, it must be underlined that unlike other groundwater bodies which sit on a well-defined barrier and aquiclude, freshwater lenses in Malta and Gozo, do not have a true and proper physical barrier as a base-level to groundwater flow. The bottom of the lens is a virtual boundary between two fluids having different densities, where due to diffusion and hydrodynamic dispersion the interface is really a mixing or transition zone, the thickness of which depends on the hydrodynamic characteristics of the aquifer system. Variations in hydrostatic head as in the case of abstraction trigger a vertical upconing of seawater resulting in the localized intrusion of salinity in the freshwater body.

The conceptual model for the Gozo MSLA system assumes (Fig. 1) that:

- the Lower Coralline Limestone aquifer is present across the whole island, locally substituted by the Globigerina Limestone when present below sea-level;
- it is extensively capped by the impermeable Blue Clay and the Greensand and by less permeable strata in the Middle Globigerina Limestone;
- the water table is controlled by abstraction and is presently only a few metres above sea level. This abstraction also leads to extensive saline upconing and an increase in salinity;
- the relatively low porosity indicates a higher-rate of downward movement in the aquifer matrix, where unsaturated zone travel time is expected to be long in the thicker parts of the aquifer. This is confirmed by the lack of detection of coliforms in monitoring wells;
- CFC data shows that the residence time in the saturated zone is in the range 30–60 years. Combined with the low estimates of transmissivity from pumping tests this suggests that the effect of secondary permeability may be limited;
- there are a number of possible mechanisms for recharge to the part of the aquifer capped by the Blue Clay. The single groundwater age from this part of the aquifer was in the older part of the range of the rest of the aquifer. Possible mechanisms include:
    - slow infiltration through the Blue Clay from the upper aquifers;
    - enhanced recharge at the edge of the Blue Clay; and
    - rapid infiltration along faults or fractures.

4.2 Water policy targets

Malta's 2nd River Basin Management Plan assesses the Mean Sea Level Aquifer system in the island of Gozo as being in poor quantitative status. In fact, water balance models developed for this aquifer system indicate the mean annual abstraction to marginally exceed the mean annual recharge.

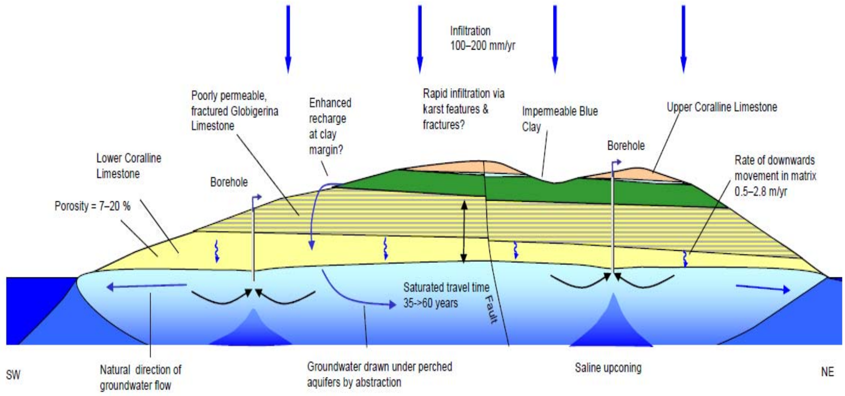

Figure 1: Conceptual model of groundwater movement in the Gozo mean sea level aquifer system. (*Source: Stuart et al.*)

Overall, the 2nd RBMP therefore estimates that the mean sea level aquifer in the island of Gozo still suffers from overexploitation, and hence is classified as being in poor quantitative status. The aquifer system is utilized for the abstraction of water intended for human consumption by the Water Services Corporation (the public utility in the Maltese islands) and the agricultural and commercial sectors. However, the main component of the water balance of the aquifer system (Fig. 2 below) is represented by the natural discharge of groundwater at the coast, which accounts for around 50% of the total withdrawals from the aquifer system. The strategic importance of groundwater for the islands therefore calls for the development of tools for its protection, in order to protect from over-abstraction and related risks of sea-water intrusion.

The issue to be addressed under the FREEWAT project therefore focuses on the development of a management tool (numerical model) of the Gozo mean sea-level aquifer system which will permit the reliable evaluation of the status of the water body. The model will also permit the reliable assessment of subsurface groundwater discharge which is a key-parameter in the water balance. Furthermore, the model will introduce a spatial dimension in the water balance assessment by taking due consideration of the spatial variation of groundwater abstraction, and therefore help identify regional water management issues. The model will thus permit the optimized management of this aquifer system through increasing the reliability of quantitative status assessments.

Malta's 2nd RBMP, therefore sets as one of its objectives, the achievement of Good Quantitative Status for this body of groundwater by 2021 at the latest. In order to achieve its objectives, the 2nd RBMP outlines a series of measures (under its Programme of Measures) which need to be undertaken to address the imbalance between recharge and water demand.

The development of the numerical groundwater model for the aquifer system will increase reliability in the water balance estimations to assess the achievement of Good Quantitative Status and its assessment in the 3rd RBMP. It will also permit the testing (on a virtual platform) of the proposed measures, and the projection of their impact on the status of the groundwater body.

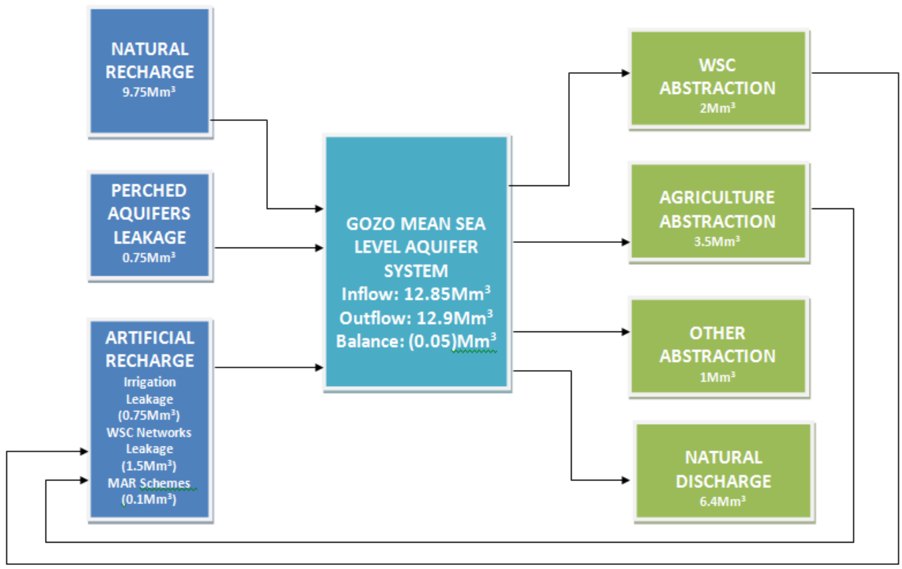

Figure 2: Water balance assessment for the Gozo mean sea level aquifer systems.

The Water Policy target applicable to the Gozo Mean Sea Level body of groundwater is therefore the achievement of the good quantitative status conditions as required under Article 4 of the EU's Water Framework Directive (2000/60/EC) by 2021.

The achievement of good quantitative status will also support the achievement of sea-water intrusion good-qualitative status related conditions. Sea-water intrusion related impacts in this body of groundwater are primarily a direct consequence of its current poor quantitative status. Issues related to the presence of these parameters in groundwater, are therefore expected to be addressed through measures ensuring the progressive achievement of good quantitative status by 2021. In as much, achievement of good quantitative status will also address the conditions related to the achievement of good qualitative status under the EU Groundwater Directive (2006/118/EC).

4.3 Measures under the 2nd river basin management plan

The measures developed under the Programme of Measures in Malta's 2nd River Basin Management Plan therefore include specific measures to progressively support the achievement of good quantitative status conditions, namely that the annual abstraction from the groundwater body is less than the mean annual recharge, in the Gozo mean sea-level aquifer system.

The measures developed thus target an increased efficiency in water use in those sectors dependent on groundwater abstracted from these bodies of groundwater, as well as the development of alternative water resources which can be utilised by these sectors in substitution of groundwater. Furthermore, the restoration of good status will be further supported through the development of Managed Aquifer Recharge schemes aimed at increasing the mean annual recharge to the groundwater body.

The projected impact of these water management measures on the Gozo Mean Sea Level aquifer system accounts to:

- The development of alternative water resources to be used in substitution of groundwater by the agricultural sector resulting in an increase in the national water resource base of 1.2 million m^3/year;
- The rehabilitation of existing and development of new Managed Aquifer Recharge schemes resulting in an increase in the mean annual recharge of 0.4 million m^3/year, with the recharge source water being primarily derived from alternative water resources.

The cumulative impact of the 2nd Water Catchment Management Plan's measures on the Gozo Mean Sea Level aquifer system is projected to range between 0.8 and 1.6 million m^3 per year.

The application of the impact of these measures on the water balance scheme of the aquifer system (Fig. 3) shows that their quantitative impact can be considered as sufficient to ensure the achievement of good quantitative status in the Gozo Mean Sea-Level groundwater body by the end of the 2nd WFD planning cycle, that is by 2021.

4.4 Numerical model

The numerical model for the Gozo Mean Sea Level Aquifer system developed on the FREEWAT platform is defined within a rectangular domain of 6.8km width and 11.9km length and the spatial reference system used was ED50 /UTM zone 33N. The model domain was buit upon the spatial extend of the island of Gozo, defined by the coordinates of the lower left corner of 33N 430040mE and 3986668mN. The model domain is divided in the vertical

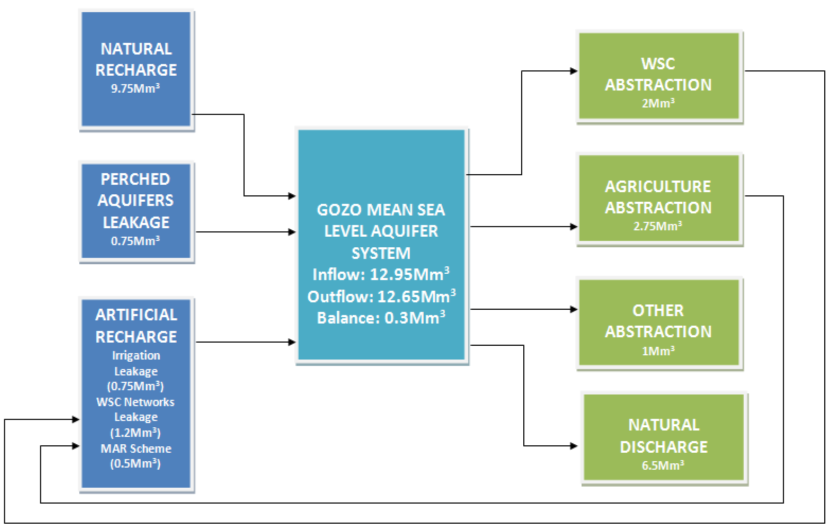

Figure 3: Gozo mean sea level aquifer system – Quantitative status assessment 2021 (projected).

dimension into 22 layers, three above sea-level each of thickness 50m, a layer of 20m thickness at sea-level and 19 layers each of 10m thickness below sea-level. The increased discretisation beneath sea-level was introduced to permit an improved representation of the freshwater-seawater interface. In the horizontal dimension, the model domain was divided into 49,824 square cells, each of 50m by 50m size.

The active area of the model domain represents the aquifer matrix and is defined as bounded by a 0-head boundary condition along the coast of the island and a no-flow boundary condition representing the effect of the Ghajnsielem-Qala fault at the south-western region of the island. The boundary conditions are represented in Fig. 4.

The modelling matrix assumes the main aquifer formation as the Lower Coralline Limestone, locally replaced by the Globigerina Limestone in the uppermost saturated layers. The different hydrodynamic characteristics of these formations, in particular the lower hydraulic conductivity levels of the Globigerina Limestone formation can potentially have a determining effect on the development of the freshwater lens. The hydrodynamic properties of these formations in the model are assumed as:

Globigerina Limestone:

Hydraulic Conductivity: 0.86m/day; Storativity: 10–6 m^{-1}; Effective Porosity: 40%

Lower Coralline Limestone:

Hydraulic Conductivity: 8.6m/day; Storativitiy: 10–4 m^{-1}; Effective Porosity: 10%

Recharge from rainfall (natural recharge) was assumed to be the only input to the aquifer system for the purpose of this initial model and was introduced in the third layer of the model with a spatial distribution depending on the surface (outcropping) geology, namely:

- areas where the Lower Coralline Limestone outcrops – 383mm/year,
- areas where the Globigerina Limestone outcrops – 283mm/year, and
- areas beneath the Blue Clay formation – 63mm/year, where inflow to the mean sea-level aquifer system is through leakage from the perched aquifer systems through the Blue Clay formation.

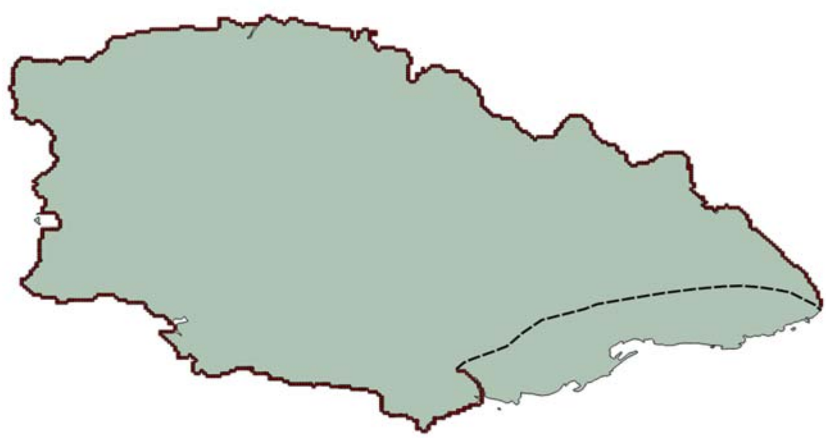

Figure 4: Initial model boundary conditions – 0-head at the coast and no-flow boundary condition along the Ghajnsielem fault.

Constant annual recharge values are assumed, ignoring seasonality and inter-annual variability due to the expected homogenising effect as a result of the long-travel time of recharge through the unsaturated zone. The spatial distribution of natural recharge is shown in Fig. 5.

Initial hydraulic conditions were obtained for a single stress period under steady state conditions, assuming a non-exploited aquifer system (no abstraction). Maximum water levels for an elongated strip island were calculated according to Henry's solution assuming a sharp interface and the results were used for calibration purposes. Calibration was then carried out on these values, given the lack of real water level data for the aquifer system under unexploited conditions, by trial-and-error with small adjustments to the values of the hydraulic conductivity of the main Lower Coralline Limestone Formation. Following the calibration exercise, the value for the hydraulic conductivity of the Lower Coralline Limestone formation was set at 1.0m/day. An order of magnitude difference was also set between vertical (Kz) and horizontal (Kxy) values of hydraulic conductivity.

Following the initial calibration exercise, twelve stress periods of one month each were developed in the model to assess the behaviour of the aquifer system under transient conditions.

For the assessment under transient conditions, groundwater abstraction was introduced in the model through the mapping of 34 public groundwater abstraction wells, with a mean monthly abstraction rate of 176,475m^3, and 382 private groundwater abstraction wells (agricultural sector) with a mean monthly abstraction rate of 62,062m^3. All the abstraction wells were assumed to abstract groundwater from the fourth layer of the model, i.e. between 0 and 20m bmsl; to reflect the limited depth of wells in the mean sea-level aquifer systems. The location of all groundwater abstraction wells is shown in Fig. 6.

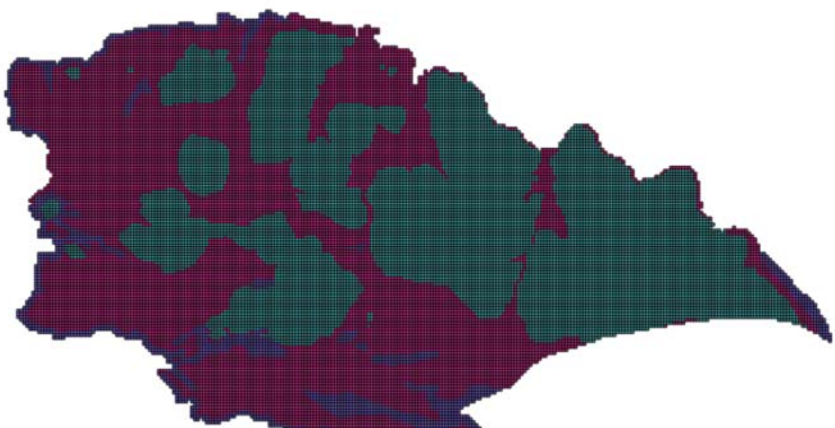

Figure 5: Natural recharge distribution (green – areas under the blue clay, violet – outcrops globigerina limestone and blue – outcrops of the lower coralline limestone.

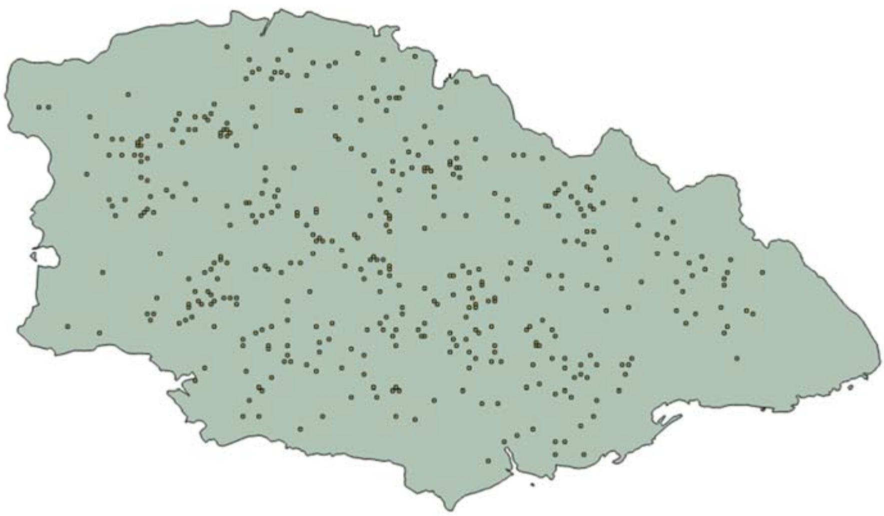

Figure 6: Groundwater abstraction stations.

Solute transport conditions were introduced in the model by assigning values of 38mg/l chloride concentration to cells lying along the coastal boundary in layers 4 to 11; and all active cells from layer 11 to 22. These new boundary conditions introduce sea-water in the modelling framework and enable the modelling of the aquifer under density-dependent flow conditions.

4.5 Assessment of status achievement

A model run under transient conditions was then performed over 12-stress periods of one-month duration, the results of which are shown in Fig. 7. The results show the effect of groundwater abstraction on groundwater levels, particularly in the central region of the island, which shows a marked sea-water intrusion impact. This effect can be associated with the high density of public abstraction groundwater sources located in this region of the aquifer system. The impacts of groundwater abstraction from the agricultural and private sector are not pronounced on a local level, however their impact on a regional level results in the general lowering of the hydraulic head and consequent rise of the freshwater-seawater interface facilitating the intrusion of sea-water in zones of high abstraction for public supply purposes.

The model results also compute a water balance for the aquifer system which shows a prevalence of discharge of freshwater at the coastal boundary. The model estimates this discharge to stand at levels of the order of 50% of the mean annual recharge. Furthermore, the model also shows that the volume of freshwater storage in the aquifer system is stable, indicating that under the input and output conditions envisaged under the 2nd River Basin Management Plan the groundwater body would tend to reach a steady stage condition and hence achieve good quantitative status conditions.

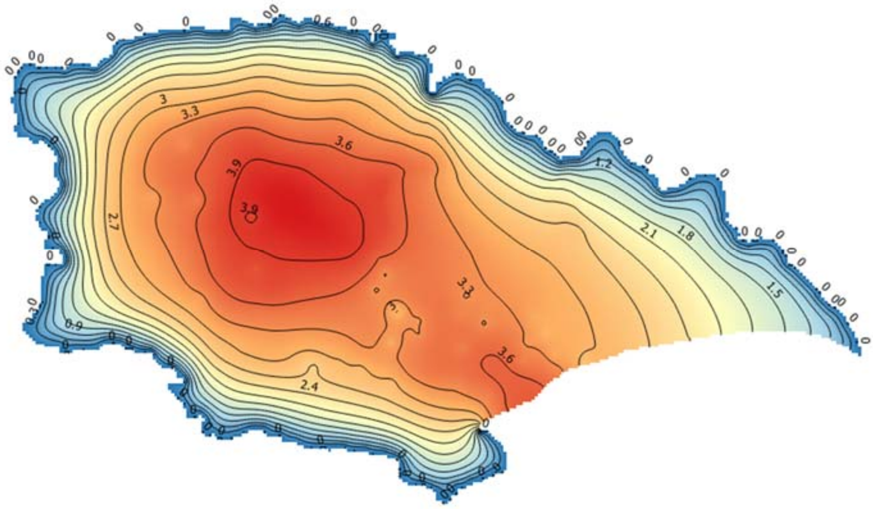

Figure 7: Hydraulic head levels for the model following 12-stress periods of one month duration each.

5 CONCLUSIONS

The application of the FREEWAT numerical modeling framework to the Gozo Mean Sea Level aquifer system can permit the more reliable estimation of water balance parameters, and the impact of water management measures planned over the implementation period of Malta's 2nd River Basin Management Plan. The modeling framework can thus support the reliable assessment of the achievement of good groundwater status conditions under the implementation process of the Water Framework Directive.

Furthermore, the model has the potential of projecting the impact of water management measures on the groundwater body over the short- and medium-term and thus enable water planners to assess in advance the need for additional water management measures to enable the maintainment of the good quantitative status conditions. In addition, the model also has the potential to include future water demand and supply trends arising from conditions such as those due to climate change, and therefore support the development of adaptation measures to ensure the sustainability of water resources.

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