2nd International LIFE REWAT Summer School

Digital water management and water-related agroecosystem services: geostatistics, hydroinformatics and groundwater flow numerical modelling

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Scuola Superiore Sant'Anna
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2nd FREEWAT International Workshop

Development of groundwater models to support groundwater management in the Maltese islands

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Motivations

- This study is part of a larger project co-financed by the LIFE Programme of the European Union to the Government of Malta, whose scope is to support the implementation of Malta's 2nd River Basin Management Plan 2015 – 2021, in compliance with the EU Water Framework Directive (WFD) [project **LIFE16 IPE/MT/000008**].
- According to the 2nd Water Catchment Management Plan, **groundwater abstraction** from all the groundwater bodies in the Maltese Water Catchment District, was estimated to reach around 38 million m^3 in 2014, corresponding to **61%** of the total national water demand. The agricultural sector has the highest dependence on groundwater resource and it accounts for almost half of the total groundwater abstraction in the Maltese islands.
- The groundwater abstraction assessment undertaken as part of the quantitative status assessment under the 2nd WCMP, indicates that **cumulatively the sea-level aquifer systems are being over-abstracted**, whilst the perched aquifer systems show an overall positive balance.

Motivations (ctd.)

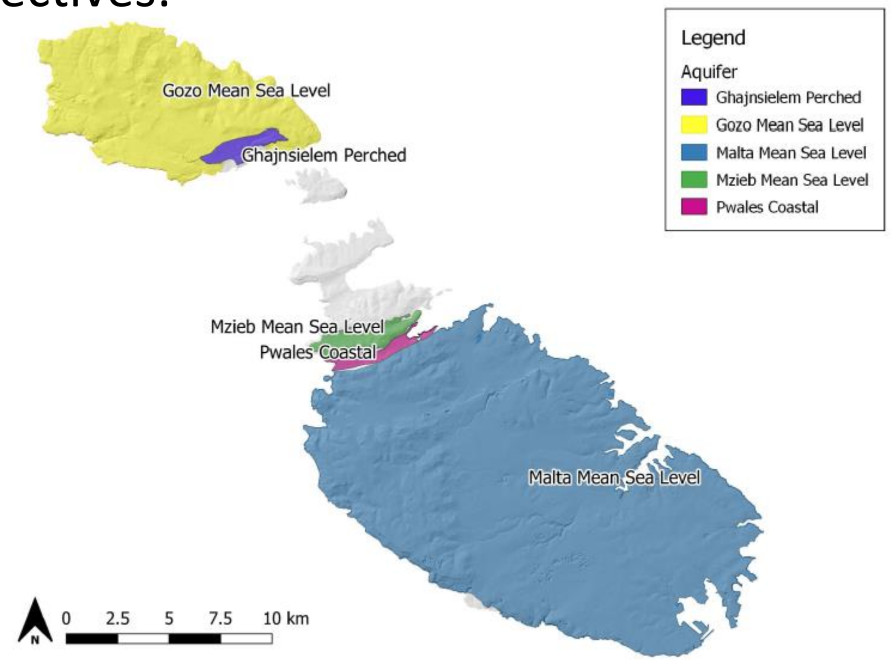
- Therefore, **groundwater abstraction remains a key pressure factor for the two main mean sea-level aquifer systems in the Maltese Islands (Malta and Gozo Mean Sea Level Aquifer)**, which still suffer from **over abstraction of groundwater** and the related impacts of **seawater intrusion**.
- To better understand such issues, and to assess the impact on groundwater status in the future, the 2nd RBMP implementation will take advantage of **numerical modelling** to include a prediction capacity in the chain of water management decision making.
- In October 2018 EWA awarded the Joint Venture (TEA, STEAM, CGT-UNISI, ADI) to run this study.

Objectives

The general objective of the study is to develop numerical groundwater models to support the implementation of Malta's 2nd RBMP and to set up a capacity building process together with the Energy and Water Agency staff.

In particular, there are 6 specific objectives:

1. *<u>Data review and gap-analysis</u>*.
2. *<u>Calibrated steady-state models</u>*:
   - **Malta mean sea-level** aquifer.
   - **Gozo mean sea-level** aquifer.
   - **Mizieb mean sea-level** aquifer.
   - **Ghajnsielem perched** aquifer.
   - **Pwales coastal** aquifer.



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Objectives (ctd.)

3. *Transient models*

4. *Groundwater Management Scenarios*

5. *Capacity building*

6. *Dissemination*

Data review and Gap analysis

- Before defining conceptual models, a deep review and analysis of existing data has been carried out.
- Data range: since late 40’s until nowadays.
- Some of them required digitalization from the scratch.
- The goal of this activity was to get a new definition of hydrogeological conceptual model, as main source for the numerical models.
- Data concerning the whole Maltese archipelago have been considered.

Data review and Gap analysis

The following main topics have been investigated:

- ❑ Climatic conditions (temperature, rainfall)
- ❑ Geological and structural setting (geological maps, stratigraphy, geological cross sections, …)
- ❑ Hydrogeological setting.
- ❑ Wells and water galleries
- ❑ Land use and soil classification
- ❑ Groundwater management and use in Maltese islands
- ❑ Existing groundwater balance

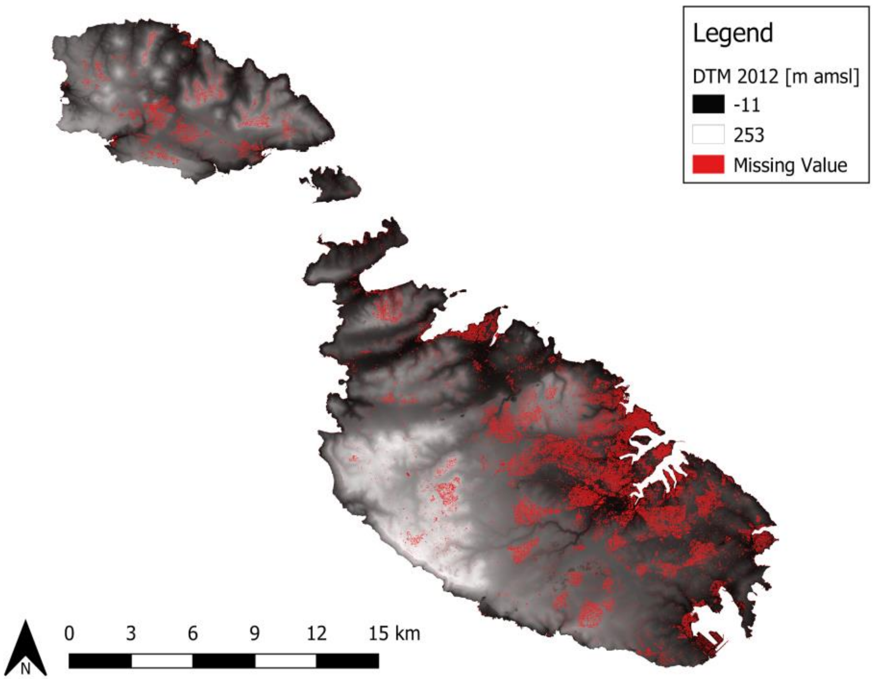
Several steps in this analysis made use of QGIS (this is and advantage, since we had the objective of applying FREEWAT!)

Data review and Gap analysis: QGIS

Examples of QGIS application

Filling no-data in DTM

SAGA and GRASS libraries used through QGIS to run interpolation algorithms (e.g. *fillnulls, spline, stepwise resampling, …*).



Missing values distribution in high-resolution DTM of Maltese archipelago.

Data review and Gap analysis: QGIS

Examples of QGIS application

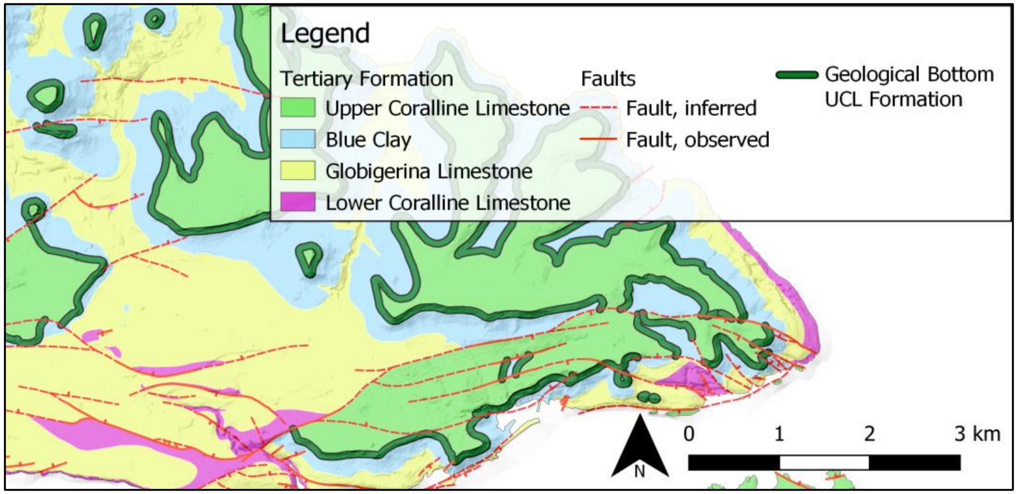
***Geological formations surfaces interpolation:** formation boundaries*

The boundaries of each geological formation were extracted from the spatially adjusted geological map, as lines corresponding to the polygon boundaries.

To get this result, two QGIS tools were applied:

✓ *Densify by interval*: to get a better definition of vertexes in lines representing the formation boundary

✓ Drape: to assign an absolute elevation value to each vertex, using the rasterized DEM



Example of geological boundaries used to interpolate the bottom boundary of the UCL formation (south east Gozo).

Data review and Gap analysis: QGIS

Examples of QGIS application

Organizing the dataset in a QGIS project

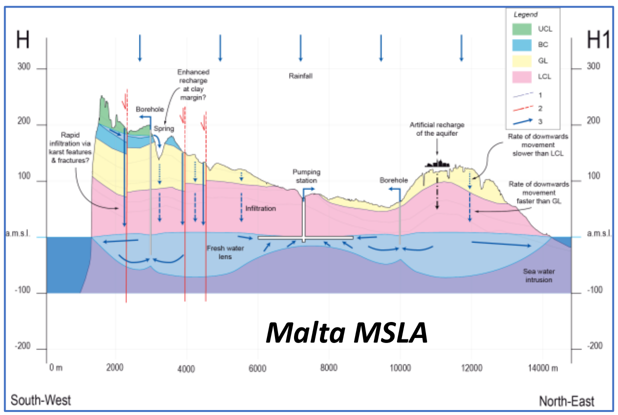
The main results of the geospatial data analysis has been collected in a QGIS project, used as reference for developing numerical models

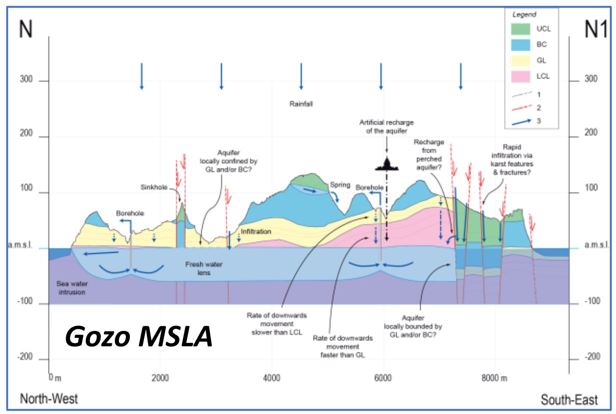
Data review and Gap analysis:
Defining Conceptual Models

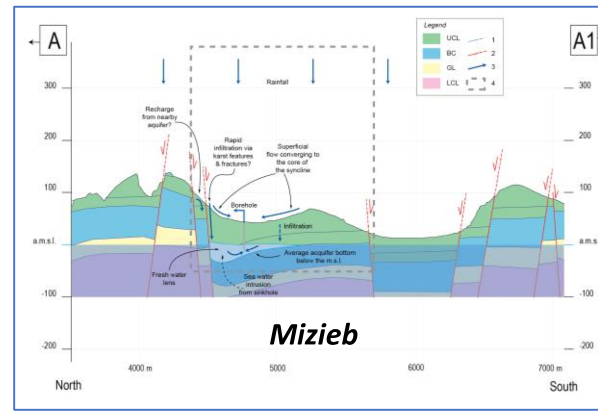
The final goal of this activity was to get an updated definition of Conceptual Models for the five aquifers.

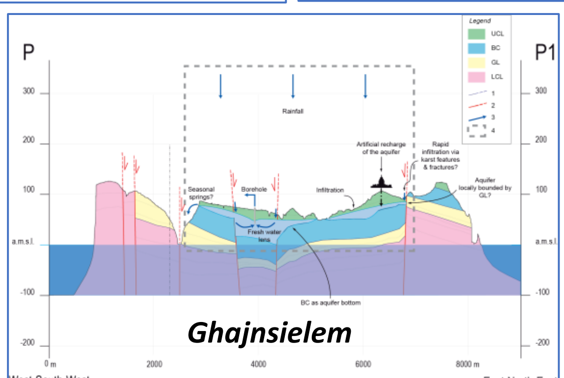
Some issues are still pending (data available are not enough to support a specific conceptualization). For instance: *which are the natural outflow in Ghajnsielem aquifer?*

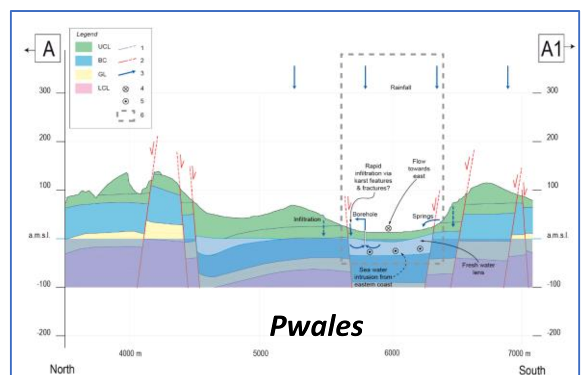
- One goal of the modeling activity is to study the effects of these *uncertain* settings, and to compare alternative settings.











Gozo MSLA : numerical model

Model objectives

The calibrated steady state models aim at:

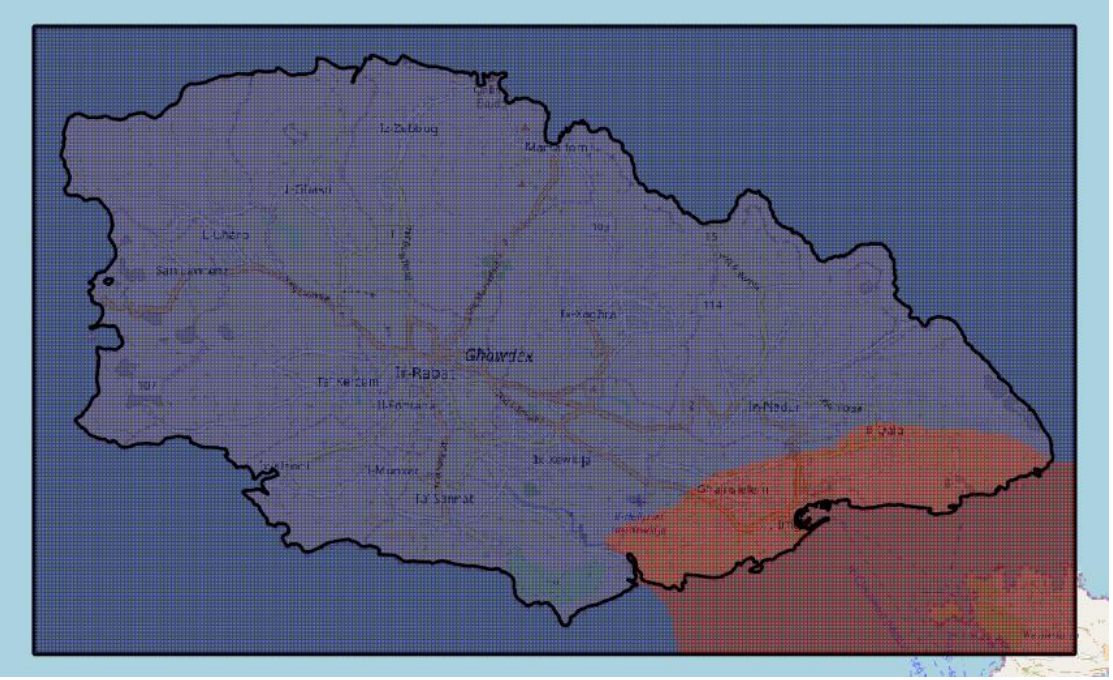
- Representing the water balance at the early stage of exploitation (1941-1944).
- Representing the fresh/salt-water interface at that time
- Identify potential inconsistency in data assessment, and underlining more significant targets for future monitoring campaigns.

Gozo MSLA : numerical model

Domain and discretization

The model domain covers all the island, having a length of around 8.6 km (along the North-South direction) and a width of around 14 km (along the West-East direction).

This domain is discretized with a grid having a cell size of 50m, and resulting in **49824 cells** (173 rows by 288 columns).



The MSLA aquifer is represented (only a portion of the aquifer (on the south east part) is neglected: here MSLA goes down the Ghajnsielem aquifer, but water storage in this zone seems negligible.

The large buffer of active cells on the seaside is considered because of the application of SWI package (see later on).

Gozo MSLA : numerical model

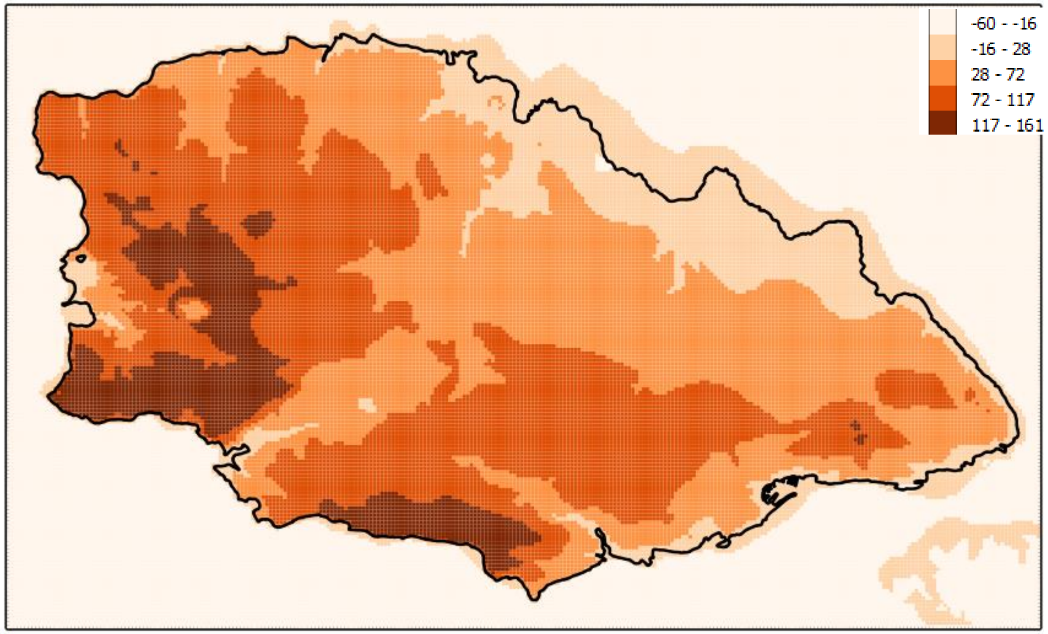
Domain and discretization

Vertical sicretization: 1 model layer is considered, representing the lithology Globigerina + Lower Coralline.

The Model Top is taken as the top of Globigerina

The Model Bottom is firstly taken as (TOP-200m), to mimic a constant saturated thickness. Where this results in a Bottom higher than -200 m, the value is put down to -200 m, so that almost the whole aquifer has a constant bottom equals to -200 m.

Elevation of Model Top (m)

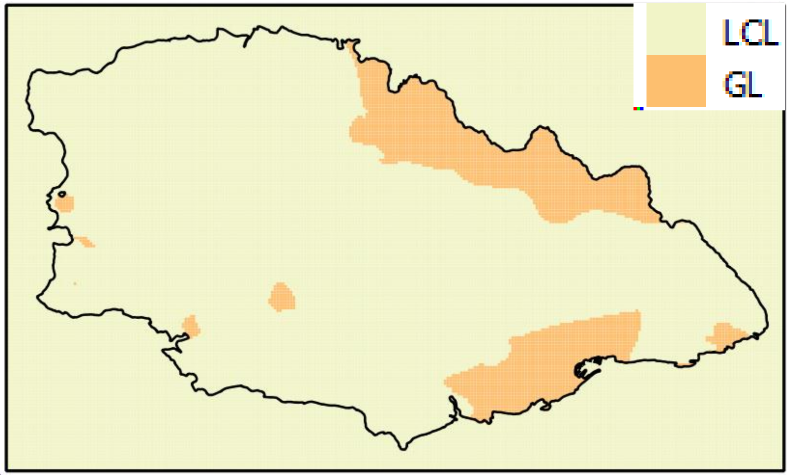


Gozo MSLA : numerical model

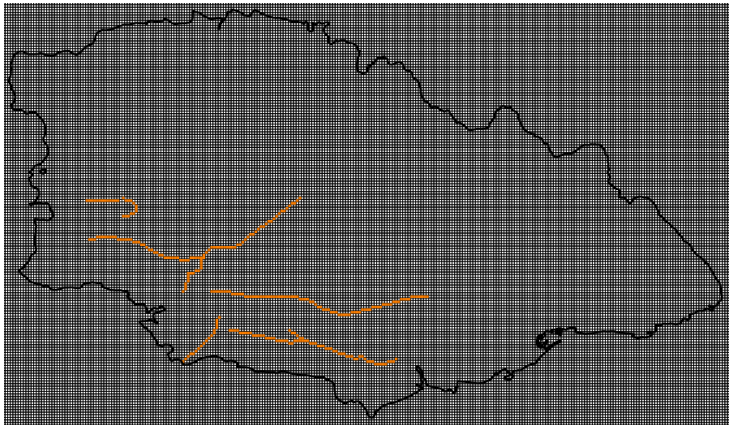
Hydrodynamic parameters and faults

Hydraulic conductivity has been set as almost everywhere equal to Lower Coralline, except where bottom of Globigerina is under the sea level.

The guess values for K are the following: LCL (zone 1) = 13.5 m/day; GL (zone 2) = 1.35 m/day



The presence of several faults in the islands is accounted by applying the HFB (horizontal Flow Barrier) package, which is activated along the fault lines



Gozo MSLA : numerical model

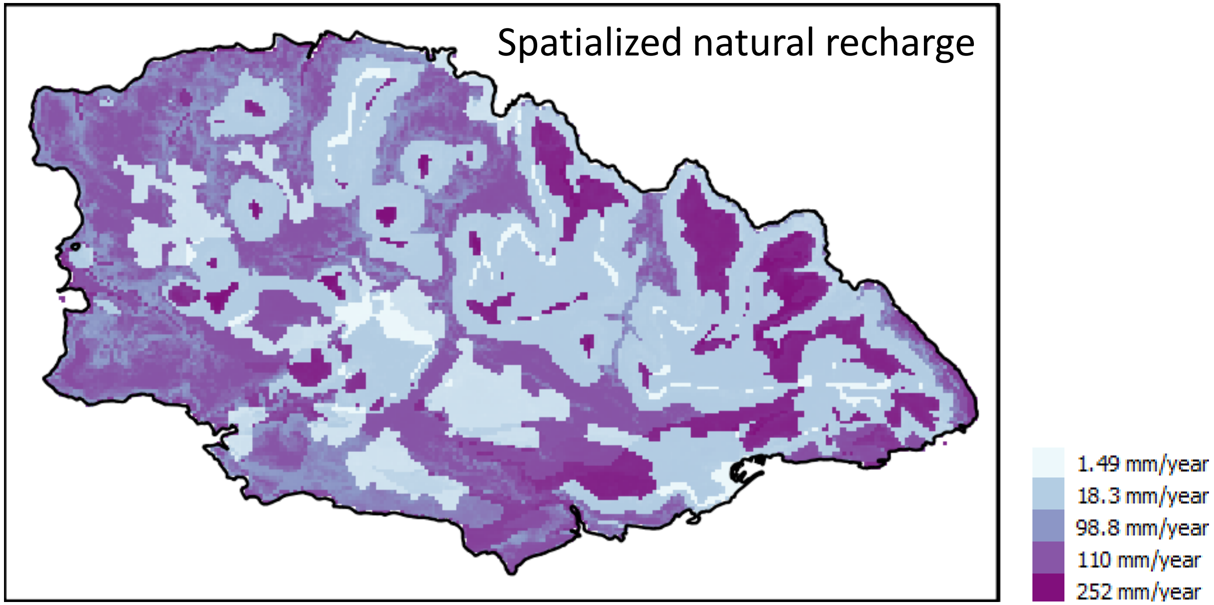
Boundary Conditions

- **General Head Boundary (GHB)** to represent the sea with elevation = 0 m asl. *GHB is used instead of CHD to apply SWI2 package.*
- Wells to represent pumping wells and galleries that were active in 1944.
- **Hydraulic flow barrier (HFB)** to represent the main faults discontinuities.

Gozo MSLA : numerical model

Inflow: aquifer recharge

- A uniform value for natural recharge due to infiltration (namely precipitation - evapotranspiration), accounting for 37% of the mean annual rainfall is taken as reference (ref. BRGM - 1991). It gives a reference recharge of **5.57e-4 m/day**.
- A more detailed spatial distribution of recharge is obtained by applying the following methodology (initially defined for Malta MSLA – for which data are available):
  - ❑Compute the **Surplus** (rain- evapotranspiration) using **Thornthwaite** method, and spatialize it using data on Soil classification
  - ❑Weight this spatialized datum with 3 other coefficients: **urbanized area**, **geology** (type of formation characterizing the model layer), **morphology** (terrain slope).

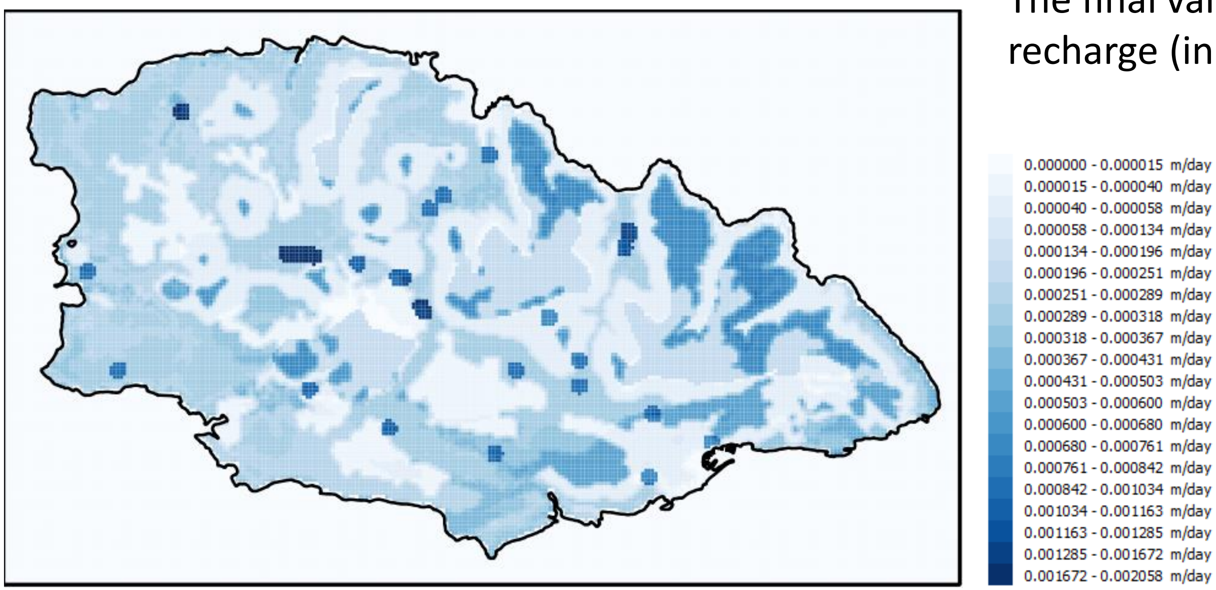


Gozo MSLA : numerical model

Inflow: aquifer recharge (ctd.)

The value of natural recharge is then summed up with two additional terms:

- ✓ Leakage from perched aquifers
- ✓ Contribution of dam



The final value of spatially distributed recharge (input for RCH Package)

Gozo MSLA : numerical model

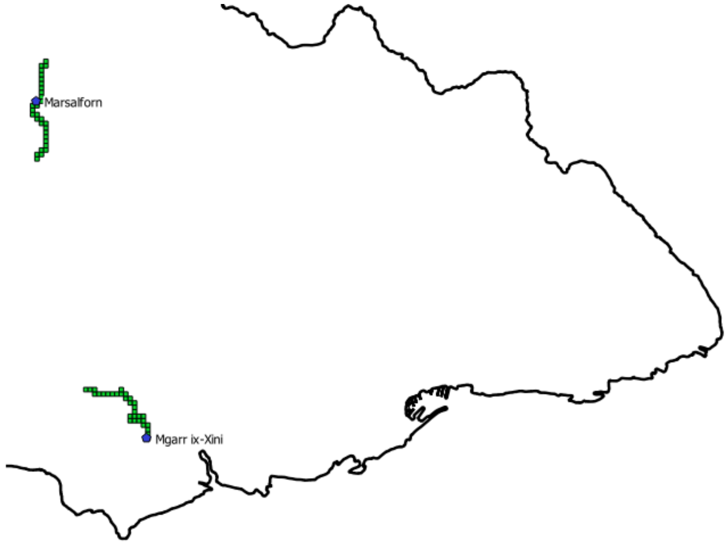
Outflow: abstraction

In 1940’s, only two pumping stations were active in Gozo (and no borehole was active at that time)

Pumping stations active since 1941 are:

- Marsalfolrm, with an average abstraction rate of 230 m3/day;
- Mgarr ix-Xini, with an average abstraction rate of 400 m3/day.

These rates has been distributed along the water galleries corresponding to the related pumping stations.

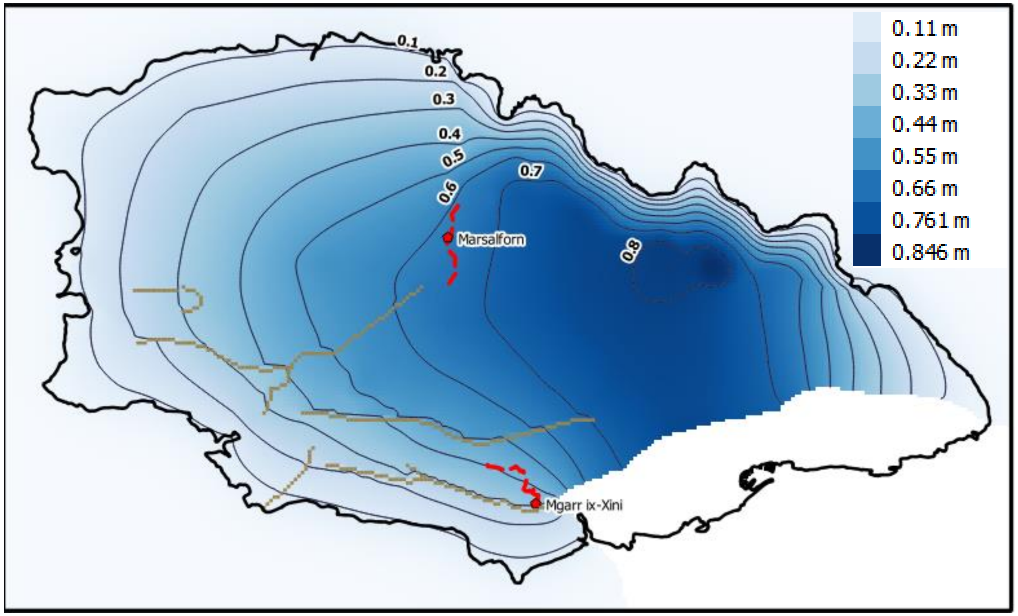


Gozo MSLA : numerical model

Model run (not calibrated)

Using PCG Solver with the following settings.

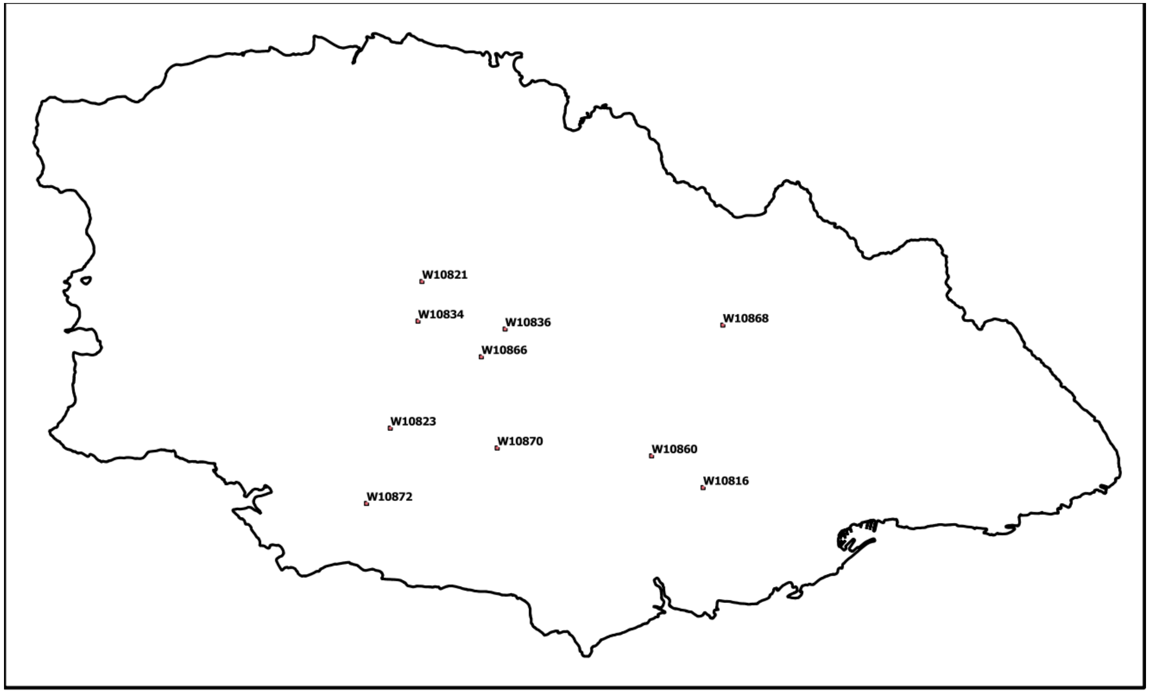
Outer iterations: 500; Inner iterations: 50;
Hclose = 0.001 (first convergence criterium);
Rclose = 0.001



Gozo MSLA : numerical model

Sensitivity and Calibration (using UCODE in FREEWAT)

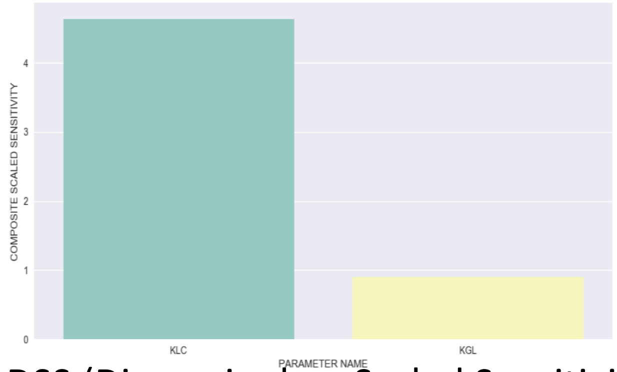
- The calibration study focuses on getting the **best value** for the two **conductivity parameters**, KLC and KGL.
- Firstly, a **sensitivity analysis** has been run before to start the calibration to investigate the effect of variation of these parameters on model results, and also to understand the importance of the observation.
- 12 borehole observations.



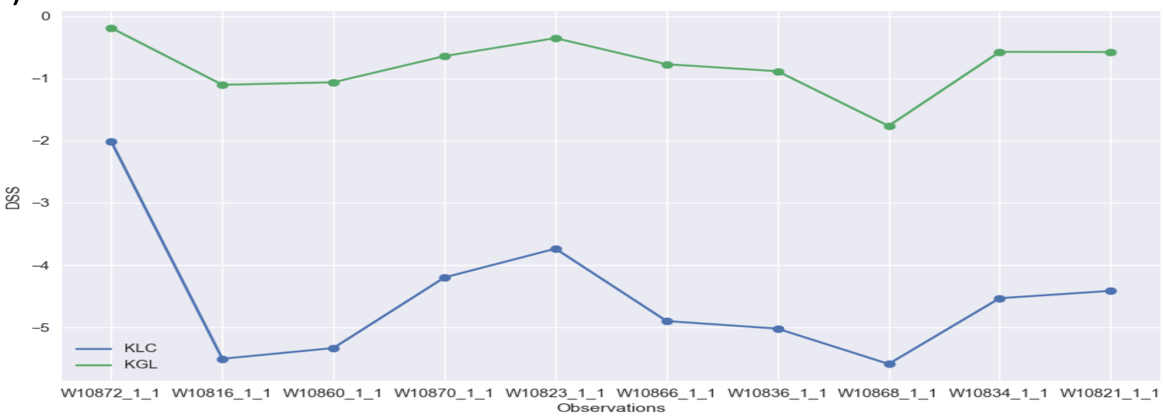
Gozo MSLA : numerical model

Sensitivity: results

- KLC and KGL are highly correlated (correlation coefficient = -0.91289). It means that for sure a non-unique solution will be achieved by the automatic calibration code.
- The statistics CSS (Composite Scaled Sensitivity) confirms KLC to be the most important parameter.



- The statistics DSS (Dimensionless Scaled Sensitivity) which shows the most important observations to estimate KLC (and this could guide measurements campaigns, especially in data scarcity situation like in Gozo)



Gozo MSLA : numerical model

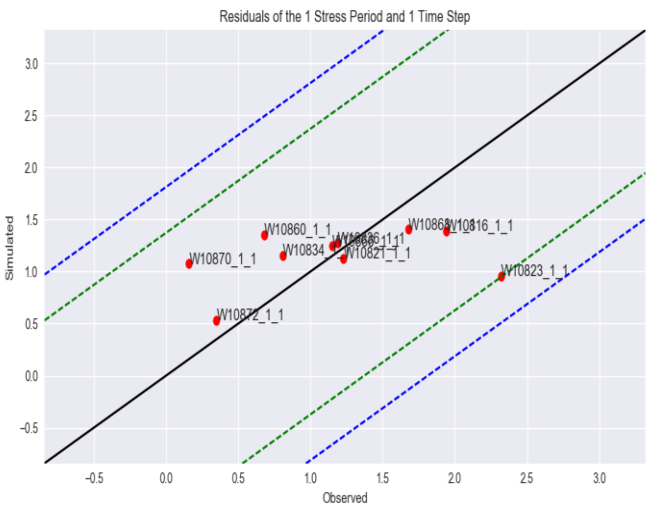
Parameters estimation

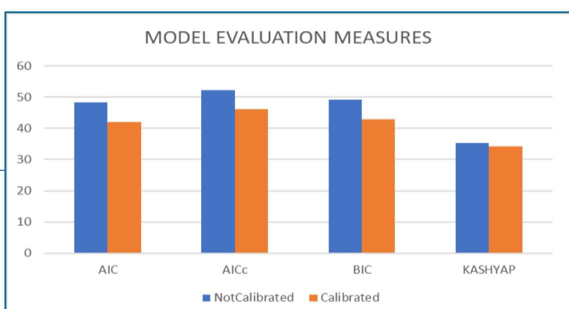
Model optimization algorithm converged smoothly, and it gets the following optimal values for the hydrodynamic parameters:

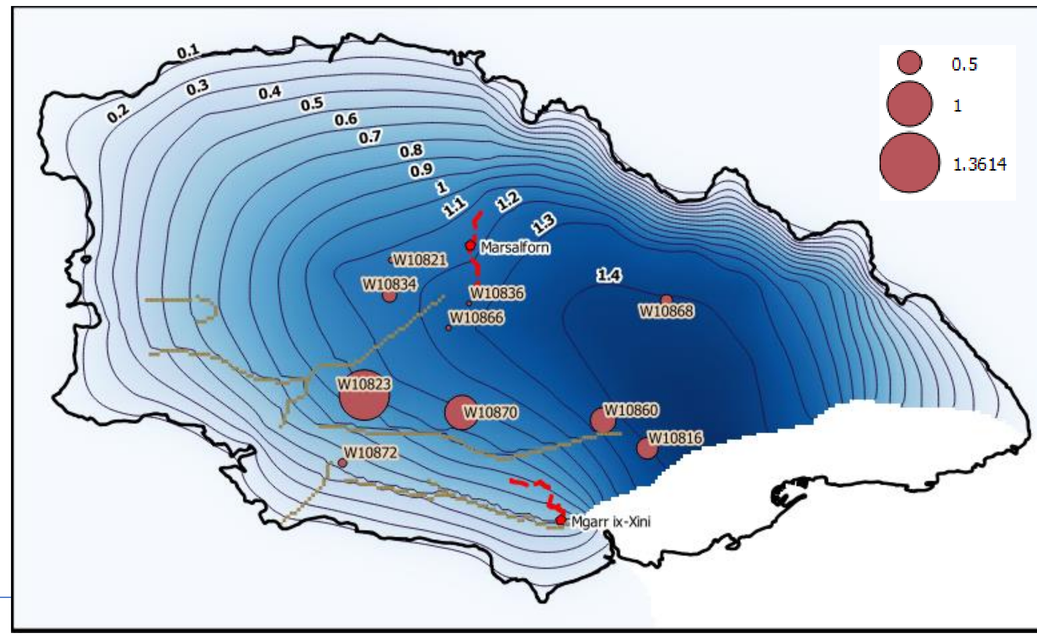
- KLC = 5.528 m/day
- KGL = 1.446 m/day

	Not Calibrated	Calibrated
ME	5.44E-01	2.63E-03
MAE	6.33E-01	4.58E-01
RMSE	6.74E-01	6.08E-01

ME = Mean Error; MAE = Mean Absolute Error; RMSE = Root of Mean Squared Error.



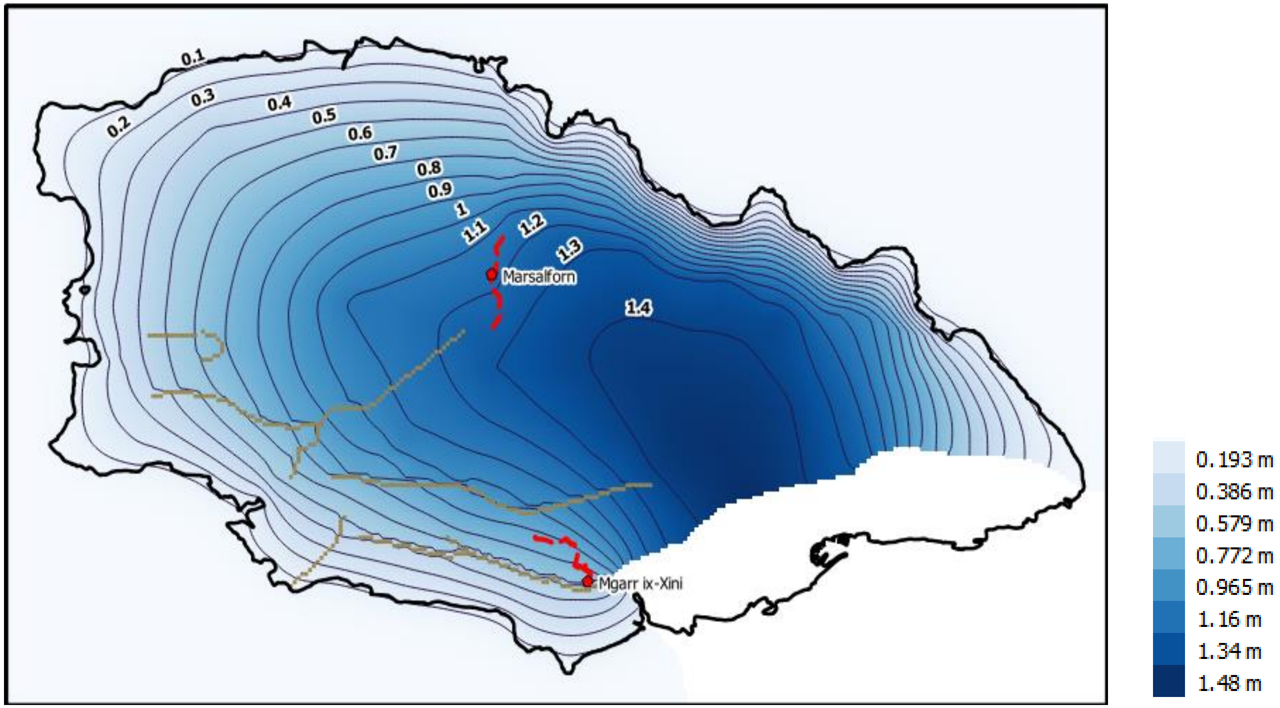




Bubble plots of absolute residual

Gozo MSLA : numerical model

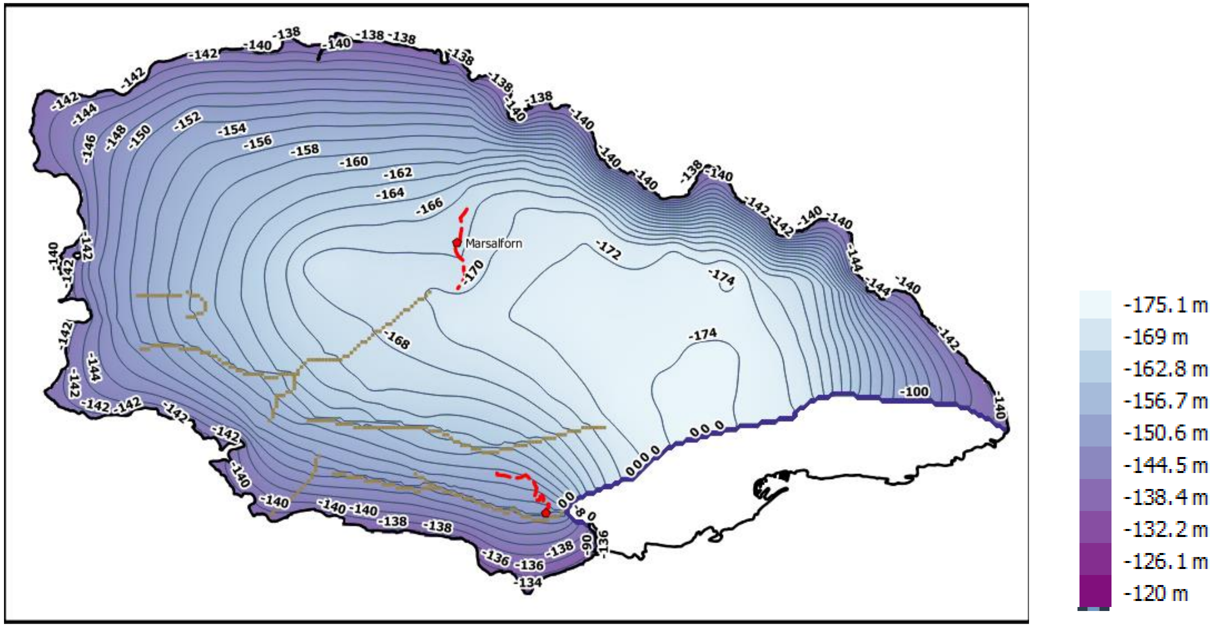
Result using calibrated parameters



Gozo MSLA : numerical model

Seawater intrusion

- The calibrated version is used to calculate the interface freshwater/saltwater by means of the package SWI (Sea Water Intrusion). The latter is applied with the following settings:
- Initial guess of the interface set according to the Ghyben-Herzberg formula (z = -40*h) using as potentiometric head the solution of the calibrated flow model.
- Effective porosity is taken equal to 0.2

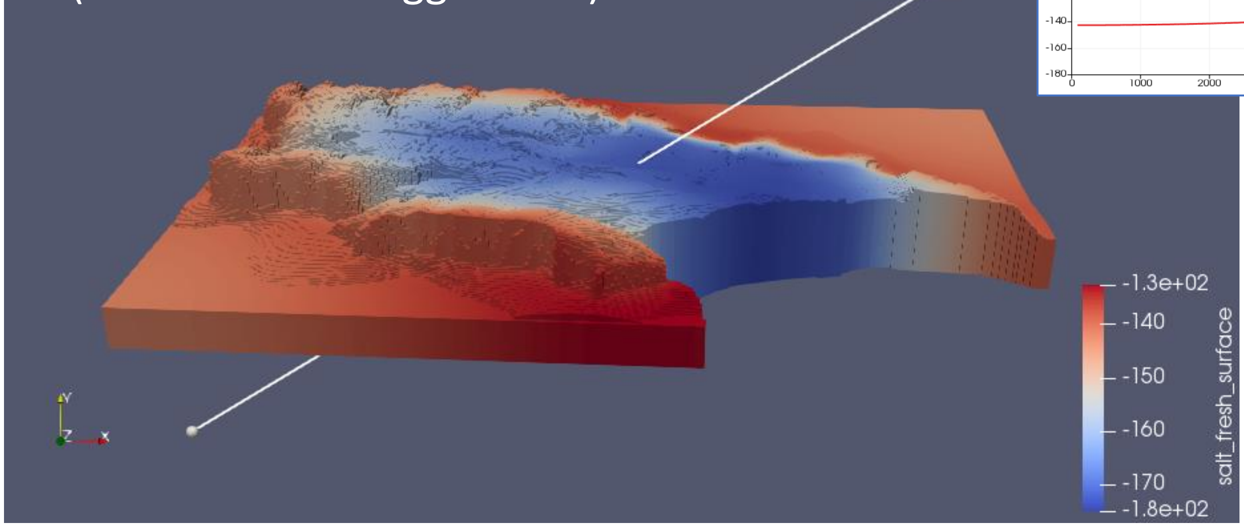


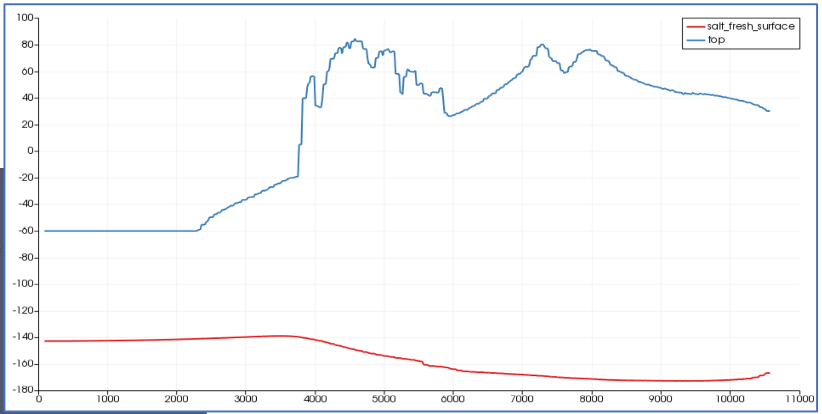
Gozo MSLA : numerical model

Seawater intrusion: post-processing VTK results

from FREEWAT to ParaView

Model Cells colored by Interface Elevation
(with vertical exaggeration)





Top and Interface elevation along a cross section of the 3D model

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Malta MSLA : numerical model

Model objectives

The calibrated steady state models aim at:

- Representing the water balance at the early stage of exploitation (1941-1944).
- Representing the fresh/salt-water interface at that time
- Identify potential inconsistency in data assessment, and underlining more significant targets for future monitoring campaigns.

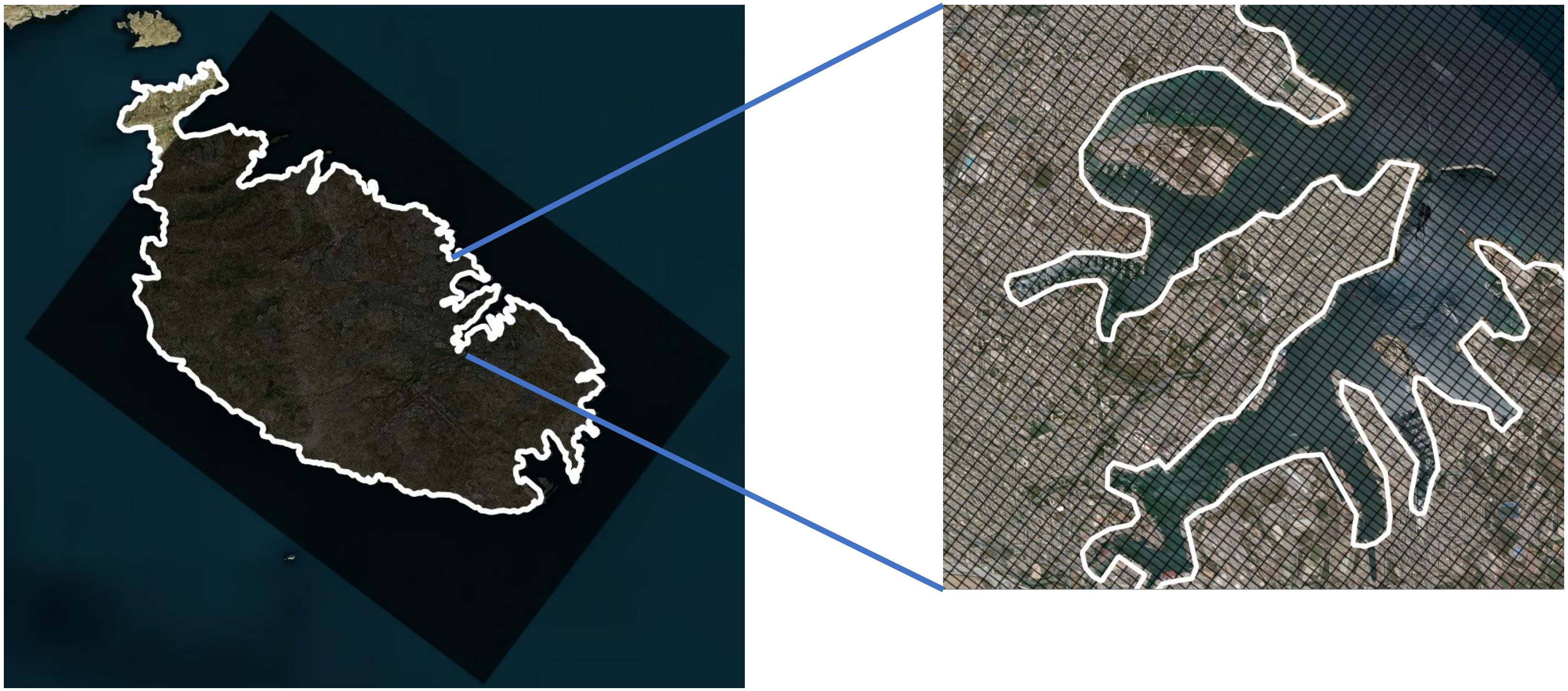
Malta MSLA : numerical model

Domain and discretization

The MLSA model consists of 105536 cells with dimension 50x100 m.

3150 cells are set no-flow to exclude the northern area of the island

59068 represents the sea and 43318 cells cover the aquifer (aquifer surface equal to 216.6 km2).



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Malta MSLA : numerical model

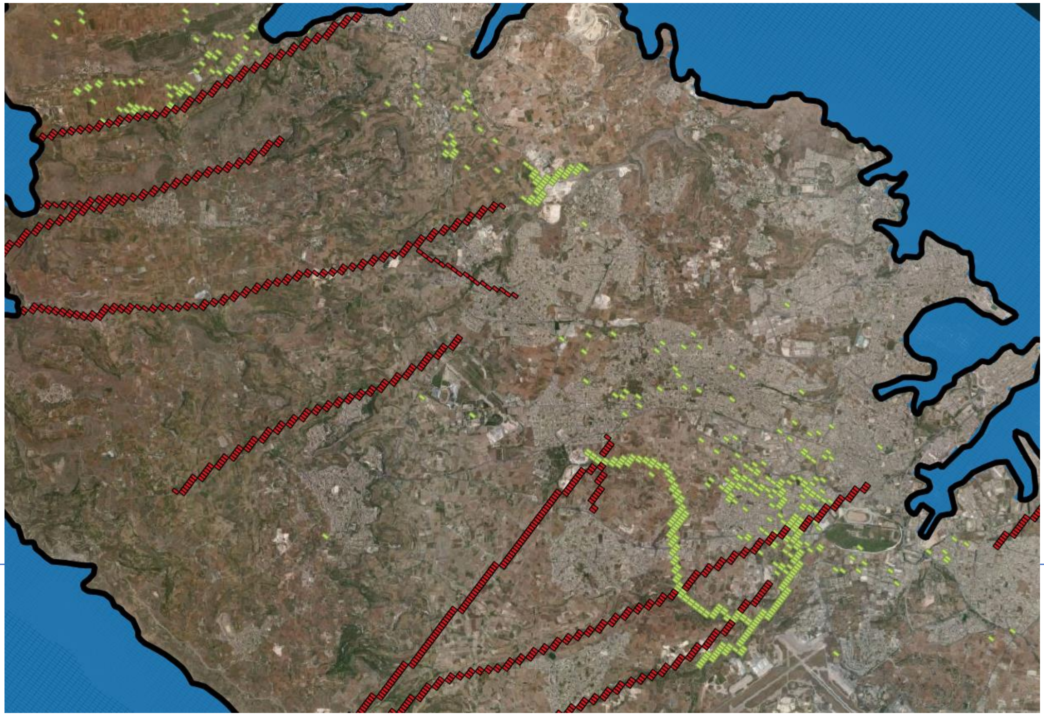
Domain and discretization

- The thickness of the MSL aquifer is assumed to be about 150 m
- The aquifer is represented as 1 Model Layer.
- The bottom elevation was set as top elevation (ground surface and bathymetry) - 150.
- In case of absolute bottom elevations > -150, the bottom was rectified to -150 m asl elevation.

Malta MSLA : numerical model

Boundary Conditions

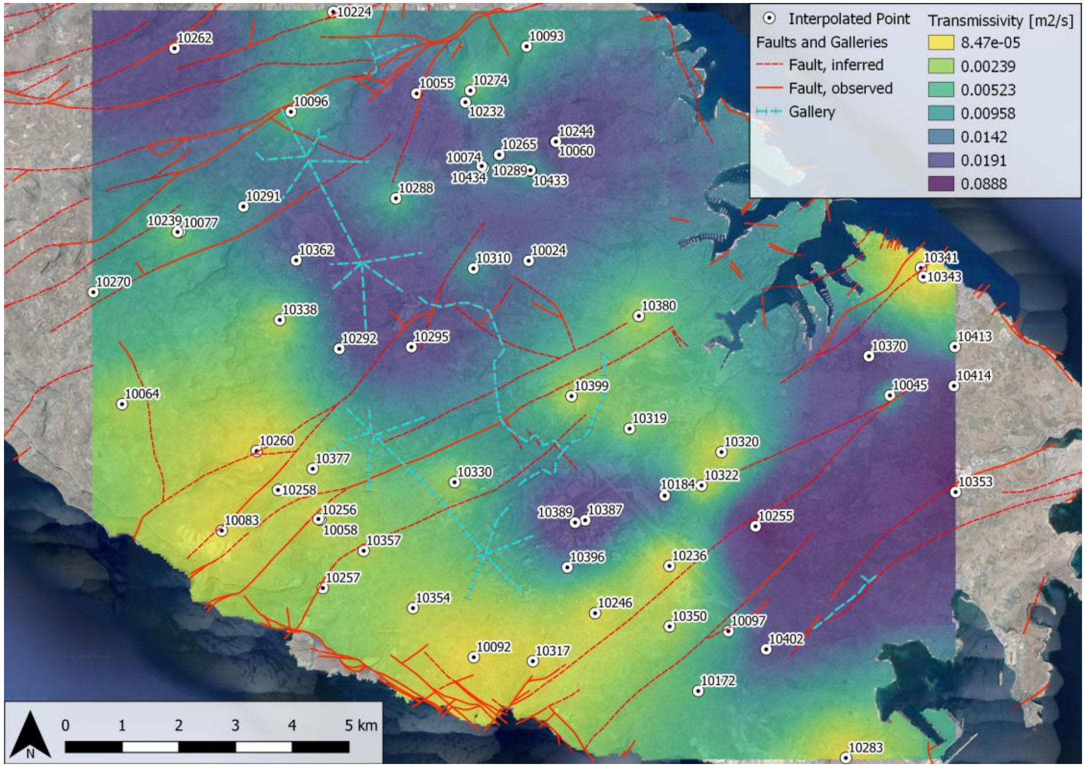
- **General Head Boundary (GHB)** to represent the sea with elevation = 0 m asl, K = 0.001 m/s and conductance = K x cell length x width = 5 m3/s. *GHB is used instead of CHD to apply SWI2 package.*
- **Wells** to represent pumping wells and galleries that were active in 1944.
- **Hydraulic flow barrier (HFB)** to represent the main faults discontinuities with an initial K = 1E-8 m/s



Malta MSLA : numerical model

Initial transmissivity values

- All data gathered about hydrodynamic parameters have been analyzed.
- The result is the distribution of conductivity (or trasmissivity) on the domain. This is the information used to run the first stage of model (not calibrated)

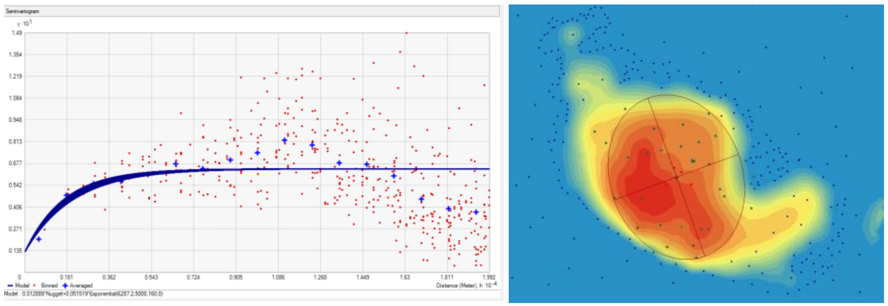


Ordinary Kriging representing the distribution of T in m2/s

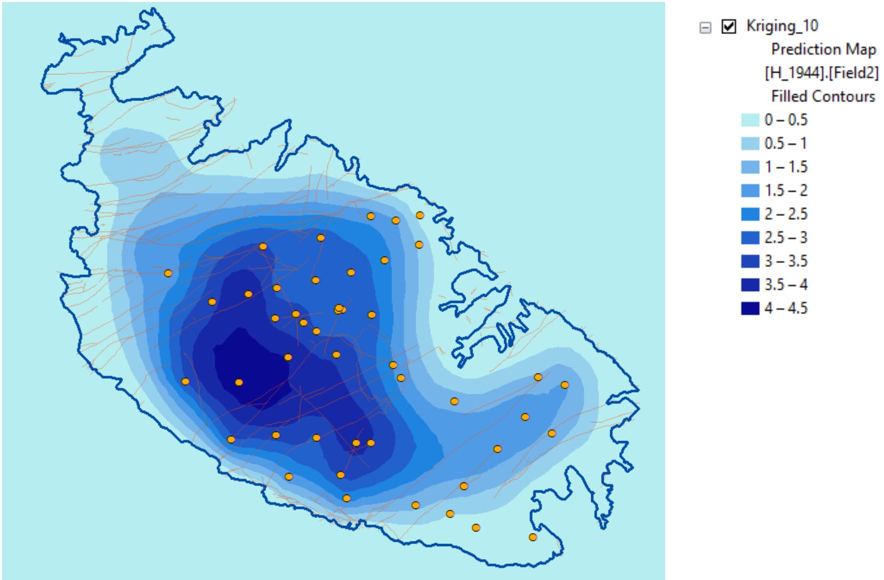
Malta MSLA : numerical model

Initial values for head

- Potentiometric surface was built with the available data from 1944. The borehole data have been integrated with fictitious points to introduce the seawater elevation at 0 m asl.
- After a geostatistical description of the data (variogram surface, trend, anisotropy, etc.), an Ordinary Kriging was applied to get a potentiometric surface as reference.



Semivariogram and semivariogram map of data, used to select the interpolation method.



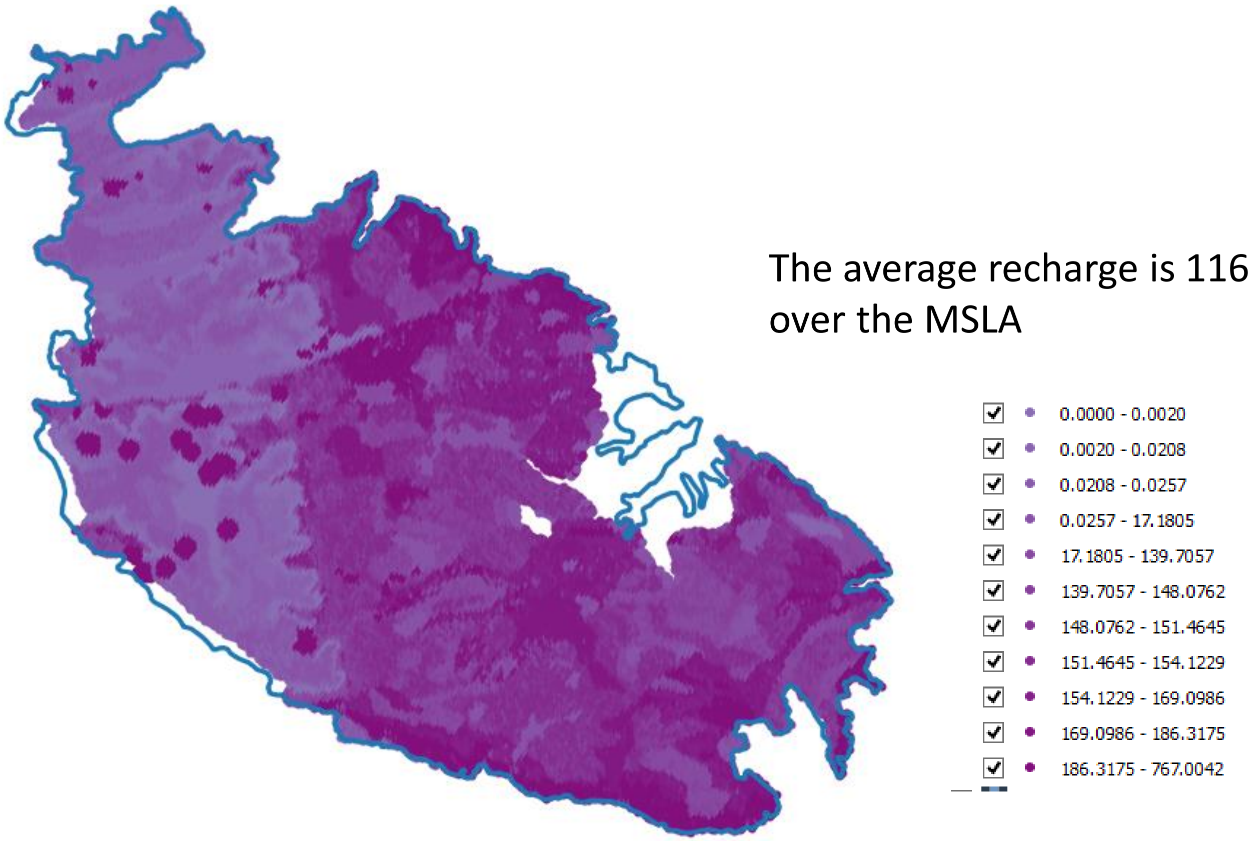
The interpolation assumes spatial continuity of the potentiometric surface. Given the geological structure of the island, this is just a rough approximation used to assigned the initial heads to the model and to do preliminary water budget calculations. It surely has no bearing on reality.

Malta MSLA : numerical model

Estimate of Recherge

- This term of the water budget is the most critical in Malta islands
- We decided to apply an in-depth definition of the spatially distributed recharge value
- *[Details on the method showed later on for Gozo MSLA model]*

The average recharge is 116 mm/y over the MSLA



Malta MSLA : numerical model

First model run

- The first model run represent the starting point for the calibration procedure.

- **Two stationary Stress Periods** were imposed: the first one with no abstraction, the second one with abstraction active.

- The model was run using the **PCG Solver**, with the following settings. Outer iterations: 100; Inner iterations: 25; Hclose = 0.001 (first convergence criterium); Rclose = 0.001.

- The elapsed run time was about 20 mins.

Malta MSLA : numerical model

Model Calibration: observations

- The head target are the same points used to build the potentiometric map (52 points)

Malta MSLA : numerical model

Model Calibration: methods

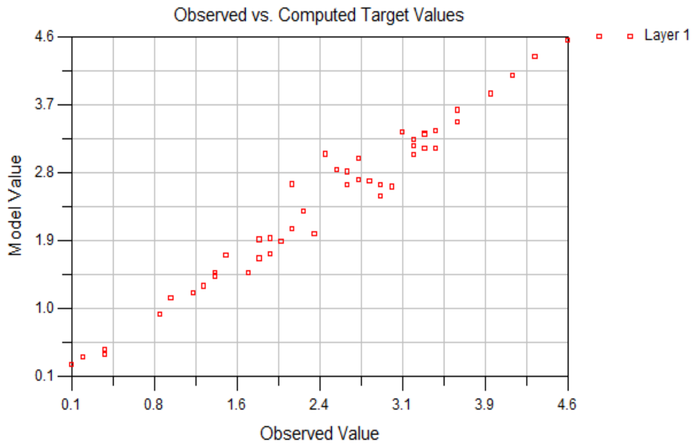
2 Methods were applied:

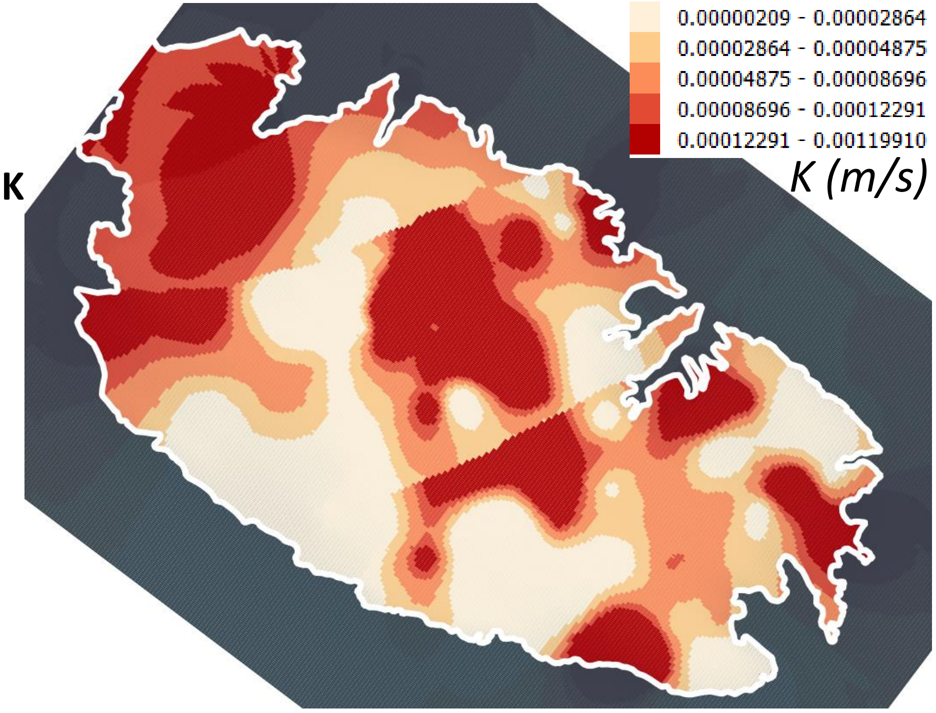
- PEST with Pilot Points, Zones and Regularization (outside FREEWAT)
- UCODE with Zones

Here the results using PEST are showed (UCODE application is presented in Gozo model part).

This activity aimed at get the model sensitivity

to *faults,* and **estimate the best distribution of K**

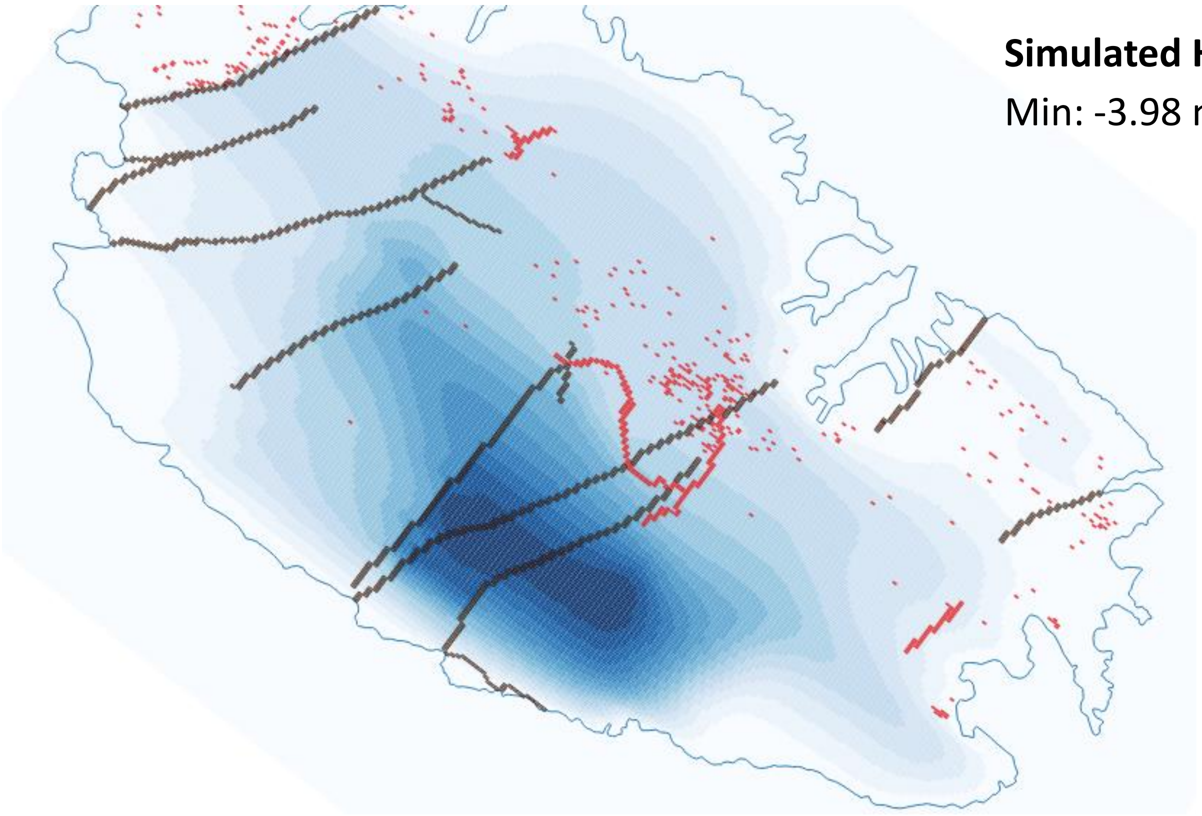




Malta MSLA : numerical model

Running the calibrated model and applying SWI2

The PEST-calibrated model has been newly uploaded in FREEWAT, and the model was run there.

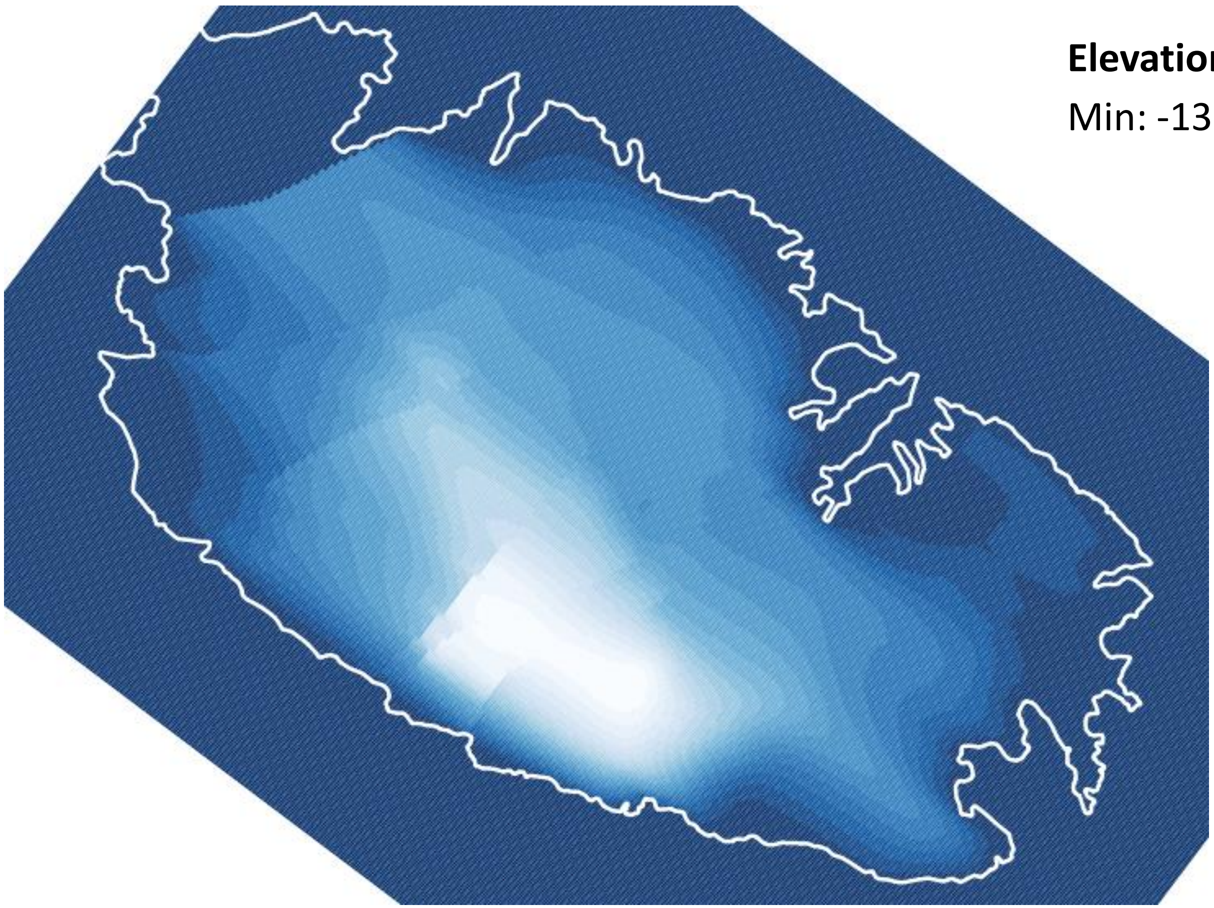


Simulated Heads in FREEWAT

Min: -3.98 m; Max 7.16 m

Malta MSLA : numerical model

Running the calibrated model and applying SWI2



Elevation of seawater interface

Min: -133.21 m; Max 0.0 m

The way forward …

- **Development of transient models** (and their **calibration**, when data are available)
- New **training sessions** for EWA's Officers
- **Scenarios for WRM srategies, and related simulations**
- **Dissemination**

Thanks a lot for your attention!

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