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Deliverable 3.3a: Report on cost efficiency and cost-benefits of selected preventive scenarios

WP	3	Socio-economic assessments		
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[1] Dissemination level: **PU** = Public, **PP** = Restricted to other programme participants (including the JU), **RE** = Restricted to a group specified by the consortium, **CO** = Confidential, only for members of the consortium
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Summary

This report presents the main activities of the WP3 team on the project Sustain-COAST in the topic cost efficiency and cost-benefits of selected preventive scenarios. Efforts were spent to identify the cost-benefit use of water resources and to mitigate groundwater depletion and degradation in each case study of the four Sustain-COAST demonstration sites. The choice of the appropriate mitigation technique in each case study mainly depends on the site conditions. This task is presented as a pilot for each demonstration site and will be updated in part b (D3.3b), considering local data and the final suggestions by all stakeholders in each case study.

To this end, the full cost-benefit methodology is presented, and the optimal options for managed use of groundwater and surface water is presented for each case study. The mapping of those options is a dynamical process and will be adjusted over the course of the project, where key stakeholders can be added at a different stage to enrich the multi-stakeholder partnership process. The provided information will give insights into assessing the sustainability of the current and future groundwater management strategies. This analysis will identify the impact of the adequate mitigation option considering sustainable water resources availability, management, and pollution risks.

1. Introduction

Decision-making is an effective tool in water resources management applications. This work addresses the global management decision dilemma for the sustainability of the groundwater resources of a watershed: should stakeholders use groundwater for irrigation and human consumption, or should they apply alternatives schemes to protect groundwater resources. The former constitutes an easy but non-sustainable solution, while the latter protects the groundwater body from over-pumping, avoids the associated over-pumping penalties, and utilizes both surface and groundwater watershed resources. The main question arising in the second case relates to the amount of surface water that can be used taking into consideration water scarcity and potentially dry hydrological years. Therefore, this proposed decision-making tool will provide the best management solution for the water needs of the study areas based on the balanced use of surface and groundwater resources, considering the ecosystem sustainability and the surface and groundwater sustainability. In addition, this work can help decision-makers to examine and compare various scenarios using different approaches before making a decision regarding the cost and capacity of a hydrologic/hydraulic project and the varied economic charges that water table limit violations can cause inside an audit interval.

2. Cost-benefit analysis

Groundwater sustainability relies on the optimal management of water resources. In order to address the water resources management decision dilemma, the required volume of water must be identified first and the available sources second. As mentioned above, the use of groundwater is the easy option, but the combined use of surface and ground water ensures the sustainability of groundwater resources.

A decision-making tool for sustainable water resources management is developed in this work. The tool addresses the optimal collection of the required water volume by taking into consideration the needs for irrigation (including industrial use) and human consumption, the availability of surface water in the watershed, the statistical characteristics of surface water availability with time as well as the state and availability of groundwater. The action with the lowest economic and environmental cost is the optimal decision. In addition, aquifer recharge is examined as a safety measure in order to protect groundwater from overexploitation. In the case where the use of groundwater pumping is more economical but results in a substantial drop-down of groundwater levels, an alternative approach based on using both the collection of surface water and reduced groundwater pumping will be examined to ensure sustainability. A combination of two approaches is proposed in order to ensure the sustainability of groundwater. The first is based on risk analysis in terms of financial and environmental criteria, and the second on a hydrological risk analysis. In the first approach, Bayesian decision analysis that will consider the prior behavior of the aquifer in terms of safe groundwater levels and the prior behavior of surface water will be applied for the decision-making process. In the second approach, statistical hydrology tools will be applied to evaluate the groundwater volume that must be pumped in the case where the water needs cannot be covered from the surface water availability.

Recently a published work (Varouchakis et al., 2016) related these two topics for the sustainable groundwater management of a watershed. Considering the space-time aquifer behavior and the historical dry years of a watershed in Crete, Greece, they developed a global decision-making tool under the principles of Bayesian risk analysis that aids the decision-making in groundwater management problems and ensures groundwater sustainability. The tool considered the construction of a reservoir and a set of penalty fines for over-pumping violations.

However, this study extends this previous works expanding the parameters that affect the decision making under uncertainty considering the groundwater cost, the lost value of groundwater as a source and overall, the hydrological variables that would affect water resources management. In addition, it considers the combined use of surface and groundwater to cover the water needs in terms of sustainability. The proposed work falls in the goals of UNEP, FAO and other international organizations because it belongs to groundwater sustainability topic that is one of their priorities.

3. Nature, scope, and objectives

Groundwater has an invaluable cost for the hydrological cycle and the ecosystem viability. The sustainability of groundwater is based on optimal management. To protect groundwater resources from overuse, local authorities around the world and especially in the US, have developed exploitation schemes that, when they are violated, then penalties are applied to the end-users. In most of the cases, the penalties vary depending on the level and the frequency of over-exploitation. Therefore, a decision-making dilemma for the stakeholders would be the infrastructure development at a watershed instead of over-pumping penalties also providing the sustainable use of groundwater.

In the decision-making tool, the historical hydrological characteristics of the watershed should be considered, such as drought years, the statistical behavior of rainfall, runoff, and evapotranspiration. The target is the decision-making tool to provide the optimal decision regarding aquifer recharge development and balanced use of surface and groundwater to cover the water needs.

The expected results should indicate that the hydrological probability uncertainty is the driving issue that determines the optimal decision. Depending on how the unknown probability is handled, the methodology may lead to a different optimal decision. Thus, in contrast to practices that assess the effect of each proposed action separately, considering only current knowledge of the examined issue, this tool aids decision-making by considering prior information and the sampling distribution of future successful audits.

Most of the recent decision-making research on groundwater sustainability regards multi-criterion decision-making approaches or multi-objective optimization to integrate different objectives into the planning, management, and decision-making processes. A variety of criteria in terms of economic, social, and environmental dimensions are applied for the analysis. As a result, different management scenarios are proposed that include reductions in irrigated areas, optimization of pumping, improved irrigation efficiencies, increased system loss for groundwater irrigation, and changes in cropping patterns e.g., (Geng and Wardlaw, 2013; Kumar et al., 2014; Pathak and Hiratsuka, 2011; Rothman and Mays, 2014; Yeh, 2015). However, the difference of these works compared to the proposed is that they suggest a solution based on the status of the groundwater and the needs that have to cover by optimizing its use without considering the prior and posterior hydrological behavior of the watershed in terms of surface and groundwater.
Furthermore, hydrological probability risk assessment has been applied to determine under uncertainty an optimal management decision so in subsurface flow and transport e.g. (Tartakovsky, 2007)as in surface waters and especially to flood events e.g. (Efstratiadis et al., 2015; Salas and Obeysekera, 2013; Tartakovsky, 2013). However, this approach considers only the prior information to estimate statistical characteristics and the uncertainty of the variable of interest using parametric or non-parametric methods e.g, probability runoff and rainfall to cover the water needs, but without considering the future uncertainty.
On the other hand, this work provides a decision-making tool under uncertainty (using probability density functions) that provides a framework on how groundwater should be managed in each watershed based on the hydrological characteristics and the water needs. Therefore, a decision can be made on groundwater volume that is required in excess of the available surface water considering its sustainable use. In advance, it includes the designing of an aquifer recharge to exploit surface water according to the hydrological potential of the watershed in contrast to the excess use of groundwater that has an economic impact (over-pumping penalties, pumping costs, lost value of groundwater) and environmental impact.

Therefore, herein Bayesian decision theory in association with the statistical hydrology risk assessment can provide the optimal decision for groundwater resources management.
An initial application of Bayesian decision theory in hydrology was for the assessment of the costs of overdesign of a flood level in the face of flood frequency uncertainty (Davis et al., 1972). Since then, it has been used in many applications. For example, it has been used to determine optimal groundwater sampling frequencies (Grosser and Goodman, 1985) and in decision analyses to engineering design projects, groundwater flow and transport, and monitoring networks in which the hydrogeological environment plays an important role (Freeze et al., 1990). It has been used to address the problem of permitting waste sites under conditions of imperfect information (Marin et al., 1989; Medina et al., 1989) and for the engineering design of a groundwater interception well used to capture a contaminant plume (Wijedasa and Kemblowski, 1993). Moreover, it has been used to select the best experimental design for groundwater modeling and management design under parameter uncertainty (McPhee and Yeh, 2006) and investigate the value of collecting hydraulic conductivity data for optimal groundwater resources management (Feyen and Gorelick, 2005).
In most of the early decision analysis studies, it was assumed that decisions would be made by a rational, financially driven decision-maker, who might be risk-averse, but who would otherwise make decisions that maximized his or her economic position. However, decisions are strongly influenced by the profile of the decision-maker. Thus, water resources management experts need to be aware of the complexity of the decision process, the close relationship that exists between the technical input and the risk term in decision analysis, and the widely differing views toward the methodology and value of risk calculations (Freeze, 2015).
This work will consider the water volume necessary to cover the watershed needs in terms of groundwater but without exceeding a sustainable aquifer level threshold. Such an integrated decision-making approach has not been met in hydrological applications and consists of a useful tool for the sustainable management of groundwater resources.

4. Methods and procedures

Groundwater sustainability depends on the availability of surface waters that due to ecosystem viability only a part of them can be used. So initially, a hydrological design should be performed considering the historical data of the watershed in order to determine the hydrological balance. The users of the proposed tool should determine the water needs of their area and then the historical hydrological characteristics. In addition, from the hydrogeological characteristics, a groundwater level threshold can be set in order to establish a sustainable aquifer level budget.
The proposed controlled water resources management positively affects the sustainability of groundwater. Water needs W are supposed to be covered by surface water S and groundwater G.

$$W = S + G \tag{1}$$

The surface water inflows are denoted with *I* and *IR* is the required irrigated volume. If *W* is not covered from *IR* then *Δw* is covered by groundwater that should not drop the aquifer further from the set threshold.

$$\Delta w = I - IR \tag{2}$$

The decision-making problem introduces the possible actions set and the parametric space by establishing the expected loss function for each decision. Herein, two actions are considered: (i) Action A(0): Use only groundwater, and (ii) Action A(1): alternative option plus mitigation measure.

The decision-making process involves two stages: state estimation (equations that express the proposed actions and decision-making. For state estimation, firstly, all the state parameters are defined. However, in the Bayesian approach, a state parameter is an unknown quantity and is considered a random variable that must be determined. The procedure of estimating each parameter involves previous knowledge on the examined issue and the use of the subjective prior distribution that expresses the prior information for each state parameter. Next, the Bayesian risk function is obtained to estimate the optimal decision or the decision with the minimum expected risk. The latter also applies in terms of a cost-benefit analysis procedure and denotes the preferable action. Thus, the Bayesian decision-making process follows these four steps:

1. *Set up the decision-making problem by introducing the possible actions set and the parametric space. Establish the expected loss function for each decision.*

In this proposal, two actions are considered:

Action A(0): Use only groundwater

Action A(1): Surface water – Aquifer recharge

The use of groundwater only as a major source can easily lead to overexploitation. Over-pumping violation policy is proposed to be based on a scaled linear function with a scaling coefficient (*K*) that varies with the frequency (*n*) of violations because of the importance of the problem. *Y* is a random variable that expresses the total number of over-pumping violations during an auditing period. More specifically *Y* variable indicates when the water table of an aquifer is below a threshold that is considered to be the limit that distinguishing whether we have a violation or not.
A variable *X*, also known as Bernoulli variable, expresses the probability of over-pumping (*X(j)* = 1) as:

$$\begin{cases} X(j=1), \text{ probability } \theta \\ X(j=0), \text{ probability } 1-\theta \end{cases} \tag{3}$$

The variable *Y* then is the sum of probable over-pumping events.

$$Y = \sum_{j=1}^{N} X(j=1) \tag{4}$$

Its expression is given below in terms of Loss functions:

$$L\left(A(0),Y\right)=\begin{cases} K_1Y^2+GC+LGV, & 0\le Y\le n_1 \\ K_2Y^2+GC+LGV, & n_1<Y\le n_2 \quad ; \quad K_1<K_2<K_3 \\ K_3Y^2+GC+LGV, & Y>n_2 \end{cases} \tag{5}$$

where *GC* denotes the groundwater cost (pumping and volume) and *LGV* the lost value of groundwater as a sustainable source as soon as it is removed from the aquifer.

Whereas for the action *A(1)* the following applies,

$$L\left(A(1),\theta_1\right)=C+AC+M\theta_1 \tag{6}$$

where *C* is the mitigation measure cost and *AC* its annual operational cost for the examined auditing period. In case there is a risk (probability) ϑ_1 water needs not to be covered from available water resources of the study area, an additional cost *M* is applied denoting a supplementary water supply (i.e., water transport) that should be considered. The condition, that shows which action is riskier, is the expression *R=R(A(1))- R(A(0)).*

2. *Provide the state of the goal function. If, at this step, the parameters are considered known, then the decision process is called a cost-benefit analysis, and Step 4 is directly applied. If not, then both Steps 3 and 4 apply.*

The goal function is the expected value of the loss function. Thus, for action *A(0)* the goal function is expressed as follows:

$$G\left(A(0),\theta_0\right)=\mathrm{E}\left[L\left(A(0),Y\right)\right]=GC+LCV+\left[K_2\mathrm{E}\left[\mathrm{Y}^2\right]+K_{1,2}\sum_{Y=0}^{n_1}Y^2 f\left(Y\right)+K_{3,2}\sum_{n_2+1}^{N}Y^2 f\left(Y\right)\right] \tag{7}$$

Where $\mathrm{K}_{1,2}=\mathrm{K}_1-\mathrm{K}_2$ and $\mathrm{K}_{3,2}=\mathrm{K}_3-\mathrm{K}_2$

$$G\left(A(1),\theta_1\right)=E\left[C+AC+M\theta_1\right]=C+AC+ME[\theta_1]=C+AC+M\theta_1 \tag{8}$$

If θ and $θ_1$ the state parameters considered known from hydrological information then the cost benefit approach applies by means of Expected Net Loss Present Value (*ENLPV*).

$$\text{ENLPV}=(C+AC+M\theta_1)-L\ (\text{A}(0),\theta_0) \tag{9}$$

Positive ENPLV leads to decision *A(0*), while negative in decision *A(1)*.

3. *Develop the subjective prior distributions for each parameter quantifying the previous information.*

If *Y* and Y_1 the state parameters considered unknown then Bayesian analysis is applied in the terms of the Bayesian Risk function that considers prior information in terms of probability density functions to determine *Y* and Y_1.

$$R(A(0)) = E^{\pi}\left[G\left(A(0),\theta_0\right)\right] = \int_0^1 G\left(A(0),\theta_0\right)\pi\left(\theta\right)d\theta \tag{10}$$

$$R(A(1)) = \text{E}\left[G\left(A(1),\theta_1\right)\right] \tag{11}$$

Where *π(ϑ)*denotes the conjugative prior distribution in each case that depends on the fitted probability density function to the data. The probability that over-pumping or a drought year would occur or the necessary surface water would not be available is denoted as a "success" and as a "failure."

The appropriate conjugative prior distribution that matches with Binomial distribution is the beta distribution (Lerce and Paleologos, 2001), with the form of:

$$\pi(\theta) = Be(t;r;\theta) = \frac{(t-1)!}{(r-1)!(t-r-1)!}\theta^{r-1}(1-\theta)^{t-r-1} \tag{12}$$

with mean value and variance:

$$\mu = \frac{r}{t}\ \ and\ \sigma^2 = \frac{r(t-r)}{t^2(t+1)}. \tag{13}$$

Parameters r and t are extracted from the use of historical data of the aquifer's water level. More specially, we set a threshold *Δh* as the maximum water level drop due to the pumping. If water level will be reduced more than *Δh*, a violation event occurs. So, the *t* parameter denotes the total number of water level historical data, whereas the parameter r denotes the fraction of water level data that exceed *Δh*.

For decision *A(1)* the risk function is:

$$R(A(1)) = \mathrm{E}\left[G\left(A(1),\theta_1\right)\right] = \mathrm{E}\left[C + AC + M\theta_1\right] = C + AC + M\,\mathrm{E}\left[\theta_1\right] = C + AC + M\theta_1 \tag{14}$$

We can see that if the probability is considered as a known variable, the risk function is the same as goal function. For decision *A(0)* the corresponding risk function is

$$R(A(0)) = \int_0^1 G\left(A(0),\theta_0\right) Be(t;r;\theta)\,d\theta \tag{15}$$

By substituting the $G(A(0),\theta_0)$ and $Be(t;r;\theta)$ in the equation above, we gain the expression for R(A(0)).

$$R(A(0)) = \int_0^1 \left\{ GC + LCV + \left[K_2 \mathrm{E}\left[\mathrm{Y}^2\right] + K_{1,2} \sum_{Y=0}^{n_1} Y^2 f\left(Y\right) + K_{3,2} \sum_{n_2+1}^{N} Y^2 f\left(Y\right) \right] \right\} Be(t;r;\theta)\,d\theta \tag{16}$$

The condition, that shows which action is riskier, is the expression

R=R(A(1))- R(A(0)) (17)

If *R* is positive, then decision *A(1)* is riskier than decision *A(0)*, and thus, we need to redesign the mitigation measure. On the other hand, for negative values of *R*, we estimate the volume of groundwater needed to cover the water demands. However, the appropriate volume, *G*, must not exceed the groundwater threshold ($GW_{threshold}$). If Δh is greater than $GW_{threshold}$, then either a water supply-demand rebalance is required or an additional water volume *WT* needs to be supplied occasionally in the area as an extra water source to cover the needs. Then, the decision-making process is re-examined to obtain the least-cost approach (Fig 1).

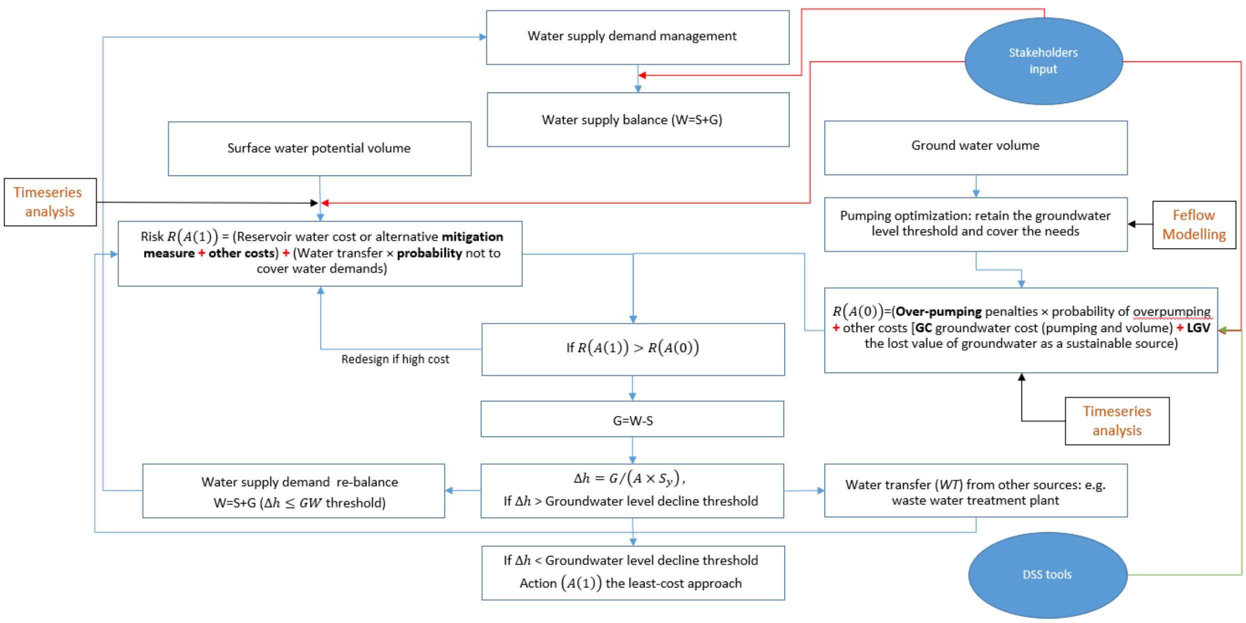

Fig 1. Cost Benefit Analysis/Flowchart.

5. Results and Discussion

Considering the methodological steps previously described for the proposed decision-making process a realistic application was performed for the project study sites considering at least three types of mitigations measures, such as: 1) Reservoir (variable sizes) and construction cost (Fig 2), 2) Application of managed aquifer recharge (variable cost in terms of volume: 2-5.5 M€ for 1.5-12Mm³ recharge), and 3) Optimal water allocation schemes.

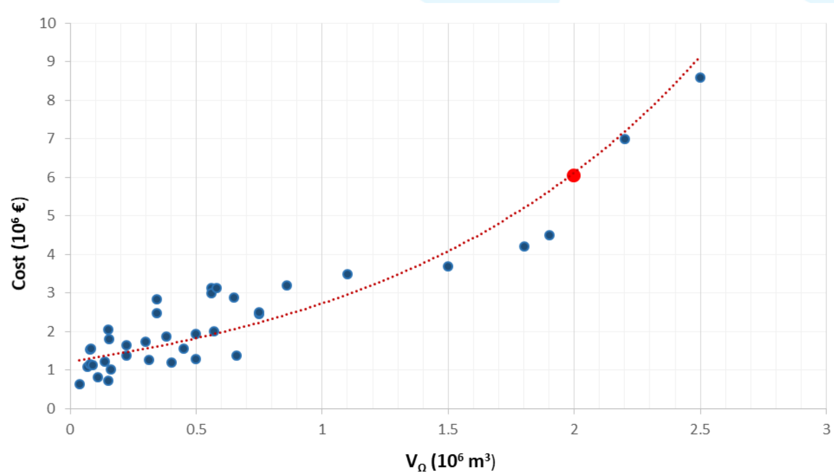

Fig 2. Estimated cost for reservoir construction as a function of reservoir's usable volume.

In this report, the results of the methodology are presented in terms of global datasets output as a measure of comparison to the local data that will be used in the next steps. Specifically, the global database from the GRACE mission will be used for the groundwater data and precipitation info from the PERSIANN CCS database, downscaled for the study areas.

The following figures present the variability of groundwater in terms of water equivalent thickness and the average precipitation of specific months since the year 2000. All these information was considered in the Bayesian cost-benefit approach in terms of probability density functions using standardized options for aquifer level thresholds in each study area from the global groundwater level risk atlas: Aqueduct Water Risk Atlas.

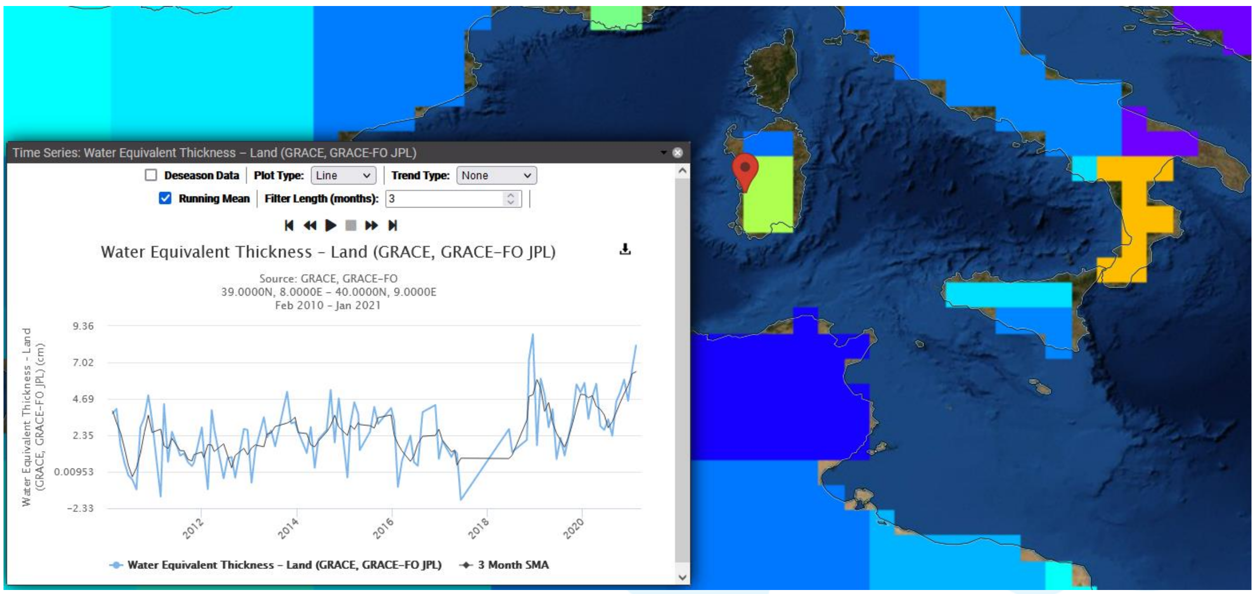

Fig 3. Variability of groundwater in terms of water equivalent thickness for Arborea case study (Italy).

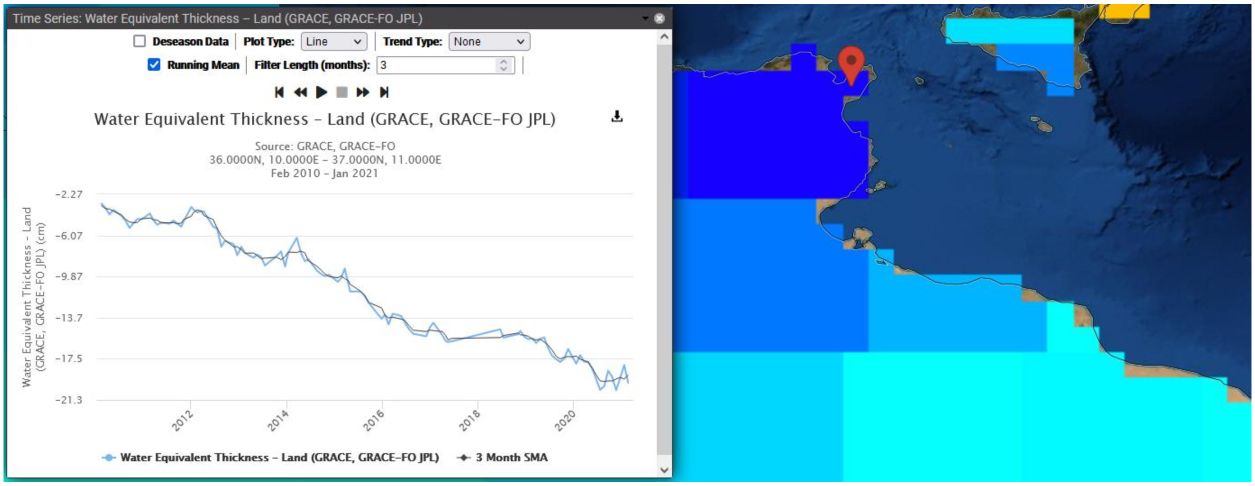

Fig 4. Variability of groundwater in terms of water equivalent thickness Wadi El Bey case study (Tunisia).

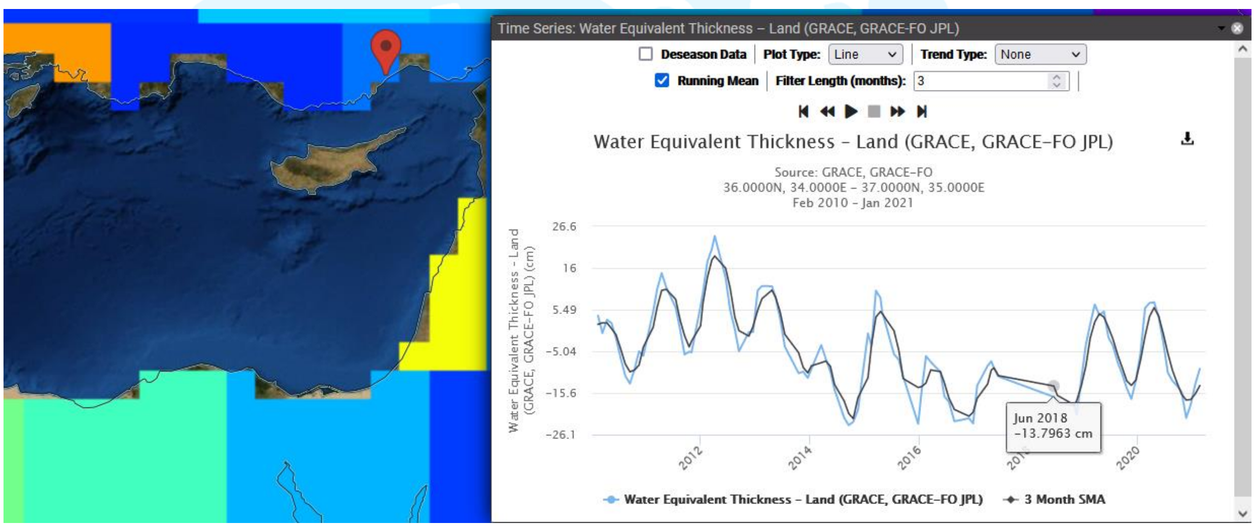

Fig 5. Variability of groundwater in terms of water equivalent thickness Erdemli case study (Turkey).

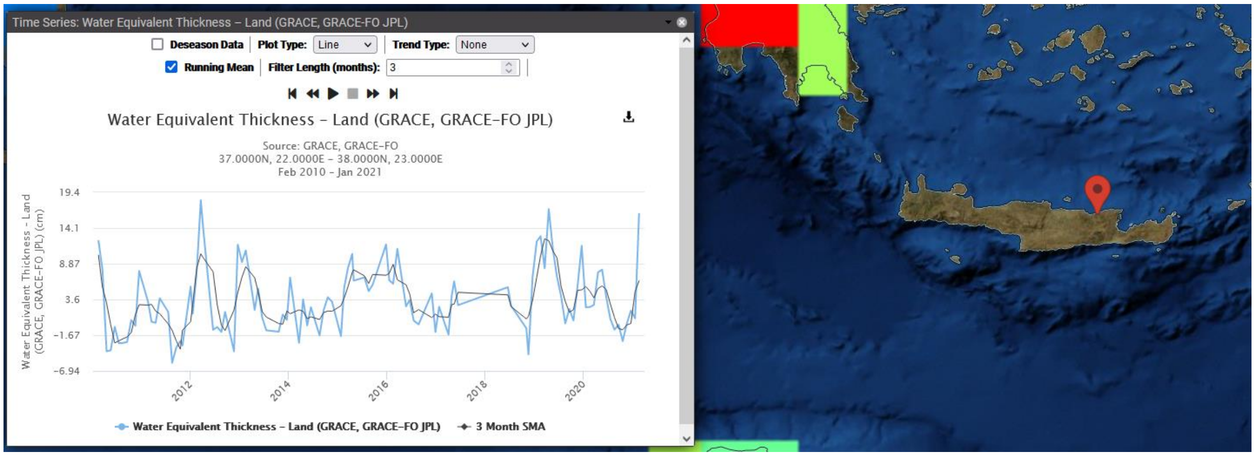

Fig 6. Variability of groundwater in terms of water equivalent thickness Malia case study (Greece).

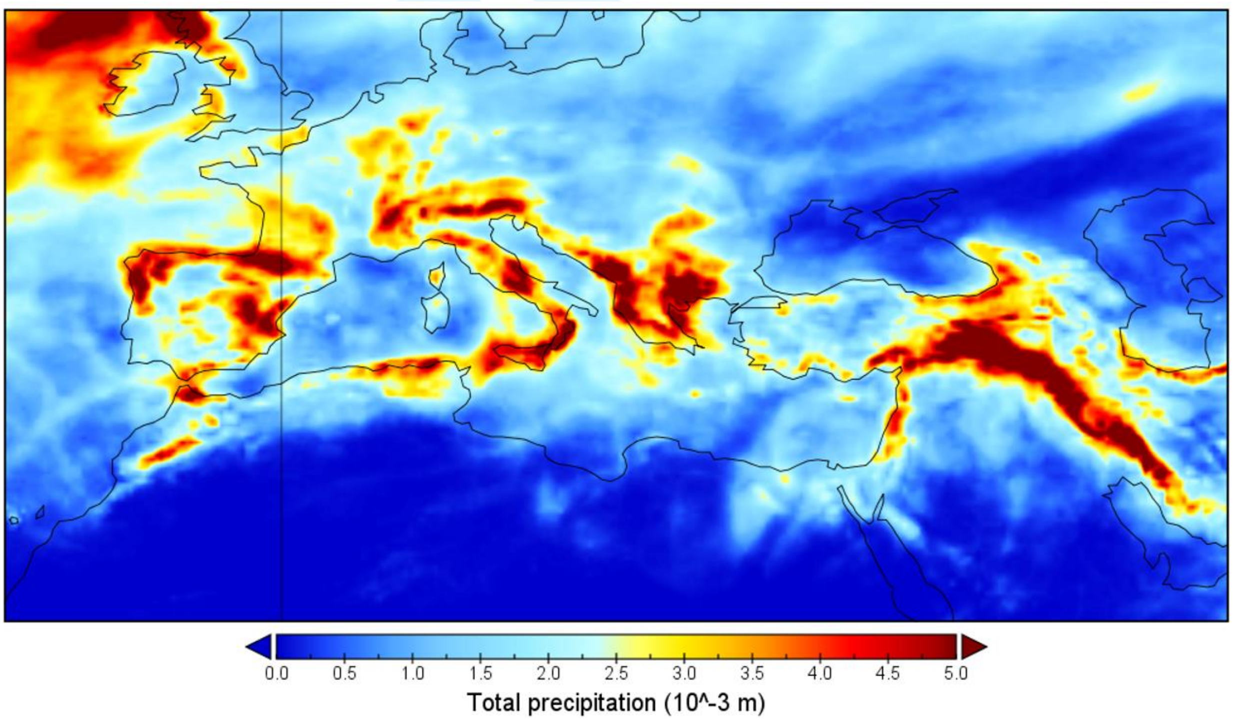

Fig 7. Average monthly precipitation (March).

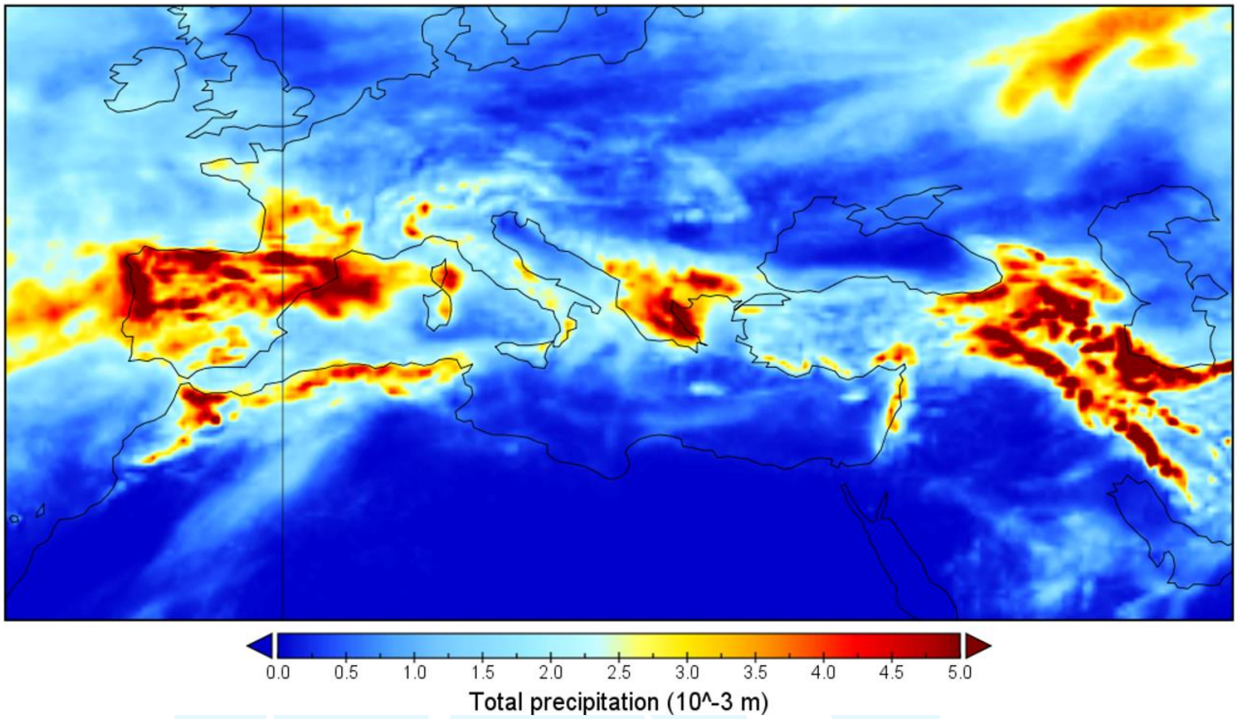

Fig 8. Average monthly precipitation (April).

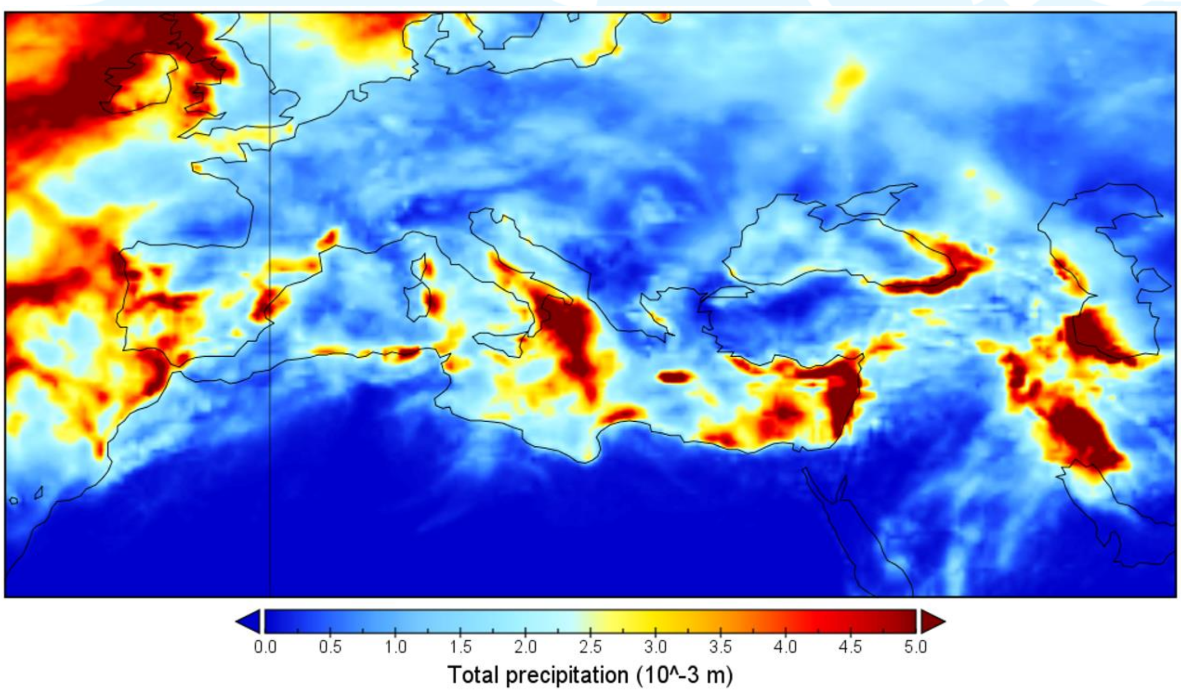

Fig 9. Average monthly precipitation (October).

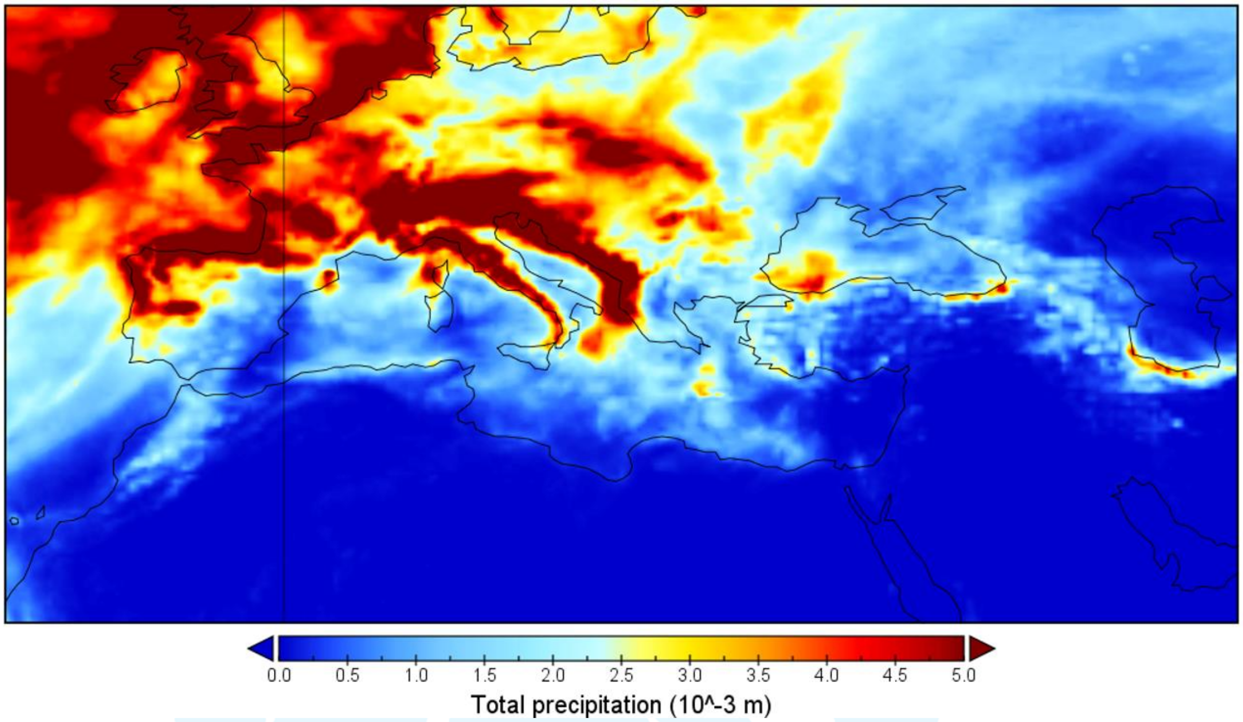

Fig 10. Average monthly precipitation (November).

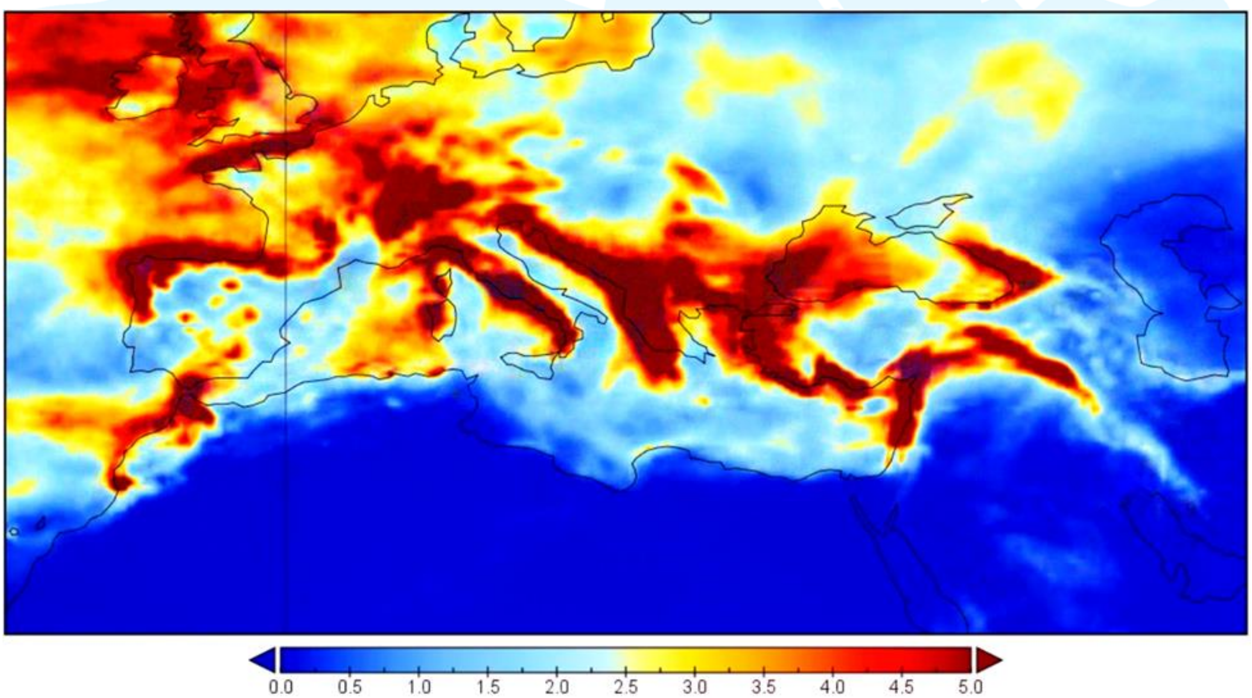

Fig 11. Average monthly precipitation (January).

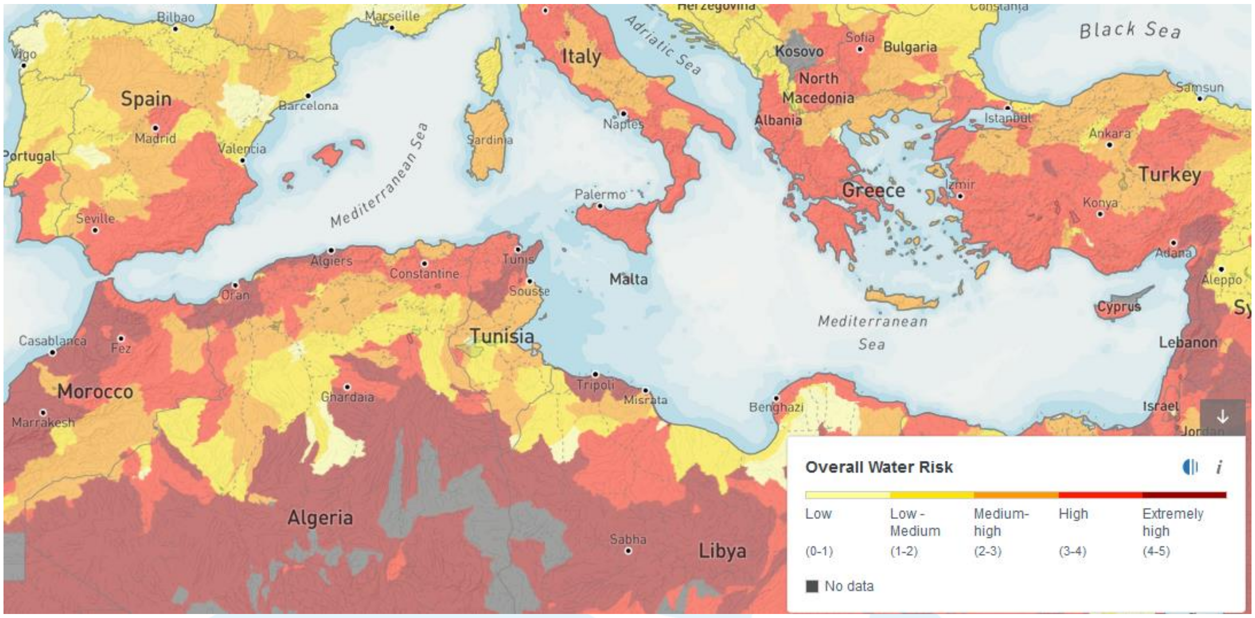

Fig 12. Groundwater risk Atlas (Aqueduct).

The results presented in Table 1 are validated for the Malia area only, as up to now, full available information exist only for the Malia case study.

Table 1. Proposed sustainable water resources use and management in each case study

Case studies	**Wadi El Bey, Tunisia**	**Erdemli Turkey**	**Arborea, Italy**	**Malia, Greece**	
	Bayesian approach	Bayesian approach	Bayesian approach	Bayesian approach	Measured data
Groundwater use	35%	40%	32%	27%	24%
Surface water use	25%	40%	45%	55%	64%
Other sources e.g. waste water treatment plant effluent	40%	20%	23%	18%	12%
Aquifer recharge	70% of groundwater use	85% of groundwater use	75% of groundwater use	85% of groundwater use	-

The area of Malia in Crete, Greece will be used as a pilot to validate the proposed methodology. Typical average water demand for agriculture and tourism in similar areas such as Malia in the Mediterranean region is V_{Demand} = 5 Mm^3 annually. The hydrological characteristics of the basin in terms of the frequency of dry years denote an 80% probability (*Zp*) for the demand to be covered from surface water resources and the nearby reservoir considering a potential allocation scheme. Therefore, an alternative approach to mitigate the area's aquifer is considered, such as aquifer recharge. Thus, the development cost *C* of the scheme is considered based on typical costs of similar works, while the annual operational *AC* was typically calculated equal to 1% of the development cost (Stephenson 2012). The probability ϑ_1, water demands not to be covered is close to 20% calculated from the number of dry years in the area during the last 40 years, while the cost *M* of transferring water from another source to support the mitigation scheme requirements e.g. local waste water treatment plant effluent for irrigation use, is also considered. The treated wastewater is distributed free of charge, but the transferring cost needs to be covered.

On the other hand, in the area more than 300 wells are in operation. According to available information, when overpumping of the aquifer occurs in the area more than 70% of the wells violate the agreed rules. This work proposes a scaled variation of the pumping cost and of environmental cost due to the lost value of groundwater. The probability ϑ_0 of overpumping follows the binomial distribution (monthly monitoring of overpumping, i.e. success or failure) with a Beta prior distribution as conjugate according to the literature also identified from the optimal fit of groundwater level variations of the last 30 years in the area. In addition, the groundwater cost *GC* for the area of the case study is considered, while the lost value of groundwater as a sustainable source *LGV* can be calculated considering its potential value as of fresh potable water.

Considering the available information and applying the proposed methodology it is obtained that for up to 18 overpumping violations using scaled cost effects, action *A(0)* is more affordable compared to action *A(1)* which involves aquifer recharge of 1.5 Mm³ (**30%**) plus 1.7 Mm³ (**34%**) from the reservoir to cover the needs, 1.2 Mm³ (**24%**) groundwater and 0.6 Mm³ (**12%**) waste water treatment plant effluent for irrigation. For more violations, the financial and environmental costs of the mitigation measure: aquifer recharge and surface water use are lower compared to groundwater use only. According to the decision-making flowchart (Fig. 1) an assessment follows for the impact of the groundwater level decline in the aquifer considering the withdrawal amount to cover the demand. The study area *A* and the storativity coefficient *s* are considered. Therefore, the expected aquifer level decline was calculated, $\Delta h = G/\left(A \times S_y\right)$, equal to 0.25 m/yr, less than 2.5 m/yr that may affect the set aquifer level threshold, which is 10 meters above sea level according to the coastal area average. Therefore, considering the sustainable water resources policy that the local authorities desire to follow and the history of aquifer overpumping in the area, the investment in an integrated aquifer recharge scheme with balanced use of the available water resources of the basin is suggested.

As shown in Table 1, the results considering data from global datasets and from local measurements applying the same methodology are similar, providing a reliable source of data to substitute missing information and assess future scenarios. Therefore, a similar and more detailed approach incorporating more details will be applied in the next steps of the project according to the methodology flowchart considering the other case studies as well.

6. Conclusions

The output of this research work is a global decision-making framework for sustainable and economic viable groundwater management. The methodology considers the demands by only pumping water from the aquifer with the risk to overexploit the resources or covering the water demands by a balance use between surface and groundwater resources involving aquifer recharge. A detailed water resources management plan is presented using information from global datasets for each case study. Each decision is expressed by an expected loss function that is described in monetary terms. The expected losses and consequently the anticipated risks of any decision can be estimated, providing the user with the potential to assess different scenarios depending on the application. The proposed framework combines historical hydrological data with statistical approaches to quantify any useful available information to offer a holistic methodology for water resources management. Therefore, decision-makers can apply or modify the proposed framework appropriately to perform a cost-benefit and risk analysis of the potential considered actions depending on the case study. Terms such as the lost value of groundwater and the pumping cost were appropriately considered. The proposed framework was validated for the Malia case study to provide a guide for the application with local data in all four case studies of the project.

References

Davis, D.R., Kisiel, C.C., Duckstein, L., 1972. Bayesian decision theory applied to design in hydrology. Water Resour. Res. 8(1), 33-41.

Efstratiadis, A., Nalbantis, I., Koutsoyiannis, D., 2015. Hydrological modelling of temporally-varying catchments: facets of change and the value of information. Hydrolog. Sci. J. 60(7-8), 1438-1461. DOI:10.1080/02626667.2014.982123

Feyen, L., Gorelick, S.M., 2005. Framework to evaluate the worth of hydraulic conductivity data for optimal groundwater resources management in ecologically sensitive areas. Water Resour. Res. 41, W03019.

Freeze, A., 2015. Hydrogeological Decision Analysis Revisited. 2015 NGWA Groundwater Summit, San Antonio, TX, United States.

Freeze, R.A., Massmann, J., Smith, L., Sperling, T., James, B., 1990. Hydrogeological decision analysis: 1. A framework. Groundwater 28(5), 738-766.

Geng, G., Wardlaw, R., 2013. Application of Multi-Criterion Decision Making Analysis to Integrated Water Resources Management. Water Resour. Manag. 27(8), 3191-3207. DOI:10.1007/s11269-013-0343-y

Grosser, P.W., Goodman, A.S., 1985. Determination of groundwater sampling frequencies through Bayesian decision theory. Civil Eng. Syst. 2(4), 186-194.

Kumar, T., Gautam, A.K., Kumar, T., 2014. Appraising the accuracy of GIS-based Multi-criteria decision making technique for delineation of Groundwater potential zones. Water Resour. Manag. 28(13), 4449-4466. DOI:10.1007/s11269-014-0663-6

Marin, C.M., Medina, M.A., Butcher, J.B., 1989. Monte Carlo analysis and Bayesian decision theory for assessing the effects of waste sites on groundwater, I: Theory. J Contam. Hydrol. 5(1), 1-13.

McPhee, J., Yeh, W.W.G., 2006. Experimental design for groundwater modeling and management. Water Resour. Res. 42, W02408.

Medina, M.A., Butcher, J.B., Marin, C.M., 1989. Monte Carlo analysis and Bayesian decision theory for assessing the effects of waste sites on groundwater, II: Applications. J Contam. Hydrol. 5(1), 15-31.

Pathak, D.R., Hiratsuka, A., 2011. An integrated GIS based fuzzy pattern recognition model to compute groundwater vulnerability index for decision making. Journal of Hydro-environment Research 5(1), 63-77. DOI:http://dx.doi.org/10.1016/j.jher.2009.10.015

Rothman, D.W., Mays, L.W., 2014. Water Resources Sustainability: Development of a Multiobjective Optimization Model. Journal of Water Resources Planning and Management 140(12), 04014039. DOI:doi:10.1061/(ASCE)WR.1943-5452.0000425

Salas, J., Obeysekera, J., 2013. Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events. Journal of Hydrologic Engineering 19(3), 554-568. DOI:10.1061/(ASCE)HE.1943-5584.0000820

Tartakovsky, D.M., 2007. Probabilistic risk analysis in subsurface hydrology. Geophys. Res. Lett. 34(5), n/a-n/a. DOI:10.1029/2007GL029245

Tartakovsky, D.M., 2013. Assessment and management of risk in subsurface hydrology: A review and perspective. Adv. Water Resour. 51, 247-260. DOI:http://dx.doi.org/10.1016/j.advwatres.2012.04.007

Varouchakis, E.A., Palogos, I., Karatzas, G.P., 2016. Application of Bayesian and cost benefit risk analysis in water resources management. J. Hydrol. 534, 390-396. DOI:http://dx.doi.org/10.1016/j.jhydrol.2016.01.007

Wijedasa, H.A., Kemblowski, M.W., 1993. Bayesian decision analysis for plume interception wells. Groundwater 31(6), 948-952.

Yeh, W.W.-G., 2015. Review: Optimization methods for groundwater modeling and management. Hydrogeol. J. 23(6), 1051-1065. DOI:10.1007/s10040-015-1260-3