



Innovative and Sustainable Groundwater Management in the Mediterranean

M 6.1 Initial DSS algorithm at an operational level

VERSION 1.0



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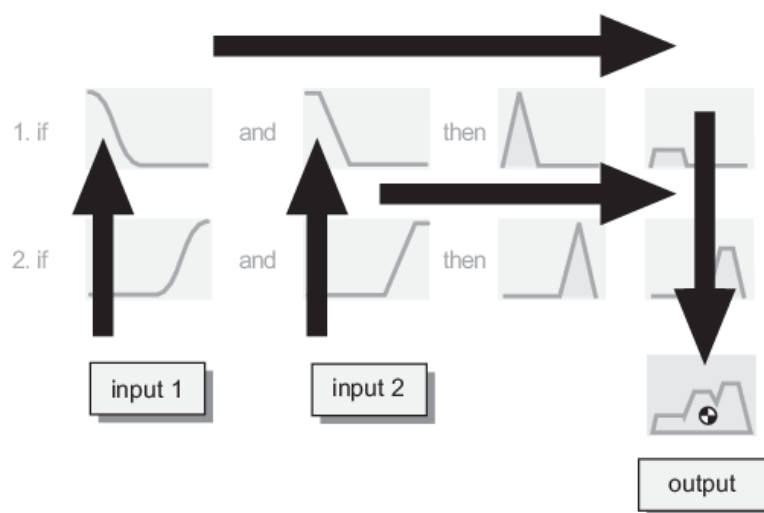
Executive Summary

This milestone, namely M6.1, is part of Task 6.1 “Initial development and testing of an innovative Decision Support System” (Lead TUC, participants: UPV, UFZ, IST-ID, CERTE and BU), (Month 1 – Month 18). The aim of M6.1 is to describe the operation of the algorithm that is developed and will be applied to enable the decision support system (DSS). The DSS will aid groundwater managers in the sustainable management of groundwater resources taking into consideration multiple criteria: socio-economic and environmental. The algorithm is based on the multi-criteria optimization approach, thus meaning the formation of more than one objective functions. These objective functions refer to the respective criteria: optimum socio-economic management, optimum environmental management in terms of groundwater quantity and optimum environmental management in terms of groundwater quality.

Due to the fact that optimization processes are usually applied within iterative simulation runs of the study area model, they consist a time-demanding procedure. Along with the non-linear nature of the problem, the model complexity and time needed are increased. Therefore, main focus has been given on efforts to overcome these difficulties, in order to provide the model with as much automation as possible.

1. The DSS tool

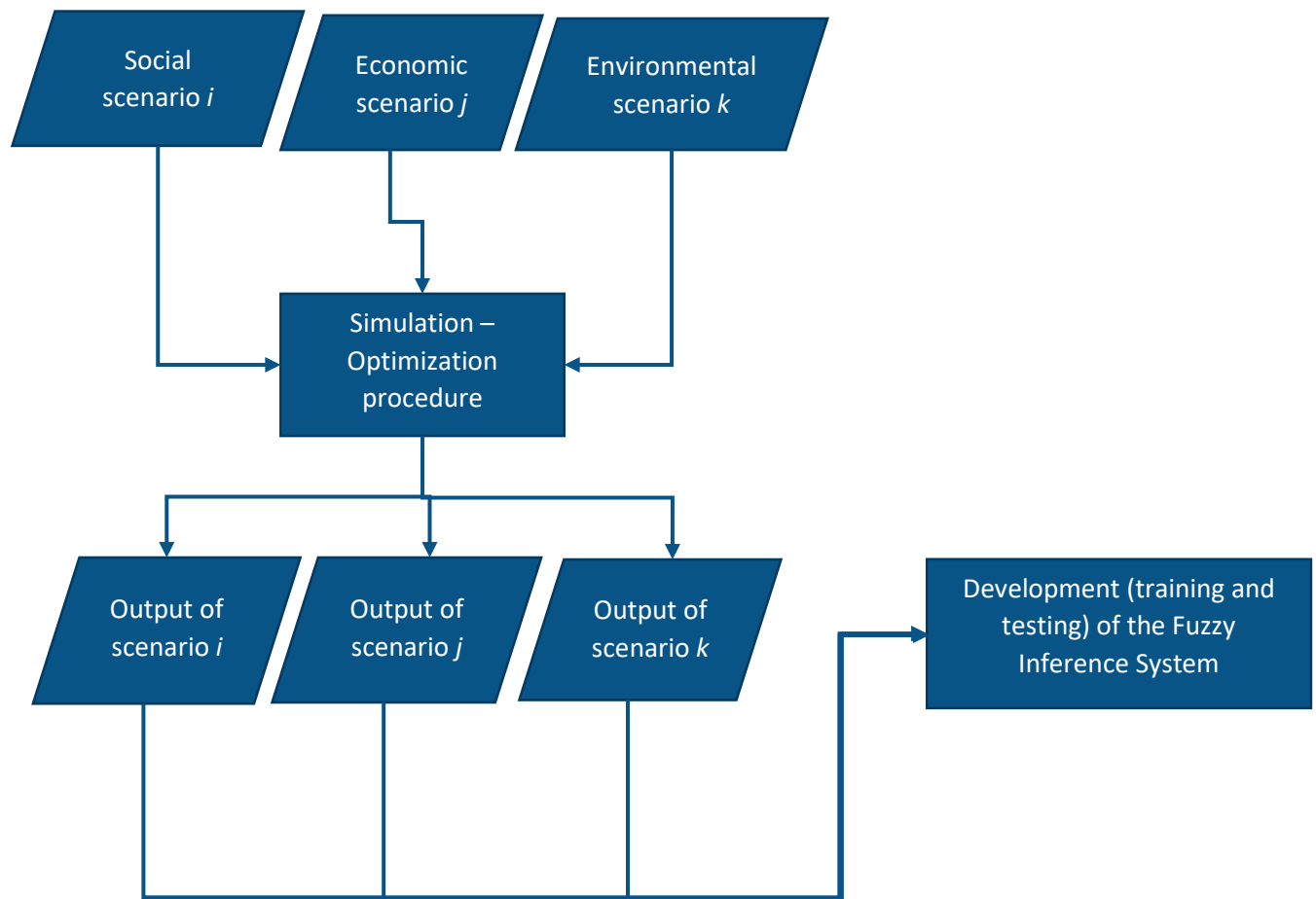
The aim of Work Package 6 is the development of a Decision Support System tool in order to aid decision-making for sustainable groundwater resources management. The decision-making tool will be based on a novel multi-criteria optimization methodology that will operate within a Fuzzy logic web-based Decision Support System. The multi-criteria optimization methodology will serve as the evaluation model for the assessment and recommendation of the optimum alternative solution(s). The fuzzy approach will be deployed in the development, training and testing of a Fuzzy Inference System (FIS). The Fuzzy Inference System (FIS) will be trained according to the data and the results achieved by the social, economic and environmental modelling and for the optimized results. In parallel, it will also be trained and tested under different scenarios, in order to retrieve a wide spectrum of fuzzy rules that will serve to finding the optimum alternative for all the considered criteria.



As the criteria are of different nature, the quantitative values of the optimum results cannot be in the same scale. Therefore, fuzzy sets are used in order to provide a means of normalization and overlay of the criteria. The optimum results for each criterion and scenario are used in order to train a Fuzzy Inference System. Each criterion consists a different fuzzy rule, taking as input the problem variables. Through the FIS, the different fuzzy rules are overlayed and give as output the optimum result. Therefore, different alternatives can be evaluated under different scenarios through the FIS. This way, the FIS will serve as a Decision Support System.

2. The Simulation – Optimization Procedure

The simulation – optimization procedure refers to the separate simulation and optimization of each criterion that is taken into consideration. For each criterion, a different analysis is conducted according to its nature. This way, the optimum value for the examined scenario is obtained for each criterion. The objective functions (criteria) and constraints were selected so as to be applicable in all five case study areas of InTheMED project by addressing to the environmental issues that these areas have in common; overexploitation (except Castro Verde) and groundwater pollution (except Requena – Utiel), along with the socio-economic criteria.



In the following sections, the simulation model and the optimization procedure for the selected criteria are described.

2.1. Socio-economic criteria

A socioeconomic approach was established for the area considering socioeconomic data analysis and Shared Socioeconomic Pathways (SSP) scenarios using a statistical model and the WEAP model to identify the dynamics of social factors (population, economy) and agriculture (production, efficiency) in terms of water availability and use. Basic socioeconomic indicators (population, GDP, agriculture production) in the region are explored and the future trends are determined considering three different climate change RCP scenarios and relative Shared Socioeconomic Pathways (SSP) scenarios (IIASA - International Institute for Applied Systems Analysis) e.g Fig 1. The development of more specific socioeconomic indicators such as agricultural intensity, crops, and land use is also investigated. The indicators' projected development is examined combining climate change RCP scenarios with SSP and the associated projected water availability to provide the expected climate change effect in the socioeconomic context. Another significant indicator that was investigated under green socioeconomic development was the capacity of the reservoir located in the area of study. The task considered the climatic scenarios effect in the reservoir's capacity. The WEAP model and a statistical model, is used to provide the projections on socioeconomic factors and water availability (basin, reservoir) Fig 2 and 3.

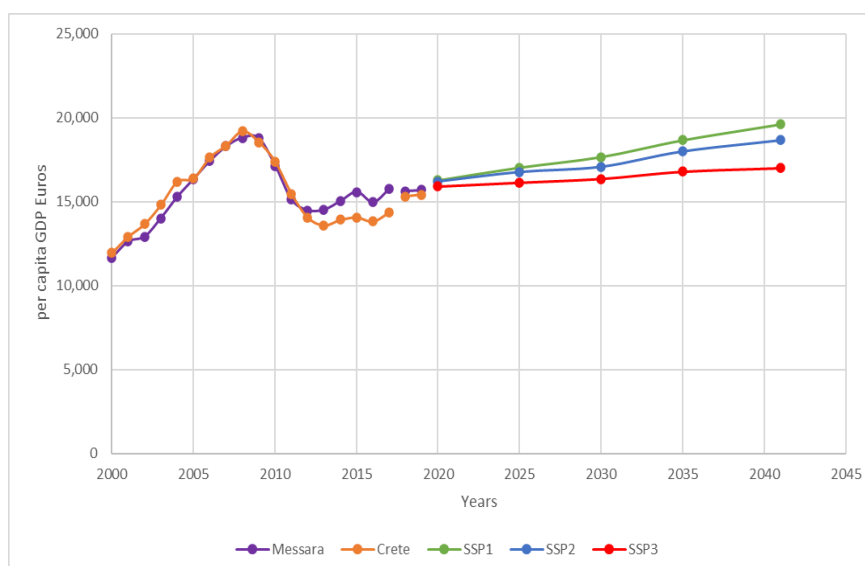


Fig 1 GDP projection under Shared Socioeconomic Pathways (SSP) scenarios

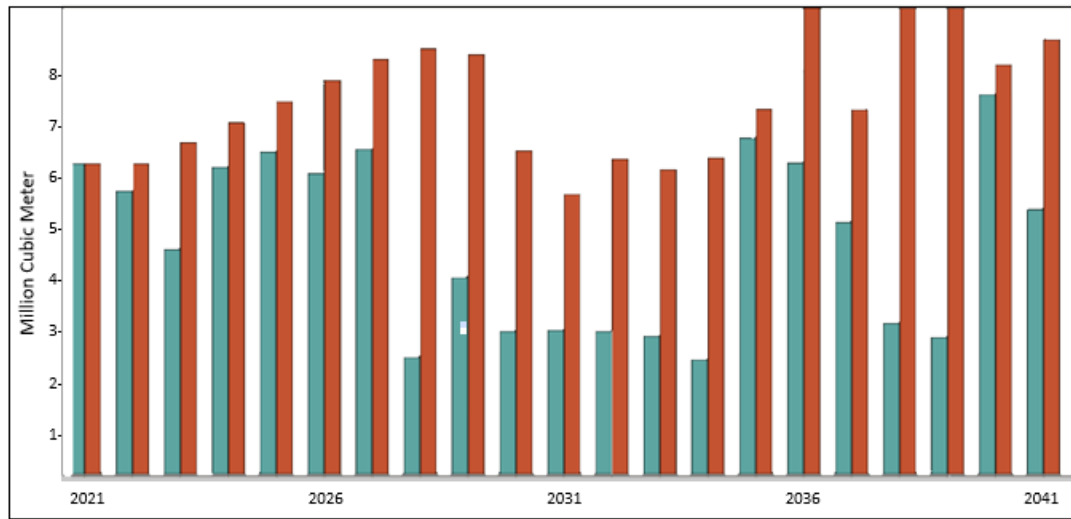


Fig 2 Projected Irrigation demand and water allocation from groundwater (green) and Faneromeni reservoir (red) using climate change scenarios, population variation, agricultural water demand and projected water availability through WEAP model

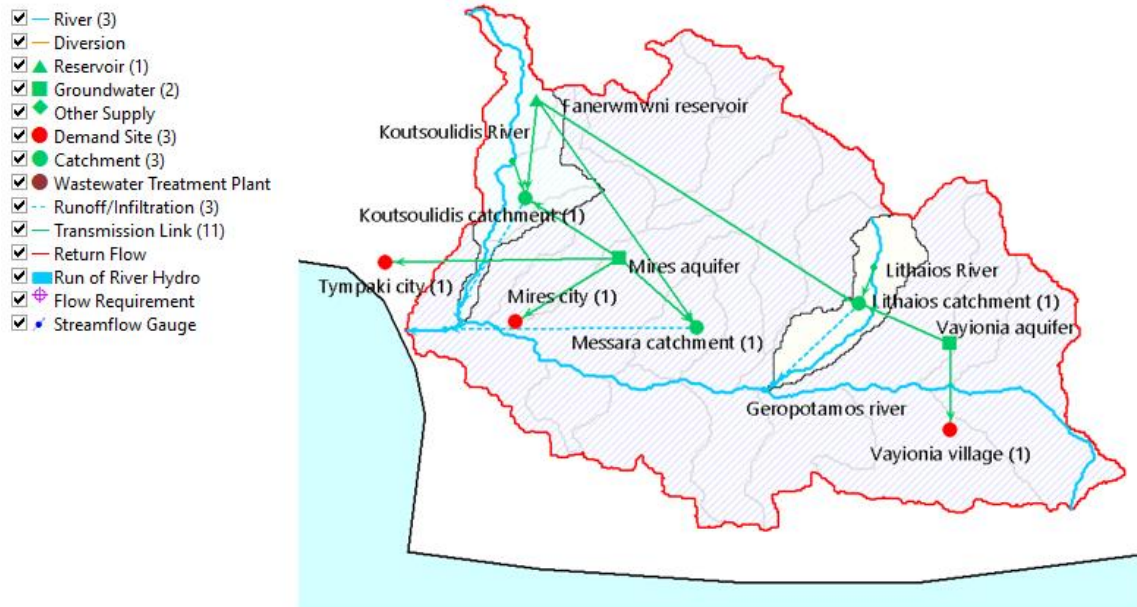


Fig 3 Schematic approach of the main demand sites and water sources, and their interconnections in Messara basin using WEAP model

a. Cost – Benefit Analysis (CBA)

Bayesian decision analysis is usually employed to make decisions in the presence of uncertainty. A common cost-benefit analysis approach coupled with Bayesian decision analysis are applied to aid the decision making of implementing mitigation measures for groundwater resources management. To this end, the full cost-benefit methodology has been established and the optimal options for managed use of groundwater. 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 potential pollution risks.

The decision-making process involves two stages: state estimation and decision making. For state estimation, firstly, all the state parameters θ_i 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 θ_i involves previous knowledge on the examined issue and the use of the subjective prior distribution $\pi(\theta_i)$ 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. The Bayesian decision-making process follows these four steps, while a detailed approach is presented in the flowchart of Fig. 4:

1. Set up the decision-making problem by introducing the possible actions set A and the parametric space θ .
2. Establish the expected loss function for each decision $A(i)$, and provide the state of the goal function. If at this step, the parameters θ_i 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.

3. Develop the subjective prior distributions for each θ_i quantifying the previous information.
4. Combine Steps 1, 2, and 3 via the risk function. The decision with the minimum expected risk is the optimal decision.

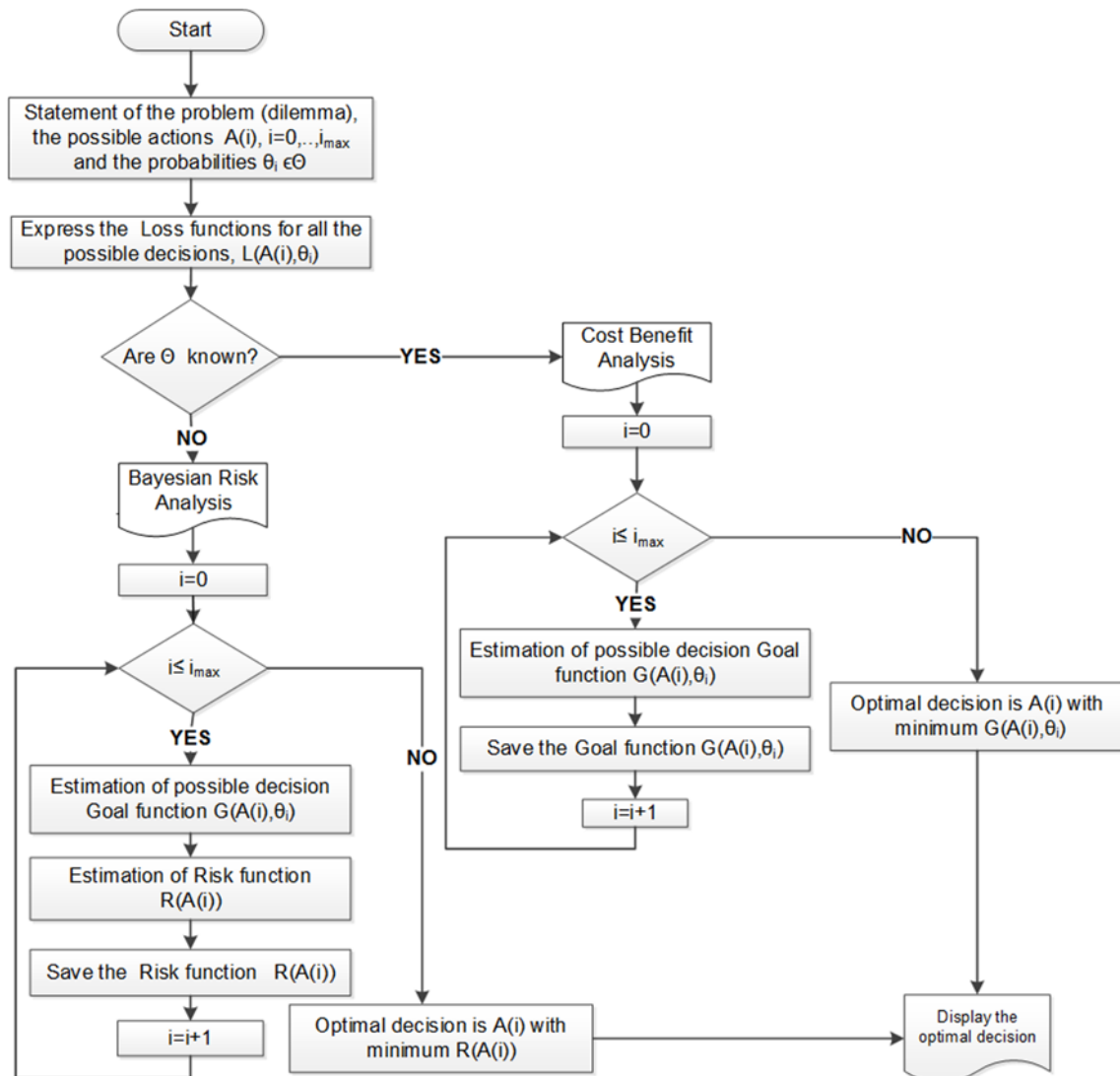


Fig. 4 Flowchart of Bayesian Risk and cost-benefit risk analysis

2.2. Environmental criteria

a. Groundwater quantity

The simulation – optimization procedure consists of 2 components/sub-routines.

1. The construction of a response matrix based on iterative simulation runs of the groundwater model.
2. The optimization of the pumping rates by using the response matrix.

The response matrix is created by sequentially disturbing the initial pumping rates of the m pumping wells, then running the simulation model and obtaining the hydraulic heads in n observation wells. The response matrix A is the $n \times m$ matrix, with its elements consisting of the values of hydraulic head's response to the disturbance of the pumping rate: $\frac{\partial H}{\partial Q}$.

Then, the optimization problem is set as:

$$\max Q$$

$$s. t. : H \geq H_{ref}$$

Where: $H = H_o + \partial H$ and $\partial H = A * \partial Q$

Therefore, the constraint:

$$H_o + \partial H \geq H_{ref} \rightarrow$$

$$H_o + A * \partial Q \geq H_{ref} \rightarrow$$

$$H_o + A * (Q - Q_o) \geq H_{ref} \rightarrow$$

$$A * Q \geq H_{ref} - H_o + A * Q_o$$

The problem is transformed to be in line with the requirements of Matlab optimization tool as:

$$\begin{aligned} & \min(-Q) \\ & s.t.: -A * Q \leq H_o - H_{ref} - A * Q_o \end{aligned}$$

$-A$, the constraint coefficients matrix and

$b = H_o - H_{ref} - A * Q_o$, the vector of constraints of the linear problem.

Although the problem is not linear, it is solved by using the Simplex method in the frame of the piece-wise linear technique. Thus, after the first simulation – optimization cycle, the results for the optimum pumping rates are used in order to run again the simulation procedure, create the response matrix and apply the optimization procedure. The cycle is repeated until the results of two consecutive cycles converge to the same value.

The preliminary results of the previously described simulation – optimization procedure show that a reduction of up to 50.2% (from $6.231 \cdot 10^3 \text{ m}^3$ to $3.103 \cdot 10^3 \text{ m}^3$) should be applied on the pumping rates during the summer period in order to achieve a m raise of the groundwater level and push back the salinization front. In the following figure 5, the tendency of the pumping rates to converge towards similar values along the simulation – optimization runs are shown as for the first 6 realizations of the procedure.

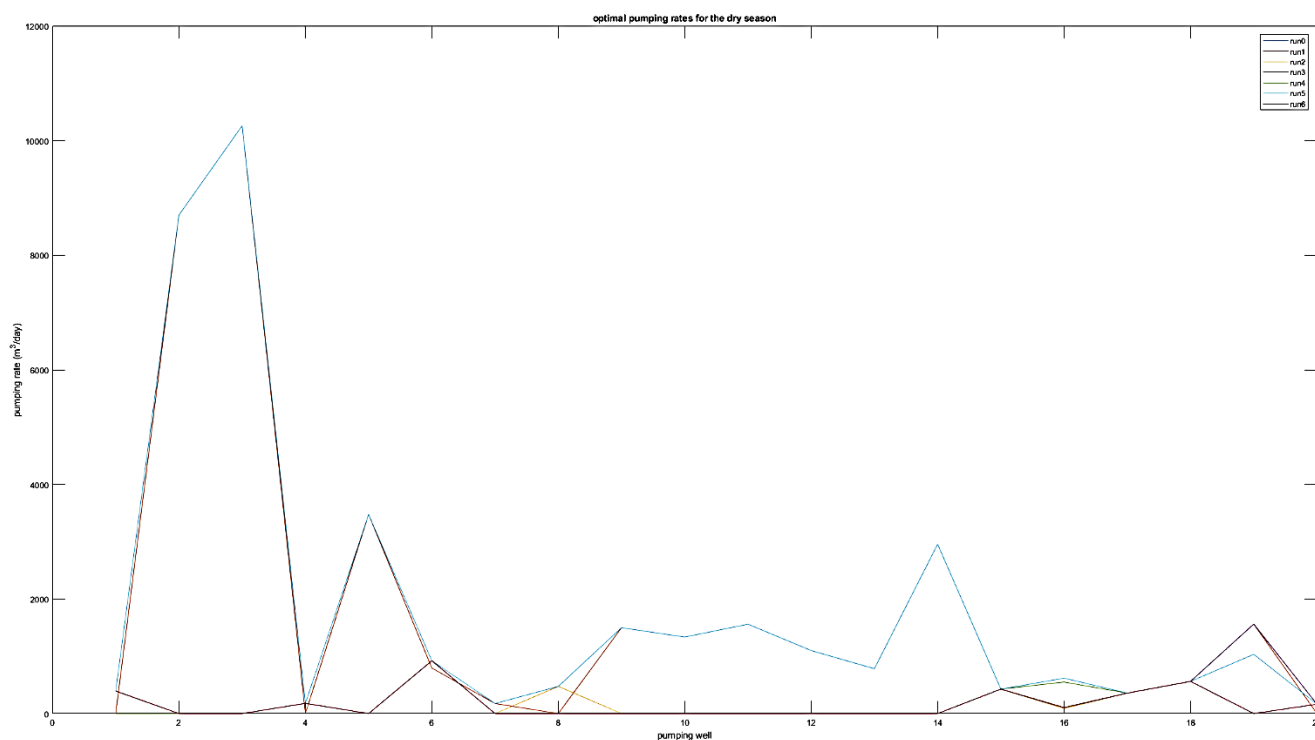


Fig.5. Optimal pumping rates for the dry season for the different model runs

In order to overcome the difficulties of the time-demanding runs of the groundwater simulation model, the response matrices can be constructed by using the results of the hydraulic heads and pumping rate values retrieved from a corresponding surrogate model. The ANN groundwater model that is being developed in WP3 of the project will be taken into consideration for integration into the simulation – optimization procedure. This way, the procedure can be fully automated, with no dependencies on the manual handling of a mainstream computational groundwater model.