Geropotamou basin, Greece—A HarmoniRiB Case Study
November 2006

Harmonised techniques and representative river basin data for assessment and use of uncertainty information in integrated water management
Contract EVK1-CT-2002-00109
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Geropotamou basin, Greece

A HarmoniRiB Case Study

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The Water Resources Department of the Prefecture of Crete (WRDPC) is the main managing authority in charge of the water resources within the Geropotamou Watershed and generally in Crete. Its mission is to serve the public by organizing, overseeing and accrediting management and structural projects related to the water resources quality and quantity. Through these actions, its goal is to provide a safe and sustainable system that will guarantee quality and quantity for benefit of the community.

The infrastructure of the WRDPC includes a number of wells and meteorological stations that help control environmental parameters in some of the major watersheds of Crete.

The WRDPC collaborates closely with the Technical University of Crete (TUC) in common areas of interest. This way TUC’s research and scientific expertise can be used to incorporate state of the art methodologies in the various projects.

During the European Project "HarmoniRiB", the WRDPC assisted TUC by providing all the available data and information that was required for the development of the Geropotamou Case Study. The results of this study will help get a better understanding of the uncertainty issues related with the decision making process and assist in producing a well established management plan for future infrastructure development within the Geropotamou Watershed.

Hopefully this attempt to establish an uncertainty framework can be standardized and expanded so that the same techniques and methodologies can be applied to other watersheds in Crete. In this case, the results can be incorporated in the decision making process for the whole Prefecture of Crete and assist towards the implementation of the European Water Framework Directive.
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Executive summary

The main objective of the Geropotamou Case study is to collect, organise and provide a well documented dataset, suitable for studying the influence of uncertainty on management decisions and to apply it in the development of an integrated water management plan.

In order to process this dataset, which is now publicly available, TUC applied the methodology and tools provided by HarmoniRiB. This way, the uncertainty originating from data and models used in decision making processes was assessed and described in order to be integrated into a decision support concept applicable for implementation of the WFD.

TUC applied the conceptual model for data management produced by HarmoniRiB in order to evaluate its ability to handle uncertain data. The Geropotamou Case Study is focused on the severe groundwater resources availability problems faced in the semi-arid Watershed of Geropotamou stream in Crete, Greece.

Providing a set of deliverables including this Case study report, TUC will assist HarmoniRiB in its attempt to improve the understanding and assessment of uncertainty for the purpose of providing more robust integrated water management plans under the implementation of the WFD.
We would like to acknowledge the Water Resources Department of the Prefecture of Crete (WRDPC) which provided most of the data, as end user, and assisted us with their valuable practical experience. In particular, Mr. Marinos Kritsotakis of the WRDPC, who acted as their representative and assisted us with the quality control of the metadata. He also contributed with his practical experience on several issues related to the application of hydrological models. Moreover, we would like to acknowledge the Hellenic National Weather Service for the valuable information on the instrumentation and data collection procedures. Finally, the technical personnel of the local Land Reclamation Services assisted in the collection of information on field equipment.
Scientific summary

Geropotamou basin in Crete, Greece, faces a severe groundwater resources problem due to the overexploitation of the aquifer, mainly for the irrigation of the 250km² of agricultural land located in the Messara Valley. This situation has led to Messara Valley being threatened by desertification. This environmental issue calls for an immediate application of measures that will aim at both deterring the adverse effects of human activities but also have a positive environmental impact for the faster restoration of the ecosystem. In order to demonstrate the role of uncertainty in the decision making process an uncertainty analysis was undertaken for all measurements and models used in the Geropotamou Case Study. The dataset from the study area was provided to the HarmoniRiB Data Center and the uncertainty was associated to the related historical time series. Following the data collection, a surface/groundwater model (Sacramento) and groundwater model (MODFLOW) were applied to describe the temporal and spatial variability of the water resources in the basin. The models were calibrated with the existing data and a proper uncertainty analysis was undertaken in order to examine the propagation of the uncertainty through the models. A set of alternative measures aiming to remediate the groundwater problem faced in the basin was established. Following that, a socio-economic analysis was conducted in order to evaluate the effectiveness of each measure. The results of the analysis show that a combination of measures can deal with the problem of groundwater over-exploitation. Specific effects on groundwater level by the year 2015 when the WFD is due to be implemented are presented.
Abbreviations

In this report some the following abbreviations are being used:

ASL: Above Sea Level
AAP: Average Areal Precipitation
CSF: Community Support Framework (Κοινοτικού Πλαισίου Στήριξης - ΚΠΣ)
FAO: Food and Agriculture Organization
HNWS: Hellenic National Weather Service (Ελληνική Μετεωρολογική Υπηρεσία – ΕΜΥ)
LOLR: Local Organisation of Land Reclamation (Τοπικός Οργανισμός Εγγείων Βελτιώσεων – ΤΟΕΒ)
TUC: Technical University of Crete (Πολυτεχνείο Κρήτης – ΠΚ)
WFD: Water Framework Directive (Κοινοτική Οδηγία για τη Διαχείριση των Υδάτων)
WRDPC: Water Resources Department of the Prefecture of Crete (Τμήμα Διαχείρισης Υδάτινων Πόρων της Περιφέρειας Κρήτης)
1 Introduction

1.1 The Geropotamou basin - A summary description

1.1.1 Geographical area

The Geropotamou basin covers an area of 600.5 km$^2$ and is located in the central southern part of Crete, about 50 km south of the city of Heraklion (see Figure 1.1). About 250 km$^2$ of the total basin, the Messara Valley is cultivated and the remaining area (highland) is used for livestock. The main land-use activities are olive growing (about 175 km$^2$, see Figure 1.2) and grape vine cultivation (40 km$^2$). The remainder of the cultivated land is used for vegetable, fruit and cereal growing. The Messara Valley has remained rural with a small population of about 40 000 inhabitants. The main source of irrigation and domestic water supply is groundwater (almost 400 water wells).

![Figure 1.1: Location of Geropotamou basin on Island of Crete. The Messara Valley, on which the Greek case study focuses, is shown as a shaded relief - Landsat TM image.](image)

The Messara valley is a typical graben, formation of parallel system of faults with an east-west direction. The Plain is covered mainly by Quarternary alluvial clays, silts, sands and gravels with thickness ranging from a few metres up to 100 m. The inhomogeneity of the plain’s deposits give rise to great variations in the hydrogeologic conditions even over small distances (Vardavas et al., 1997)
1.1.2 Brief description of problems

The Messara Valley located in the Geropotamou basin is threatened with desertification. A dramatic drop of about 20 m in the mean annual groundwater level during the last 30 years due to uncontrolled use reduced the available water and created tension amongst the users. The groundwater level dropdown started with the introduction of pumping of the groundwater store for drip-irrigation of the main crop which is olive trees. Following that, pumping became uncontrolled with farmers making an unknown number of unregistered wells. Illegal use of groundwater water is difficult to be policed.

Presently, it is common practice for most municipalities not to share the water amongst them, even if they belong to the same basin. An allegedly oversized dam has been constructed and is current being filled, aiming to fulfil the irrigation water needs in the basin. Future plans include transporting water from neighbouring basins to fill it up. These methods of management lay far from being characterised as effective but are currently common practice. There are also concerns on water quality, but these are beyond the scope of this study.
1.2 Objectives

Environmental policy makers usually rely on scientific advice for collection, processing and modeling of environmental data. These data are rarely certain and free of biases. Rather, the combined effects of measurement error, sampling, interpolation and re-scaling, among others, can lead to uncertainties about nature’s behavior which is significant for some applications (Zhang and Goodchild, 2002).

Since the inputs of an environmental model are uncertain, predictions are often also uncertain, as uncertainties propagate through a model. Other sources of uncertainty in model predictions include the structure, parameters and solution methods used. Together, these uncertainties can adversely affect policy or management decisions because the accuracy and precision of the model predictions is insufficient or poorly quantified.

In the frame of the HarmoniRiB project, the effects of parameter and modeling uncertainty on the water resources management practices will be analyzed. The Geropotamou Case study aims to apply the proposed methodologies and tools in order to assist in their evaluation and provide useful results and conclusions. This way, a better understanding of the role of uncertainty will be possible.

1.3 Relevance for Water Framework Directive Implementation

The EU WFD is a management directive that defines specific objectives which have to be achieved by river basin management planers, mainly the WRDPC. Although the WFD recognises uncertainty as a relevant factor, it does not contain a comprehensive framework for describing and handling it. In fact, the term ‘uncertainty’ is not used by the WFD; instead, two other expressions in the context of uncertainty can be found: “Adequate level of confidence and precision” and “risk”. The former is used in relation to: (i) the process of establishing the reference conditions for surface water body types; (ii) monitoring the ecological and chemical status of surface waters and (iii) the identification of trends in groundwater pollution. Presumably these three domains should be regarded as representative because the problem of uncertainty also arises in other domains (Myšiak and Sigel, 2004). The present Case Study applies methodologies and tools dealing with uncertainty in practice. The Geropotamou Case Study examines the achievement of environmental good status over the Messara Valley which faces a severe problem of depletion of groundwater resources.
The End User of the Geropotamou Case study (Water Resources Agency of the Regional Authority of Crete) is the most important water managing authority of the area. Even before this study, it has already been known that the hydrological data collected in the greater area suffers from lack of accuracy and precision in all scales. Thus, an in-depth assessment of uncertainty for each variable and the effect this uncertainty yields for the final decisions is of major importance. For this reason it is estimated that the information provided through this project will greatly assist the End User in decision-making.

One of the key activities under the joint implementation for the WFD is the improvement of the information exchange between countries, European institutions, the various stakeholders and the interested public. Aligning itself with this activity, most of the available hydrological data of Messara Valley have been uploaded to the HarmoniRiB server with the agreement of the legal owners.

Finally, the results of the Geropotamou Case Study regarding uncertainty and its effects in water management can be a useful reference to the settlement of similar environmental and socio-economic issues in areas with similar status.

1.4 Reading guide

The Case Study report is divided in seven chapters. Chapter 7.8.1 provides an introduction to the HarmoniRiB project. It also includes a summary description of the geographical area and the problems of the case study area and presents the objectives of the study and the relevance with the WFD. Chapter 7.8.2 presents a detailed description of the Geropotamou basin and Messara Valley including data availability and the associated uncertainty issues. It also provides an overview of the models used in the case study. A physical impact analysis of the possible measures is explained in Chapter 7.8.3. Starting from the conceptualization of the analysis, the effects of uncertainty on data and models are illustrated. This is followed by a prediction of the effect of alternative pumping scenarios on the groundwater level which in turn is included as a criterion in a multi-criteria decision matrix. Chapter 7.8.4 provides the calculation of the cost of implementation of each alternative as well as long term expenses. Chapter 7.8.5 compares results based on the multi-criteria matrix and the Promethee II decision support method. HarmoniRiB products are being evaluated in relation to the present case study in Chapter 7.8.6 and finally, Chapter 7.8.7 presents the conclusions of this report.
2 The Geropotamou basin

2.1 General overview

2.1.1 General

The island of Crete is located in the south eastern Mediterranean region of Europe and has a dry sub-humid climate, according to the definitions of the June 1994 Paris Convention on Desertification (UNCED, 1994). The main climate characteristics are clemency and amiability. It is a region that is designated susceptible to land degradation arising both from climatic variation, rock type formations and land-use activities.

About 40% of the annual precipitation occurs in the winter months while there is negligible rainfall during the summer. Snowfall is restricted to the main mountain ranges. The precipitation ranges from 440 mm/year on the plain of Ierapetra to more than 2000 mm/year on the Askifou upland. The mean annual precipitation in Crete is 927 mm. The mean annual temperature ranges from 17°C to 20°C. The prevailing wind direction is north and north-west. The potential evaporation varies from 1370 mm/year to 1570 mm/year, whereas the mean annual actual evapotranspiration has been estimated to represent 60% - 70% of the mean annual precipitation. Furthermore, the mean annual precipitation is estimated at 7.69 billion m³ and the potential amount of groundwater that can be sustainable extracted at 2.23 billion m³. The actual water use is about 375 million m³, approximately 5% of the mean precipitation.

The major water use in Crete is irrigation (84.5% of the total consumption) while domestic use is 12% and other uses 3.5% (Chartzoulakis, 2001). Crete shows significant regional variations in water availability, especially in coastal, eastern and southern regions due to tourism and agriculture. The Messara Valley within the Geropotamou Watershed constitutes the most important agricultural region of Crete and is threatened by desertification due to falling groundwater levels.

The Geropotamou basin covers an area of 600.5 km² and is located in the central southern part of Crete, about 50 km south of the city of Heraklion (see Figure 2.1). About 250 km² of the total Valley area are cultivated and the remaining area (highland) is used for livestock. The main land-use activities are olive growing (about 175 km²) and grape vine cultivation (40 km²). The remainder of the cultivated land is used for vegetable, fruit and cereal growing. The Messara Valley has remained rural with a small population of about 40 000
inhabitants. The main source of irrigation and domestic water supply is groundwater (almost 400 water wells).

Figure 2.1: Location of Geropotamou basin

The main geomorphologic characteristics of the catchment are:

Total area: 600.5km$^2$
Max hydraulic route: 42km
Max altitude: 2200m
Mean altitude: 399m
The Messara valley is a typical graben, formation of parallel system of faults with an east-west direction. Steep mountains rise on the north and south sides. To the north, the divide varies from 2200 m to 600 m from west to east, with the highest point being part of the Ida mountain range (peak at 2540 m) which is a limestone massif. To the south is the Asterousia mountain chain which rises 600 m in the west to 1200 m in the east and constitutes the southern most mountain range of Europe. At the Phaistos constriction in the west, the catchment outlet of the Geropotamos River is at 30 m above sea level (ASL). The Plain is covered mainly by Quarternary alluvial clays, silts, sands and gravels with thickness from a few metres up to 100 m. The inhomogeneity of the plain’s deposits give rise to great variations in the hydrogeologic conditions even over small distances. The northern slopes are mainly silty marly Neogene formations while the southern slopes are mainly schists and limestone Mesozoic formations (Vardavas et al., 1997).

The Geropotamos hydrological year may be divided into a wet and dry season. About 40% of precipitation occurs in the months of December and January while from June to August there is negligible rainfall. This poses a problem since pumping for irrigation purposes follows the reverse pattern, thus stressing the aquifer. Although the Valley receives on average (long-term) about 700 mm of rainfall per year it is estimated that about 65% is lost to evapotranspiration, 10% as runoff to sea and only 25% goes to recharging the groundwater store.

Rainfall increases with elevation from about 500 mm on the Plain to about 800 mm on the basin slopes while on the Ida massif the annual precipitation is about 2000 mm and on the Asterousian mountains it is 1100 mm. Pan evaporation is estimated at 1500±300 mm per year while the winds are mainly north-westerly. The potential evaporation is estimated at 1300 mm per year and so the ratio of mean annual rainfall to potential evaporation for the Valley is about 0.5 and hence it is classified as dry sub-humid according to UNCED (UNCED, 1994)) definitions. The average winter temperature is 12°C while for summer it is 28°C. Relative humidity in winter is about 70% while in summer it is about 60%. The Plain contains several aquifers and aquicludes of complex distribution and properties.

Groundwater levels are at their maximum in March or April with long recessions until recharge occurs in winter. The aquifers were high yielding with discharge rates as high as 300 m³/hr in the early seventies but now are reduced to about one tenth of this. From pumping tests, the specific yield (S) ranges between $5 \cdot 10^{-2}$ and $15 \cdot 10^{-2}$ while the horizontal Transmissivity (T) ranges between $1.7 \cdot 10^{2}$ and $6.9 \cdot 10^{5}$ m²/s. Lateral groundwater outflow from the Valley is small compared with the vertical groundwater outflow. Before the
installation of the groundwater irrigation system, the average discharge out of the Valley was about 20 Mm³/year corresponding to 50 mm of the annual rainfall lost as runoff to the sea.

Today the Western Messara area is the most important organic olive production centre in Crete. The “Organic Farmers of Messara” cooperative includes around 200 olive growers. Most of these growers have small-scale operations, 1.5 - 10ha size. Members of the cooperative have formed a producer group (Organic Olive Growers of Messara) consisting of young and older farmers. Farmers have joined the cooperative for economic, environmental, health and social reasons as well as for the services the cooperative offers. The cooperative has its own employees and manages the quality control, processing, storage, bottling and marketing of the olive oil and olives produced by its members. Olive products are marketed in local and international markets.

2.1.2 Description of problems

General

The Messara Valley located in Geropotamou basin is threatened with desertification due to uncontrolled use. A dramatic drop of about 20 m in the mean groundwater level during the last 30 years has reduced the available water and has created tension amongst the users. The groundwater level dropdown started with the introduction of pumping of the groundwater store for drip-irrigation of the main crop, olive trees. Municipalities sometimes do not share the water with other Municipalities in the same basin. Concern is large on the water quality. Illegal use of groundwater is difficult to be policed. An oversized dam was constructed that is partially filled and water is transported from other basins to fill it up.

The current rate of abstraction from the study area is estimated to be 25.1 Mm³/year. However, some uncertainty about the reliability of these estimates still remains since monitoring of borehole discharge is only carried out in some western parts of the valley around Mires. Over much of the eastern area, where there a large number of private boreholes exist, there is no reliable monitoring at all. However, the estimates we have are the best available in the light of current information.

Although there is a lack of historical borehole discharge data it is possible to provide an estimate of past discharge by examining the area of land under irrigation at different times using the series of Landsat images that are available for the past 30 years. The mean water usage for various crops is known. For example olive and GRAPES use approximately 250 m³ per year per stremma (1000 m²); vegetables on the other hand need 600m³/year per
stromma. Based on this data the current abstraction from the Mires Sub-basin is estimated at 16 Mm3/year, which is in line with the estimates provided by the Land Use Department. (GRAPES, 2000)

The Faneromeni Dam (Figure 2.2), the construction of which was finished in 2005, has a capacity of 30Mm³. The size of this dam is larger than the natural recharge capacities of the watershed which is estimated at about 5Mm³. For this reason, the construction of a second dam in the neighbouring Watershed of Platys is under way. According to the designs, a pipeline will carry water from Platys to Faneromeni Dam in order to increase the inflow and replenish the resources of the latter (personal communication with M. Kritsotakis).

![Figure 2.2: Faneromeni Dam (capacity of 30Mm³)](image)

The Faneromeni Dam has been constructed to cover irrigation demand through an extensive irrigation pipe network. Currently, the irrigation system covers only part of the required area.
Description of problem

Experts assess that the Messara Valley is threatened with desertification. Figure 2.4 shows evidence of the dramatic drop of more than 30m in the mean groundwater level during the period 1989-2002. The depletion of the aquifer has reduced water availability as groundwater is a major resource for irrigation. The causes can be traced to the uncontrolled pumping and use and has created tension amongst the users. The groundwater level dropdown started with the introduction of pumping of the groundwater store for drip-irrigation of the main crop which is olive trees.
It should be underlined that the limiting factor of water sufficiency is not the average precipitation availability. Local and seasonal variations that occur throughout Crete have greater significance with respect to demand and supply. About 70 – 80% of the annual precipitation depth occurs within three or four months whereas the summers are extremely dry and long. This condition is intensified by the local and seasonal variations of water demand. Agriculture and tourism demand increasing amounts of freshwater late in spring, during the summer and in early fall when water resources are more scarce. Moreover, domestic water use increases during the warmer and drier season. On average, Crete has a low per capita water sufficiency, about 4800m$^3$/inhabitants per year, which is the lowest in Greece (average of 6700m$^3$/inhabitants per year) (Chartzoulakis, 2001).

The impact of groundwater abstraction on the ecosystem of the Watershed became obvious when the springs in the surrounding hills dried up and the environment around these springs died, with the loss of birds, small animals and flowers. The wetlands of the Messara Plain were once known for the large number of waterfowl and wild ducks. The Geropotamos stream was known for its large eel population, and its banks for their significant wild rabbit and hare populations. These populations are now almost extinct, partly due to the drying up of the wetlands and partly due to agricultural pesticide poisoning.
There is some concern by land ecologists that African plant species might be replacing the native Aegean species in the Valley. The wetlands have virtually disappeared. Olive mill slurries discharged into the streambeds during the winter months are becoming a major concern, as they are toxic and are infiltrating into the aquifer system. There has been some discussion about using oil mill wastes for some other purpose in order to stop them being dumped into the streams. Another problem is that the stream channels are often used as dumps for rubbish, including plastic. Waste trucks are also using the riverbed as a dumping ground. (GRAPES, 2000)

**Framing the decision making problem**

*Identifying the problem*

The main threatened water bodies in the Gero potamou basin are the aquiferous zone which is getting depleted and the stream which becomes drier each year. Currently these water bodies are not in good status and the prolongation of the current situation will surely lead to a worse condition. The current fear of the community is desertification.

The problem of excessive water abstractions is multifold:

a) Illegal pumping: It is the most important cause of the groundwater availability issue in the area. Apparently there is no control over the area where boreholes are made or whether they interfere with other existing systems. Also, there is little or no control over the amount of water pumped from private wells and apparently there are ways to override the simple system of measuring the irrigation water consumption.

c) Excessive irrigation: This is another issue in the area. So far water prices have not been a deterrent for over-pumping and farmers tend to prefer being on the safe side of irrigation water use in order to maximise production.

d) Illegal irrigation water trading: Private well owners earn a significant amount of money by selling water to neighbouring farmers at 0.50€/ m³. The illegal trading takes place even though the cost of legal water sold by LOLR (Local Organisation of Land Reclamation) is 0.10€/ m³ since the expenses of connecting to LOLR’s pipe network can be high depending on the distance of each farm from the valve.

e) The LOLR irrigation network reliability is questionable and there are no estimates on the potential water leaking losses throughout its length.
The issues mentioned above have to be faced as one complex problem as controlling just one aspect (excessive irrigation) could be inadequate (e.g. network losses could still make demand larger than the required water quantity).

2.1.3 Identifying the decision maker

In the Geropotamou Case study, the decision maker is the Water Resources Department of the Prefecture of Crete (WRDPC). Also, the Local Organisation of Land Reclamation (LOLR) has some administrative authority in agreement with the decisions of the WRDPC.

Many decisions are based on politics rather than technical advice and objective management. This causes the priorities of the managing authority to become less important in the actual decision making. Nevertheless it is very difficult to anticipate such decision or even speak a priory about their outcome since they many right purposes can be served for the wrong reasons and via versa.

Even thought farmers unions exist, they are very poorly organised and the potential pressure they can exert is questionable and often hindered by interest conflicts. On the other hand, there is undoubtedly a sense of community that is often expressed in the form of authority defiance by a group of civilians. This behaviour can act as leverage to political decisions in micro-scale (in the form of small individual favours) as well as macro-scale (in the form of mass protests that can put pressure to political figures or authorities.

The Technical University of Crete (TUC) provides scientific support to the decision maker.

2.1.4 Identifying the problem and uncertainty

The identification of the problem is the basic step of any analysis. The investigation of uncertainties builds on this. An explicit analysis of the uncertainty of this first and fundamental step is rather difficult.

Preliminary list of objectives:

The main objective in the Geropotamou Case Study is to achieve good status in the groundwater resources availability issue. In order to achieve this objective, groundwater levels in the area have to return to the levels observed in the 1970’s which used to be the situation when only minor human interventions had taken place (pre-pumping status). If that
is not possible then the levels observed in the early 1980’s when human intervention was still not excessive can also be satisfactory.

Secondary objectives include the good quality of water resources and the restoration of the ecosystem which are beyond the score of this research. Nevertheless, it is believed that these issues are strongly related to the groundwater availability which controls a major part of the ecosystem as well.

Finally, it is important to achieve these objectives without disrupting the fine socio-economic balances in the area, since public can have a direct influence to the politicians. This can be a big issue since decreasing irrigation in any way can be considered unacceptable by farmers in the first place. Therefore, the decision making process is a rather difficult task, essentially aiming to combine a set of alternative solutions in such a way that a set of criteria is optimised.

Criteria

The criteria chosen in order to make a decision between alternative measures are the following:

i) Acceptance: a categorical value depicting the ratio of satisfied to dissatisfied people between those who are affected directly or indirectly by the implementation of a measure. In this case the scale of Acceptance criterion has 3 values: (Low, Medium, High). The acceptance of a measure can play an important role in decision-making when it is related with political costs and measures affecting voters. For each alternative, the goal is to maximise Acceptance.

ii) Cost: a numerical value equal to the direct and indirect costs of a measure in Euros (€). In this case these costs have been projected until the year 2015. For each alternative, the goal is to minimize Cost.

iii) Groundwater level: a numerical value equal to the observed or simulated level of the aquifer. In this case, the Groundwater level is always a negative value in meters, showing the distance of the groundwater from the surface at a given point. For each alternative, the goal is to bring Groundwater to an acceptable pre-pumping level

Preliminary list of potential measures

i) Control illegal pumping and trading (actor related)
This measure involves assembling a special task force to police the area, check wells, discover illegal works and impose penalties to offenders, aiming at stopping illegal pumping and water trading. Recently, the rural police, a force similar to forest guards that had been abolished, was announced to be re-installed. So, instead of forming a new task force, part of the rural police could be allocated under the supervision of the Water Resources Department of the Prefecture of Crete in order to make surveys for illegal pumping incidents.

The cost of implementing this measure can be broken down in two parts: a) the initial cost of hiring, training, equipping and managing personnel that could range at 50,000€ and b) the annual cost of maintaining the task force (salaries - 17,000€ per officer, expendables etc). For a 10 person force, the annual cost can sum up to 200,000€.

Furthermore, “intelligent” techniques could be utilized to assist the work of this task force. For example, remote sensing can be used to give hints as to where excessive pumping and irrigation takes place, through the indirect measurement of soil moisture or other indexes. In order to incorporate these techniques in the practices of the rural police, the task of issuing a periodic report can be assigned to a research institute. The initial cost of this task will range at 100,000€.

### Table 2.1: Control illegal pumping and trading measure evaluation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater level</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

**ii) Price policy for irrigation water (actor related)**

This measure involves designing a new pricing policy for they water the Local Organisation for Land Reclamation provides to farmers for irrigation. It can be argued that this measure conforms with a policy of transferring the costs of solving the groundwater problem in the area to the users who are responsible for causing it. Even if the cost of water does not deter excessive irrigation, the incomes from this policy could be used by the managing authority to invest into alternative solutions. An alternative solution that has already been applied by some LOLR services is to retain the current price of water for a water consumption that
doesn’t exceed the irrigation needs of each producer. The price of water is then augmented according to a scale, depending on the amount of over-consumption.

For this measure to be successful, a financial assessment should be carried out, specifying the sustainability of the desired agricultural production and the cost of potential solutions that could be funded. Several issues, like the transfer of cost of water to the cost of agricultural products, the competitiveness of the production in the local and international market and the reaction of farmers (who in Greece are a very politically active social class), have to be taken into account. Augmenting water prices will almost certainly have an advert effect in illegal water pumping and trading, causing the problem to transfer to controlling these activities. Other reactions could include switching to more irrigation demanding cultivations.

The cost of the financial assessment for the study area could range to 250,000€, whereas the cost of implementing this measure is negligible.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater level</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

All the above measures have the potential of positively affecting the groundwater level. The amount or water saved from each action remains to be estimated and it is uncertain whether the new status will be characterised as good.

i) Irrigation Network (environmental related)

This measure/ action includes the construction of the main channel that will allocate the water from the Phaneromeni Dam to the local networks as well as the restoration of these networks. All channels have been designed to be underground and under pressure.

The cost of the construction is calculated to 25,200,000€ and the study has been conducted by the prefecture of Crete (Investor’s World, June 2005).
Table 3: Irrigation Network construction measure evaluation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Groundwater level</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Preliminary set-up of the decision matrix

Summarizing the above actor related and environmental measures, the following table arises. Table 4 is the decision matrix containing the alternatives and the criteria for the specific case study.

Table 4: Preliminary decision matrix

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Criteria</th>
<th>Cost (direct + indirect)</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Groundwater level</td>
<td>M Euros</td>
<td>Categorical</td>
</tr>
<tr>
<td>Stop illegal pumping</td>
<td>meters from surface</td>
<td>2.342</td>
<td>Medium</td>
</tr>
<tr>
<td>Water price</td>
<td>Low</td>
<td>0.250</td>
<td>Bad</td>
</tr>
<tr>
<td>Irrigation Network</td>
<td>High</td>
<td>25.200</td>
<td>Good</td>
</tr>
</tbody>
</table>

Even though this is a simple decision matrix, the application of a multi-criteria analysis is not equally simple. Specifying the value (numeral or categorical) of each alternative can not be done with certainty. Especially for actor related measures, “soft” criteria like “acceptance” are rather fuzzy and have an uncertain impact as they are affected by various parameters (farmer community tolerance, current socio-economic conditions, conflicting interests, etc.)
Further on each criterion will be individually analyzed regarding each alternative:

- For the criterion “Groundwater level”, the models that have been calibrated will be used to predict the effect of each alternative until the year 2015 (WFD). The results are included in paragraph 3.6 – predictions.

- For the “Cost” criterion there will be a calculation of direct and indirect costs of each alternative. The results will be included in chapter 4 – Cost calculation.

- Regarding the “Acceptance” criterion, this will be assessed taking into account the current socioeconomic status in the Case study area.

Furthermore, absolute weights have to be set for each criterion defined above. Weight values are entirely up to the decision maker to specify and depend on personal judgment. The crucial effect absolute weights have to the results of the case study will be described in Chapter 5 – Results. The empirical values of the absolute weights are:

- Groundwater Level = 0.5
- Cost = 0.2
- Acceptance = 0.3

The structure of the Geropotamou Case Study decision making process is summarized in Figure 2.5.
2.1.5 Previous studies and historical development

One of the greatest considerations for past management plans in Messara Valley, was the increase of olive groves cultivations. As early as 1920 the slopes of the Messara Valley, which were once used for cereal growing, were first abandoned as a result of the introduction of mechanical harvesting. Grazing during the winter months was then introduced, which led to overgrazing and the destruction of the natural vegetation. The versatility of olive trees, which can grow in rough terrain and are resistant to the local drought conditions, has caused cultivations to expand since 1961, leading to the current status where they outnumber all other agricultural activities.

There has been a sequence of studies related to the management of Messara Valley water resources:

- The 1951 ADSCO Study: the English firm ADSCO was assigned the first study on the development and management of the water resources of the Valley.
• The 1956 HYDRO-ETME Study: the Greek firm HYDRO-ETME undertook the study of storage potential and use of the surface waters.

• The 1961 Department of Agriculture Study: the Land Reclamation Office in Crete engaged a private firm to examine the development and management of an irrigation network. This study was concerned with the surface waters and twelve locations for the siting of dams were examined. The sites were to be mostly in areas outside but near the Messara Valley. The first evaluations showed that it was possible to store 194 Mm$^3$, over 200 times the irrigation needs of the Valley at that time.

• The FAO WATER Resource Programme: in 1966, the Greek government and the FAO commenced a comprehensive management programme for the groundwater and surface water resources of the whole of eastern Crete that mainly focussed on the Messara Valley. The programme was of four and a half years duration and commenced in 1968. The plan was to irrigate up to 20 000 ha in two phases. The region was divided into three irrigation areas which were Timbaki 2000 ha, Mires 4000 ha and Protoria 4100 ha. Timbaki and Protoria were to be based on dam water. The dams were never built. However, due to the ease with which groundwater could be obtained and based on the prototype irrigation networks, the exploitation of the groundwater increased rapidly. It should be noted that the FAO recommended that the groundwater resources be as fully exploited as possible (FAO, 1972)

• The Prototype Small Irrigation Networks: in 1970, two irrigation systems were constructed as prototypes for a future extensive network. One was a 600 ha plot at Timbaki, outside the catchment outlet of the Valley, while a 400 ha plot was sited at Pombia within the Valley. The Timbaki network comprised seven boreholes with a supply of 1200 m$^3$/h and which involved 52 km of drip-irrigation plastic tubing. The Pombia network comprised four boreholes with a supply of 800 m$^3$/h.

• The GRAPES research project (1996-2000, Groundwater and River Resources Action Programme on a European Scale): In the framework of the GRAPES project, historical data was collected and analyzed for the Messara Valley. Hydrological and hydrogeological modelling of the basin was undertaken, providing groundwater recharge estimations. The historical development of the catchment’s resources was assessed with the problems and solutions of the over-exploited basin, concluding to the guidelines for the sustainable management of groundwater fed Messara Valley.
• The BEWARE pilot project (2003-2005, Best Water Use Innovative Practices towards a Sustainable Water Resources Management). In the framework of the BEWARE project and aiming at a rational and sustainable use of irrigation water in agreement with the farmers, telemetric meteorological stations were installed in the area of Messara. The data that is collected is being processed giving results regarding the actual irrigation water needs, also taking in account the type of crop, soil etc. This way a local farmer can connect to a voice portal and get information on the appropriate amount of water he needs to dispense for irrigation by giving the type of crop and the area his field covers.

• Faneromeni Dam (2006): This is the first year of operation of this great construction project that aims at saving 5-6Mm³/year having a total capacity of about 30Mm³. there is the potential of filling up the rest of the dam from neighbouring basins.

2.2 Data availability - Uncertainty overview

Most data was provided to TUC in the form of hardcopy entry books where observers note observations in roughly fixed time intervals. Observation time intervals vary according to the observed variable as well as the punctuality and fidelity of the observer. Observers in our case are mainly assigned farmers and, where possible, more experienced technical personnel.

Data includes weather, groundwater and various other parameters. A large part of the data refers to the time interval 1973 – 2003. There is also data that dates from 1963. The authority in charge of a large part of data collection and archiving is the Service of Land Reclamation of the Prefecture of Heraklion, where Geropotamou basin is located. Another part is collected by the Department of Water Resources Management of the Region of Crete which is the End User of the Geropotamou Case Study.

Access to the spatial information has been granted to TUC by the Regional authority of Crete for the needs of the HarmoniRiB project. This spatial data has resulted from an earlier study commissioned by the Regional authority

Generally, the classification regarding uncertainty according to Van Loon et. al., of the meteorological measurements can be seen in Table 2.3. Summarizing, all meteorological data was classified as P1, B2 and M1. Also, depending on the various conditions taking place in each station, the adequacy of stuff and funding etc, the uncertainty depending on the instruments, sampling and overall method (indices I, S, O) were estimated to be between classes 1 and 3 with most measurements classifying as 2.
<table>
<thead>
<tr>
<th>Uncertainty type</th>
<th>Description</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positional Uncertainty</td>
<td>Single point</td>
<td>P1</td>
</tr>
<tr>
<td>Attribute Uncertainty</td>
<td>Varies in time not in space</td>
<td>B2</td>
</tr>
<tr>
<td>Empirical Uncertainty</td>
<td>Probability distribution or bounds</td>
<td>M1</td>
</tr>
</tbody>
</table>

**Methodological Quality**

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument quality</td>
<td>Instrument well suited for the field situation and mostly calibrated</td>
<td>I3</td>
</tr>
<tr>
<td>Sampling strategy</td>
<td>Mostly historical field data, mostly uncontrolled or just small samples</td>
<td>S2</td>
</tr>
<tr>
<td>Overall method</td>
<td>Reliable or acceptable method depending on the station</td>
<td>O2 or O3 depending on the station</td>
</tr>
<tr>
<td>Variable</td>
<td>Measurement space support</td>
<td>Measurement -Time support</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Precipitation</td>
<td>200 cm²</td>
<td>1 day</td>
</tr>
<tr>
<td>Temperature</td>
<td>10 cm³</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporation</td>
<td>10 cm³</td>
<td>1 day</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>10 cm³</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunshine</td>
<td>10 cm³</td>
<td>1 day</td>
</tr>
<tr>
<td>Wind speed</td>
<td>10³ cm³</td>
<td>1 day</td>
</tr>
<tr>
<td>Morphology</td>
<td>1 cm²</td>
<td>-</td>
</tr>
<tr>
<td>Runoff</td>
<td>1 m²</td>
<td>1 day</td>
</tr>
<tr>
<td>Springs</td>
<td>1 m²</td>
<td>1 day</td>
</tr>
<tr>
<td>Wells</td>
<td>0.1 m²</td>
<td>1 day</td>
</tr>
</tbody>
</table>
2.3 Model use overview

2.3.1 The Thiessen polygon approach

The Thiessen polygon approach (Thiessen, 1911) is used to calculate empirically the average areal precipitation over the Geropotamou Watershed. Although it is essentially a very rough averaging approach, scientifically inferior to methods like IDW and Kriging, this approach is used by the WRDPC in order to produce precipitation input for all subsequent modelling. For this reason, in this document it is regarded as an approach for modelling the mean areal precipitation or rather pre-processing precipitation observations for model input.

2.3.2 The Sacramento Hydrological Model

The rainfall-runoff model used in this project is the modified Sacramento model, a conceptual spatially lumped soil model. A deterministic version was reported in Burnash et al. (1973) and Peck (1976). Modifications of the original Sacramento soil-moisture accounting model were made by Kitanidis et al. (1980) and Georgakakos (1986). As shown by Bae et al. (1944), for large areas of the Midwestern US, the Sacramento model may be used to estimate the variability of aggregate soil water over an area, provided that all significant basin inflows and outflows are accounted for and model verification yields good agreement between observed and simulated stream flow.

2.3.3 MODFLOW

MODFLOW is probably the most widely-used 3-D groundwater flow model. MODFLOW can represent the effects of wells, rivers, streams, drains, horizontal flow barriers, evapotranspiration, and recharge on flow systems with heterogeneous aquifer properties and complex boundary conditions to simulate groundwater flow.

Groundwater flow within the aquifer is simulated in MODFLOW using a block-centered finite-difference approach. Layers can be simulated as confined, unconfined, or a combination of both. Flows from external stresses such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds can also be simulated.

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2 Sacramento (SAC-SMA) can be found at [http://www.nws.noaa.gov/oh/hrl/hydro.htm](http://www.nws.noaa.gov/oh/hrl/hydro.htm).

3 MODFLOW can be found at [http://water.usgs.gov/nrp/gwsoftware/modflow.html](http://water.usgs.gov/nrp/gwsoftware/modflow.html).
In this project, MODFLOW has been used in order to simulate groundwater level fluctuation under pumping pressure in the alluvial part of the Geropotamou Watershed.

2.4 Uncertainty issues overview

Uncertainties considered previously

According to GRAPES EC Project (ENV4-CT95-0186), uncertainties are present in all hydrological studies. These may relate to the physical, hydrological, ecological, economical or social aspects of the problem. Under these circumstances unique deterministic predictions are difficult to justify. Instead it seems more advisable to produce an 'envelope' of results incorporating the range of stresses known to be present. The 'envelopes' can be obtained using sensitivity tests in which realistic ranges of parameters are used to produce a range (envelope) of likely outputs. This type of approach provides the decision maker with an indication of the uncertainties involved in any decisions that are made. Another element of uncertainty is introduced by rapidly changing economic conditions in an area. For this reason predictive management runs should be limited to economic planning horizons: 10-15 years.

The only uncertainties considered in the past for the Messara Valley were in the frame of the GRAPES EC Project (providing guidelines for a step by step guide to managing a groundwater-fed catchment). According to the technical report of the project: for the Messara Valley, the difference between the measured rainfall for the 13 rainfall stations and the fit given in technical note 8 gives a standard deviation of 0.10 ((measured-fit)/measured). Therefore, it is estimated that the error in the total rainfall for the catchment based on the available rainfall data is assumed to be approximately 10%. The model does not allow for variations in the potential evaporation with altitude, and is based on pan evaporation data obtained on the plain, which contains the bulk of the soil and vegetation. The error in the potential evaporation is assumed to be approximately 10%. For the measured discharge at the Phaistos gauging station, the scatter in the data used to calibrate the flow station is approximately 10%. For high flows (>10m$^3$/s), the calibrations are based on a small number of observations, and thus have a larger uncertainty. The variation in the recorded calibration curves is approximately 20%. If we assume that the residual calibration error is approximately half this value, then the estimated error in the measured discharge is approximately 15%. Thus the combined error in the input data used by the model may be as high as 20% for the Messara Valley.
Uncertainties considered currently

Under the scope of the HarmoniRiB project, three types of uncertainties were considered:

- the uncertainties associated with observations which are considered as model input variables, described in previous chapters;
- the uncertainties associated with the pre-processing of data for model use (e.g. spatial averaging)
- the uncertainties associated with model parameters.

Model parameter uncertainty combined with input uncertainty affects output uncertainty. For each one of the models and pre-processing techniques used in this study, different issues arose regarding the effect of uncertainty and in some cases this effect is difficult to assess.

Uncertainty of Thiessen polygons

Unlike geostatistical methods, the Thiessen polygon approach does not account for uncertainty due to upscaling support from point measurements to space estimations. Geostatistical methods rely on the estimation of variograms depicting the spatial relationship between uncorrelated point measurements. Under various assumptions, such techniques can be extremely useful and scientifically superior in calculating spatial variability and block averages when a large amount of observations is available. In the case of the Geropotamou basin, variogram estimations are inefficient because of the small number of point observations (8 stations) for precipitation measurements. For this reason geostatistical techniques are very difficult to apply. Moreover, it would be difficult to assess whether the derived uncertainty estimation is meaningful.

The uncertainty related with the Thiessen Polygon approach can be targeted at approximating the actual influence area of each polygon or the actual weight of each station in the resulting \( A_A P' \). The uncertainty in the area of each polygon can be considered to follow a normal PDF, described by:

\[
N(\mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right), \quad -\infty < x < \infty
\]  

(4)

where \( \mu \) the mean and \( \sigma \) the standard deviation of the distribution.

In order to vary the area of all 8 polygon at the same time but also keep their sum equal to the total area of the Watershed, the polygons where derived from normally distributed
realizations of the (X, Y) coordinates of each station. After tests, the initial location of each
gauge was considered the centre of the normal PDF and the standard deviation was set to
0.01 degrees (or about 1000m in the WGS84 projection system) for both X and Y. These
specifications were used in DUE to produce 100 spatial gauge realizations from which the
Thiessen polygons were calculated and plotted as shown in Figure 2.6. The detail view of
Figure 2.6 shows the distribution of the boundaries of each polygon.

![Figure 2.6: Uncertainty in the polygons of the Thiessen Method](image)

**Uncertainty in Sacramento**

The environment originally used (HYMOS implementation of Sacramento) was not suitable
for batch run. Sacramento was implemented in FORTRAN so that Monte Carlo could be used.
The four parameters UZTWC, UZFWC, LZFPC and LZFSC, which appear to be the most
sensitive when modeling runoff with Sacramento, were considered uncertain following a
normal distribution with a 10% standard deviation.
3 Physical Impact analysis

3.1 Purpose & conditions

In order to make any conclusions on the status of groundwater in Messara Valley, the hydrogeology of the Watershed has to be modelled. The goal is to make predictions of the groundwater fluctuation until 2015 under different pressure scenarios. In order to reach this point, the groundwater fluctuation first needs to be modelled using historical data to calibrate and validate physical based models. When these models have reached a certain level of efficiency and can be trusted to simulate current conditions well, artificial input is introduced to simulate scenarios that include weather conditions and strategic changes in system manipulation.

At the same time, a range of climatic scenarios are being considered. These scenarios are not being considered in the same framework as uncertainty but only as two separate plausible conditions under which uncertainty can be investigated. The scenarios, together with a set of alternative remediation policies are being associated with an impact on the modelled system. Empirical assessments have to be made in order to directly connect the combined impact of climate and policy with the groundwater fluctuation. Only then can there be a comparison between present and future predicted status as well as among different scenario results. Following these principles, a range of plausible climatic scenarios and alternative policies have been compiled. After translating each set of conditions to the previously determined impact the models can be executed, determining the status of the basin.

Nevertheless, the series of intermediate steps that are required to reach this level of awareness is haunted by individual uncertainties that propagate through every step. For each one of the steps, different variables, parameters and models are involved, including uncertainties. A general obstacle is data availability and the ability of models to simulate the natural environment under these conditions. A large compromise is made when assuming that models simulate accurately the natural environment. Other assumptions include unbiased datasets and constant conditions through time for several parameters. Finally, the soundness of climatic scenario predictions and policy impact is probably the most difficult component to determine.
3.2 Conceptualisation

In order to model groundwater fluctuation two physically based models have to be used. Initially, MODFLOW (structure presented in Figure 3.1) was chosen to simulate the behaviour of the aquifer. MODFLOW requires knowledge of the soil characteristics of the basin as well as water sinks and sources. For the purposes of HarmoniRiB, it has to be set up in such a way that the various scenario impacts are reflected by the results. This is accomplished by transferring all impacts on the sink inputs of the model (pumping rates) making certain assumptions about the trends of the sources (precipitation) and also assuming that all other conditions are steady.

Figure 3.1: Structure of the MODFLOW model (source: USGS).

MODFLOW requires a recharge component as a source input, the recharge of the groundwater. This component $R$, is equal to:

\[ R = P - ET - Q \]  \hspace{1cm} (8)

where $P$ the precipitation, $ET$ the actual evapotranspiration and $Q$ the runoff from the Watershed, all measured in mm. Since actual evapotranspiration is not known, a second model has to be used. For this reason, the Sacramento rainfall runoff model (structure presented in Figure 3.2) was used, since together with the runoff simulation it also produces $ET$ estimations from the available pan evaporation and temperature data.
The workflow from data collection to the final results is presented in Figure 3.3.

Figure 3.2: Structure of the Sacramento rainfall-runoff model (source: CHRS, 2006).

Figure 3.3: Linking models
3.3 Model setup

3.3.1 Data analysis

The eight rain gauge stations of the Geropotamou basin were tested for homogeneity with the method of double mass curve. For the method to be accurate the correlation coefficient between the tested station and the base station must be higher than 0.8. According to that, the results were satisfactory, since the correlation coefficient for each station was close to 0.99. The homogeneity test showed that the precipitation time series of the stations Vorizia and Moroni had inhomogeneities and were corrected based on the recent measurements, since they are considered to be more accurate. The fill-in of the gaps, in order the time series to be complete for the time period analysis 1981-2002, was made via the spatial filling-in method. The precipitation time series that have been filled in come from the station Asimi for the time periods 9/1982-8/1985 and 9/1990-8/1991, the station Vagionia for the period 9/1991-8/1993 and the station Agios Kirillos for the time period 1/1999-8/1999. The inter-annual precipitation of each rainfall station of the Geropotamou basin was calculated and the total rainfall-altitude lapse rate of the basin was estimated. The correlation coefficient of that lapse rate turned out to be low (0.35) and could not be considered reliable and representative. The basin was therefore divided into two parts, the north and the south part, and two individual rainfall-altitude lapse rates were estimated in order better results to be obtained.

3.3.2 The Thiessen Polygon approach

Rainfall is intermittent and spatially discontinuous. Precipitation datasets contain a large number of zero values and because of this, among other reasons, a reliable spatial interpolation is inherently more difficult than for many other variables. (Dirks et al., 1998). While existing geostatistical methods like Kriging have been known to provide better results for the spatial interpolation of precipitation (Tabios and Salas, 1985), the degree of complexity and the computational effort they require do not justify their use for high resolution networks (Dirks et al., 1998). Therefore, a simpler method was chosen to model daily Average Areal Precipitation ($AAP$) from daily precipitation values. The Thiessen Polygon (Thiessen, 1911) approach is probably the most common method for determining $AAP$ over a given catchment area. The basic concept is to divide the Watershed into several
polygons, each one around a measurement point, and then take a weighted average of the measurements based on the size of each polygon. \( AAP \) is calculated by:

\[
AAP = \frac{\sum_{i=1}^{n} P_i A_i}{\sum_{i=1}^{n} A_i}
\]

(1)

where \( P_i \) is the measured precipitation at each gauge and \( A_i \) is the areas of each polygon.

Fig. 1 shows the division of a typical Watershed with the Thiessen polygon method. The Thiessen Polygons, also known as the Voronoi diagram (Voronoi, 1908) can be easily produced between a set of points with the use of ArcGIS 9.

For the needs of this study \( AAP' \) is introduced as Average Areal Precipitation with an uncertainty component.

![Figure 3.4: Thiessen polygons on a typical Watershed with 4 gauges.](image)

### 3.3.3 Sacramento

The Sacramento model has 16 parameters that need to be determined by the user. The meteorological input data are precipitation and potential evapotranspiration. Precipitation is provided in the form of mean areal precipitation. These inputs are processed in accordance with the catchment characteristics, which interact with mathematical representations of those hydrologic processes that govern catchment outflow. The outputs from the model are
estimated evapotranspiration and channel outflow. The latter is converted into streamflow by means of a unit hydrograph. The model makes a distinction between the land phase and the channel. The land phase consists of pervious and impervious areas. The pervious area is divided into the upper zone (soil moisture) and the lower zone (groundwater). Both of the zones contain reservoirs for tension water and free water. The direct runoff contributes to the river outflow from the impervious area and the surface runoff from the pervious area, the interflow and the base flow (Burnash, 1995).

Based on the given hydrological inputs and the initial contents of the reservoirs the model generates, among others, the water (in mm) stored in the reservoirs of the two zones at the end of each month for the simulation period. The model generates as well the groundwater storage changes, by which the groundwater discharge for each hydrological year is obtained and used for the groundwater abstraction estimates. The term of storage refers to the total amount of water that is stored into the ground, after subtracting the surface and subsurface losses.

A sensitivity analysis was conducted in order to determine the most sensitive parameters of the Sacramento model. All the parameters were varied within 20, 40 and 60 percent lower and higher values than the optimum. It was shown that out of the 16 parameters, eight are more sensitive and that if any of these parameters is very far from its optimum value (60 percent lower or higher), the model efficiency reduces remarkably. The parameters representing the initial contents of the reservoirs, i.e. UZTWC, UZFWC, LZFPC and LZFSC affect mostly the coefficient of determination, which is in agreement with Finnerty et al., since they represent the initial conditions of the basin that the model simulates. It was shown that a 20 percent variation of these parameters reduces the coefficient of determination by an average of 5 percent and a 60 percent variation reduces the coefficient of determination by an average of 30 percent. Second in importance are the parameters that influence the filling of the reservoirs, i.e. LZSK, LZPK and PFREE. The parameters that represent amounts of water that are either detained in the ground or lost and do not contribute to the river outflow mainly affect the simulated streamflow component volume. These are UZTWM and LZTWM, i.e. the needs for soil moisture and SIDE and SSOUT i.e. the losses and the amount of water that is not measured to the river outflow. It was shown that if any of these four parameters is 20 percent higher or lower than the optimum value, the simulated streamflow component varies by 10 percent. A 60 percent variation of these parameters varies the simulated streamflow component by an average of 25 percent.
3.3.4 MODFLOW

Once the MODFLOW simulation has been initialized, the next step is to enter the data required by the Global Options/Basic package. This includes data defining fundamental program options such as the computational time intervals (stress periods), an array defining which cells are inactive and which cells have constant heads, an array of starting head values for a transient simulation, and a set of flags defining which of the other packages are to be used. The input data for this package should be entered before editing any of the other packages. The MODFLOW Global Options\Basic Package Dialog is accessed through the Global Options command in the MODFLOW menu. The options in the dialog are as follows:

This package is an alternative to the BCF and HUF packages and is similar to the "true layer" option used with the BCF package. With MODFLOW 2000, the layer elevations (top and bottom) are defined as input, regardless of which flow package is being used. With the LPF package, the user then defines the horizontal and vertical hydraulic conductivity for each layer. MODFLOW then computes the cell by cell conductance using the K values and the layer geometry.

Other noteworthy features include the ability to enter horizontal anisotropy values on a cell by cell basis. There is also an option to specify vertical anisotropy factors rather than vertical hydraulic conductivity values. This option is particularly useful when performing automated parameter estimation since it ties the Kv to Kh and eliminates the need to define Kv as an independent parameter.

Another feature of the LPF package is that there are now only two layer types: confined and convertible. A convertible layer is similar to the LAYCODE = 2 and LAYCODE = 3 types in the BCF package. The layer can be either confined or unconfined depending on the elevation of the computed water table.

The solver used is the Preconditioned Conjugate Gradient Package which is an iterative solver based on the preconditioned conjugate gradient technique.
3.4 Calibration / Validation

3.4.1 Sacramento

The model was calibrated manually by achieving the best possible agreement between the measured and the simulated river outflow. In order to evaluate the goodness of the simulation the coefficient of determination ($R^2$) of the measured versus simulated river outflow and the streamflow error i.e. the total volume of the simulated river outflow to be equal to the actual (measured) one. The total period of model calibration is 25 years (1977-2002). Since the irrigation system was installed in 1984 and set in full operation in 1989 a sensitivity analysis is performed by taking the calibration period as follows (a) full period, (b) individual year calibration, and (c) two periods prior (1977-1989) and after (1989-2002) the full operation of the irrigation system. Sensitivities of calibrated model parameters to simulated streamflow and model efficiency was investigated to find out the sensitive parameters of the Sacramento model. In particular, the percentage change in the $R^2$-values and the simulated streamflow component volume are investigated, when changing each parameter per 20, 40 and 60 percent while holding the input data and the other parameters constant. The model parameters can be divided into four basic categories, according to their estimation procedure.

Table 3.1 shows that most of the parameters are within the suggested range of values, except from the parameters UZTWI, that represents the needs for moisture in the upper zone and UZK, which represents the interflow rate in the upper zone. The value of UZTWI was considered to be larger than suggested, since the needs for soil moisture in Geropotamou basin are increased, due to the climate conditions of the area, the low precipitation and the great drop in the groundwater level. Owing to that drop, the percolating water moves downwards without any resistance and is not discharged as interflow, therefore the value of UZK was considered to be much smaller than suggested. As mentioned before the indices of model efficiency used in this study to evaluate the goodness of the simulation were the coefficient of determination ($R^2$) of the measured versus simulated river outflow and the streamflow error. The calibration resulted in $R^2 = 0.75$ and streamflow error close to zero. Generally, one cannot know whether the located optimum is also the global one. Since the optimisation was guided manually, a different initialisation would have likely given a different final set. Nevertheless, in practise, it is usually sufficient...
to find a parameter set that gives low error measures (in this case, high $R^2$-value) and reasonable physical behaviour.

Figure 3.5 shows the observed and simulated values of runoff for the Geropotamou basin. Both Figure 3.5 and Figure 3.6 which presents the efficiency of the model show that high flows are depicted quite well while low flows can be overestimated. The overall fit is acceptable with an $R^2$ of 0.75 for the period 1977-2002, taking higher values for isolated annual calculations and single events. The good fit indicates that Sacramento, although a conceptual rainfall-runoff model, can also be used for estimating the groundwater potential of a basin. The differences are mainly due to the model’s lump, since it considers the conditions to be uniform throughout the basin and also due the uncertainty of some field parameters, such as the horizontal porosity value and the depth to the groundwater store, which are also considered to be unvaried throughout the basin.

*Figure 3.5: Observed VS Modeled runoff (m$^3$/s) – monthly data*
Table 3.1: Sacramento Parameters with their suggested and calibrated values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated Value</th>
<th>Suggested Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UZTWC</td>
<td>155.0</td>
<td></td>
</tr>
<tr>
<td>UZFWC</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>LZTWC</td>
<td>10.00</td>
<td></td>
</tr>
<tr>
<td>LZFSC</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>LZFPC</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>ADIMC</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>UZTWM</td>
<td>400.0</td>
<td>25-175</td>
</tr>
<tr>
<td>UZFWM</td>
<td>20.0</td>
<td>10-100</td>
</tr>
<tr>
<td>UZK</td>
<td>0.005</td>
<td>0.18-1.0</td>
</tr>
<tr>
<td>PCTIM</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>ADIMP</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>SARVA</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>ZPERC</td>
<td>180.0</td>
<td></td>
</tr>
<tr>
<td>REXP</td>
<td>2.75</td>
<td>1-3</td>
</tr>
<tr>
<td>LZTWM</td>
<td>120.0</td>
<td>75-600</td>
</tr>
<tr>
<td>LZFSC</td>
<td>90.0</td>
<td></td>
</tr>
<tr>
<td>LZFPM</td>
<td>300.0</td>
<td></td>
</tr>
<tr>
<td>LZSK</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>LZPK</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>PFREE</td>
<td>0.30</td>
<td>0-0.4</td>
</tr>
<tr>
<td>SIDE</td>
<td>0.75</td>
<td>0-5</td>
</tr>
<tr>
<td>SSOUT</td>
<td>1.70</td>
<td></td>
</tr>
</tbody>
</table>

The variables of Table 3.1 represent the following properties or capacities:

**UZTWM**: the depth of water which should be reached before free storage occurs in permeable areas.

**UZFWM**: the free water of the upper zone
LZTWM: the maximum volume of water under pressure in the lower zone
LZFSM: the maximum volume of free water.
UZK: the degree of side drainage of the upper zone
LZSK: the degree of side drainage of the secondary free water tank of the lower zone
ZPERC: shows the change of infiltration from saturated to dry state
REXP: shows the change of water demand from dry to wet conditions
PFREE: the part of water that infiltrates directly to the free aquifers of the lower zone
PCTIM: the constantly impervious part of the basin which is adjacent to the flow channels. It can be specified during short precipitation events of small intensity
ADIMP: the part of the basin that becomes impervious when all demand of water under pressure is covered
SARVA: the part of the basin that is covered by channels, lakes and riverside vegetation under normal conditions
SIDE: the part of the baseflow that can't be observed in the channel flow
SSOUT: the groundwater leakage along the channel.
Figure 3.6: Sacramento Monthly Calibration - Bars: observed runoff (m$^3$/s) / Points: Modelled runoff. Complete dataset results (1977-2002)

Figure 3.7: Potential ET (green) and Actual ET (blue) estimated by Sacramento. Bars: monthly precipitation. All units in mm.
3.4.2 MODFLOW

Initially the model grid was built by assigning material properties and elevations to the alluvial part of the basin which is of interest for the Case Study. Figure 3.8 presents the way the basin is visualised by MODFLOW, segmented into cells of different roles and properties.

![Figure 3.8: Segmentation of the alluvial part of the hydrological basin](image)

After assigning initial values to those characteristics the model can be calibrated assuming steady state conditions.

**Steady state**

For constant flow conditions, the hydrometeorologic variables were fixed so as to they agree with the values that were measured between 1969 and 1979. Thus for the medium surface rainfall of this period (629mm), the corresponding aquifer recharge is 0.00112m/day as estimated from Sacramento.
Table 3.2: Main MODFLOW variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge Rate</td>
<td>0.00112 m/day</td>
</tr>
<tr>
<td>Aquifer depth</td>
<td>Equal to surface</td>
</tr>
<tr>
<td>Horizontal K</td>
<td>$10^{-2}$ to $10^{0}$ m/day</td>
</tr>
<tr>
<td>Horizontal Anisotropy</td>
<td>1</td>
</tr>
<tr>
<td>Specific Yield</td>
<td>$10^{-3}$ to $10^{-2}$</td>
</tr>
<tr>
<td>Stream Conductance</td>
<td>$10^{3}$ to $10^{4}$</td>
</tr>
</tbody>
</table>

Taking into account the level of a number of wells in the basin for which only one historical value of the 1970s was known, the horizontal K of different materials was adjusted in order to produce the smallest possible error in levels. Figure 3.9 shows the location and error associated with the simulation of each well. Red markers show errors greater than 10% whereas green markers show errors smaller than 5%. Once the model has been calibrated, the steady state simulation of the basin can be visualised (Figure 3.10) together with flow vectors and head contours.

Figure 3.9: Groundwater level and calibration wells for steady state
After calibrating the model in steady state, the results were used as initial conditions for the calibration of a groundwater level simulation through time. Using a number of wells for which biannual depth measurements exist, model parameters were adjusted. The driving variables for the groundwater fluctuation are recharge (during the rainy season) and well pumping rates (during the irrigation season). Since the actual water levels are already known in some areas of the Watershed, what needs to be calibrated is the average pumping rate of wells in Messara Valley. Only a subset of the wells was used for calibration and results were validated with the rest of the set. Since the exact amount of total (legal and illegal) pumping was not known, MODFLOW was calibrated so that the resulting groundwater level fluctuation could be simulated. The validation results for two typical wells located in near the outlet in Phaistos are shown in Figure 3.11 and Figure 3.12. The model appears to be very efficient proving that the inferred pumping rates (Figure 3.13) are accurate.
Figure 3.11: Comparison between Observed and Simulated values at Well 104

Figure 3.12: Comparison between Observed and Simulated values at Well B1
From Figure 3.13 it’s obvious that pumping rates have dramatically increased after 1988 reaching a cumulative peak of 77.7Mm$^3$/year which has remained steady for 2001 and 2002.

3.5 Effects of uncertainty

3.5.1 Thiessen polygons

After all times series were generated by DUE, a statistical analysis was conducted in order to verify that all values followed the attributed distributions. The generated histograms (example in Figure 3.14) were satisfactory, depicting exponential distributions for precipitation time series and normal distributions for Thiessen polygon area estimations.
Following statistical analysis, 100 realizations of $AAP'$ were calculated by randomly sampling model variables and parameters for each time step. Even thought $AAP'$ was calculated on a daily basis (Figure 3.15), daily values were considered less significant than monthly and annual sums.
From Figure 3.15 it is obvious that the total estimated uncertainty in precipitation measurements is always positive. This reflects the initial assumption that rain gauges always underestimate precipitation due to various water losses and that there are no important biases involved in the measurement. Following this assumption, all model results are expected to have a similar behavior regarding uncertainty.

The original $AAP$ was compared with $AAP'$ after averaging all generated datasets. The comparison can be seen in Figure 3.16 and shows an almost uniform increase of precipitation by 3% at all gauges. This result was expected since the same set of rules was used for all the gauges. It was assumed that all gauges behave similarly and all observers allow for similar biases, something that it doesn’t reflect the actual measurement uncertainty correctly but is a valid assumption given the lack of metadata.

For the period 1974-2003, regarding the hydrological year as a period from September to August, the average estimated $AAP'$ was 722mm; 3% higher than when disregarding model and measurement uncertainty. On an annual basis, $AAP$ before and after uncertainty assessment introduction to the calculations, can be seen in Figure 3.17. The annul augmentation of AAP is consistent with the previous result at an average of 3%.
Further analysis of $AAP'$ showed that for dry months there is a small estimated deviation from $AAP$ values (±5mm per month) with no evident trend. For wet months there is an obvious trend for smaller losses with larger $AAP$ values.

Histograms of various $AAP'$ intervals showed that for small values the principal component of the resulting PDF is the exponential one, originating from precipitation uncertainty. Likewise, for larger values (greater than 10mm) the principal component is that of the normal PDF originating from model parameter (gauge weights) uncertainty.

Monte Carlo was only used for deriving the composite PDF for areal precipitation through the Thiessen polygon method, since for the rest of the models only one uncertain input was used. Initially, DUE was used to generate 100 time-series for each one of the 8 rain gauges involved in the estimation. Also, 100 rain gauge spatial realizations were generated in DUE and the imported in ArcGIS® for the estimation of the respective Thiessen polygons weights. For the average areal precipitation estimation, Matlab® code was written to aggregate the uncertainties of each rain gauge and that of the Thiessen method polygons. Out of a
population of 10,000 (100x100) resulting datasets only 50% was calculated by Matlab® since the process was very time consuming (7 hours for the whole population on an Athlon 4400+ with 2GB of RAM). The derived datasets where analyzed with the Matlab® statistical toolbox and it was concluded that a close approximation of the uncertainty of average areal precipitation $AAP$ follows the rule:

$$N(\mu = 0.031, \sigma = 0.002) \text{ for } AAP = 0$$

$$N(\mu = AAP + 3.748, \sigma = 1.372) \text{ for } AAP \neq 0 \text{ during wet months (November to February)}$$

$$\Exp(\mu = AAP, \lambda = 1.224) \text{ for } AAP \neq 0 \text{ during dry months (March to October)}$$

(7)

100 realizations of $AAP$ were generated using MATLAB® in order to be used as input for Sacramento and MODFLOW.

### 3.5.2 Sacramento

The uncertainty in Sacramento simulations is a result of uncertainty in precipitation input and the uncertainty in the four most sensitive model parameters. Figure 3.19 shows the reference simulated runoff (runoff estimated before any uncertainty was introduced in the modelling process) and the uncertainty interval produced at the final steps of modelling. For all runs the $R^2$ of the observed with the simulated $Q$ was kept at acceptable levels, over 0.7. Nevertheless, the uncertainty associated with predicting the resulting flow increased as monthly flow increased (Figure 3.18).

For the purposes of this Case Study, the most important result of Sacramento is the actual evapotranspiration estimation. Figure 3.18 presents the estimated ET along with the included uncertainty for the period 1977 – 2002. Uncertainty intervals for both runoff and evapotranspiration are exclusively positive (appear above the reference estimation). This is due to the fact that the considered uncertainty for the main input (precipitation) follows this same principal.
Figure 3.18: Observed VS Modelled runoff (m$^3$/s) – monthly data. For larger events, uncertainty increases as well.
Figure 3.19: Sacramento Run with precipitation uncertainty plus 3-parameter uncertainty (normal distribution ±10%) VS normal Sacramento Run (bars).

Figure 3.20: Uncertainty in Evapotranspiration Estimation. The continuous black line depicts the initially estimated values.
3.5.3 MODFLOW

The uncertainty in MODFLOW simulations is a result of the uncertainty in the precipitation, evapotranspiration and runoff input that produces the input of recharge. In addition to this, a part of the uncertainty also derives from the estimation of K for the materials of the basin. Since MODFLOW is a distributed model, the uncertainty in every grid cell is different, making the overall uncertainty difficult to estimate. Nevertheless, for the purposes of this case study it is only important to produce results for the sites where water is already pumped and which provide the current resources. For this reason it is safer to focus on the uncertainty in the simulation of the cells that represent wells where observed data already exists.

Figure 3.21 and Figure 3.22 show the simulation of the groundwater level for two characteristic sites near the outlet of the basin in Phaistos. In most cases the reference simulation (where no uncertainty is included) showed excellent results with $R^2 > 0.9$ and simulations including uncertainty had an efficiency of the same range. It is interesting that as groundwater fluctuation increases after 1988-1989 uncertainty in results also increases. Since general precipitation characteristics don’t change throughout the simulation, this can be attributed to the uncertain properties of the basin as described in the model or a propagating effect.
Figure 3.21: Observed and Simulated values from Well 104

Figure 3.22: Observed and Simulated values from Well B1


3.6 Prediction

3.6.1 Climatic changes in the Mediterranean

Confidence in local and regional climate predictions, as in the case of Mediterranean and Greece, is low due to the weakness of models in predicting the regional and local effects of climate change. Projections vary widely depending on the model and the test area. In order to estimate climatic changes on this scale, a better knowledge of many complex processes is required.

Global temperatures are expected to increase about 0.2°C/decade and climb by between 1.7 and 4°C by the year 2100. A number of models indicate that precipitation will increase in mid and high latitudes, especially in winter, and decrease in subtropical zone.

All model simulations for Europe agree that on the average the range of temperature rise is expected to be higher in North Europe in comparison to the Mediterranean areas. Despite that the prediction of the temperature change varies widely, most of the models suggest that the winter temperature will increase more over North Europe while in summer the increase will be higher over South Europe. Moreover, the winter temperature increase over North Europe will be higher than the increase in summer whereas the summer temperature increase over South Europe will be slightly higher than the increase in winter.

Concerning precipitation, most of the models agree in winter increase over North Europe and give some indications for increase in summer precipitation. These results could be positively correlated with the observed general increase over North Europe in 20th century. On the contrary, all models suggest that the summer temperature over South Europe will be declined whereas there are only some indications for an increase in the summer precipitation.

Models offer conflicting evidence about how climate may change on average over the Mediterranean region and particularly over Greece; thus it is very difficult to distinguish possible future climatic changes on this scale. All model simulations, however, have one common feature: temperature will increase considerably during the next decades. However, specific findings are summarised below:

Temperature

Temperatures over Mediterranean may increase to as high as 3.5°C by the year 2050 assuming a doubling of the CO₂ concentration. The estimation of warming range over
Mediterranean presents a considerably high variation (2.0 to 6.0°C by the year 2100). A lower temperature increase is expected over the sea and the coastal regions compared to the inland Mediterranean areas. The regions presenting the maximum temperature increase and sensibility are over the southern part of the Mediterranean.

Summer temperature increase over Mediterranean is substantially higher than the one over North Europe. Concerning the seasonal differences, warming over Mediterranean in winter is of the same order (or it is slightly lower) with the corresponding warming in summer.

**Precipitation**

Most projections point to significantly less precipitation in summer over the region as a whole. Contrary to some projections, several models suggest an overall increase in winter precipitation mainly over the north part of the Mediterranean region; this increase however is quite less than the one in North Europe.

In general, the prospects for precipitation over the Mediterranean region in a warmer world are still highly uncertain due to the general weakness of general circulation models (GCMs) in predicting regional precipitation. Most models offer conflicting evidence about how precipitation may change on average over the Mediterranean region. A common feature, however, of many projections is that the increase of annual precipitation over much of the Mediterranean region north of 40° or 45° N is more likely, whereas to the south of this projections, where Crete is located, point to less precipitation.

**Extreme weather events**

Despite the uncertainties over exactly how climate variability and extremes will change in the Mediterranean region, the overall picture does suggest an increase in the frequency of extreme events and, in particular, of droughts in the western Mediterranean. In general, warmer conditions over the Mediterranean region should lead to an increase in the occurrence of extremely high temperatures and a decrease in extremely low temperature events. In areas experiencing a general decrease in precipitation, droughts are likely to become more frequent as the probability of dry days and the length of dry spells increases.

The climate system consists of a series of fluxes and transformations of energy (radiation, heat, and momentum), as well as transports and changes in the state of matter (e.g., air, water, and aerosols). Received solar radiation is the major energy source that powers the entire system. The flows and transports occur between and within the main components of the system: the atmosphere, oceans, land, biota, and cryosphere (the domain of ice and
The system varies regularly due to the shape of the earth’s orbit, its angle, and daily rotation, but also irregularly because the atmosphere and the oceans are both fluids subject to internal movements associated with random turbulence, as energy is transported and transformed through the climate system. These latter variations result in climate extremes.

Climate is defined as the prevalent pattern of the weather observed over a prolonged period of time. Climate variables (e.g., temperature, precipitation, wind speed) can be time-average on a daily, monthly, yearly, or longer basis. Associated with the average states of climate variables are indications of their oscillations or variations about their mean values. The term climate change refers to an overall alteration of mean climate conditions, whereas climate variability refers to fluctuations about the mean. The changing climate will bring changes in climate variability, and may already be doing so.

Through burning fossil fuels and eradication of forests, human activity has caused the carbon dioxide (CO$_2$) concentration of the atmosphere to increase by some 25% since the industrial revolution, and that increase continues. Measurements made on Mauna Loa in Hawaii since 1956 reveal the recent CO$_2$ trend.

CO$_2$ plays an important role in inhibiting the escape of the heat radiated by the earth. The sun beams short-wave radiation to the earth, which sends long-wave radiation back to space. Greenhouse gases in the earth’s atmosphere (carbon dioxide, water vapour, methane, nitrous oxide, and the chlorofluorocarbons) absorb the outgoing radiation, thereby holding heat near our planet. This process occurs naturally: without the natural greenhouse effect, our planet would be near freezing. Instead, this process warms the earth to its current mean temperature of about 15°C.

**Climate Change and Agriculture**

While agriculture is a complex sector, the system is still dependent on climate, because heat, light, and water are the main drivers of crop growth. Plant diseases and pest infestations, as well as the supply of and demand for irrigation water are also dependent on climate. There is now concern that the effects of climate variability on food production and costs will be exacerbated due to global warming with its potential for affecting the climatic regimes of entire regions. Furthermore, such shifts in climate in different nations may have different effects on agricultural productivity and costs.

World food production varies by several per cent from year to year, largely as a result of weather conditions such as the inter-annual climatic variability in the Mediterranean and Sahel regions. But agriculture in some regions is more sensitive than in others. Typically,
sensitivity to weather is greatest firstly in developing countries, where technological buffering to droughts and floods is less advanced, and secondly in those regions where the main physical factors affecting production (soils, terrain and climate) are less favourable to farming. A key task facing those concerned with conducting climate impact assessments is to identify those regions likely to be most vulnerable to climate change, so that impacts can be avoided (or at least reduced) through implementation of appropriate measures of adaptation. The key questions for vulnerability/adaptation assessment are likely to be:

- Will climate change significantly affect domestic agricultural production?
- Will climate change cause food shortages and lead to an increase in hunger?
- Will climate change threaten exports?
- Will climate change affect key government policies such as agricultural pricing, support, research and development?
- Will climate change increase food prices to consumers?
- Will climate change, acting through agriculture, place greater stress on natural resources or contribute to environmental degradation (e.g., through land-use change, soil degradation, changes in water supply and water quality, pesticide use, etc.)?

While for the national policy maker the primary questions are likely to include:

- What components of the farming system are particularly vulnerable, and may thus require special attention?
- Can the water/irrigation systems meet the stress of changes in water supply/demand?
- What policies and programmes exist to protect populations from hunger/financial distress and how will they operate under climate change?
- Is the agricultural research/extension system capable of providing adaptation advice to farmers?
- What technological options should be investigated? Does the country have access to potentially useful options developed in other countries?
- Should domestic agricultural policies be reformed?
- Are the natural resource management programmes adequate?
If domestic production is threatened, will the country be able to import food, and (if so) at what cost? (http://www.fao.org/sd/climagrimed/c_2_02.html)

3.6.2 Climatic Scenarios

Following the uncertainty assessment and calibration phase, the models were used to predict future groundwater level responses according to the effect of the different measures referred in the decision matrix. The predictions have been made to the year 2015 when the goals of the WFD have to be reached. In this section the intention is not to provide an exhaustive assessment of all possible measures, but to simply illustrate the type of predictions that can be made according to the needs of this case study. The most important factor that has to be taken into account, at least for the scope of this research, is the variation in the average annual precipitation until 2015.

The Hadley Centre for Climate Prediction and Research\(^4\) publishes a range of climate scenarios that cover the Messara region. Some of these are based on the impact of greenhouse gas and sulphate aerosol emissions, others on the impact of greenhouse gasses alone. The scenarios predict the impact on future rainfall as a percentage of the current long-term average calculated for the period 1961-1990. The predictions are presented as a monthly percentage change.

In Crete most rainfall and, therefore, most aquifer recharge, takes place in the winter months between November and May. The Hadley Center scenarios predict a significant reduction of rainfall at this time. The scenarios chosen for the Geropotamou case study include the effects of sulphate aerosols and the monthly percentage change is presented in Table 3.3.

Mean areal precipitation was extrapolated for the period 2002 – 2015 according to the above scenarios, using as a basis the period 1977 – 1990. The following prediction runs have been based on these precipitation time series.

\(^4\) http://www.metoffice.com/research/hadleycentre/
Table 3.3: Climatic change scenarios from the Hadley centre, focused on precipitation

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatescenario 1</td>
<td>-8.52</td>
<td>-9.28</td>
<td>-4.99</td>
<td>-3.41</td>
<td>-4.89</td>
<td>6.1</td>
</tr>
<tr>
<td>Climatescenario 2</td>
<td>-16.9</td>
<td>-12.5</td>
<td>-10.56</td>
<td>-12.52</td>
<td>-16.76</td>
<td>-17.96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatescenario 1</td>
<td>9.95</td>
<td>0</td>
<td>-9.12</td>
<td>-0.29</td>
<td>-8.9</td>
<td>-12.28</td>
</tr>
<tr>
<td>Climatescenario 2</td>
<td>0</td>
<td>-34.36</td>
<td>-14.2</td>
<td>-0.24</td>
<td>-23.99</td>
<td>-26.33</td>
</tr>
</tbody>
</table>

3.6.3 Impacts of climatic change

In order to compare the results of each measure with the present situation conditions, initially the groundwater level was simulated in a “business as usual” scenario. In this scenario pumping rates were kept equal to the 2002 estimation of annual extractions (77.7Mm$^3$) while recharge rates of the aquifer were calculated from Sacramento using the same uncertainty intervals as the ones used so far. The results of this scenario are shown in Figure 3.23, where a single well level is simulated assuming that it characterises the whole aquifer behaviour.

The aquifer fluctuation also depends on the climatic scenario under which the simulation is run. Climatescenario 1 (CS-1) which predicts only a slight decrease of precipitation has a favourable impact on the groundwater level for the period 2007-10 but in the long term the status remains unchanged and very similar to the Climatescenario 2 (CS-2) predictions. The projected precipitation pattern includes an uncertainty interval which has propagated to the groundwater level fluctuation simulation. This uncertainty is shown in the following figures in the form of a grey area.

Recent observations (2005-6), which have not been included in the study, agree with this predicted improvement. Nevertheless, the same simulation predicts that the system will gradually return to the present unsatisfactory state. It’s evident that the aquifer partially recovers by 2007-8 because of temporary changes in the precipitation patterns. Also, for
Climatic Scenario 2 the aquifer in 2015 appears to be under the sea level. This is already a problem in the adjunct basin of Tympaki where the possibility of salt intrusion is being investigated.

![Figure 3.23: Prediction of groundwater level fluctuation in the "business as usual" scenario for 2 different Climatic Scenarios](image)

a) Control illegal pumping and trading.

The results of this measure are highly uncertain since it depends on the human factor. The reaction of farmers to such a measure will definitely be negative. There are numerous examples of misbehavior of the local society when strict legislation is about to be inflicted, often seen as a peculiarity of the rural way of life in Crete. Local authorities estimate that illegitimate pumping add up to an annual 10Mm$^3$, depending on irrigation needs. Assuming that the constitution of controlling force will yield results in deterring illegitimate pumping, the amount of groundwater that will be saved needs to be calculated. It is estimated that this measure will stop about 35% of the uncontrolled pumping or save 3.5Mm$^3$ on an annual bases. Keeping in mind the current total amount of pumping in the area has been estimated at 77.7Mm$^3$/year a projection will made assuming a constant annual pumping rate of 74.2Mm$^3$/year. The results of this scenario are presenting in Figure 3.24 where they are compared with the "business as usual" scenario.

From Figure 3.24, at the end of the measure implementation (01/01/2015) the resulting groundwater level is -31.0m± 2.5m (asl) depending on the uncertainty included in precipitation. This is equivalent to the levels of 1991 and 1997.
Figure 3.24: Prediction of groundwater level fluctuation after Measure (a) implementation for the Climatic Scenario 1

Figure 3.25: Prediction of groundwater level fluctuation after Measure (a) implementation for the Climatic Scenario 2
b) Price policy for irrigation water

The policy of augmenting the water tariff will certainly bring undesirable reactions, probably even more so than the illegal pumping control method. The reason is that pumping control will be aimed only on wrongdoers who might be singled out by the community whereas a price policy will probably affect more farmers and cause a wave of discontent. Apart from the small acceptance, drawbacks of this measure can be seen in other fields as well, as the competitiveness of the production due to irrigation cost increases. Furthermore, this measure could result in chain effects like the increase of illegal water trading which already takes place to some extent. Another side effect could be the increase of production cost which will probably end up burdening the consumer with all the socio-economic consequences this could bring about.

Taking into account current measure results in other basins, it is estimated that the price policy will decrease irrigation water consumption by 3Mm$^3$ annually. Thus, in order to assess the effect of this measure in the groundwater level the simulation was initialised with a constant annual pumping rate of 74.7Mm$^3$/year.

The modelling results are presented in Figure 3.26 and Figure 3.27. These figures show that by the end of the simulation period (01/01/2015) the measure has resulted to an average groundwater level of -33.9 to -36.4 depending of the Climatic Scenario

c) Irrigation Network

The construction of the irrigation network, aside from the costs it induces, has only positive effects. Acceptance from farmers is certain and the impact on the groundwater level will be the optimum in comparison to other measures since the project is due to save 5 to 6 Mm$^3$ according to the estimates of the Department of Water Resources of the Prefecture of Crete. Results are presented in Figure 3.8 and Figure 3.9.
Figure 3.26: Prediction of groundwater level fluctuation after Measure (b) implementation for the Climatic Scenario 1.

Figure 3.27: Prediction of groundwater level fluctuation after Measure (b) implementation for the Climatic Scenario 2.
**Figure 3.28:** Prediction of groundwater level fluctuation after Measure (c) implementation for the Climatic Scenario 1.

**Figure 3.29:** Prediction of groundwater level fluctuation after Measure (c) implementation for the Climatic Scenario 2.
The final results of groundwater level prediction that are used in the decision matrices are summarized in Table 3.4.

**Table 3.4: Average groundwater levels (asl) in 1/1/2015 as they are used in the decision making process**

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>Measure</th>
<th>Effect on Groundwater Level (m) (below surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No measures implemented</td>
<td>-39.8</td>
</tr>
<tr>
<td></td>
<td>Control illegal pumping</td>
<td>-32.8</td>
</tr>
<tr>
<td></td>
<td>Price Policy</td>
<td>-33.9</td>
</tr>
<tr>
<td></td>
<td>Irrigation Network</td>
<td>-30.8</td>
</tr>
<tr>
<td>C1</td>
<td>No measures implemented</td>
<td>-41.2</td>
</tr>
<tr>
<td>C1</td>
<td>Control illegal pumping</td>
<td>-35.2</td>
</tr>
<tr>
<td>C1</td>
<td>Price Policy</td>
<td>-36.4</td>
</tr>
<tr>
<td>C1</td>
<td>Irrigation Network</td>
<td>-33.0</td>
</tr>
<tr>
<td>C2</td>
<td>No measures implemented</td>
<td>-41.2</td>
</tr>
<tr>
<td>C2</td>
<td>Control illegal pumping</td>
<td>-35.2</td>
</tr>
<tr>
<td>C2</td>
<td>Price Policy</td>
<td>-36.4</td>
</tr>
<tr>
<td>C2</td>
<td>Irrigation Network</td>
<td>-33.0</td>
</tr>
</tbody>
</table>
4 Cost calculation

4.1 Financial Costs

Cost calculation has been done separately for each alternative measure of the decision matrix. This cost depends on many factors and for that reason the uncertainty included in the calculation is large. More specifically, two of the most important factors involved in the cost calculation are the following:

The financial instability of Greece after the monetary union with the rest of the European Community that has caused all services and products prices to rise and

The instability of international markets due to the uncertainty following the price of fuels that directly influences local markets of services and products.

i) Control illegal pumping and trading (actor related)

Operating: the annual cost of maintaining the task force (salaries – 17,000€ per officer, expendables etc). For a 10 person force, the annual cost can sum up to 200,000€.

External costs cannot be easily predicted in this case.

The total cost of this measure until 2015 can be determined as the investment cost of hiring, training, equipping and managing personnel (50,000€) plus the annual costs (200,000€) taking into account an average inflation rate (3%). This adds up to 2,342,776€ by the year 2015.

ii) Price policy for irrigation water (actor related)

Investment: For this measure to be successful, a financial assessment should be carried out, specifying the sustainability of the desired agricultural production and the cost of potential solutions that could be funded. The cost of the financial assessment for the study area could range to 250,000€.

Operating: The cost of implementing this measure is negligible. There will only be incomes which have to be properly managed.

External: Several issues, like the transfer of cost of water to the cost of agricultural products, the competitiveness of the production in the local and international market and the reaction of farmers (who in Greece are a very politically active social class), have to be taken into account. Augmenting water prices will almost certainly have an advert effect in illegal water
pumping and trading, causing the problem to transfer to controlling these activities. Other reactions could include switching to more irrigation demanding cultivations.

i) **Irrigation Network (environmental related)**

In June 2005, a new plan of land reclamation efforts was announced by the Ministry of Agricultural Development and Food Products and the Secretary of planning and implementation of the 3rd CSF. These plans include 15 development projects estimated to cost 181 M€ were reported to serve as a bridge between the 3rd and 4th CSF and will be concluded after 2007. One of these projects is the connection channel of the Faneromeni Dam with the local irrigation networks. The budget of this project has already been announced to 25,200,000€, which means that this sum will probably not be surpassed. Maintenance and operation costs should be similar to the present costs of maintaining the local irrigation networks.

### 4.2 Evaluation method

In the present case study, cost-effectiveness considerations cannot easily undertaken because there are large uncertainties in the prediction of costs or acceptance effects, so multicriteria analysis is considered the best way out. The multicriteria method selected for the present analysis in PROMETHEE. PROMETHEE is one of many so-called outranking methods.

The preference functions and the methodology are explained with detail in the WP3 documents of the HarmoniRiB project. According to that, the PROMETHEE method acknowledges that there are (at least) two possible ways to create a complete rank order of alternatives in a set \( A \) of all alternative actions. The rank of an alternative \( a \in A \) could be measured by the sum of the pairwise preferences of this alternative over all the alternatives in the set \( A \):

\[
\Phi^+(a) = \sum_{x \in A} \Pi(a, x)
\]

(9)

where \( a \) is preferred to \( b \) if \( \Phi^+(a) > \Phi^+(b) \). Alternatively the rank of \( A \) could be measured by the sum of the preferences of the other alternatives in the set \( A \) over \( a \):

\[
\Phi^-(a) = \sum_{x \in A} \Pi(x, a)
\]

(10)
where $a$ is preferred to $b$ if $\Phi^-(a) < \Phi^-(b)$. If weak preference exists in some of the criteria, i.e. if some of the thresholds $p_i$ and $q_i$ are nonzero, then the sum $\Pi(a,b) + \Pi(b,a)$ is not a constant for all pairs of alternatives $(a,b)$ and thus $\Phi^+(a) > \Phi^+(b)$ does not imply $\Phi^-(a) < \Phi^-(b)$.

Now PROMETHEE combines both measures and defines:

- $a$ preferred to $b$ if $\Phi^+(a) > \Phi^+(b)$ and $\Phi^-(a) < \Phi^-(b)$;
- $b$ preferred to $a$ if $\Phi^+(a) < \Phi^+(b)$ and $\Phi^-(a) > \Phi^-(b)$;
- $a$ and $b$ are indifferent if $\Phi^+(a) = \Phi^+(b)$ and $\Phi^-(a) = \Phi^-(b)$;
- $a$ and $b$ are incomparable otherwise.

Consequently, if there are weak preferences in one or more criteria incomparability can occur and lead to a partial rank order.

There exist different variations of PROMETHEE: The described definition of the preference, indifference and incomparability relations are called PROMETHEE I. In contrast to this version in PROMETHEE II it is $\Phi(a,b) = \Phi^+(a,b) - \Phi^-(a,b)$ and $a$ is preferred to $b$ iff $\Phi(a,b) > 0$. In PROMETHEE II the result is always a complete rank order of the alternatives.

1 If only normal preferences are used in PROMETHEE the intensity of preferences have no impact on the ranking of the alternatives. This is – at least to a certain degree – not the case if weak preferences are applied.

If only normal preferences are used in PROMETHEE the intensity of preferences have no impact on the ranking of the alternatives. This is – at least to a certain degree – not the case if weak preferences are applied.
5 Results

Based on the previous analysis, two scenarios are being developed. Each scenario has been generated in accordance with two different precipitation scenarios from the Hadley Centre for Climate Prediction and Research until 2015. Both scenarios predict a decrease in annual precipitation but differ in the rate. It is important to note that these scenarios affect only the criterion of Groundwater level in the decision matrix.

The scenarios which are investigated are the following:

Climatic Scenario 1

This scenario predicts a moderate decrease in precipitation and its decision matrix is presented in Table 5.1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Alternative</th>
<th>Groundwater level</th>
<th>Cost (direct + indirect)</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stop illegal pumping</td>
<td>-32.8</td>
<td>2,342</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Water price</td>
<td>-33.9</td>
<td>0,250</td>
<td>Bad</td>
</tr>
<tr>
<td></td>
<td>Irrigation Network</td>
<td>-30.8</td>
<td>25,200</td>
<td>Good</td>
</tr>
</tbody>
</table>

The values for the Groundwater Level criterion are taken from Table 3.4, as they were estimated from the projection of measures. The cost has been analysed in Chapter 4 and the Acceptance criterion is based on the analysis made in the paragraph “Framing decision making process” of Chapter 2.

As described in the same paragraph, in order to set the absolute weights for the decision processes, the values (Groundwater Level = 0.5, Cost = 0.2 and Acceptance = 0.3) were used. These values can change according to the judgement of the decision maker and the current socioeconomic status.

Climatic Scenario 2
This scenario predicts a larger decrease in precipitation and its decision matrix is presented in Table 5.2.

Table 5.2: Decision matrix for Climatic Scenario 2

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Alternative</th>
<th>Groundwater level</th>
<th>Cost (direct + indirect)</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>meters from surface</td>
<td>M Euros</td>
<td>Categorical</td>
</tr>
<tr>
<td>Stop illegal pumping</td>
<td></td>
<td>-35.2</td>
<td>2,542</td>
<td>Good</td>
</tr>
<tr>
<td>Water price</td>
<td></td>
<td>-36.4</td>
<td>0,250</td>
<td>Bad</td>
</tr>
<tr>
<td>Irrigation Network</td>
<td></td>
<td>-33.0</td>
<td>25,200</td>
<td>Good</td>
</tr>
</tbody>
</table>

The values in the decision matrix have been filled in according to the same principals used for the previous scenario. In this case the decision maker has to face a more severe problem; that of the precipitation decrease. For this reason it is assumed that an extra 200,000€ is being dispensed under the umbrella of controlling illegitimate pumping actions. The new actions can include a publicity campaign informing farmers of the future environmental hazards arising from illegal pumping and trading of water. This campaign will have a positive effect on the measure’s acceptance changing its scale from Medium to Good. The absolute weights are also set to the same values as in Scenario.

**Scenario Results:**

The results of PROMETHEE I and II ranking methods for the two scenarios are included in the following figures.

1. Irrigation Network
   - $\Phi = 0.60$

2. Control Pumping
   - $\Phi = 0.00$

3. Price Policy
   - $\Phi = -0.60$
It is evident that the alternative of constructing an irrigation network is by far the best solution in the groundwater availability problem, followed by the control of illegal pumping and the price policy adjustment. Ranking is the same for both scenarios that have been developed, although the preference functions are different. In the second scenario, the illegal pumping control alternative becomes more effective while the irrigation network construction effectiveness decreases as shown in Figure 5.5.
Resulting from the multi-criteria analysis, the optimum solution is the construction of the irrigation network, a solution that is more or less obvious given the situation in the Messara Valley. Nevertheless, this measure alone does not guarantee that the status of the aquifer will improve. This is evident in Figure 3.28 and Figure 3.29 where in April 2014 the groundwater level has relapsed at 21 to 23 meters below the ground surface depending on the climatic scenario. The relatively bad status in the last years of simulation is mainly due to the predicted dry period of 2013-2015 and not to the small effectiveness of the measure. Integrated management has to take account of these climatic fluctuation so a combination of alternative measures in being examined.

**Combined alternatives:**

Even though the results from the contraction of connecting channel of the Phaneromeni Dam with the irrigation network is the obvious solution to the problem, the impact on the groundwater level is not enough to bring good status. For this reason the combination of alternatives has been considered in order to evaluate their results as well. A comparison has also been made between the two climatic scenarios.

MODFLOW was setup and run according to the ranking output of PROMETHEE, so as to predict, initially the effects the combination of alternatives (a) and (c) for both climatic scenarios and then of all alternatives together. The predicted effects of those measures can be seen in Figure 5.6 and Figure 5.7 as well as in Table 5.3.
The effects of these combined alternatives are supplementary. The best results can be seen in the case of the Climatic scenario 1 when there is more precipitation to assist the groundwater level restoration and at the same time all measures are being implemented at once. It can be observed that in this case the groundwater level for April 2014 is at 13.3m from the surface. The fact that the groundwater level is so high, comparatively to the current conditions, even though the period 2013-2015 is predicted as dry can be interpreted as the achievement of good status.
Figure 5.6: Prediction of groundwater level fluctuation after Measure (a) and (c) are implementation for the Climatic Scenario 1.

Figure 5.7: Prediction of groundwater level fluctuation after Measure (a), (b) and (c) are implementation for the Climatic Scenario 1.
Figure 5.8: Prediction of groundwater level fluctuation after Measure (a) and (c) are implementation for the Climatic Scenario 2.

Figure 5.9: Prediction of groundwater level fluctuation after Measure (a), (b) and (c) are implementation for the Climatic Scenario 2.
Table 5.3: Impact of alternative measures on the groundwater level

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Measure</th>
<th>Groundwater Level from surface April 2007</th>
<th>Groundwater Level from surface April 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-9.8 ± 1.1</td>
<td>-28.9 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>(a) Control illegal pumping</td>
<td>-7.8 ± 0.9</td>
<td>-23.0 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>(b) Price Policy</td>
<td>-8.1 ± 0.9</td>
<td>-23.9 ± 2.6</td>
</tr>
<tr>
<td></td>
<td>(c) Irrigation Network</td>
<td>-7.2 ± 0.8</td>
<td>-21.3 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>Measures (a) and (b)</td>
<td>-5.6 ± 0.7</td>
<td>-17.0 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>Measures (a), (b) and (c)</td>
<td>-4.4 ± 0.4</td>
<td>-13.3 ± 1.5</td>
</tr>
</tbody>
</table>

Climatic Scenario 1
(small precipitation reduction)

|                           | No measures implemented  | -10.3 ± 1.2                                | -30.6 ± 2.6                              |
|                           | (a) Control illegal pumping | -8.5 ± 1.0                                | -26.0 ± 2.8                              |
|                           | (b) Price Policy          | -8.2 ± 0.9                                | -25.1 ± 2.7                              |
|                           | (c) Irrigation Network    | -7.6 ± 0.8                                | -23.3 ± 2.3                              |
|                           | Measures (a) and (b)      | -5.9 ± 0.7                                | -18.3 ± 2.0                              |
|                           | Measures (a), (b) and (c) | -4.6 ± 0.5                                | -14.5 ± 1.6                              |

Climatic Scenario 2
(large precipitation reduction)
6 Evaluation of HarmoniRiB products

HarmoniRiB has provided the Geropotamou Case Study with the methodology and tools to incorporate uncertainty in decision making for local water resources remediation purposes. Throughout the duration of the HarmoniRiB project, all Work Package products have assisted in the successful understanding or implementation of the required procedure.

Framework - Coordination

Work Packages 1 and 9 assisted in the overall coordination and communication between partners, from requirements and guidelines, communication through meetings and information exchange to intermediate and final reports. The internal website that supported HarmoniRiB served its purpose well by being a dynamic repository of past and current shared documents. It also acted as a virtual space of exchanging ideas and keeping track of progress among Case Studies and project partners.

Methodology

Work Package 2 provided the methodology for uncertainty assessment. The reports on data and model uncertainty were a practical set of guidelines that helped define uncertainty information about common variables such as meteorological and hydrogeological data as well as modelling concepts. Even though most uncertainty information in the Geropotamou was site specific and the approach quite generic, this product gave an explanatory first outline on how approach the subject of data uncertainty. Also, DUE, the software that was developed for the purposes of HarmoniRiB was an indispensable pre-processing tool that solved many issues of managing storing data uncertainty.

The role of Work Packages 3 was to integrate socio-economic approaches to decision making and provide guidelines for multi-criteria analysis leading the optimum solution. Here WP3 products supported the Geropotamou Case Study report by providing insight on issues that lay beyond the research scope of engineering.

Database

Work Package 4 which was in charge of database design did not offer direct assistance to the Case Study but database documentation was sufficient for an overall understanding of the principals behind the organization of the uploaded data. On the other hand, training on data uploading and general database use, which was provided by Work Package 5, was very important for the task of providing publicly available datasets. Far from the workshops help
during HarmoniRiB meeting, Work Packages 5 and 6 also gave support and solutions for the uploading and storing processes as well as the data sharing and downloading from the end users.

**Application**

This Case Study is part of the application of the methodologies and tools provided by HarmoniRiB. Work Package 7 which includes it, together with 7 more Case Studies has assisted in the integrated presentation and overall presentation of the results. At this point the product of this WP are difficult to evaluate but the expectation is that they will provide a good example and a strong argument for the point the HarmoniRiB project is attempting to demonstrate on the role of uncertainty on decision making.

**Dessemination**

Finally, HarmoniRiB results are being disseminated under the supervision of Work Package 8. Its products have to be evaluated by the end users and the public.
The Geropotamou Case Study is focused on the severe groundwater resources availability problems faced in the semiarid Watershed of Geropotamou steam in Crete, Greece.

In the frame of the HarmoniRiB project a well documented dataset has been created, organized and stored in the HarmoniRiB’s database. Uncertainty information has been assessed in every uploaded dataset, which are now publicly available. In order to attach the uncertainty information, tools and methodologies provided by HarmoniRiB has been applied.

In order to deal with the groundwater resources problem in Messara Valley, this study proposes the implementation of a set of measures:

- initially, the connection of the currently constructed dam of Phaneromeni with the local irrigation network, then
- the establishment of a task force to control illegitimate pumping and trading and finally,
- the modification of the water price policy.

These measures were evaluated according to specific criteria as their predicted effect on the groundwater level, their cost and their acceptance. The above measures and criteria were the components of a decision matrix which frames the decision making process. The absolute weights were set according to the priorities of the WRDPC. In order to complete the matrix, each criterion was studies separately.

For the groundwater level criterion, a modelling process had to be followed. Initially, two physical models (Sacramento and MODFLOW) were setup and calibrated and later run using timeseries that includes uncertainty. During the transition from Sacramento to MODFLOW the propagation of uncertainty was studied, as well as the effect of the uncertain modelling parameters. Successively, the models were used to simulate the groundwater level for the period 2006-2015 and the results of this simulation were used in the decision matrix. These values also include uncertainty information and are suitable for studying the influence of uncertainty on management decisions in order for them to be applied in the development of an integrated water management plan. Also, in order to specify the Cost and Acceptance criteria, information was used from the present socioeconomic conditions in the area. This procedure took place for two different Climatic Scenarios of reduced precipitation.
Even though the uncertainties that have not been considered so far in this study are many, they have been regarded as unimportant. Such uncertainties are included in measured variables like runoff, temperature and well levels as well as various model parameters that have been kept constant throughout the simulations. For some of them, like runoff, uncertainty can be neglected especially now that flow is reduced to a minimum. For others, like in the case of Sacramento parameters, the resulting uncertainty can be important but difficult to take into account. Moreover, for a number of variables and parameters, uncertainty was underestimated so that models would still behave as well as in the calibration phase.

Another type of uncertainty that was neglected in order to simplify the study has to do with the effects of alternative measures and the weights of criteria. In case the uncertainties of such socio-economic parameters have to be incorporated, there should be a turn to more complex techniques in the decision making process. Cost calculation is also a large issue. For all measures some costs differences may exist due to various factors (maintenance, infrastructure risks, technological development uncertainties etc.) so a more extensive study should be undertaken to identify them.

Furthermore, in the present study, the alternative measures that were considered were only the most obvious. In order to make an integrated study of the decision making process under uncertainty, a complete set of alternative (educating farmers to irrigate responsibly, alternating cultivations to less water-demanding crops, building several small reservoirs to serve local needs, and more) and their effects need to be considered. For some of these alternatives it will be possible to implement in phases in order to partition cost and for others to delay implementation in order to spread expenses. Considering these parameters will add new dimensions to the problem and complicate the solution but also provide a better decision support system.

The multi-criteria analysis method PROMETHEE was chosen to rank the alternative measures in effectiveness order. From the results it can be concluded that the isolated implementation of each measure may have positive results but will not help achieve good status of the groundwater resources by 2015. For this reason the alternative of combining more that one measure was considered. This combination resulted in satisfactory predictions for the condition of the aquifer even though the levels of 1980 when the system was undisturbed were not achieved. Nevertheless, the average effectiveness of all measures is partially due to the predicted dry period of 2013-2015.
It can be argued that this prediction increases the uncertainty in the effectiveness of each measure. Furthermore, new climate change scenarios exist, predicting an increase in precipitation in the next years. If these scenarios are taken into account the previously mentioned alternatives are bound to yield better results.

In order to cope with the groundwater resources problem of the Geropotamou basin, an integrated approach is needed so that the decision process is more realistic. The Technical University of Crete through the present case study attempts to improve the understanding and assessment of uncertainty for the purpose of providing more robust integrated water management plans under the implementation of the WFD.
References


Investor’s World, June 2005 (Greek Newspaper)


