WaterJPI project

SMARTControl

Smart framework for real-time monitoring and control of subsurface processes in managed aquifer recharge (MAR) applications

Deliverable D7.4

Value of information associated to MAR real-time monitoring and control

Authors

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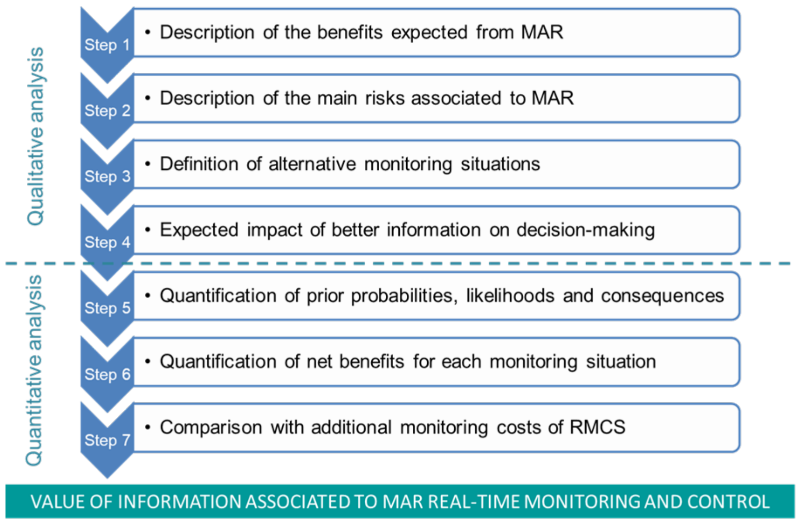


https://www.smart-control.inowas.com

July 2022

Project funded by:

Deliverable D7.4

Value of information associated to MAR real-time monitoring and control

Short summary

This report describes the principle of the evaluation of Value of information (VoI) and presents a generic stepwise approach for assessing the VoI associated to SMART-Control monitoring system that can be implemented on a wide variety of contexts. It then presents the implementation of the stepwise approach to two operational MAR sites of the project: Berlin-Spandau (Germany) and Ezousa (Cyprus).

Work package	WP7. Strengthening the SMART-Control approach
Deliverable number	D7.4
Partner responsible	BRGM
Deliverable author(s)	Cécile Hérivaux (BRGM), Konstantinos Panagiotou (UCY), Christoph Sprenger (KWB), Catalin Stefan (TUD)
Quality assurance	Jean-Christophe Maréchal (BRGM), Jana Glass (TUD)
Planned delivery date	
Actual delivery date	July 2022
Dissemination level	PU (Public)

Project funded by:

ABSTRACT

SMART-Control proposes to develop and implement an innovative web-based, real-time monitoring and control system in combination with risk assessment and management tools. SMART-Control tools will allow operators to optimize the performance of MAR systems by enhancing risk assessment and management, by increasing the probability to take good management actions. Additional monitoring and data collection may be costly, but also brings higher benefits than classical monitoring systems. **The question then is whether the decisions related to the MAR scheme should be made on the basis of the classical monitoring system or whether it is worth investing in SMART-Control system providing additional information.** In economics, the concept of the value of information (VoI) compares the expected net benefits of collecting additional information to reduce or eliminate uncertainty associated with the outcome of a decision and the expected net benefits of a preferred uninformed alternative.

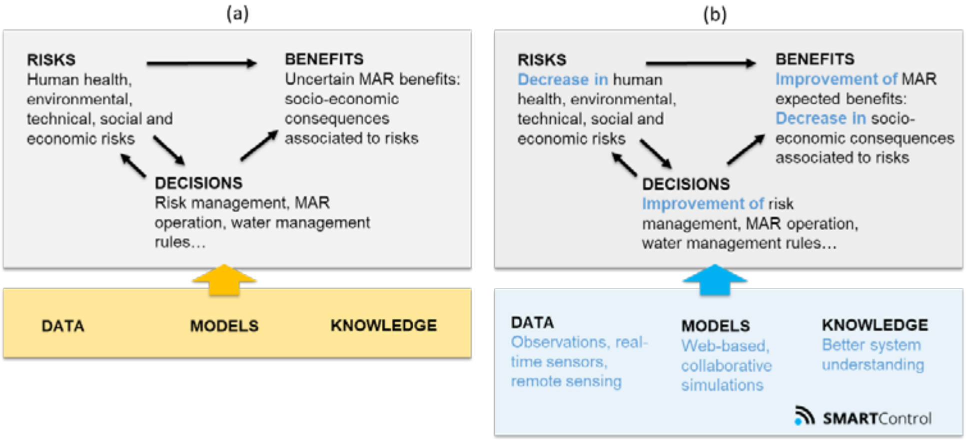


Figure. Benefits expected from MAR real-time monitoring and control: risks, decisions and benefits with (a) classical monitoring and (b) SMART-Control real-time monitoring and control

This report describes the principle of VoI evaluation and presents a generic step-wise approach for assessing the VoI associated to SMART-Control monitoring system that can be implemented for a wide variety of contexts. The approach first relies on a qualitative evaluation (steps 1-4) aimed at understanding the benefits, risks, and how the SMART-Control tools can improve decision-making at each study site. If better information has a potential impact on decision-making and on benefits, the quantitative analysis of the economic consequences and probabilities can be implemented (steps 5-7) to assess VoI.

The report then presents the implementation of the stepwise approach to two operational MAR sites of the project: Berlin-Spandau (Germany) and Ezousa (Cyprus). In the Berlin-Spandau case (Germany), MAR is used to sustain drinking water production capacity, while maintaing support to groundwater dependent ecosystems. The qualitative analysis highlights that better information does not translate into changes in decision-making by the drinking water company with associated economic consequences. Two types of improvement are however provided by the real-time monitoring and control: 1) improved knowledge of hydraulic residence time (HRT), making it possible to guarantee that the HRT is greater than 50 days for all production wells and therefore to reduce the residual risk for human health in terms of DALYs and 2) faster detection of the type of problem and its origin in the event of an emergency, making it possible to have a more efficient management system. An interesting perspective to highlight the VoI on this site would be to implement a hybrid approach, combining QMRA and Bayes' theorem, by expressing the VoI in DALYs, not in monetary terms. In the Ezousa case (Cyprus), MAR plays a major insurance role for irrigation water supply. The full analysis (steps 1-7) is implemented, with a stakeholder-oriented approach based on the consultation of institutional stakeholders and farmers. We developed a survey aiming to improve the knowledge of the consequences of different drought and water shortages conditions in the Paphos district. Based on the results obtained with 54 farmers, the analysis provides first estimates of the net benefits associated with SMART-Control monitoring to secure irrigation volume from MAR at 260 €/ha, or 0.033 €/m^3. This equals a net benefit of approximately 27 000 €/year on the sample scale and

310 000 €/year if extrapolated for the 8 Paphos districts (rough estimation). Compared to the investment, operation and maintainence costs of the monitoring network (estimated at 4 400 €/year), the proposed SMART-Control monitoring solution could provide a solid and cheap technical solution to secure seasonal irrigation water supply with positive net benefits.

LIST OF ABBREVIATIONS

BWB	Berliner Wasserbetriebe
CAPO	Cyprus Agricultural Payments Organisation
DALY	Disability Adjusted Life Years
Dca	Decare
EU	European Union
FCM	Flow Cytometry Measurements
GDE	Groundwater Dependent Ecosystem
Ha	Hectare
HRT	Hydraulic Residence Time
IBF	Induced Bank Filtration
MAR	Managed Aquifer Recharge
Mm3	Million cubic meter
QMRA	Quantitative Microbial Risk Assessment
SAT	Soil Aquifer Treatment
VoI	Value of Information
WDD	Water Development Department
WHO	World Health Organisation
WWTP	Waste Water Treatment Plant

CONTENT

FIGURES

TABLES

1. INTRODUCTION

Storing water in surface reservoirs as a means to ensure water security has a very long history across many countries (Nandha et al., 2015). However, the high financial, social and environmental costs of reservoirs, coupled with their vulnerability to contamination, high evaporation rates and the decreasing availability of land have driven investigations into alternate storage methods such as Managed Aquifer Recharge (MAR) (Nandha et al., 2015). In MAR, a water source, such as recycled water (e.g., derived from urban stormwater or treated sewage) or natural water (e.g., from a lake or river), is used to recharge an aquifer with water under controlled conditions. The aquifer is used to store surplus water for later use or environmental benefits (NRMMC, 2004).

MAR is being utilised to buffer against drought and changing or variable climate, as well as provide water to meet growth in demand, by making use of intermittent excess surface water supplies and recycled waters (Megdal and Dillon, 2015). As such, MAR can be seen as a major contributor to alleviating the projected shortfall in water supplies to cities (NRMMC, 2004) and food security through irrigation. Additional benefits may also result from the water being in place in the aquifer: e.g., reduced groundwater-pumping costs, avoidance of the need to replace or deepen production wells, restoration or maintenance of environmental (e.g., spring) flows, avoidance of land subsidence, and prevention of saline water intrusion (Maliva, 2014). MAR systems using stormwater can also contribute to mitigate flooding of downstream urban areas, and increase the value of land and homes surrounding ponds and parks (NRMMC, 2004). Potential benefits of MAR schemes are numerous, and differ according to the types of MAR schemes and site characteristics. These benefits can be assessed with different types of methods (for an overview, see Maliva 2014) in order to justify the investment in a MAR project and measure its overall welfare impact on society.

MAR is a nature-inspired technique vulnerable to site-specific and operational conditions. Therefore, MAR schemes may not always operate as expected. They may face some risks (human health, environmental, technical, social and economic, governance and legislation risks) at different stages of their implementation and operation (Imig et al., 2022) that may decrease performance indicators of the systems and even threaten their long-term viability (Figure 1). In fact, although the subsurface component provides water storage and treatment functions, it may add hazards to stored water and create other environmental problems (NRMMC, 2004). For instance, potential changes in water quality during storage due to the interactions between the aquifer rock, the native water and the recharge water constitute a significant risk to the safe operation of MAR schemes (Nandha et al., 2015). There is additionally an uncertainty related to the quantity of water that will remain in storage as a result of potential losses due to dispersion, other abstractors, etc. all of which reduce the quantity of recoverable water (Nandha et al., 2015). As a result, recharge may not result in anticipated changes in aquifer water levels and anticipated additional water may not be available when needed (poor recovery efficiency), thus leading to additional costs for water utilities that may have to purchase water from other resources. Although several methods exist to incorporate potential risks and uncertainties in cost-benefit analysis (Pearce et al., 2006), they are still a neglected aspect of the economics of MAR (Maliva, 2014).

These risks can be reduced but never entirely eliminated through high quality and more detailed aquifer characterisation (Nandha et al., 2015). Monitoring can play a key role in the risk assessment and management process. Operational monitoring systems are of particular importance as they provide timely information for use as critical control points in the risk management plan, often include supervisory control and data acquisition and web-based reporting systems that provide near real-time data (NRMMC, 2004). SMART-Control proposes to develop and implement an innovative web-based, real-time monitoring and control system in combination with risk assessment and management tools. The online sensors measure the most common operational, chemical and biological parameters that influence the risk at MAR facilities: i.e., infiltration water volume, groundwater level, temperature, electrical conductivity, microbial content, chemical oxygen demand, nitrate, spectral adsorption coefficient, total suspended solids and dissolved organic carbon. SMART-Control tools allow operators to optimize the performance of MAR systems by enhancing risk assessment and management, by increasing the probability to take good management actions. Additional monitoring and data collection may be costly, but also bring higher benefits than classical monitoring systems (Figure 1).

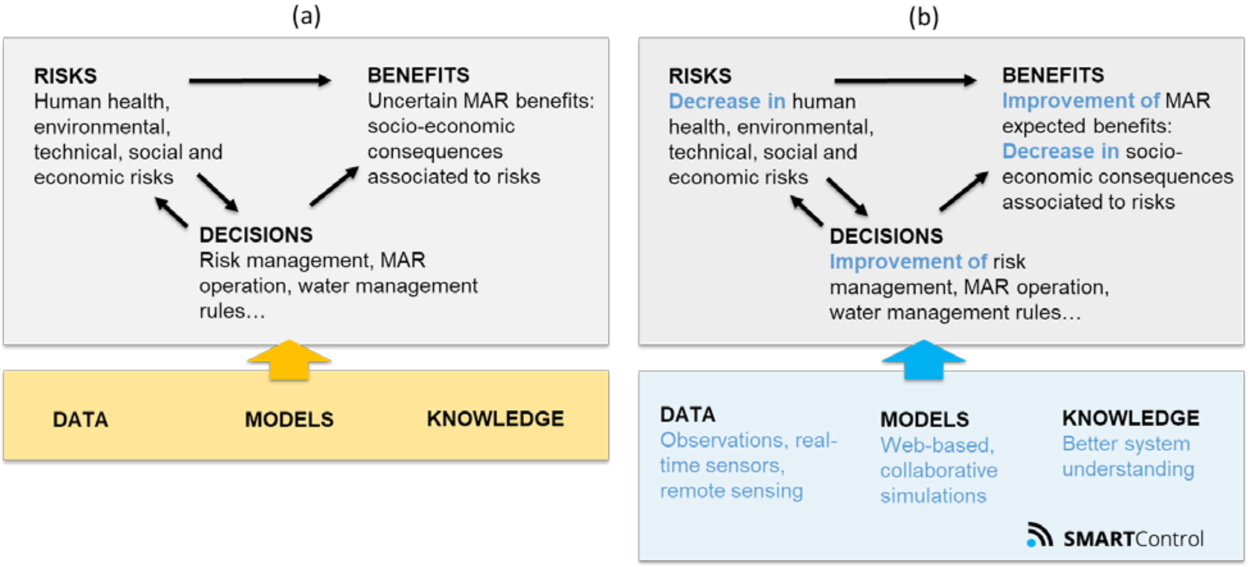


Figure 1. Benefits expected from MAR real-time monitoring and control: risks, decisions and benefits with (a) classical monitoring and (b) SMART-Control real-time monitoring and control

The question then is whether the decisions related to the MAR scheme should be made on the basis of the classical monitoring system or whether it is worth investing in SMART-Control system providing additional information. Figure 1 describes the relationship between the level of information available, the decisions, the level of risk and the benefits associated with the MAR scheme. The risks associated with MAR may make the benefits uncertain. Decision-making is made on the basis of the information available, influencing the level of risks and expected benefits (situation a). In case of uncertainty, better information (situation b) should allow better decisions to be made, reducing the risks and/or improving the expected benefits. However, increased quality and availability of information does not necessarily translate into benefits due to better decisions: information can improve decision-making only if decision-making is uncertain. If decision-makers are completely certain about the outcomes of their decision-making, then additional information will have no influence and, hence, will have no significant welfare impact (Bouma et al., 2009). It is the capacity of the user of information to change decisions as a result of new information being available to them that largely determines the value of that new information (Linés et al., 2018). A good understanding of the role that information plays or could play in supporting decisions, as well as the resulting benefits, is useful both for the users and the data providers and helps improve the connection between these two groups (Linés et al., 2018).

In economics, the concept of the value of information (VoI) compares the expected net benefits of collecting additional information to reduce or eliminate uncertainty associated with the outcome of a decision and the expected net benefits of a preferred uninformed alternative (Khader et al., 2013). We use and apply this VoI concept to the SMART-Control project. The rest of this report is structured as follows: Chapter 2 describes the principle of VoI evaluation, Chapter 3 presents the application of this principle to the SMART-Control project, and Chapters 4 to 5 present the application of the approach to two operational MAR sites of the project.

2. VALUE OF INFORMATION (VOI)

2.1. PRINCIPLE

"The decision-maker chooses among actions, while Nature may be metaphorically said to choose among states"
(Hirshleifer and Riley, 1979)

The Value of Information (VoI) analysis is a means of valuing the expected gain from reducing uncertainty through some form of data collection exercise (Wilson, 2015). It is based on the Bayesian decision theory that considers that the best decision maximizes the expected utility of action x resulting from the decision itself. If only experience knowledge is available about the state of nature, the decision theory's problem corresponds to choose the action x that maximises the expected utility:

$$\text{Maximize } u(x, \pi_s)$$

$$u(x, \pi_s) = \sum_{s=1}^{S} \pi_S \times c_{xs}$$

With π_s the perceived probability of state s, c_{xs} the consequences associated with action x in state s, and S the number of possible states of the world (Bouma et al., 2009). The consequence matrix (Table 1) illustrates the decision problem for two potential states of the world ($s=s_1$, s_2) and two possible actions ($x=x_1$, x_2).

Table 1. Consequence matrix

State s	Decision	Consequences
s_1	Action x_1	$c_{x_1s_1}$: consequences of doing x_1 when s_1
	Action x_2	$c_{x_2s_1}$: consequences of doing x_2 when s_1
s_2	Action x_1	$c_{x_1s_2}$: consequences of doing x_1 when s_2
	Action x_2	$c_{x_2s_2}$: consequences of doing x_2 when s_2

To illustrate this matrix of consequences, let us consider for example the risk of clogging of a MAR scheme, which depends (among other things) on the Total Suspended Solid (TSS) concentration (Table 2). This concentration is not known *a priori*. In the absence of information on the TSS concentration, the operator can decide (1) to do nothing or (2) to implement preventive actions (water treatment for example). If the operator decides to do nothing, and the concentration is finally high, damage may appear in the long term, or even threaten the viability of the MAR facility; if, on the other hand, the concentration is low, the right decision was indeed to do nothing. If the operator decides to implement preventive actions, in case the concentration is finally low, he will have spent unnecessary pre-treatment costs; whereas if the concentration is high, he will have made the right decision, which avoids damage. The consequence matrix below illustrates these different possibilities and their economic consequences. The "right decision" for a given state of nature (in this case TSS concentration) is the one that maximizes the net benefits. The assumption underlying the VoI concept is that access to better information increases the chances of making the right decision.

Table 2. Consequence matrix in a context of clogging risk

State Θ	Decision	Consequences
TSS high	Do nothing	Damages due to clogging (e.g. purchase of drinking water from other sources → additional costs)
	Preventive action	Costs of pre-treatment actions and avoided damages
TSS low	Do nothing	-
	Preventive action	Costs of pre-treatment actions

Without information about the probability of alternative states, a decision-maker must act upon his own (prior) beliefs (Bouma et al., 2009). If data about the probability of alternative states is available, we assume that the decision-maker will update his beliefs, according to the informational message. A formal way of expressing the process of belief updating is reflected in the Bayes theorem:

$$\pi_{s,m} = \Pr(s/m) = \frac{\Pr(m/s)Pr(s)}{\Pr(m)} = \frac{q_{m,s}\pi_s}{q_m}$$

With $\pi_{s,m}$ the posterior probability (updated belief), π_s the prior probability (belief before the additional information), $q_{m,s}$ the conditional probability of receiving message m given state s (the likelihood of receiving message m given state s), and q_m the unconditional probability of receiving informational message m. The unconditional probability of receiving message m is related to the conditional probabilities of receiving message m in state s by:

$$q_m = \sum_{s=1}^{S} q_{m,s}\pi_s$$

Subsequently, with the updated beliefs, the decision-maker might choose a different action than what he would have chosen with his prior beliefs. The value of message m is the difference between the utilities of the action that is chosen given message m (x_m) and the action that would have been chosen without additional information (x_0):

$$\Delta_m = u\left(x_m, \pi_{s,m}\right) - u(x_0, \pi_s)$$

Then, since we do not know in advance which message the information service will produce, the expected value of the information is the expected difference in utilities of actions given the likelihoods of receiving message m (q_m):

$$\Delta(\mu) = E(\Delta_m) = \sum_m q_m(u\left(x_m, \pi_{s,m}\right) - u(x_0, \pi_s))$$

$\Delta(\mu)$ is the expected utility of the new information and can thus be used as an indicator of the value of this information.

In summary, three types of data are required: π_s, $q_{m,s}$ and $v(c_{xs})$

- π_s is the prior probability of having the state s (belief before the additional information);
- $q_{m,s}$ is the probability of receiving message m given state s (the likelihood of receiving message m given state s): this corresponds to the chance that the information delivered by the message m is correct;
- c_{xs} is the consequences of the actions given the different states of the world.

2.2. EXAMPLES OF APPLICATION

To our knowledge, the VoI concept has already been used in the context of flood risk, water quality or water level monitoring networks, but not in the context of MAR.

Flood risk

Alfonso and Price (2012) proposes an approach for designing monitoring networks in a water system using the concept of value of information (VOI). The methodology uses a water level time series generated by a hydrodynamic model at every computational point, each one being a potential monitor site. The method is tested in a polder system in the Netherlands, where monitoring is required to make informed decisions about the operation of a set of hydraulic structures to reduce flood impacts. The consequence matrix is created arbitrarily for this example.

Alfonso et al (2016) propose a framework to incorporate probabilistic flood hazard information (maps) into spatial planning (VoI maps). VoI maps highlight floodplain locations where additional information is valuable with respect to available floodplain management actions and their potential consequences. The methodology is illustrated with a simplified example and also applied to a real case study in the South of France, where a VoI map is analysed on the basis of historical land use change decisions over a period of 26 years. Flood damage is assessed as a function of the receptor exposure and susceptibility to the magnitude of the flood hazard. Value factors were determined in terms of either willingness to pay or monetary value of the receptor. No stakeholders consultation.

Water quality

Bouma et al. (2009) develops a frramework for assessing the VoI of global earth observation (GEO) by combining Bayesian decision theory with an empirical, stakeholder-oriented approach. The analysis focuses on the use of satellite observations for Dutch water quality management in the North Sea (eutrophication, potentially harmful algal blooms and suspended sediment and turbidity). They estimate pay-offs associated with the prevention of economic damage resulting from algal blooms on the basis of historic losses observed by the Dutch mussel cultivation sector. No stakeholders consultation.

Ammar et al. (2011) formulate a conceptual framework to analyze groundwater quality monitoring networks. Disability adjusted life years approach of the global burden of disease (DALYs) is used for quantifying the health risk consequences. Other consequences such as economic or environmental are not covered. This is demonstrated through a case study application to nitrate contamination monitoring in the West Bank, Palestine. No stakeholders consultation.

Graveline and Maton (2006) evaluate the interest of Screening Methods and Emerging Tools (SMETs) integration in monitoring networks. The basic assumption is that SMET deliver better information than classical monitoring on water quality. Better information means less uncertainty on the data than with classical monitoring. Less uncertainty is characterised as inducing more chance to take the best decision. The best decision being, among the state possibilities, the decision inducing less costs or maximum benefits. The VoI is the quantification of the benefits induced by the use of SMET in water monitoring for different agents. Benefits are estimated as avoided damage based on a literature review. No stakeholders consultation.

Khader et al. (2013) estimate the VoI provided by a groundwater quality monitoring network located in an aquifer (Palestine) whose water poses a spatially heterogeneous and uncertain health risk. The VoI is estimated as the difference between the expected costs of implementing the monitoring network and the lowest-cost uninformed alternative. The expected cost of each alternative is estimated as the weighted sum of the costs and probabilities associated with the uncertain outcomes resulting from the alternative. Outcome costs include health-care for methemoglobinemia, purchase of bottled water, and installation and maintenance of the groundwater monitoring system. Uncertain outcomes include actual nitrate concentrations in the aquifer, concentrations reported by the monitoring system, whether people abide by manager recommendations to use/ not use aquifer water, and whether people get sick from drinking contaminated water.

Destandau and Zaiter (2020) show how the estimation of the economic VoI can be used to determine the spatio-temporal design of a water quality monitoring network aiming to detect accidental pollution on a stretch of river. They calculate the economic VoI according to the spatial and temporal network design (number and location of stations, temporal accuracy of measurement). They provide a methodology for answering key questions such as: are the costs of monitoring justified by generating benefits in excess of costs? What network design (spatial and temporal intensity of the measurement) should be adopted to maximise the net benefit generated? What is the optimal network design when working with a fixed budget? But parameters of probabilities, damages and costs are arbitrarily chosen. Nothing on the impact of improved information on decision-making nor on the types of damage to be considered.

Destandau and Diop (2016) define the value of additional information in relation to three parameters: initial assumptions (priori probabilitiesà on the states of nature, costs linked to a poor decision (error costs) and accuracy of additional information. They then analysed the impact of these parameters on this value, particularly the combined role of prior probabilities and error costs that increased or decreased the VoI depending on the initial uncertainty level. Their main aim is to use the VoI to rationalize the design of water quality monitoring networks. They apply the methodology on a stream in the Bas-Rhin department in France affected by eutrophication. They estimate the damage linked to eutrophication based on a literature review (in €/household/year) and an estimation of the population in the studied area. Nothing on the impact of improved information on decision-making nor on the types of damage to be considered.

Water availability

Galioto et al. (2020) develop a methodology to assess the comparative advantages of new methods to plan irrigation with respect to prevailing existing irrigation practices. The methodology consists of a comparative cost-benefit analysis based on the VoI approach that makes it possible to analyse whether an improvement in the information available to farmers generate economic benefits. Benefits are estimated based on data collected on experimental plots on soil moisture, water use and yields. Results show that under favorable conditions, the use of alternative technology generates a 0-20% increase in gross margin and a 10-30% water savings with respect to prevailing existing irrigation practices. Nothing on the impact of improved information on decision-making.

Linés et al. (2018) follow a user-based approach to examine how information supports operational drought management decisions in the Ebro basin and how these can benefit from additional information such as from remote sensing data. First, they consulted decision-makers at basin, irrigation district and farmer scale to investigate the drought-related decisions they make and the information they use to support their decisions. They then built a decision model representing the interrelated decisions of the irrigation association and the farmers. The decision model was then extended to include additional information on snow cover from remote sensing. The additional information was found to contribute to better decisions in the dimulation and ultimately higher benefits for the farmers. Benefits are estimated based on the choice of the crop, expected yields and percentages of reduction in crop yield.

3. IMPLEMENTING THE VOI FRAMEWORK TO SMART-CONTROL

3.1. A STEPWISE APPROACH

We developed a stepwise approach for assessing the VoI associated to MAR real-time monitoring and control, structured in two main parts (Figure 2):

First, **the contribution that information makes to decision-making has to be made explicit** (Bouma et al., 2009). For that, we conducted a qualitative evaluation (Steps 1-4) aimed at understanding the benefits, risks, and how the SMART-Control tools can improve decision-making at each study site. Step 1 aims to provide a clear qualitative description of the benefits expected from each MAR scheme. Step 2 leads to the identification of main risks associated to each MAR scheme and potential impacts on costs and benefits. Step 3 describes alternative monitoring situations: a base case (without real-time monitoring and control: with classical monitoring or without any information) and one or several improved monitoring situation(s). Step 4 provides a qualitative description of the impact expected from improved information on decision and on benefits. **This step is decisive for the further evaluation: the quantitative analysis (steps 5 to 7) only starts if better information has a potential impact on decision-making and on benefits from MAR**.

Second, **the contribution of better decision-making to welfare has to be assessed**. For that, we developed a quantitative analysis of the economic consequences and probabilities (steps 5-7). Step 5 provides a quantification of prior probabilities π_s, likelihoods $q_{m,s}$ and consequences c_{xs}. Step 6 aggregates the expected net benefits of each monitoring situation according to the Bayesian formula (Bayesian decision theory). Step 7 compares net benefits to the additional monitoring costs. The VoI is equal to the difference between net benefits and additional monitoring costs.

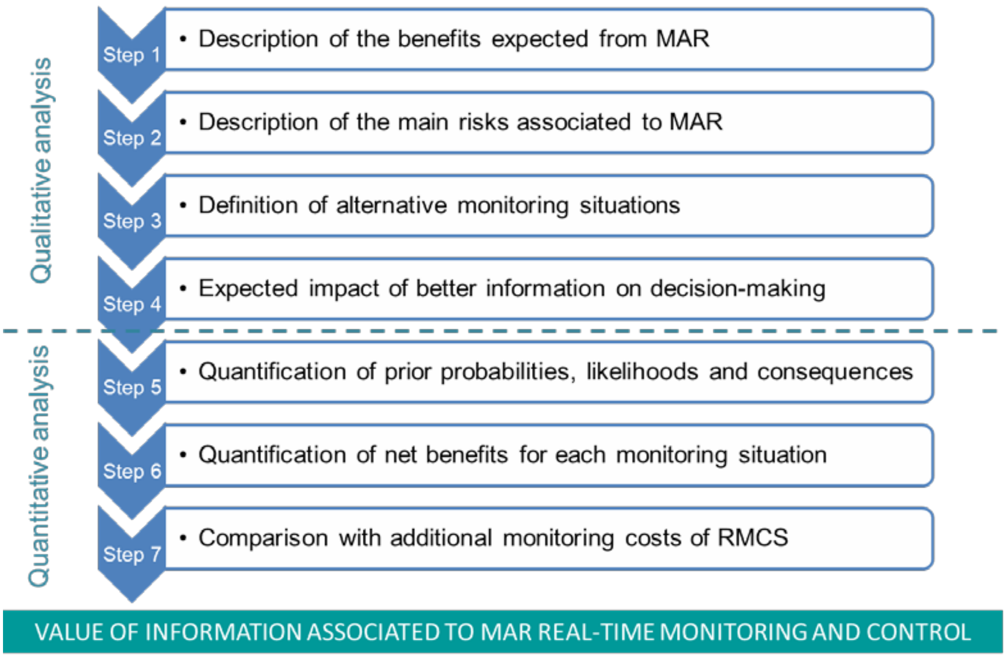


Figure 2. Proposed stepwise approach for VoI assessment in the SMART-Control project

3.2. IMPLEMENTATION TO CASE STUDIES

Potential risks, benefits, decision-making and type of information delivered by MAR real-time monitoring and control strongly depend on the characteristics of the case studies.

We carried out the first qualitative phase on the two operational MAR sites by completing an Excel file "SMARTControl_VoI_QualitativeAnalysis.xls" with the help of SMART-Control partners in charge of each case study. The Excel file details each step in several questions:

STEP 1: Description of the benefits expected from the MAR scheme	
A. Does the MAR scheme contributes to maintain/ increase water supply?	
If yes, please describe HOW, as precisely as possible : - Type of water use, - Period of the year, - Additional volumes that can be abstracted, - Beneficiaries.	
B. Does the MAR scheme contributes to mitigate flooding?	
If yes, please describe HOW, as precisely as possible : - Type of water source, - Period of the year, - Volume that can be infiltrated, - Beneficiaries.	
C. Does the MAR scheme contributes to support Groundwater Dependent Ecosystems (GDE)?	
If yes, please describe HOW, as precisely as possible : - Type of GDE, - Period of the year, - Additional flow in GDE expected from MAR, - Benefits provided by an additional flow, - Beneficiaries.	
D. Does the MAR scheme contribute to provide other benefits to society?	
If yes, please describe HOW, as precisely as possible : - Type of benefits, - Beneficiaries.	
STEP 2: Description of the risks associated to the MAR scheme	
Risk 1	Description
	Potential impacts on expected benefits described in STEP 1
	Potential management actions and associated costs
Risk 2	Description
	Potential impacts on expected benefits described in STEP 1
	Potential management actions and associated costs
Risk 3	Description
	Potential impacts on expected benefits described in STEP 1
	Potential management actions and associated costs
(insert as many risks as necessary)	
STEP 3: Definition of alternative monitoring situations	
A. The "base case" situation	
Describe as precisely as possible the "base case" situation	
B. The "SMART-Control" situation	

Describe as precisely as possible the "SMART-Control" situation, in comparison with the "base case". Describe differences between 2 situations. Describe the type of additional costs.
C. The ideal "SMART-Control" situation
Describe as precisely as possible what would be an ideal "SMART-Control" situation, in comparison with the "base case". Describe differences between 2 situations. Describe the type of additional costs.
STEP 4: Expected impact from SMART-Control on decision making
A. Impacts on decision making regarding potential risks
Will SMART-Control make it possible to better manage risks identified in STEP 2? If yes, which ones? How will it improve the decision making process? Increases the probability of taking the "right" decision? changes in the type of actions undertaken? economic implications?
B. Other impacts
What other types of impacts do you think SMART-Control may have on your study area?

Collected information for each site is provided in Annex. The decision on the case studies on which the quantitative analysis could be carried out was taken in a second step, based on the qualitative information collected. The following chapters present the implementation of this framework to two operational MAR systems studied in SMART Control: Berlin-Spandau/ Germany (Chapter 4), Ezousa/ Cyprus (Chapter 5).

Table 3. SMART-Control case studies description

	Ezousa catchment, Cyprus	Berlin-Spandau, Germany
MAR type	SAT	IB
Source water	Waste water	River water
Operational scale of recharge (Mm^3/year)	3-4	20-25
Primary benefit	Irrigation water supply	Drinking water supply
Other benefits	Mitigation of saltwater intrusion	Conservation and restoration of GDE
Potential risks	Saltwater intrusion Pathogens Turbidity and organic chemicals	Low residence time for some wells (<50 days) Pathogen breakthrough in drinking water wells Limited source water availability (Havel River)
Main benefits provided by additional information	Decrease in economic consequences resulting from environmental and technical risks Replacement of costly manual monitoring Increased efficiency of the MAR system	Decrease disease burden (DALYs) with Hydraulic monitoring of abstraction wells with critical residence time + microbial risk assessment

ASR: aquifer storage and recovery; IBF: induced bank filtration; SAT: soil aquifer treatment; IB: infiltration basins;
* operates from November to April only

4. BERLIN-SPANDAU (GERMANY)

Authors: Cécile Hérivaux and Christoph Sprenger. This analysis is based on the information collected in the qualitative analysis file, completed by a literature review (grey and scientific literature).

4.1. STEP 1. DESCRIPTION OF THE BENEFITS EXPECTED FROM MAR

The Berlin-Spandau MAR site is located in the north-western part of Berlin, in the Spandau forest. It supplies approximately 12% of the drinking water in Berlin. A brief description of the Berlin's drinking water supply scheme is necessary to understand the role of the Berlin-Spandau MAR site.

4.1.1. Historical background

The glacial sediments in Berlin and in the surrounding area represent excellent aquifers. The City of Berlin has been able to sustain its own water supply with drinking water exclusively using its own groundwater resources (Fritz et al., 2003). 100% of Berlin's drinking water (217 Mm3 in 2017, 3.5 million inhabitants) comes from groundwater. Groundwater is pumped in nine waterworks, almost entirely within the city area, with the exception of the waterworks Stolpe (Figure 3). The use of bank filtered water (induced bank filtration, IBF) and artificial groundwater recharge is very important due to the limited available quantity of natural groundwater. Bank filtration and artificial groundwater recharge is known as a low cost and efficient technology for pre-treating surface waters for drinking water supply. The Berlin Water works are located near the surface water system and their abstraction wells are drilled mostly in a short distance (1-600 m) around the rivers and lakes near the bank to abstract bank filtered surface water.

Figure 3. Location of the waterworks which supply Berlin with drinking water (Source: Berlin environmental atlas, 2018)

This water supply system has been operational for decades, with some waterworks in operation since the end of the 19th century (Table 4). Berliner Wasserbetriebe (BWB) is the sole provider of water and wastewater disposal in Berlin and the largest water supply and wastewater disposal company in Germany (Schaefer and Warm, 2014).

In 1989, 378 Mm³ were abstracted, compared to about 210 Mm³ since the early 2000s (Figure 4). The BWB currently still operates only nine waterworks to supply drinking water (Table 3), down from sixteen during the nineties (Berlin environmental atlas, 2018). The Berlin-Spandau MAR site contributes to approximately 12% to the total water supply (Table 3).

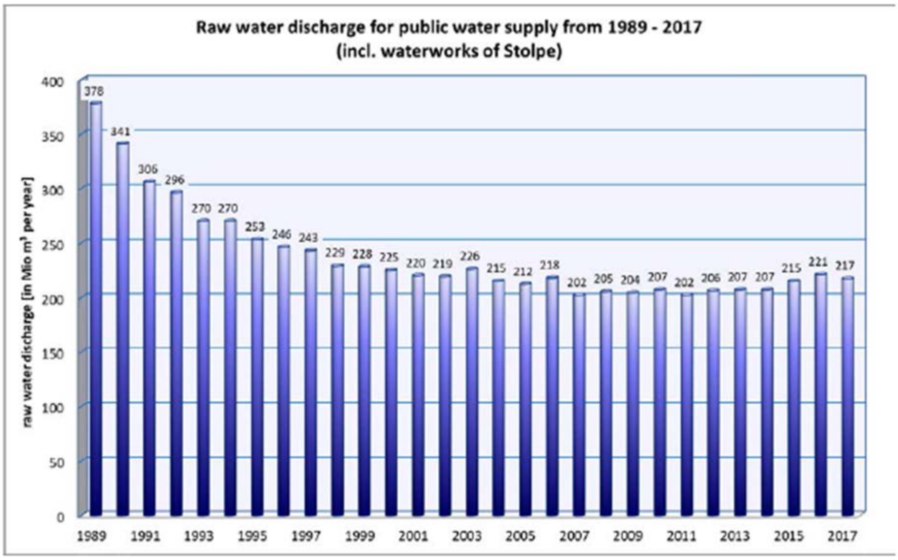


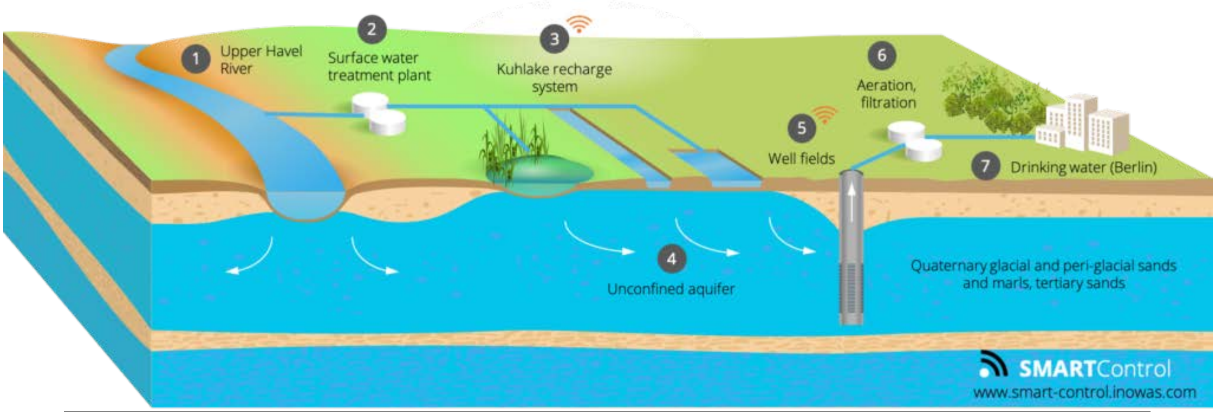
Figure 4. Evolution of groundwater abstraction over the 1989-2017 period (Source: Berlin environmental atlas, 2018)

Table 4. Description of the Berlin's MAR waterworks (from Hannapel et al., 2014)

Site name	Under operation since	Main MAR type	Specific MAR type	Water source	Number recovery wells	Filter depth (m)	Operational scale (Mm³/year)
Beelitzhof	1888	IBF	IBF	River	50 to 100	50 to 100	32.28
Friedrichshagen	1893	IBF	IBF	Lake	>100	20 to 50	53.71
Kladow	1932	IBF	IBF	River	10 to 25	50 to 100	5.35
Spandau	1897	IBF	IBF	River	25 to 50	20 to 50	26.27
Stolpe	1911	Spreading methods	Flooding	River	50 to 100		22.32
Tegel	1877	IBF	IBF	Lake	>100	20 to 50	47.81
Tiefwerder	1916	IBF	IBF	River	50 to 100	50 to 100	14.60
Wuhlheide	1914	IBF	IBF	River	50 to 100	20 to 50	8.94
TOTAL							211.28

4.1.2. MAR technical description

The Berlin-Spandau MAR site infiltrates each year between 15 and 20 Mm³ from the Upper Havel River located in the eastern part of the MAR site (❶). Water is **pre-treated before infiltration in a Surface Water Treatment Plant (SWTP) by mechanical cleaning, flocculation and rapid sand filtration (❷). The pre-treated water is then recharged to the groundwater** through constructed infiltration basins and near-natural lakes, trenches and ponds (Kuhlake) (❸). As the soil in Berlin is mostly made of sand, a water-permeable material, water can percolate easily through it and flow down to the groundwater. The upper layers of soil act like a giant filter. The natural cleaning power of the soil improves the quality of the water physically, chemically and biologically, so that it is comparable to that of natural groundwater (❹) (SMART-Control website). There are four abstraction sites (❺), with a total of 45 wells (Figure 6): (i) one horizontal well in the north, (ii) well field Kuhlake (15 wells), (iii) well field north (8 wells) and (iv) well field south (21 wells). The water is then aerated to remove Iron and Manganese and filtered through rapid sand filters (❻), before being distributed (❼).The scheme and table below summarise the main components of the MAR site (Sprenger, 2021).



MAR components	Berlin-Spandau MAR site
❶ Capture zone	River Water (Upper Havel River)
❷ Pre-treatment	Shell filter, flocculation, rapid sand filtration
❸ Recharge	Wetlands, ditches, ponds, infiltration basins
❹ Subsurface	Quaternary glacial and peri-glacial sands and marls, tertiary sands
❺ Recovery	3 well fields (44 vertical wells, 1 horizontal well)
❻ Post-treatment	Aeration, rapid sand filtration
❼ End use	Drinking water, ecosystem

Figure 5. Schematic overview of MAR components at Berlin-Spandau (SMART-Control website; Sprenger, 2021; Sprenger et al., 2020)

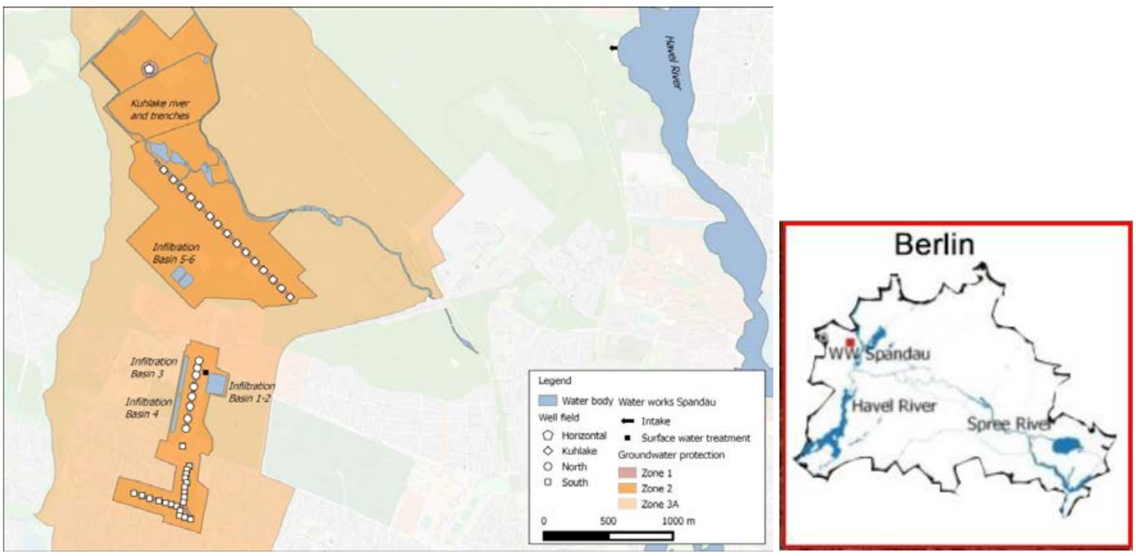


Figure 6. Overview of well fields and infiltration basins and trenches of the water works Berlin-Spandau (SMART-Control website)

4.1.3. Benefits associated to Berlin-Spandau MAR site

The main benefit of this recharge site is to sustain drinking water production capacity, while maintaining support to groundwater-dependent ecosystems.

Sustain drinking water production capacity

Between 20 and 25 Mm^3 are abstracted each year by BWB for drinking water supply in the Berlin-Spandau MAR site, i.e. an average of 75,000 m^3 per day over the period 1995-2017. This volume corresponds to the drinking water supply of 300,000 to 350,000 inhabitants of Berlin.

Support to groundwater-dependent ecosystems

The Spandau forest "is one of the largest forest areas in Berlin and home to numerous groundwater-dependent ecosystems (GDE), such as the Kuhlake river system, swamps and wetlands" (Sprenger et al., 2020). The wetlands are designated as nature reserves and the entire Spandau forest is a Natura 2000 protected site listed under both, the European Union (EU) Birds Directive and the Habitats Directive (Figure 7) (Sprenger et al., 2020). These groundwater dependent ecosystems are hydraulically supported by the water inflow into the Kuhlake system.

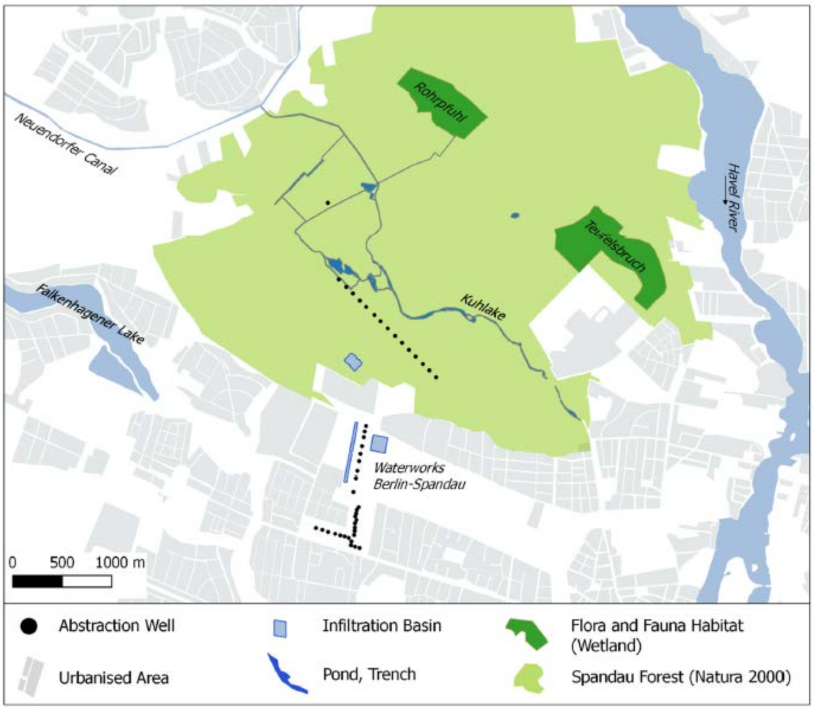


Figure 7. The Spandau forest and groundwater dependent ecosystems *(Sprenger et al., 2020)*

4.2. STEP 2: DESCRIPTION OF THE RISKS ASSOCIATED TO MAR

The main risk associated with the Berlin-Spandau MAR site is the risk of microbial breakthrough at wells with low hydraulic residence time – HRT (Sprenger et al., 2020). The surface water used for groundwater recharge may indeed contain pathogens, and groundwater is not treated by desinfection after abstraction. The objective of the water supplier BWB is to maintain a natural water treatment without additional technical (physical or chemical) treatment. The elimination of these pathogens therefore relies on the purifying capacities of the natural environment. This natural purifying capacity (removal rates), is a function of water residence time, temperature, redox conditions and aquifer characteristics. In particular, the travel time between the infiltration basin and the pumping well is a critical parameter or the MAR system. This travel time must be long enough to allow the pathogenic elements to be eliminated. The German Drinking Water Guidelines (DVGW, 2006) sets this minimum travel time at 50 days. Most abstraction wells of the waterworks Berlin-Spandau are in sufficient distance and depth to the area of recharge and subsurface residence times are estimated to be higher than 50 days. However, some wells at the well field north (between infiltration basins) show subsurface residence times measured by environmental tracers around 50 days (Sprenger et al., 2020). They require additional investigations to evaluate hazard attenuation processes during infiltration and recovery.

According to the Drinking Water Ordinance (TrinkwV, 2011), pathogens may not be contained in drinking water "at concentrations which cause damage to human health" (§5)[1]. In order to achieve higher confidence of the subsurface as a hygienic barrier, and to confirm that safe water quality is being achieved, verification measurements and theoretical principles based on WHO guidelines (WHO, 2016) may be carried out.

The potential consequences of microbial contamination**, if undetected**, are health-related: endemic waterborne illness as well as waterborne outbreaks of gastrointestinal diseases. The WHO pointed out that the societal costs for endemic waterborne illness and related gastrointestinal disease are commonly underestimated (Bergion et al., 2018). Health-related consequences can be assessed with Quantitative Microbial Risk Assessment (QMRA) approaches, and quantified in terms of Disability adjusted life years (DALYs).

If microbial contamination is detected, several actions are undertaken to ensure the supply of safe drinking water (according to the information of the responsible authority (State Office of Legal Affairs, LAGeSo):

(1) shutting down water abstraction from potentially affected wells that were under operation for 1-2 days with the consequence of the supplying water from other wells (wells from the same waterworks, no additional costs);
(2) investigating the origin of the contamination by sampling of each well, cultivation for 24-48h (analysis costs).

4.3. STEP 3: DEFINITION OF ALTERNATIVE MONITORING SITUATIONS

This section describes three situations that could form the basis for the economic assessment: the baseline situation, and two SMART-Control monitoring situations.

4.3.1. Baseline situation

The baseline situation corresponds to the situation without SMART-Control monitoring tools. According to the TrinkwV (2011), parameters to be routinely examined are shown in Table 5.

Table 5. Legal requirements of German Drinking Water Ordinance for microbiological parameter

Parameter	Analytical method	Limit value/ Requirement
Coliform bacteria	DIN EN ISO 9308-1	0/100 mL
Escherichia coli (E. coli)	DIN EN ISO 9308-1	0/100 mL
Enterococci	DIN EN ISO 7899-2	0/100 mL
Clostridium perfringens (including spores)	according to TrinkwV (2011)	0/100 mL
HPC (22 °C)	DIN EN ISO 6222	100/mL
HPC (38 °C)	DIN EN ISO 6222	100/mL

HPC = Heterotrophic plate count

The sampling frequency of the drinking water depends on the volume of water supplied or produced. In the case of Berlin-Spandau waterworks, the sampling frequency is twice a week for each parameter (Table 5). Sampling is carried out at various points in the raw water (after abstraction) and drinking water (after aeration and rapid sand

[1] The microbiological requirements for drinking water are regulated in the Drinking Water Ordinance (TrinkwV, 2011) in §5 sentence 1: "Drinking water must not contain pathogens within the meaning of §2 sentence 1 of the Infection Protection Act, which are transmitted through water, in concentrations which give rise to concern about harm to human health". Paragraphs 2 and 3 regulate the limit values for microbiological parameters. Paragraph 4 describes the requirement to minimise the concentration of microorganisms that contaminate or adversely affect drinking water. Viral indicators such as somatic coliphages or viral pathogens are not regulated.

filtration). For the raw water, each of the collector pipes of the individual well fields and the gathering basin is sampled once a week.

In case of microbial contamination of the raw water (TrinkwV § 5 sentence 1) or in case of microbial contamination in the waterworks, both the method "dosing of chlorine gas solution" and "UV irradiation (240-290 nm)" can be used. Up to now, BWB has maintained facilities for disinfection with gaseous chlorine.

In the event that the limit values (Table 5) in the collection line are exceeded, the wells in operation at the time of sampling are shut down immediately. The switched-off wells are then separated from the collection line and sampled individually. The samples are cultivated in the laboratory and the results are available after 24-48 hours. During this time, other wells within the waterworks are switched on to compensate for the loss. According to BWB, no additional costs are incurred, as such failures may also be caused by technical faults and are taken into account in the well management. A well that has been switched off can only be reconnected to the collection line and operated normally after a negative result or values below the limit values.

4.3.2. SMART-Control monitoring situation 1: on-line monitoring of groundwater residence time

This monitoring situation is the baseline, completed by the hydraulic residence time (HRT) calculation tool developed in the SMART-Control project (Sprenger, 2021). It consists of real-time monitoring of subsurface residence times. Residence time is associated to log removal during subsurface passage. The longer the residence time, the greater the log removal. This system ensures that HRT is 50 days minimum for each well (if HRT is lower, the pumping system and abstracted volumes are adapted to increase HRT). In the SMART-Control project, HRT is monitored for one well.

4.3.3. SMART-Control monitoring situation 2: assessment of microbial contamination in emergency cases by using flow cytometric measurements (FCM)

This monitoring situation is the baseline completed by flow cytometry measurements (FCM) in case of emergency (Sprenger, 2021). If microbial pathogens are detected at the water works, FCM may help to detect affected abstraction well by comparing actual measurements to previously defined reference measurements. Flow cytometric measurements (FCM) give a much faster picture of the problem than traditional cultivation, as results are available after 0.5 h.

4.4. STEP 4: EXPECTED IMPACT OF BETTER INFORMATION ON DECISION-MAKING

Benefits associated to the SMART-Control monitoring situation 1 are related to a better confidence in hydraulic residence time (HRT) calculation. Let $\pi_{HRT<50_i}$ be the probability that the water taken from the well i has an HRT < 50 days. This state of nature is unknown by default. The monitoring system in place will give an indication of the level of risk and the need for action, by delivering two types of messages: either m_1 "Danger" or m_2 "No Panic". In the first case, the message leads managers to take action to limit and manage microbial risk, in the second case the message recommends doing nothing. The contrasted monitoring situations differ on the probability of delivering the right message (i.e. detect that HRT>50 days and conversely detect HRT<50 days when it occurs), on the consequences (in terms of disease burden with the DALYs calculated by QMRA) of the actions taken, as well as on the costs of monitoring. The value of information (VoI) reflects the increase of the probability to take the right decision associated to the SMART-Control monitoring tools, in comparison with the baseline situation. An important point to make here is that the risk of distributing water that does not meet regulatory quality standards is considered negligible by BWB. Similarly, the risk of having microbial pollution such that the implementation of treatment or even the purchase of water from other water resources is also considered negligible. Such situations would imply that managers take decisions with potentially important direct economic consequences, which could be improved by a better monitoring system. However, as these risks are negligible, there are no quantifiable economic consequences that could be used as a basis for estimating the value of information of SMART-Control monitoring systems in economic terms. The proposed monitoring system secures the water quality beyond the regulatory requirements. The main benefits of this system can be quantified in terms of disease burden with the DALYs calculated by QMRA.

Benefits associated to the SMART-Control monitoring situation 2 mostly result from an improvement of the efficiency of the monitoring system and a faster resolution of the problem. This improvement of the monitoring system is not considered to result, however, in any change in decision-making nor economic consequences. The VoI framework can not be implemented in such a decision-making context.

4.5. CONCLUSION

The qualitative analysis has shown that better information does not translate into changes in decision-making by the drinking water company with associated economic consequences. As a result, the VoI framework is difficult to apply. Two types of improvement are however provided by the real-time monitoring and control: 1) improved knowledge of HRT, making it possible to guarantee that the HRT is greater than 50 on all the wells and therefore to reduce the residual risk for human health in terms of DALYs and 2) faster detection of the type of problem and its origin in the event of an emergency, making it possible to have a more efficient management system. An interesting perspective to highlight the value of information on this site would be to implement a hybrid approach, combining QMRA and Bayes' theorem, by expressing the value of information in DALYs, not in monetary terms.

5. EZOUSA (CYPRUS)

Authors: Cécile Hérivaux and Konstantinos Panagiotou. This analysis is based on the information collected in the qualitative analysis file, completed by data provided by institutional actors from the Cyprus Water Development Department (WDD) and the Cyprus Agricultural Payments Organisation (CAPO), by a literature review (grey and scientific literature) and a survey administered to 51 farmers supplied with a mix of water from MAR and the dams. It follows the full stepwise approach.

5.1. STEP 1. DESCRIPTION OF THE BENEFITS EXPECTED FROM MAR

The Ezousa MAR site is located in the south-west coast of Cyprus near Paphos (36,000 inhabitants). The coastal area has an intense agricultural activity (officially 6,177 farms cultivating 20,500 ha, including 4,320 ha irrigated[2]) and main urban centres that attract a growing number of tourists. A brief historical analysis is necessary to understand the role of the MAR site in the water supply of this coastal zone.

5.1.1. Historical background

In Cyprus, rainfall is more abundant in winter with about 60% of the average annual total precipitation falling from December to February. This varies annually between 280 mm in the central plains to 1000 mm on the Troodos mountain peak (altitude 1950 m) with a mean annual precipitation of 497 mm. Winter rainfall is the main source for the replenishment of water resources since summer rains do not contribute significantly to the recharge or refill of aquifers. Historically, in Cyprus, droughts occur every two-to-three successive years due to the decline in rainfall (Sofroniou and Bishop, 2014). This led the government of Cyprus to invest massively in water storage projects in order to secure the water supply throughout the year. In the 1980s, major government water projects were funded, with the construction of dams and the creation of irrigated perimeters. The storage capacity of the dams increased from 65 Mm^3 in 1981 to 300 Mm^3 in 1988 (WDD, 2020).

The Paphos irrigation project is one of those major projects (Figure 8). It was built between 1976 and 1982 to supply water to the coastal plain of Paphos whose water supply previously relied on the Mavrokolympos dam (built in 1966 on the river Mavrokolympos with a storage capacity of 2.18 Mm^3). The Paphos water project included the creation of the Asprokremmos dam (capacity of 52.38 Mm^3) on the Xeropotamos river, the creation of 24 boreholes in three alluvial aquifers (Dhiarizos, Xeropotamos and Ezousa for an expected abstraction of 10 Mm^3/year) and wells in the coastal aquifer (expected abstraction of 4.5 Mm^3/year). The water from the dam and the alluvial aquifers is channelled through a canal to Yeroskipou and then through a gravity pipe to Ayios Yeoryios. This project was accompanied by a reform of the agricultural land, and a reshaping of the agricultural plots to allow them to be irrigated. The initial ambition of the project was to irrigate 5000 ha in the Paphos coastal plain.

From the 1990s, however, the WDD pointed out that the dams had been oversized, without taking into account the downward trend in rainfall since the 1970s (FAO/WDD, 2002). A water saving policy was thus put in place (1991 Water saving law), the first desalination plants were built (Dekelia in 1997; Larnaca in 2001), and a law for the protection and management of resources was adopted in 2004. The MAR site in Ezousa was created in 2004, infiltrating tertiary treated water in the Ezousa aquifer, to secure water supply for irrigation (desalination is limited to domestic uses). The infiltration of treated wastewater makes it possible to compensate part of the drastic drop in the Ezousa river flows (that previously fed the Ezousa aquifer) due to the creation of the Kannaviou dam[3] in 2005 (17 Mm^3, 26 *km* upstream the MAR site) and reduce sea-water intrusion while avoiding the ecological costs of discarding wastewater in the sea (Sofroniou and Bishop, 2014).

[2] 2016 statistics, at the Pafos district scale

[3] provides 370,000 m^3 to refill the downstream aquifers; does not directly contribute to the Paphos project, but indirectly by providing amounts of water to the Asprokremmos refinery, through the Ezousa pipeline any remaining quantities are stored in the Asprokremmos reservoir (WDD, 2016).

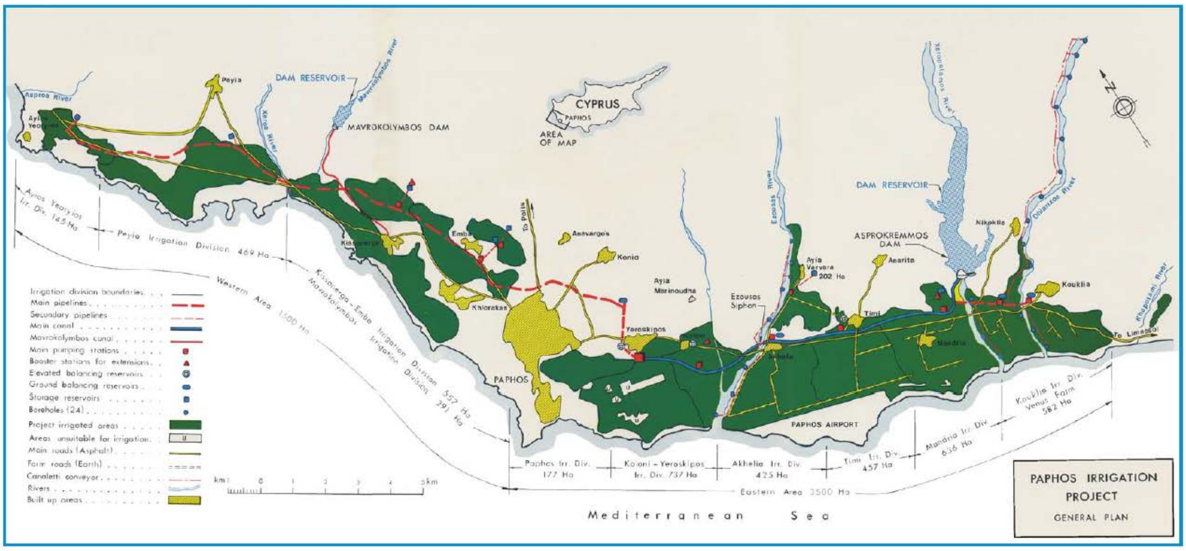


Figure 8. Map of the Paphos irrigation project (WDD, 1982)

In 2008, Cyprus faced one of the most acute and prolonged droughts (a fourth consecutive drought year) with the winter season being extremely dry and the inflow to the reservoirs being approximately only 19 Mm^3. Water reserves of underground aquifers were drastically reduced and the water storage in the dams had reached dangerously low levels (Sofroniou and Bishop, 2014). In August 2008, transportation of water from Athens to Limassol with tankers took place: 8 Mm^3 were transferred at a cost of €41 million[4]. Following this event, several temporary desalination plants were built (Moni in 2008, Garyllis in 2009, Paphos in 2010), as well as new desalination plants (Limassol in 2012, Vassilikos in 2015, Paphos signed in 2019). A second MAR site infiltrating water in the Akrotiri aquifer was developed in 2016.

This is a period of major changes in water policy. In 2010 the Integrated water management Law 79(I)/2010 introduced abstraction permits (quotas, metering), and gave the responsibilities of water management to the WDD (before there were numerous complex laws with fragmented responsibilities). The first river basin management plan (2009-2015) was adopted in June 2011, including a Drought Management Plan. The second river basin management plan (2016-2021) was adopted by the Council of Ministers on the 7th of October 2016 and accompanied by a revision of the Drought management plan (WDD, 2016).

The Ezousa MAR site therefore contributes to the water supply of the Paphos system since 2004, in addition to other water resources (three dams, alluvial aquifers and desalination plant).

5.1.2. MAR technical description

The MAR site is located in the lower section of the Ezousa alluvial plain that is 7 km long, has a lateral extent of 150–230 m, and expands to 800 m in width at its delta. The maximum thickness of the aquifer is estimated to be 25–40 m (Christodoulou et al., 2007). The MAR site infiltrates tertiary treated wastewater through 23 infiltration ponds organized in five groups of two to six basins (Figure 9) during the winter months when the irrigation demand is minimum. The annual average recharge volume was 3 Mm^3 in the 2004-2018 period, with a maximum of 4.5 Mm^3 in 2018 (Figure 10). The infiltration area of each pond is approximately 2000 m^2 and 1.5 m below ground surface. Groundwater is abstracted from nine wells, located between 100 m and 1000 m from the infiltration ponds, and channelled into a canal (mix of groundwater and dam water[5]). The average abstracted volume was

[4] Details provided by (Sofroniou and Bishop, 2014): in April 2008, an agreement was signed for the conveyance of 8 Mm^3 of water from Greece to Cyprus, at a cost of €35 million (transportation cost only) an additional €4.4 million to pay for the cost of water and the necessary infrastructure at the port of Limassol amounted to another €1.6 million, clearly not a viable repeatable. In fact, the total cost of the imported water (5.125 €/m^3) was approximately five times more than the total cost of the desalination and mobile plants over their production quantities (1.041 €/m^3) for 2009. However, the unprecedented action of water transportation was vital to supply Limassol with drinking water and marked the extraordinary severity of the drought.

[5] The canal carries water from the Asprokremmos dam to the Paphos irrigation scheme and passes across the Ezousa aquifer. Water provided by the MAR site is thus mixed with surface water in the canal. Indeed, the reclaimed water contains high

3.2 Mm^3 in the 2004-2018 period, with a maximum of 5.6 Mm^3 in 2018. Pumping is managed in order to maximise groundwater residence time. Water is distributed without post-treatment to the end-users. The Ezousa aquifer characteristics, in particular its heterogeneity, high sulphate content from the gypsum dissolution, and limited size and depth, make it unsuitable as a potable water source. Hence, the recharge system was designed solely for crop irrigation use.

MAR components	Ezousa MAR site
❶ Capture zone	Municipal wastewater
❷ Pre-treatment	Activated sludge, sand filtration, chlorination (gas chlorine)
❸ Recharge	Five infiltration basins
❹ Subsurface	Ezousa river alluvial aquifer
❺ Recovery	Nine wells
❻ Post-treatment	none
❼ End use	irrigation

Figure 9. Top: conceptual map of Ezousa riverbed. Bottom: scheme of Ezousa MAR site (SMART-Control website)

concentrations of sulphates due to the geological formation (gypsum) of the aquifer. Mixing of the reclaimed water with the fresh water obtained from the dam leads to a reduction of the concentration of sulphates and nitrates.

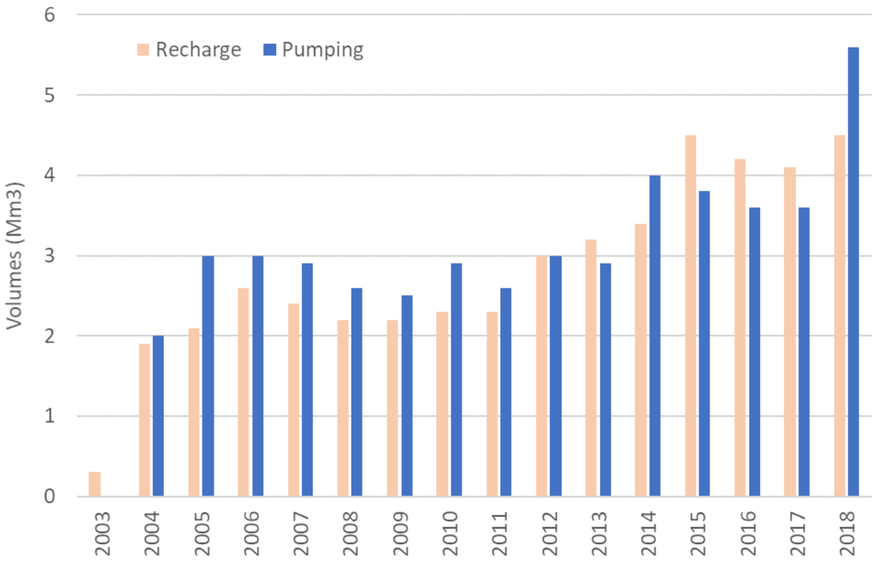


Figure 10. Evolution of water recharge and abstraction volumes in the Ezousa MAR site over the period 2003-2018 (WDD, 2019)

5.1.3. Benefits associated to MAR in the Paphos district

Mitigating sea-water intrusion

The Ezousa MAR site mitigates the risk of sea-water intrusion (Sofroniou and Bishop, 2014). Indeed, the Ezousa aquifer is located at a coastal region that encounters excessive periods of low rainfall rates and high evaporation rates, thus exhibiting risks associated with seawater intrusion and large fluctuations in groundwater levels. Moreover, the hydrological conditions of the area are unique due to the construction of the Kannaviou dam in 2005 that resulted in a significant reduction of the natural recharge of the Ezousa aquifer and a lowering of the water table levels of the aquifer to a certain degree. The extensive exploitation of the aquifer makes the saltwater-freshwater interface extremely volatile. As a result, the Ezousa alluvial aquifer is susceptible to saltwater intrusion for up to 2.4 *km* upstream. The MAR site is expected to provide an effective barrier against seawater intrusion (Christodoulou et al., n.d.), thus avoiding a potential (irreversible) degradation of groundwater quality.

Enhancing natural water purification

Where soil and groundwater conditions are favourable, MAR can result in a significant improvement of the treated effluent's water quality. The unsaturated (vadose) zone acts as a natural filter where physico-chemical and biological processes operate to remove pollutants of concern such as suspended solids, organic and inorganic materials, bacteria and viruses. Flow through the saturated subsurface provides additional natural attenuation processes to remove contaminants. Collectively these processes are termed soil aquifer treatment (SAT). Nitrogen concentrations are greatly reduced by adsorption and denitrification, and possibly by the anaerobic oxidation of ammonia (anammox) deeper in the vadose zone during the wet–dry cycles. Dissolved organic carbon also is greatly reduced, and most phosphates and metals are removed from the water although they then accumulate in the underground environment (Christodoulou et al., 2007). This natural water purification plays a key role for waste water management, either by avoiding their discharge into the sea – and potential associated ecological costs (Sofroniou and Bishop, 2014), or by avoiding costly waste water treatment processes.

Securing water availability for irrigation

The MAR system ensures long-term availability of water for crop irrigation and watering of golf courses, even in times of drought. It plays a central role in the Drought Management Plan in the Paphos district (WDD, 2016). This plan sets the rules to share water resources between the different uses at the Paphos district level, for different drought conditions. Figure 11 shows the evolution of water volume stored in the Paphos dams in the 1988-2019 period, threshold storage levels defined in the revised drought management plan of 2016 and volumes that can be abstracted from the dams.

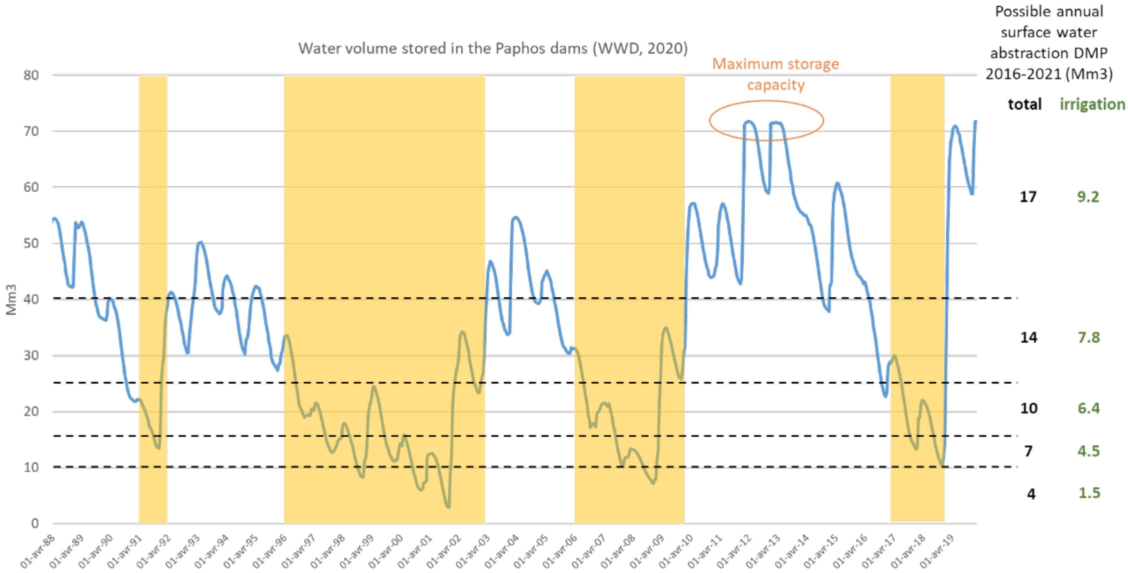


Figure 11. Evolution of water volume stored in the Paphos dams over the period 1988-2020 (data from WDD, 2020), threshold volumes defined in the revised drought management plan (2016-2021) and associated maximum water volume that can be abstracted in dams. In yellow: years with water volume stored in Paphos dams < 40 Mm3 on 1st April.

Irrigation water demand is estimated at 14.2 Mm^3 in 2021 in the Paphos district level, including stock breeding and golf courses irrigation (WDD, 2016). If the climatic and hydrological conditions are good, 65% of the irrigation water supply comes from the dams (9.2 Mm^3) and 35% from the Ezousa aquifer (4.95 Mm^3) (WDD, 2016). In case of drought, irrigation volumes abstracted from the dams can be reduced by up to 80%, depending on the level of dam storage (WDD, 2016). In all cases, water from the Ezousa aquifer plays a major insurance role for irrigation water supply.

Table 6. Drought management rules in the Paphos district according to the storage level of dams on April 1st *(WDD, 2016)*

STORAGE ON 1st APRIL	ESTIMATED RECURRENCE FREQUENCY	CATEGORY CLASSIFICATION	ALLOWED ANNUAL ABSTRACTIONS	ACTION CLASSIFICATION	IRRIGATION FROM DAMS
> 40 hm^3	40.9%	SUFFICIENCY	17 hm^3	ZERO CUTS	9.2
40 hm^3 > & <25 hm^3	22.7%	MINOR DEFICITS	14 hm^3	MINOR CUTS (15% in irrigation)	7.8
25 hm^3 > & <15 hm^3	9.1%	MODERATE DEFICITS	10 hm^3	MODERATE CUTS (30% in irrigation)	6.4
15 hm^3 > & <10 hm^3	18.2%	SEVERE DEFICITS	7 hm^3	SIGNIFICANT CUTS (~50% in irrigation)	4.5
< 10 hm^3	9.1%	EXTREME DEFICITS	4 hm^3	VERY SIGNIFICANT CUTS (more than 50%)	1.5

Water abstracted from the Ezousa aquifer is mixed with water from dams to supply eight agricultural irrigation districts located in the Wester part, two golf courses[6] and industrial uses. The three districts in the Eastern part are 100% supplied with water from dams. Approximately 1320 farmers are located in these irrigation districts, with a total agricultural area of 2245 ha[7] (Figure 12), representing approximately 2/3 of the Paphos irrigated area[8]. According to WDD, the main irrigated crops in the study area are citrus, bananas, olives and vegetables.

[6] Two companies are buying recovered water from the Water Development Department (WDD) for use in their golf activities. Based on a Decision of the Cyprus Government, the WDD is required to supply private golf facilities through the water networks, at the price of desalinated water.
[7] According to Cyprus Agricultural Payments Organization (CAPO)
[8] Based on data from the initial Paphos Irrigation Project (WDD, 1982)

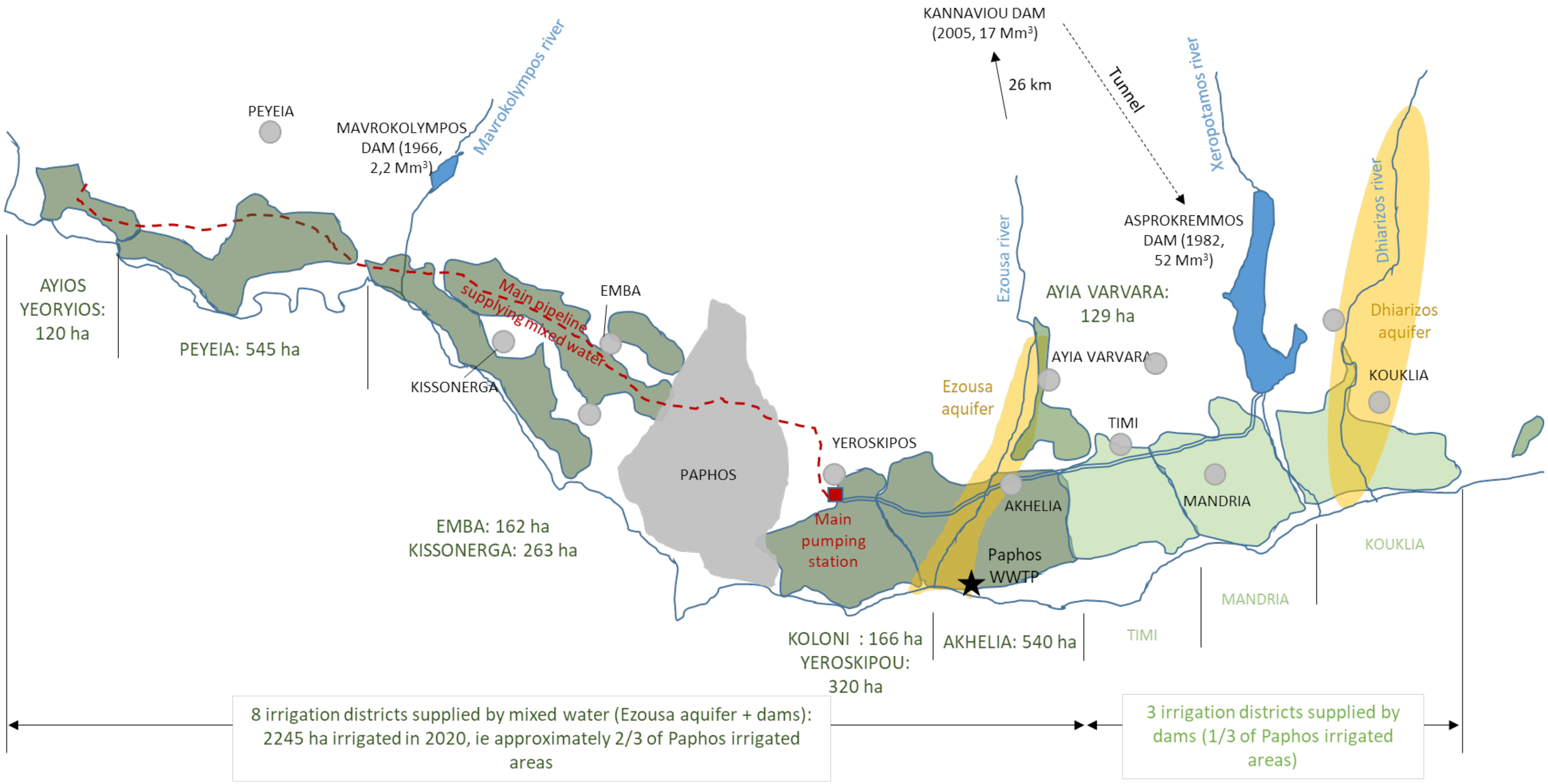


Figure 12. Schematic map of Paphos irrigation districts

5.2. STEP 2: DESCRIPTION OF THE RISKS ASSOCIATED TO MAR

Deliverable 2.1 applies a semi-quantitative risk assessment for 12 key hazards to the Ezousa MAR site, for human health, native groundwater and irrigation (Sprenger et al., 2020). Four of them were classified in "high risk": pathogens, inorganic chemicals, nutrients, groundwater levels; and four of them in "unknown risk": organic chemicals, turbidity, radionuclides and mineral dissolution. Some of them are described and discussed below.

Pathogens

The risk of microbial contamination results from potential elevated concentrations of pathogens in the treated waste water and uncertainties about the performance of the soil aquifer treatment (natural purification). Except from E.Coli, monitoring of pathogens (e.g. rotavirus, cryptosporidium) in treated wastewater and in MAR influenced groundwater are missing. High concentrations of pathogens in the recovered water are recognized as a significant crop health issue and may lead to economic and health damages (if undetected) or to a decrease in water abstraction (if detected).

Turbidity and organic chemicals (pharmaceuticals, pesticides)

Turbidity has not been monitored in the MAR project. Thus, the risk assessment of turbidity and particulates in Ezousa aquifer has been classified as unknown (uncertain risk) and requires further investigations. Similarly, measurements regarding organic chemicals, such as pharmaceuticals, are absent from the database of WDD. Consequently, hazards associated with these parameters are uncertain, and further investigations are required. Turbidity can lead to the following risks:

- reduced disinfection performance, leading to increased risk from microbial pathogens (see above);
- increased risk of transporting a range of contaminants that can sorb to particles (same types of impacts than for pathogens);
- reduced permeability due to clogging (operational risk).

Salinity and groundwater levels

As mentioned above, the MAR site is expected to provide an effective barrier against seawater intrusion. Mitigation of sea-water intrusion can be achieved through the maintenance of a certain thickness of the saturated zone throughout the year. Proper monitoring of the MAR regarding the extraction rates and artificial recharge could minimize and prevent saltwater intrusion in the coastal aquifer.

Mineral dissolution

The Ezousa aquifer recharge sources, apart from treated waste water, include seasonal surface flows infiltrating down the aquifer and underground discharges from upstream of the dam. As the surface water percolates through the alluvial material and underlying formation of lavas, marls, chalks, and gypsum it acquires dissolved solids, salinity and a high sulphate content of around 600 mg/L. The mixing of the two different waters in the aquifer (treated sewage effluent and native groundwater) may give rise to chemical reactions. For example, precipitates or increased solubilisation of the surrounding aquifer material could occur. The formation of precipitates could clog the soil–aquifer system and reduce its capacity either to accept or to transmit additional recharged water. On the other hand, dissolution of the surrounding soil particles would increase the local permeability and concentration of dissolved solids in the extracted water (Christodoulou et al., 2007).

Overall, Sprenger et al. (2020) concluded that a more efficient control of the groundwater levels should be employed in order to improve groundwater quality. They recommend the use of remote sensing technologies to monitor recharge/ discharge rates to improve the control of seawater intrusion and to maximise the removal of pollutant during percolation. Further monitoring is also required to better assess the risks associated with salinity and water levels.

These different types of hazards can compromise the achievement of the expected benefits of the MAR site. Poor management of water levels can lead to saltwater intrusion and consequently irreversible degradation of groundwater quality. Similarly, high water levels or high concentrations of pathogens and pollutants in treated wastewater can compromise the effectiveness of natural water purification. Finally, these different hazards may imply a more or less long-lasting reduction of the volumes that can be abstracted from the aquifer, thus impacting the volume effectively available for irrigation. The economic consequences for the agricultural sector will depend on the extent and duration of the decrease in water abstraction, on the level of drought, and therefore on the insurance role played by the aquifer for irrigation water supply.

5.3. STEP 3: DEFINITION OF ALTERNATIVE MONITORING SITUATIONS

This section describes three situations that will form the basis for the economic assessment: the baseline situation, the SMART-Control situation and the "ideal" RMCS situation.

5.3.1. Baseline situation

In the baseline situation, the MAR facility is only monitored manually three times a year. Controlled abstraction takes place at the lower reaches of the aquifer downstream, thus providing a semi-closed system for the detailed analysis of groundwater quality dynamics. Mixed groundwater (treated effluent and native groundwater) is extracted from several wells which are located in the area, together with native groundwater. These extractions are **performed manually** in order to investigate the evolution of groundwater composition in the Ezousa MAR site. Groundwater and reclaimed waste-water are collected **three times a year** since 2003 to analyse water quality parameters (BOD5, COD), biological parameters (*Coliforms, Escherichia coli, Intestinal Coliforms, Bacteriophages*), physico-chemical parameters (*pH, Conductivity, Total hardness*), anions ($Cl^-, SO_4^-, HCO_3^-, F^-, NO_3^-, NO_2^-$) and cations ($Na^+, K^+, Ca_2^+, Mg_2^+, NH_4^+$), Total Phosphorous (*TP*), heavy metals (*Ni, Cd, Cr, Cu, Zn, Pb, Hg, Co, V, Fe, Ba*) and metalloids (*As, Se, B*). In addition, toxicity tests are carried out (*MTX EC20, MTX EC50, Daphnia EC50*). Pesticide and insecticide residuals in groundwater and waste-water are also identified. In this situation, irrigation volumes are estimated at 4.95 Mm^3 (default value, as indicated in the Drought Management Plan 2016-2021) at the beginning of the irrigation season, but may be decreased during the irrigation season in case of problems with quality or groundwater levels. In this situation, reliability of irrigation volume is low, and updated only 3 times a year.

5.3.2. SMART-Control situation

The SMART-Control situation consists to develop an innovative web-based open source platform including modelling, monitoring and risk assessment tools. For that purpose, in-situ real-time observation system are installed: five sensors provide **automatic measurements** of electric conductivity, temperature and piezometric levels on a **daily basis**. The data are transmitted through the telemetry system of the sensors to the web-based platform, thus enabling the up-to-date diagnostic for operators, regulators and water managers. The SMART-Control situation allows to continuously monitor the effect of MAR on saltwater intrusion as well as the local water quality. Laboratory analysis of pathogens that are currently not measured (e.g. rotavirus, cryptosporidium) and heavy metals (copper) accompanies the online monitoring. As a consequence, the management and operation of the Ezousa MAR site is improved, with the reduction of associated risks.

This way, more efficient strategies can be designed in order to reduce the economic and health impacts. Monitoring can also be used to minimize the costs associated with the design of more efficient treatment processes, such as technical pre-treatment at the Waste-Water Treatment Plant (WWTP) and the soil-aquifer treatment. As result, irrigation volumes can be better estimated in advance, with higher reliability (medium level) than in the baseline situation, and regularly updated.

5.3.3. Ideal SMART-Control situation

The ideal "SMART-Control" situation consists in acquiring online sensors that measure not only electric conductivity, temperature and groundwater levels (as in the "SMART-Control" situation) but also additional ones:

in particular, sensors that can measure various operational and water quality parameters including infiltration water volume, microbial content, chemical oxygen demand, nitrate, spectral adsorption coefficient, total suspended solids and dissolved organic carbon. These parameters encompass the most common operational, chemical and biological parameters that influence the risk at MAR facilities depending on the individual system setup. This ideal SMART-Control situation leads to the highest level of risk management. Irrigation volumes can be estimated in advance, with high reliability.

5.4. STEP 4: EXPECTED IMPACT OF BETTER INFORMATION ON DECISION-MAKING

SMART-Control approach (web-based tools and in-situ real-time observation system) can provide an efficient control of the recharge and recovery processes through simulation-based optimization and control, which allows water operators to optimize the performance of MAR systems while satisfying economic and environmental constraints.

The web-based platform provides various tools that can impact decision making regarding potential risks. As stated in the SMART-Control proposal, the first tool (T1) aims at initial risk assessment with the evaluation of risks and remediation measures (Sprenger et al., 2020). The second tool (T2) can be used as a guided instrument to evaluate subsurface removal processes of pathogens (Sprenger et al., 2021; Stefan et al., 2021). In addition, real-time monitoring data is used for up-to-date optimisation and management simulations (T3) based on the numerical modelling scheme of the MAR system (Glass et al., 2022b). With the help of the prediction and advanced management tool (T4), upcoming changes regarding climate change and urban development can be incorporated into the modelling framework (Glass et al., 2022a).

As a result, the main expected benefits associated to the SMART-Control monitoring system for the owners/operators/regulators of Ezousa MAR site are:

a) the protection of the MAR insurance role for irrigating farmers, on the short- and long term, and associated significant reduction of damages caused by system's failure due to environmental and technical risks by the faster response time and tools;

b) the replacement of costly, manual monitoring (sampling, laboratory analysis) with automatic and real-time, sensor-based monitoring and risk control mechanisms, at some of the sites followed by real-time web-based modelling and scenario analysis;

c) increased public awareness on environmentally sound technologies and support to educate different stakeholder groups about the advantages of MAR for sustainable water resources management.

The following analysis focuses on the economic value associated with the MAR insurance role for irrigating farmers and integrate it in the VoI framework. The analysis consists in understanding the benefits associated with securing irrigation volumes from MAR. The VoI framework can be applied as soon as the information leads to a change of decision among the actors who can benefit from it. To understand potential changes in decision, we have implemented a stakeholder-oriented approach in order to identify the potential impact of the real-time monitoring system on decision-making. In our case, this work consisted of consulting institutional stakeholders and farmers in the districts whose water comes partly from the Ezousa aquifer, supplemented by an analysis of the rules for managing the volumes that can be withdrawn for irrigation (WDD, 2016).

5.4.1. Survey description

We (BRGM and UCY) developed a questionnaire aiming to improve the knowledge of the consequences of different drought and water shortages conditions on agriculture in the Paphos district.

The questionnaire is structured into five main parts:

Part I aims to understand which global changes (climatic, socio-economic, water resource availability) farmers experienced in the last 15 years (6 questions).

Part II aims to understand how changes in water availability (quantity and quality) for irrigation are perceived by farmers and how they may have affected them in the last 15 years. Questions are then split into three sub-parts:

- II-1 Water restrictions at the beginning of the irrigation season (4 questions + 6 questions by level of water restriction: 10%, 20%, 33%, 50%);
- II-2 Water restrictions during the irrigation season (3 questions + 7 questions by level of water restriction: 10%, 20%, 33%, 50%);
- II-3 Irrigation water quality (2 questions + 6 questions by quality issue: bad smell, water turbidity, salt-water, other).

Part III aims to understand which actions farmers plan to take or would like to see implemented in the next 15 years to secure water availability (quantity and quality) for irrigation. Two types of adaptation actions are presented: those that farmers can implement on their own and those that can be implemented by public authorities (5 questions);

Part IV aims to describe the farms (10 questions);

Part V aims to collect socio-demographic data of the respondents (8 questions).

The questionnaire is bilingual (English and Greek) and created online with the Sphynx platform (Figure 13). It was tested and administered by the Cyprus chamber of agriculture in September – October 2021. It was pre-tested (face-to-face) with a limited number of farmers (6) in order to test its understanding and finalise the questions. It was then administered (face-to-face) to a representative sample of 51 farmers spread over the eight irrigation districts supplied by the Ezousa aquifer (Table 12).

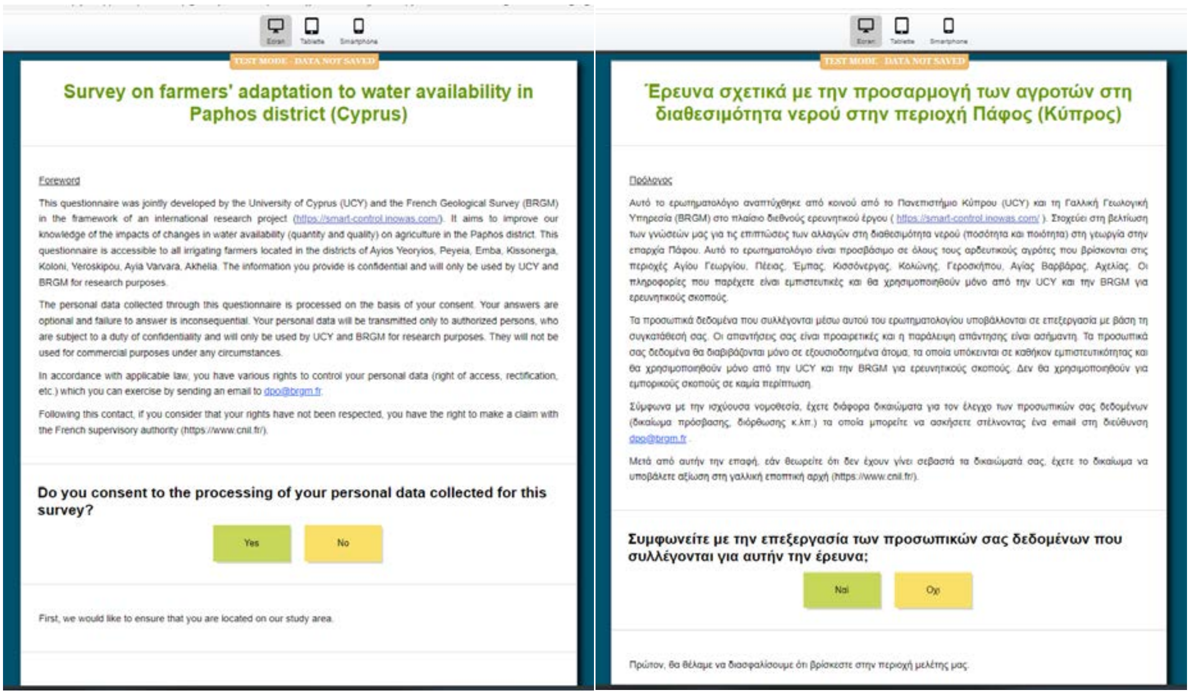


Figure 13. Homepage of the online bilingual survey

5.4.2. Sample description

Number of farms/ irrigated area/ irrigation volumes

The average irrigated area per farm is 27 decares (2.7 ha). Two farms are substantially larger than the average (150 and 190 dca). We removed them from the sample in order to have a better representation of the diversity of farms. As a result, our sample consists of 49 farms spread over the eight irrigation districts, with a total irrigated area of 1030 dca (21 dca/farm). They represent 4% of the total number of farms and 5% of the irrigated area of the 8 studied irrigated districts. Overall, there is a good representativeness of the distribution of the number of farms between the districts although three districts are slightly over-represented in terms of irrigated area (Peyeia, Kissonerga and Koloni) (Table 7).

Main crops (permanent/ annual; crops; distribution/ district; production; irrigation volumes)

Two thirds of the irrigated area are used for permanent crops (mainly bananas, citrus and olives), 1/3 for annual crops (mainly vegetables) (Table 8). Main types of crops are very different across the irrigation districts (e.g. citrus in Koloni, bananas and vegetables in Peyeia) (Figure 14). These results suggest the existence of diverse farm types in our sample. The mean irrigation volume is 803 m^3/dca. We estimate average volumes allocated in 2021 per crop with a linear regression based on data collected with the survey (Table 9). We also estimate the value of agricultural production by crop, based on statistical data provided by the statistical service of the republic of Cyprus (Table 10).

Table 7.Sample description by irrigation district

	Number of farms	Irrigated area (dca)	% district	2021 water volume (m^3)
Ayios Yeoryios	1	14	3%	9 000
Peyeia	13	340	7%	345 000
Kissonerga	8	217	9%	160 500
Emba	6	62	4%	45 000
Koloni	4	95	6%	67 500
Yeroskipou	7	103	4%	67 000
Akhelia	7	169	3%	114 700
Ayia Varvara	3	31	3%	18 400
	49	1 030	5%	827 100

Table 8. Irrigated area by crop

	Area (dca)	% total
Bananas	323	31%
Citrus	167	16%
Olive	96	9%
Avocado	34	3%
Grapes	23	2%
Walnuts	11	1%
Other permanent crops	9	1%
Total permanent crops	**663**	**64%**
Potatoes	102	10%
Tomatoes	58	6%
Other vegetables	154	15%
Peanuts	31	3%
Water melons	5	0%
Other annual	17	2%
Total annual crops	**367**	**36%**
TOTAL	**1030**	**100%**

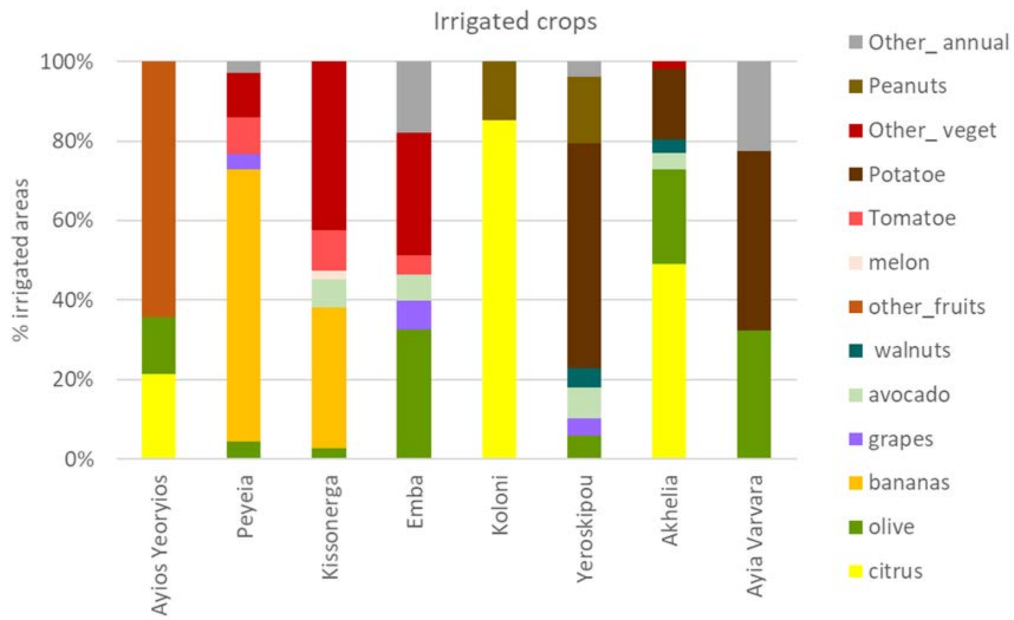


Figure 14. Irrigated areas by crop and irrigation district

Table 9. Estimated irrigation volumes by crop (results of a linear regression model)

	m^3/dca	Std. Err.	P>|t| [a]
Bananas	1197	31	****
Citrus	779	54	****
Olive	298	102	***
Avocado	745	188	****
Grapes	330	95	****
Walnuts	930	453	**
Other permanent crops	674	394	*
Potatoes	824	77	****
Tomatoes	766	170	****
Other vegetables	357	42	****
Peanuts	83	167	-
Other annual crops	888	217	****
N=51			
R^2=0.9912			
[a] Significant at * 10% ** 5% *** 1% **** 0.1%			

Table 10. Estimated production value by crop

	Mean yield [a]	Producer's price [b]	Estimated production value	
	tons/ha	€/ton	€/dca	€/m³ [c]
Citrus	47	275	1 281	1.64
Olive	1,3	876	111	0.37
Bananas	26,5	392	1 041	0.87
Grapes	3,4	417	141	0.43
Avocado	10,1	1 303	1 310	1.76
Walnuts	0,7	6 970	482	0.52
Other permanent crops	5	489	262	0.39
Water melons	37,8	303	1 142	n.a.
Tomatoes	75,6	813	6 146	8.02
Potatoes	21,3	354	754	0.92
Other vegetables	42	618	2 569	7.27
Other annual crops	4,6	164	75	0.08

[a] average on the 2010-2015 period (no water restriction) Source: 2020, REPUBLIC OF CYPRUS, STATISTICAL SERVICE
[b] year 2018. Source: 2020, REPUBLIC OF CYPRUS, STATISTICAL SERVICE
[c] based on the estimated water volume/ dca. Source: survey

Main types of farms

A hierarchical ascendant classification (cluster analysis) based on crop distribution per farm led to six main types of farms specialised in a specific type of crops (Figure 15):

- 4 types (37 farms) specialised in permanent crops:
  - 12 farms " bananas" (bananas represent 95% of the irrigated area)
  - 10 farms "olive" (71%)
  - 7 farms "citrus" (77%)
  - 8 farms "other arboriculture" (75%)
- 2 types (12 farms) specialised in annual crops:
  - 5 farms "potatoes" (81%)
  - 7 farms "vegetables" (94%)

Banana and citrus farms (38% of farms) are the main water users (63% of total volume) in our sample (Table 11).

Table 11. Description of the main types of farms

Farm types	Number of farms		Irrigated area		% permanent crops	Irrigation volume (m³)		Agricultural production			
	N	%	dca	%		m³	%	€	%	€/ m³	€/dca
Bananas	12	24%	332	32%	98%	390 000	47%	424 787	29%	1.04	1 279
Olives	10	20%	114	11%	81%	69 900	8%	22 536	2%	0.40	198
Citrus	7	14%	188	18%	91%	130 500	16%	200 037	14%	1.47	1 064
Potatoes	5	10%	139	13%	14%	100 000	5%	102 528	7%	1.03	738
Other arbo	8	16%	68	7%	100%	42 700	12%	53 085	4%	1.24	781
Vegetables	7	14%	189	18%	0%	94 000	11%	650 852	45%	7.00	3 444
	49	100%	1030	100%	67%	827 100	100%	1 453 825	100%	1.80	1 411

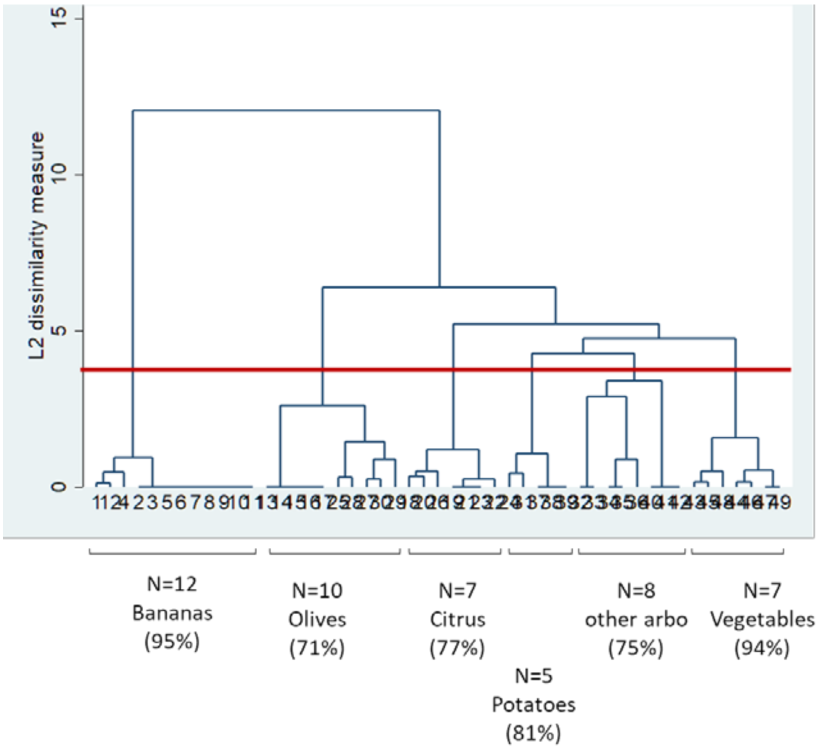


Figure 15. Dendrogram resulting from the type of farm cluster analysis

5.4.3. Main results of the survey

Perception of main changes experienced on the farm

The following figures summarize the perception of main changes experienced on the farm over the last 15 years (Figure 16), with a focus on climate changes (Figure 17) and water resources for irrigation (Figure 18). Figure 19 presents expected changes in water resources for irrigation in the next 15 years. These results are presented and discussed below.

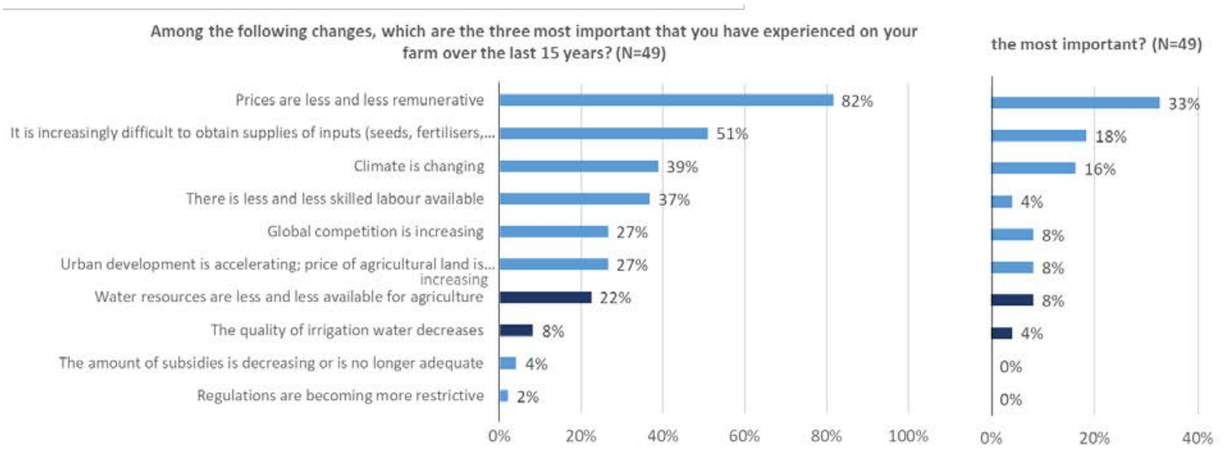


Figure 16. Main changes experienced on the farm over the last 15 years

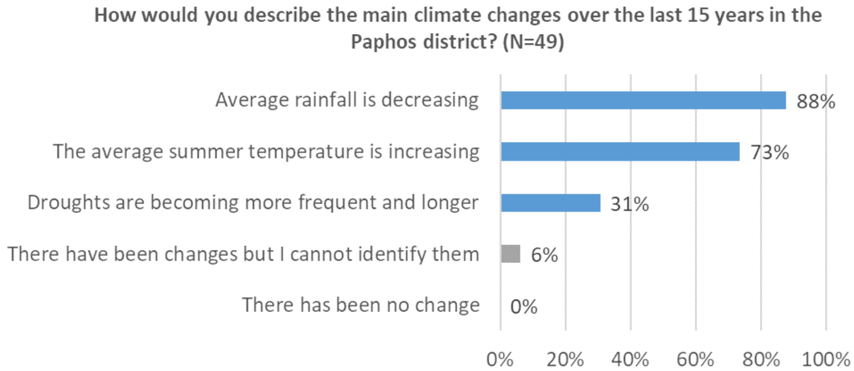


Figure 17. Perceived climate changes over the last 15 years

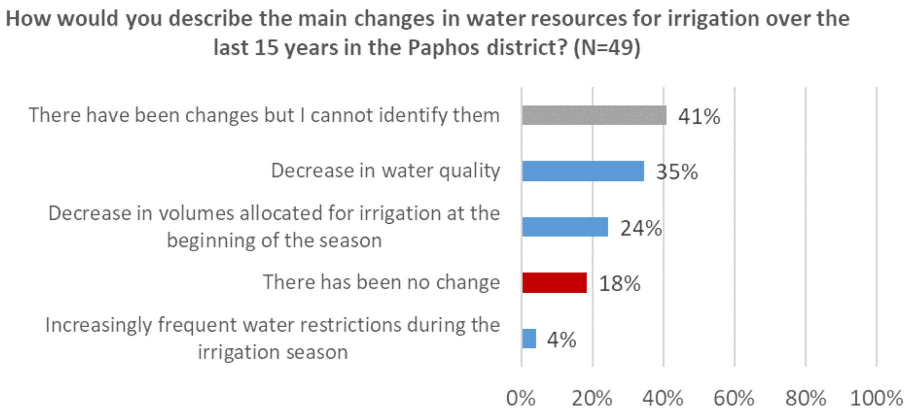


Figure 18. Perceived changes in water resources for irrigation over the last 15 years

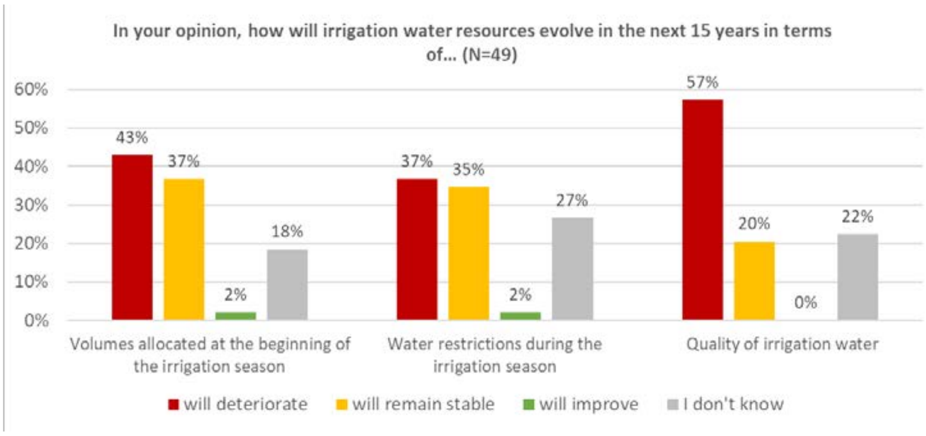


Figure 19. Expected changes in water resources for irrigation in the next 15 years

Perception and impacts of a decrease in water availability at the beginning of the irrigation season

Decrease in irrigation water availability is perceived by 22% of the farmers as one of the three main changes experienced on their farm over the last 15 years, and by 8% as the most important change (Figure 16). Twenty-four percent of the farmers consider that volumes allocated for irrigation at the beginning of the season have decreased over the last 15 years (Figure 18) and 43% expect the situation to deteriorate in the future (Figure 19). Over the last 15 years, 16 farms (33%) have been affected by water restrictions at the beginning of the irrigation season. Farmers estimate yield losses between 6% and 35% depending on the level of water restriction. They result in a mean annual damage estimated at 12 500 €/year (2.8% of the annual agricultural production of the 16 farms), or 0.56 €/m^3 (Table 12).

Table 12. Perceived impacts of water restriction at the beginning of the irrigation season

Water restriction	Beginning irrigation season				Volume (m^3)	Damage		
	Number of farms		Mean yield loss (%)	Perceived probability occurrence		Total (€)	€/year	€/m^3
	N	%						
-10%	7	14%	6%	0.27	23 400	8 322	2 219	0.36
-20%	12	24%	14%	0.22	55 000	32 162	7 058	0.58
-33%	4	8%	35%	0.14	36 960	24 151	3 227	0.65
-50%	0	0%	-	-	-	-	-	-
ALL	16	33%			115 360	64 635	12 504	0.56

Table 13. Adaptation actions to reduce the impacts of water restriction at the beginning of the season

Adaptation	N[a]	%
Improve my irrigation schedule	7	44%
No change: consumption of the necessary volume of irrigation water even if it means paying a higher water price	6	38%
Invest in more efficient irrigation systems	5	31%
Use of alternative water resources (e.g. private wells)	3	19%
Diversify my irrigation crops (to have water demand spread over the year)	3	19%
Reduce my irrigated area	2	13%
Test new, more drought-resistant varieties	0	0%
Stop irrigation	0	0%
Other	0	0%
ALL	16	100%

[a] number of farmers who implemented this adaptation at least once in case of water restriction at the beginning of the season

In case of water restriction at the beginning of the irrigation season, an important part of adaptation relies on improving the irrigation schedule (44% of the farmers), the efficiency of the irrigation system (31%), on diversifying crops (19%) and on reducing irrigated areas (13%) (Table 13). Another part of the farmers choose to use the volume they need, even if it means paying more (38%), and/or have the possibility to use other water resources (19%).

Perception and impacts of a decrease in water availability during the irrigation season

Four percent of the farmers consider that water restrictions during the irrigation season have become more frequent over the last 15 years (Figure 18) and 37% expect the situation to deteriorate in the future (Figure 19). Over the last 15 years, 41 farms (84%) have been affected by such in-season water restrictions. Farmers estimate yield losses between 23 and 49% depending on the level of water restriction. They result in a mean annual damage estimated at 71 550 €/year (5.3% of the annual agricultural production of these 41 farms; up to 23% in case of 50% water shortage), or 3.49€/m^3 (Table 14).

Table 14. Perceived impacts of water restriction during the irrigation season

Water restriction	During the irrigation season				Volume (m^3)	Damage		
	Number of farms		Mean yield loss (%)	Perceived probability occurrence		Total (€)	€/year	€/m^3
	N	%						
-10%	1	2%	0%	0.20	180	0	0	0
-20%	6	12%	23%	0.18	15 360	57 438	10 143	3.74
-33%	19	39%	30%	0.12	69 241	249 363	29 793	3.60
-50%	18	37%	49%	0.10	92 550	311 740	31 607	3.37
ALL	41	84%			177 331	618 541	71 542	3.49

Table 15. Adaptation actions to reduce the impacts of water restriction during the irrigation season

Adaptation	N[a]	%
Reduce my irrigated area	11	27%
Stop irrigation	9	22%
Improve my irrigation schedule	9	22%
Use of alternative water resources (e.g. private wells)	9	22%
Invest in more efficient irrigation systems	7	17%
No change: consumption of the necessary volume of irrigation water even if it means paying a higher water price	4	10%
Reduce irrigation practices to the minimum possible	3	7%
Diversify my irrigation crops (to have water demand spread over the year)	2	5%
Test new, more drought-resistant varieties	2	5%
ALL	41	100%

[a] number of farmers who implemented this adaptation at least once in case of water restriction during the season

In case of water restriction during the irrigation season, the main adaptation consists in reducing the irrigated area (27%), followed by stopping irrigation (22%). These proportions are much higher than for a restriction at the beginning of the season. Other adaptation consists in improving irrigation schedule (22%) and investing in more efficient irrigation systems (17%). Proportion of farmers having access to alternative resources is comparable to the previous case; while the share of those choosing to use the volume they need, even if it means paying more, is much lower (10%). These differences in adaptation probably explain, in part, the differences in damage (expressed in €/m^3) between a water restriction at the beginning and during the season.

Perception and impacts of a decrease in irrigation water quality

Decrease in irrigation water quality is perceived by 8% of the farmers as one of the three main changes experienced on their farm over the last 15 years, and by 4% as the most important change (Figure 16). Thirty five percent of the farmers consider that irrigation water quality has decreased over the last 15 years (Figure 18) and 57% expect the situation to deteriorate in the future (Figure 19). The main water quality problem is described as “bad smell” water (84% of the farmers), combined with turbidity (31%), saltwater intrusion (6%) and high pH (4%). Over the last 15 years, 41 farms (84%) have been affected by water quality problems. Farmers estimate yield losses between 2% and 30%, resulting in a mean annual damage estimated at 134 600 €/year (9.7% of the annual agricultural production of the 41 farms), or 0.20 €/m3 on average (all data considered). We can however observe that two farms concentrate 69% of the total annual damage and are facing unrepresentative water quality problems. Should we exclude their estimated damage from the analysis, the mean annual damage resulting from water quality problems is estimated at 41 800 €/year (3.9% of the annual agricultural production of the 39 farms), or 0.08 €/m^3 (Table 16).

For the majority of farmers (82%), irrigation water quality problems do not lead to any adaptation of their activity. The others are implementing adaptation, by using alternative water resources (8%), by reducing irrigation until the problem is solved (6%) or by installing filters (4%) (Table 17).

Table 16. Perceived impacts of decrease in water quality

Water quality problem	Number of farms		Mean yield loss (%)	Perceived probability occurrence	Volume (m3)	Damage		
	N	%				Total (€)	€/year	€/m3
Bad smell (only)	24	49%	2%	1.00	414 000	11 229	11 229	0.03
Bad smell + turbidity	13	27%	8%	0.79	165 200	26 952	21 292	0.16
Salt-water + bad smell	2	4%	25%	0.50	92 000	18 641	9 321	0.20
Bad smell + turbidity + high pH	*1*	*2%*	*25%*	*1.00*	*42 000*	*(22 491)*	*(22 491)*	*(0.54)*
Bad smell + turbidity + salt + high pH	*1*	*2%*	*30%*	*1.00*	*35 000*	*(70 247)*	*(70 247)*	*(2.00)*
ALL (N=41)	41	84%			748 200	149 560	134 580	0.20
ALL (N=39)	39				671 200	56 822	41 842	0.08

Table 17. Adaptation actions to reduce the impacts of quality problems

Adaptation	N[a]	%
No change	40	82%
Use of alternative water resources (e.g. private wells)	4	8%
Reduce irrigation until the problem is solved	3	6%
Installation of filters	2	4%

[a] number of farmers who implemented this adaptation at least once in case of water quality problem

Potential/ expected improvement of the management of irrigation volumes in the next 15 years

Overall, farmers are rather satisfied with the current system for allocating irrigation water volumes (Figure 22) and do not consider their improvement as a priority (Figure 21). The main actions they would like to see implemented by public authorities are the development of new resources (90%), the support for equipment to improve irrigation schedule (49%) and for investment in efficient irrigation systems (45%).

Nevertheless, only 6% of farmers consider that there is no need to improve the current system for allocating irrigation water volumes. The most expected improvements are the reduction of risk of water restrictions during the irrigation season (73%), a real-time information on water quality (45%) and by knowing the allocated volumes earlier to be able to adapt their crop rotation (39%) (Table 18). These results underline the interest of the tools developed in SMART-Control, which should make it possible to act on these three points. We focus our analysis hereafter on the benefits associated with the reduction of the risk of water restrictions during the irrigation season.

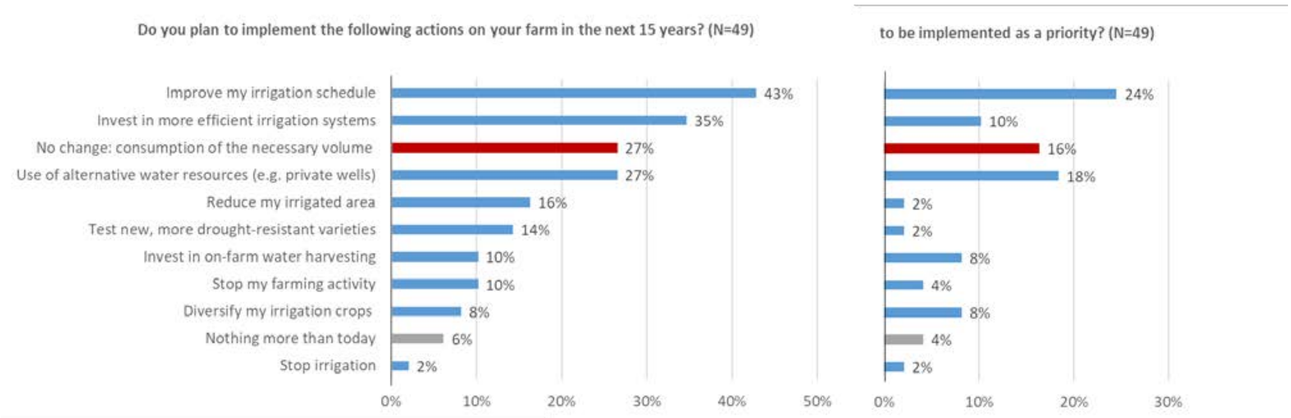


Figure 20. Actions likely to be implemented by farmers in the next 15 years

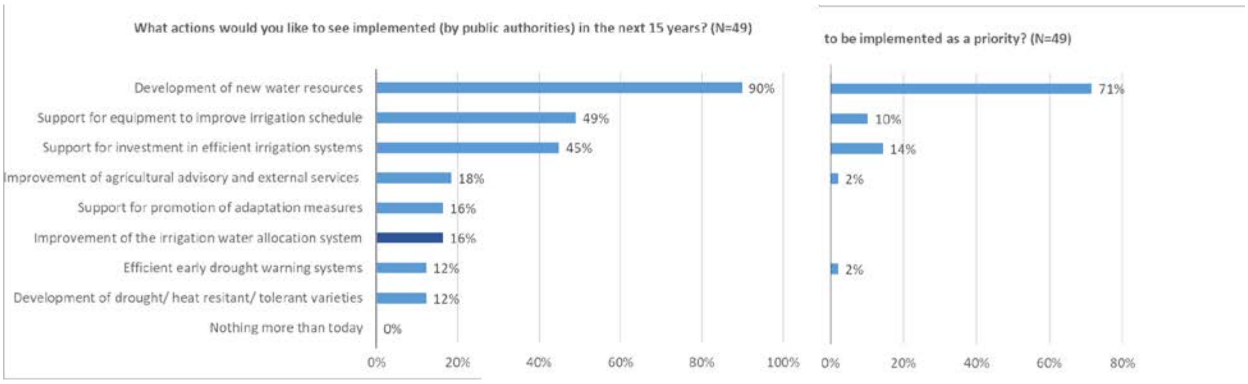


Figure 21. Actions farmers would like to see implemented by public authorities in the next 15 years

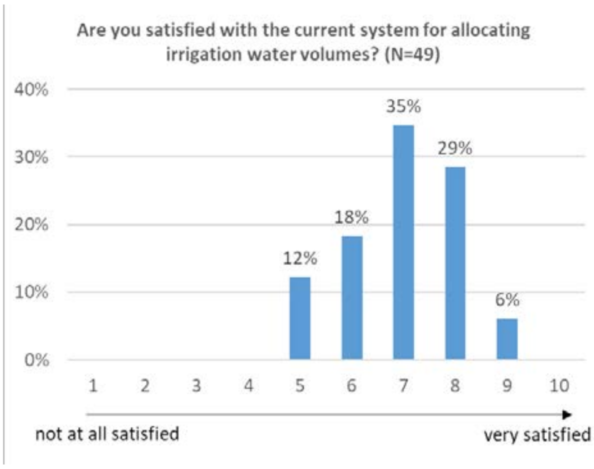


Figure 22. Farmers' assessment of the system of irrigation volume allocation

Table 18. Potential improvement of the system of irrigation volume allocation

"How do you think the irrigation water allocation system could be improved?"	N	%
By reducing the risk of water restrictions during the irrigation season	36	73%
By a real-time information system on water quality	22	45%
By knowing the allocated water volumes earlier, to be able to adapt my crop rotation	19	39%
There is no need to improve it	3	6%
Other	1	2%

Influencing factors

We used a linear regression model to test the influence of different factors on the level of yield loss in the event of water restriction. The analysis is conducted on a database listing each restriction event reported by farmers, i.e. N=67. A restriction event is characterised by the time at which the restriction occurs, the level of restriction, the probability of occurrence, the level of yield loss, and the type of adaptation implemented. In order to make the beginning- and in-season restrictions comparable, in terms of the volume involved, we created an equivalent restriction level field in the database (`level_equiv`). Indeed, a 10% reduction in volume at the beginning of the season is not equivalent to a 10% reduction in the remaining volume during the season. The in-season restriction occurs for the majority of respondents in July. According to Net Irrigation Requirements (NIR) data for bananas and citrus (Dalias et al., 2019), mid-July requirements are estimated to be around 60% of total requirements. We therefore estimate that the remaining irrigation volume in mid-July corresponds to 60% of the total volume. The in-season restriction therefore applies to 60% of the total volume. Example: a 20% restriction at the beginning of the season is equivalent to a 20% / 60% = 33% restriction mid-July (Table 18).

Table 19. Equivalence table of volume restrictions at the beginning/during the irrigation season

	Beginning season			In-season		
`Level_equiv`	Water restriction (%)	Mean yield losses (%)	Perceived probability occurrence	Equivalent water restriction (%)	Mean yield losses (%)	Perceived probability occurrence
10	-10%	-6%	0.27	-17% ~20%	-23%	0.18
20	-20%	-14%	0.22	-33%	-30%	0.12
33	-33%	-35%	0.14	-55% ~50%	-49%	0.10

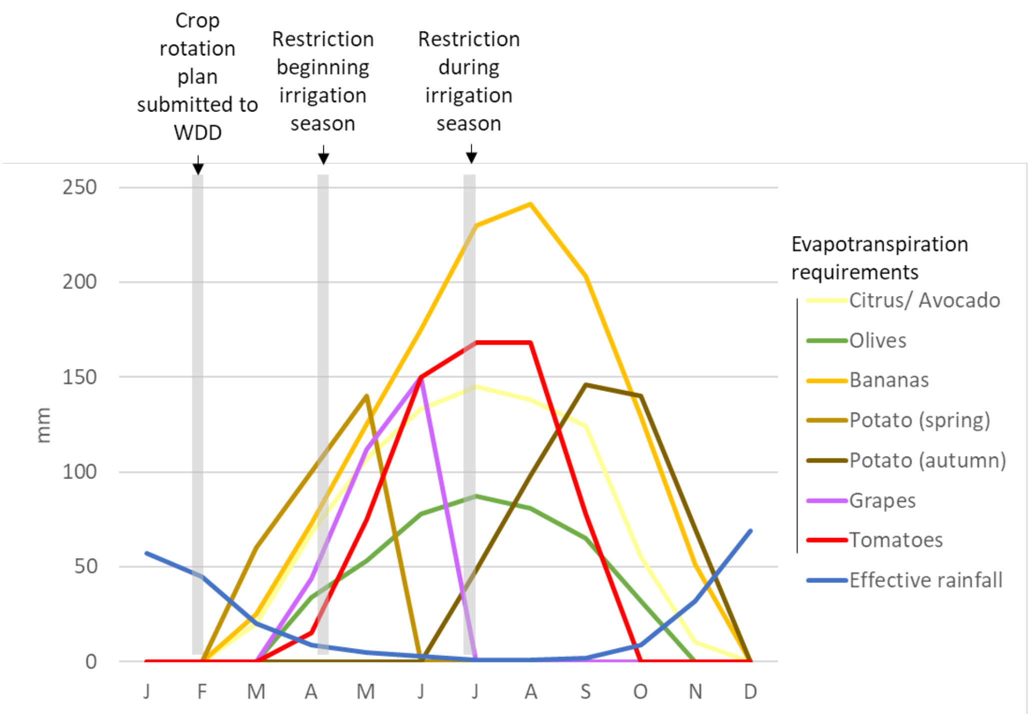


Figure 23. Evapotranspiration requirements and effective rainfall (adapted from Dalias et al., 2019)

Four factors have a significant influence (Figure 24): the time at which the restriction occurs (`diff`), the level of restriction (`level_equiv`), the consumption of the necessary volume of irrigation water even if it means paying a higher water price (`adapt_nochange2`), and the use of alternative water resources (`adapt_alternative`).

- The time at which the restriction occurs: a restriction occurring at the beginning of the season (`diff=1`) results in significantly lower yield losses than an in-season restriction (`diff=0`).
- The level of restriction (`level_equiv`) has a significant positive influence on yield loss.
- The consumption of the necessary volume of irrigation water even if it means paying a higher water price (`adapt_nochange2`) and the use of alternative water resources (`adapt_alternative`) have a significant negative influence on yield loss.

```
. regress restrict_yieldloss diff level_equiv adapt_nochange2 adapt_alternative

      Source |       SS           df       MS      Number of obs   =        67
-------------+----------------------------------   F(4, 62)        =     22.64
       Model |  184.879787         4  46.2199466   Prob > F        =    0.0000
    Residual |    126.5829        62  2.04165968   R-squared       =    0.5936
-------------+----------------------------------   Adj R-squared   =    0.5674
       Total |  311.462687        66  4.71913161   Root MSE        =    1.4289

------------------------------------------------------------------------------------
restrict_yieldl~s |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
------------------+-----------------------------------------------------------------
             diff |  -1.498311   .3842211    -3.90   0.000    -2.266358   -.7302638
      level_equiv |     .12112   .0210712     5.75   0.000     .0789993    .1632408
  adapt_nochange2 |  -1.304582   .4612986    -2.83   0.006    -2.226705   -.3824592
adapt_alternative |  -1.529442   .4746407    -3.22   0.002    -2.478235   -.5806483
            _cons |   1.232257   .5627426     2.19   0.032     .1073503    2.357163
------------------------------------------------------------------------------------
```

Figure 24. Factors influencing yield losses in case of water restriction

Type of crop or type of farm do not have a significant influence on the level of yield loss, whereas they strongly influence the economic consequences of a water restriction event i. Let's consider $restrict\_damage_i$ the economic damage associated with a water restriction event i (in €/m³).

$$restrict\_damage_i = \frac{restrict\_yieldloss_i \times \sum_j (uaa_j \times agriprod_j)}{restrict\_volume_i}$$

With $restrict\_yieldloss_i$ the level of yield loss (in %) associated with a water restriction event i, uaa_j the irrigated area of crop j (in dca), $agriprod_j$ the mean value of agricultural production of crop j (in €/dca), $restrict\_volume_i$ the restriction in water volume resulting from the event i (in m³).

5.5. STEP 5: QUANTIFICATION OF PRIOR PROBABILITIES, LIKELIHOODS AND CONSEQUENCES

5.5.1. Prior probabilities π_s

We consider five states of nature corresponding to the occurrence of different possible decrease in water volumes available for irrigation due to a problem on the MAR system (saltwater intrusion, quality problem or other...):

- S_0 No problem with MAR: no restriction during the season, the volumes allocated at the beginning of the season can be used;
- $S_{10\%}$ Problem with MAR that leads to a 10% decrease in irrigation volume;
- $S_{20\%}$ Problem with MAR that leads to a 20% decrease in irrigation volume;
- $S_{33\%}$ Problem with MAR that leads to a 33% decrease in irrigation volume;
- $S_{50\%}$ Problem with MAR that leads to a 50% decrease in irrigation volume.

Associated prior probabilities π_0, $\pi_{10\%}$, $\pi_{20\%}$, $\pi_{33\%}$ and $\pi_{50\%}$ are unknown. We propose here three options to estimate them.

Option 1: perceived probabilities of in-season water restrictions by affected farmers. We assume here that the probability of occurrence of these different states corresponds to the probability of in-season restriction perceived by the farmers that have already been affected by such in-season water restrictions (in equivalence level, cf. Table 19). We estimate prior probabilities based on Table 19:

- $\pi_{10\%}$=0.177 (N=6)
- $\pi_{20\%}$= 0.120 (N=19)
- $\pi_{33\%}$= 0.102 (N=18)
- $\pi_{50\%}$= 0 (N=0)[9]
- π_0=1-(0.177+0.120+0.102) = 0.601

Option 2: perceived probabilities of in-season water restrictions averaged by the total number of farmers. We also use the perceived probabilities, but average them by the total number of surveyed farmers (N=49):

- $\pi_{10\%}$=0.177 x 6/49= 0.022
- $\pi_{20\%}$= 0.120 x 19/49 = 0.047
- $\pi_{33\%}$= 0.102 x 18/49 = 0.037
- $\pi_{50\%}$= 0 [9]
- π_0=1-(0.022 + 0.047 + 0.037) = 0.894

Option 3: using occurrence probabilities of different drought contexts.

A problem on the MAR system implies a decrease in the MAR abstraction volumes that results in different rates of decrease in the total volume allocated, depending on the drought level. For example, let's take the case of a problem involving a 1 Mm^3 decrease. This decrease represents 10% of the allocated volume in a non-drought situation, 20% of the allocated volume in the case of a severe drought and more than 50% of the volume in the case of an extreme drought (Figure 25).

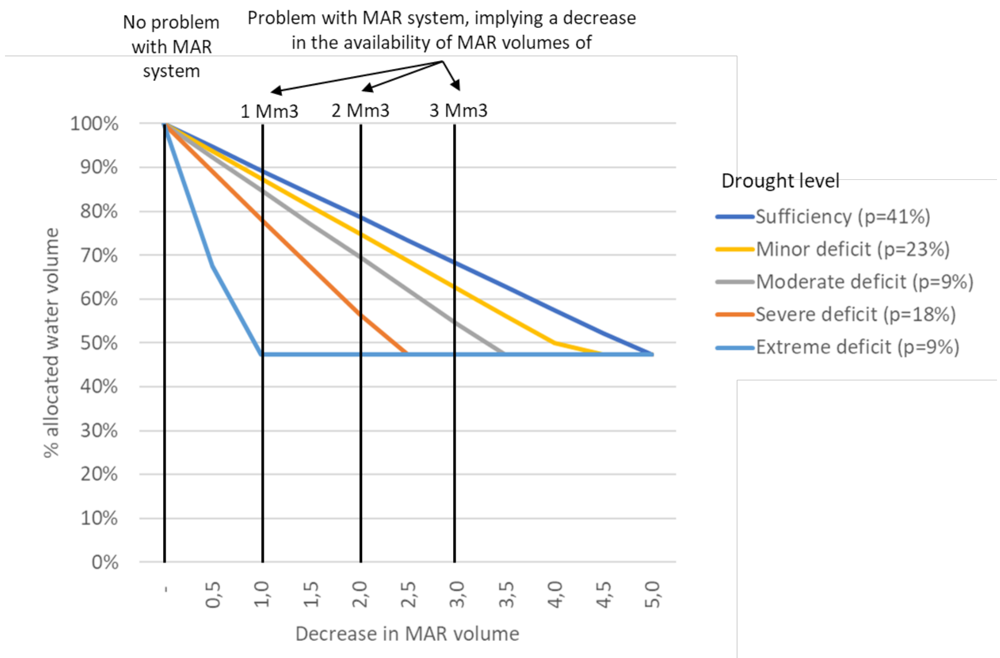


Figure 25. Impact of a problem with MAR system in terms of decrease in the total allocated water volume for irrigation

[9] Our sample does not allow to estimate prior probabilities associated to a MAR problem leading to a 50% decrease in irrigation volume. These probabilities are thus considered to be zero.

Let us consider here three possible decreases in MAR abstraction volumes: -1 Mm^3, -2 Mm^3 and -3 Mm^3, with respective occurrence frequency of 1 year out of 10 (p=0.10), 1 year out of 15 (p=0.067) and 1 year out of 20 (p=0.05)[10]. These decreases in the MAR volumes will result in decreases of 10 to 53% of the total volume allocated depending on the drought context. Probabilities associated with the different drought situations are provided by the Drought Management Plan WDD 2016 (Table 6).

Table 20. Five possible states of nature and associated probabilities

		Decrease in MAR volume (Mm3)			
		0 (p=0.783)	-1 (p=0.10)	-2 (p=0.067)	-3 (p=0.05)
Drought conditions	Extreme (p=0.09)	100%	47%	47%	47%
	Severe (p=0.18)	100%	78%	57%	47%
	Moderate (p=0.09)	100%	85%	70%	54%
	Minor (p=0.23)	100%	87%	75%	62%
	Sufficiency (p=0.41)	100%	89%	79%	68%

S_0 No problem with MAR
$S_{10\%}$ Problem with MAR that leads to a 10% decrease in irrigation volume;
$S_{20\%}$ Problem with MAR that leads to a 20% decrease in irrigation volume;
$S_{33\%}$ Problem with MAR that leads to a 33% decrease in irrigation volume
$S_{50\%}$ Problem with MAR that leads to a 50% decrease in irrigation volume

As a result, we estimate prior probabilities as a combination of the probabilities of occurrence of different drought conditions with the probabilities of occurrence of problems on the MAR system:

- $\pi_{10\%}$=0.10 x (0.41+0.23+0.09) = 0.073
- $\pi_{20\%}$= 0.10 x 0.18 + 0.067 x (0.41+0.23) = 0.061
- $\pi_{33\%}$= 0.067 x (0.18+0.019) + 0.05 x (0.41 + 0.23)= 0.050
- $\pi_{50\%}$= 0.10 x 0.09 + 0.067 x 0.09 + 0.05 x (0.09 + 0.18 + 0.09)= 0.033
- π_0=1-(0.073+0.061+0.050+0.033) = 0.783
- $\pi_0 + \pi_{10\%} + \pi_{20\%} + \pi_{33\%}$=1

The resulting probabilities have intermediate values, framed by the values obtained with options 1 and 2. We will retain these as the basis for VoI assessment in the rest of the analysis, while testing the sensitivity of the VoI to the other two options.

5.5.2. Likelihoods $q_{m,s}$

Likelihoods reflect the accuracy of the information system in predicting a potential problem with MAR at the beginning of the irrigation season. Likelihoods result from two types of potential error associated to the monitoring situations:

- The probability that the system does not predict any problem while there will be one (Type I error);
- The probability that the system predicts a problem with MAR when there is none (Type II error).

In the current monitoring situation, we consider that Type I error is equal to 1. In a perfect monitoring situation, both types of error would be equal to zero.

The SMART-Control monitoring system will be in an intermediate level. Survey results allows us to estimate the likelihood of detecting the need to reduce the irrigation volume at the beginning of the season, for all types of problems combined (availability of dam water and potential problem on the MAR). These likelihoods therefore evaluate the irrigation volume forecasting system as a whole, without distinction of the type of problem encountered (not possible to isolate problems related to the MAR system or the dam), and therefore do not reflect

[10] Please consider these probabilities only as working hypotheses proposed by the authors.

the likelihoods of detecting a problem on the MAR system specifically. The associated Type I errors range from 0.36 to 0.78, depending on the level of restriction required (Table 21). The average Type I error associated with the current allocation system is 0.52. We assume here that the likelihood of the SMART-Control system will be at least equal to this value, i.e., a Type I error of less than 0.52. Let's consider an intermediate value of 0.26. There is no data to estimate the type II error. We assume here that it is equal to 0.05. We will then test the sensitivity of the VoI to different values of of Type I and Type II errors.

Table 21. Likelihoods associated with the current water allocation system (for all types of problems combined)

	Restriction event beginning season		In-season restriction event		Total restriction events			
	N	p	N	p	N	p	q	Type I error
10%	7	0,27	6	0,18	13	0,23	0,64	0.36
20%	12	0,22	19	0,12	31	0,16	0,54	0.46
33%	4	0,13	18	0,10	22	0,11	0,22	0.78
ALL	23	0.22	43	0.12	66	0.16	0.48	0.52

5.5.3. Consequences c_{xs}

We consider two possible actions:

- x_1 consists in restricting irrigation water volumes at the beginning of the season;
- x_2 consists in doing nothing at the beginning of the season, and possibly leads to in-season restrictions in case of MAR problems.

The consequences are estimated from the yield losses associated with different levels of restriction, depending on the timing of the restriction (Table 19). As survey results do not allow to estimate yield losses associated with 50% water restrictions, we estimate them by considering that a 50% water restriction at the beginning of the season leads to -50% yield losses. Since the type of adaptation has an impact on the yield reduction (5.4.3), we formulate two options for the assessment of consequences:

- Option 1: yield loss observed for all types of adaptation;
- Option 2: yield loss observed excluding those who use an alternative water resource or who do not change their practices (on average 21% higher than for option 1).

These yield losses are applied to the value of agricultural production estimated for the sample. The analysis (5.4.3) shows that there is no significant difference in yield loss between crop types or farm types, so we assume here that the yield loss applies uniformly (Table 22).

Table 22. The consequences matrix (in k€/year)

		Option 1 : all adaptation types		Option 2: excl. alternative and no change	
		x_1: restrict beginning	x_2: do-nothing	x_1: restrict beginning	x_2: do-nothing
Scale : sample (1 030 dca)	$S_{50\%}$	-727	-1018	-831	-1101
	$S_{33\%}$	-509	-712	-581	-771
	$S_{20\%}$	-204	-436	-247	-567
	$S_{10\%}$	-87	-334	-145	-407
	S_0	-315	0	-379	0

5.6. STEP 6: QUANTIFICATION OF NET BENEFITS FOR EACH MONITORING SITUATION

5.6.1. Value of Information estimation (sample scale)

At the sample scale, when considering option 3 for prior probabilities estimation (using occurrence probabilities of different drought contexts) and option 2 for adaptation actions (excluding alternative water resources and no change), the VoI provided by the Smart-Control monitoring system (Type I error= 0.26; Type II error=0.05) is estimated at **27 k€/year, i.e., 26 €/dca, 2% of the agricultural production or 0.033 €/m^3** (Table 23). Should the monitoring situation be perfect (Type I error= 0; Type II error=0), the VoI would be equal to 57 k€/year, i.e., 55 €/dca, 4% of the agricultural production or 0.069 €/m^3.

Table 23. The decision-matrix for assessing the value of information (SMART-Control monitoring situation – scale: sample)

States (s)	Actions (x) in k€/year		Priors	Likelihoods $q_{m,s}$		Joint probabilities: $q_{m,s}.\pi_s$	
	x1: restrict beginning	x2: do-nothing	π_s	m_1: "Danger!"	m_2: "No panic"	m_1	m_2
$S_{50\%}$	-831	1101	0.033	0.74	0.26	0.024	0.009
$s_{33\%}$	-582	771	0.050	0.74	0.26	0.037	0.013
$s_{20\%}$	-247	-567	0.061	0.74	0.26	0.045	0.016
$s_{10\%}$	-145	-407	0.073	0.74	0.26	0.054	0.019
s_0	-379	-	0.783	0.05	0.95	0.039	0.745
$u(x.\ \pi_S)= \Sigma\ (\pi_S.c_{xS})$	-379	-138	Message probability: $q_m= \Sigma\ q_{m.s}.\pi_s$			0.199	0.801
$u(x_0.\ \pi_S)=\max u(x.\ \pi_S)$		-138	Posteriors:		$S_{50\%}$	0.123	0.011
			$\pi_{s.m}= q_{m.s}.\pi_s/\ q_m$		$s_{33\%}$	0.186	0.016
					$s_{20\%}$	0.225	0.020
					$s_{10\%}$	0.270	0.024
					s_0	0.197	0.930
			Expected surplus:		x_1	-379	-379
			$u(x.\pi_{s.m})=\Sigma(\pi_{s.m}.c_{xs})$		x_2	-516	-45
			$u(x_m.\pi_{s.m})=\max u(x.\pi_{s.m})$			-379	-45
			$\Delta(\mu)= \Sigma\ (q_m(u(x_m.\pi_{s.m}))-u(x_0.\pi_{s.m}))$				**27 k€/year**

5.6.2. Sensitivity analysis

VoI estimates are very sensitive to the options associated to prior probabilities estimation (5.5.1), to the Type I and Type II errors and, to a lesser exent, to the types of adaptation considered for assessing the consequences (5.5.3) (Table 24 and Figure 26). The VoI becomes zero when Type II error exceeds 15% whatever the Type I error, and is maximum when Type I and Type II errors are equal to zero (perfect monitoring system).

Table 24. Sensitivity analysis of VoI (in k€/year) to prior probabilities estimation and types of adaptation considered (scale : sample)

		π estimation		
		Option 1: perceived probabilities by affected farmers	Option 2: perceived probabilities by all farmers	Option 3: using drought occurrence probabilities
adaptation	Option 1: all	62	6	26
	Option 2: excl. altern. and no change	69	6	27

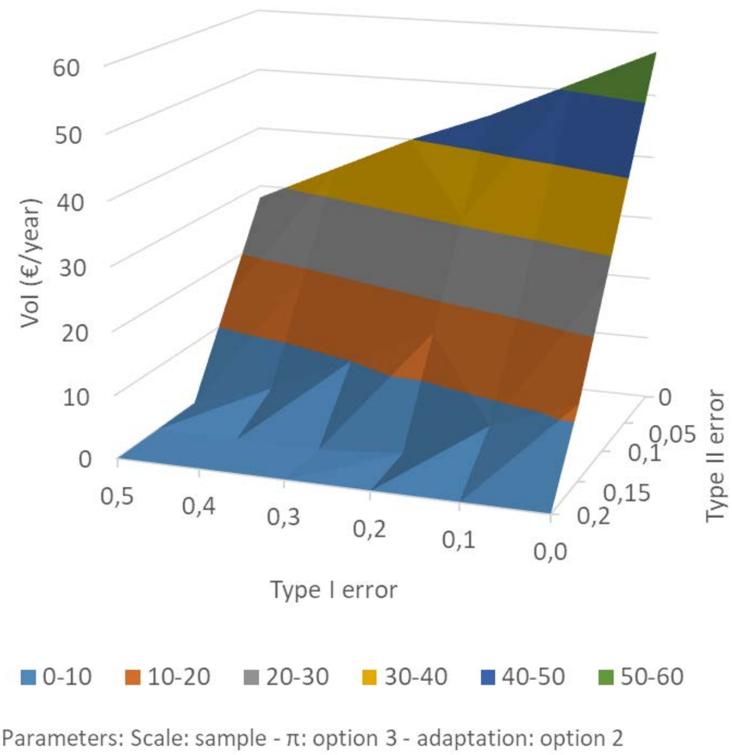


Figure 26. The value of information as a function of Type I and Type II errors

5.6.3. Value of Information extrapolation (full scale)

The SMART control monitoring system could benefit all farms in the 8 districts supplied with a mix of water from the Ezousa aquifer and the dams. Assessing VoI at this scale would require knowing exact list of crops and area per crop in the eight districts, and ensuring that our sample of farms is representative of the farms in the eight districts. In the absence of this information, a rough extrapolation of the VoI on the basis of irrigated areas (22 450 dca) of the eight districts leads to estimate VoI at 488 k€/year. Instead, if we extrapolate based on the irrigation volumes (approximately 9.4 Mm^3/year[11]), we estimate VoI at 310 k€/year. However, these figures should be considered as orders of magnitude, and with caution. An accurate VoI assessment at the scale of the eight districts would at least require a survey of a larger sample of farmers.

5.7. STEP 7: COMPARISON TO MONITORING COSTS

The SMART-Control monitoring situation relies on 5 sensors. Investment costs are estimated at 12 600 €, with a lifetime estimated at 4 years, i.e. 3 150 €/year. Operation and maintenance costs (SIM cards, accessories replacement, web-based platform and visits for maintenancel) are estimated at 1 235 €/year. Total annual costs related to the SMART-Control monitoring situation are estimated at 4 385 €/year, i.e., 16% of the VoI estimate at the sample scale, or 1 to 1.4% of the VoI rough estimate for the 8 irrigation districts.

[11] Based on WDD (2016) data : total irrigation volumes estimated at 14.2 Mm^3 for all Paphos districts, including 0.63 Mm^3 for gulf court irrigation and considering that the 8 districts represents 2/3 of the total irrigated areas (and irrigation volumes).

6. SYNTHESIS AND CONCLUSION

As MAR can be used in very different contexts, for different objectives and uses, and threatened by different risks, it is difficult to provide generic findings on the VoI associated with SMART-Control monitoring systems. This report describes the principle of VoI evaluation and presents a generic step-wise approach that can be implemented on a wide variety of contexts. The approach first relies on a qualitative evaluation (steps 1-4) aimed at understanding the benefits, risks, and how the SMART-Control tools can improve decision-making at each study site. If better information has a potential impact on decision-making and on benefits, the quantitative analysis of the economic consequences and probabilities can be implemented (steps 5-7) to assess VoI.

The report then presents the implementation of the stepwise approach to two operational MAR sites of the project: Berlin-Spandau (Germany) and Ezousa (Cyprus).

- In the Berlin-Spandau case (Germany), MAR is used to sustain drinking water production capacity, while maintaing support to groundwater dependent ecosystems. The qualitative analysis highlights that better information does not translate into changes in decision-making by the drinking water company with associated economic consequences. Two types of improvement are however provided by the real-time monitoring and control: 1) improved knowledge of HRT, making it possible to guarantee that the HRT is greater than 50 on all the wells and therefore to reduce the residual risk for human health in terms of DALYs and 2) faster detection of the type of problem and its origin in the event of an emergency, making it possible to have a more efficient management system. An interesting perspective to highlight the value of information on this site would be to implement a hybrid approach, combining QMRA and Bayes' theorem, by expressing the value of information in DALYs, not in monetary terms.
- In the Ezousa case (Cyprus), MAR plays a major insurance role for irrigation water supply. The full analysis (steps 1-7) is implemented, with a stakeholder-oriented approach based on the consultation of institutional stakeholders and farmers. We developed a survey aiming to improve the knowledge of the consequences of different drought and water shortages conditions in the Paphos district. Based on the results obtained with 54 farmers, the analysis provides first estimates of the net benefits associated with the SMART-Control monitoring to secure irrigation volume from MAR at 26 €/dca (260 €/ha), or 0.033 €/m^3. This equals a net benefit of approximately 27 000 €/year on the sample scale and 310 000 €/year if extrapolated for the 8 Paphos districts (rough estimation). Compared to the investment, operation and maintainence costs of the monitoring network (estimated at 4 400 €/year), the proposed SMART-Control monitoring solution could provide a solid and cheap technical solution to secure seasonal irrigation water supply with positive net benefits.

This report proposes, for the first time, to apply the VoI concept to assess the benefits provided by an improvement of MAR monitoring systems. The proposed approach makes it possible to capture the economic benefits associated with a change in decision due to better information. Better information can also lead to other benefits that cannot be quantified in economic terms. In the case of Berlin, it would be relevant to express the benefits in DALYs for example. More generally, improved information can enable managers of MAR systems to improve the transparency of their management methods for stakeholders in the territories. The characterisation of these non-economic benefits would require the development and/or mobilisation of complementary approaches (beyond the scope of this report).

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8. ANNEX

Data collected for each MAR site through the Excel file describing value of Information associated to SMART-Control tools : Qualitative assessment:

- Berlin/ Spandau (Germany)
- Ezousa (Cyprus)

Value of Information associated to SMART-Control tools : Qualitative assessment		
Title of Your Case: Berlin-Spandau (Germany)		
Name & email of the contributors: Christoph Sprenger (KWB) christoph.sprenger@kompetenz-wasser.de		
STEP 1: Description of the benefits expected from the MAR scheme		
A. Does the MAR scheme contributes to maintain/ increase water supply?		
If yes, please describe HOW, as precisely as possible : - Type of water use, - Period of the year, - Additional volumes that can be abstracted, - Beneficiaries.		YES, drinking water, supply 20-25 Mm3 per year, ~300 000 - 350 000 citizens of Berlin
B. Does the MAR scheme contributes to mitigate flood?		
If yes, please describe HOW, as precisely as possible : - Type of water source, - Period of the year, - Volume that can be infiltrated, - Beneficiaries.		NO
C. Does the MAR scheme contributes to support Groundwater Dependent Ecosystems (GDE)?		
If yes, please describe HOW, as precisely as possible : - Type of GDE, - Period of the year, - Additional flow in GDE expected from MAR, - Benefits provided by an additional flow, - Beneficiaries.		YES, swamps and lakes deignated as EU Natura 2000 area, additional information here (germany only): https://www.berlin.de/senuvk/natur_gruen/naturschutz/natura2000/de/gebiete/spandauer_forst.shtml
D. Does the MAR scheme contribute to provide other benefits to society?		
If yes, please describe HOW, as precisely as possible : - Type of benefits, - Beneficiaries.		
STEP 2: Description of the risks associated to the MAR scheme		
Risk 1	Description	pathogen breakthrough in drinking water wells
	Potential impacts on expected benefits described in STEP 1	limited water supply
	Potential management actions and associated costs	shut down of concerned wells, must be compensated by other wells
Risk 2	Description	limted source water availability (Havel River)
	Potential impacts on expected benefits described in STEP 1	limited water supply
	Potential management actions and associated costs	water supply compensated by other water works

STEP 3: Definition of two monitoring situations	
A. The "base case" situation	
Describe as precisely as possible the "base case" situation	microbial parameters monitored by conventional cultivation of microbiol paramteres in laboratory, results available after 12-24h, hydraulic residence time not monitored
B. The "SMART-Control" situation	
Describe as precisely as possible the "SMART-Control" situation, in comparison with the "base case". Describe differences between 2 situations. Describe the type of additional costs.	microbial parameters monitored by flow through cytometry, results available after 0.5 h, hydraulic residence time monitored in "real-time"
C. The ideal "SMART-Control" situation	
Describe as precisely as possible what would be an ideal "SMART-Control" situation, in comparison with the "base case". Describe differences between 2 situations. Describe the type of additional costs.	
STEP 4: Expected impact from SMART-Control on decision making	
A. Impacts on decision making regarding potential risks	
Will SMART-Control make it possible to better manage risks identified in STEP 2?	Yes, hygienic control of individual wells by hydraulic residence time monitoring and QMRA
B. Other impacts	
What other types of impacts do you think SMART-Control may have on your study area?	

Value of Information associated to SMART-Control tools : Qualitative assessment	
Title of Your Case: Ezousa (Cyprus)	
Name & email of the contributors: Konstantinos Panagiotou (UCY)	
STEP 1: Description of the benefits expected from the MAR scheme	
A. Does the MAR scheme contributes to maintain/ increase water supply?	
If yes, please describe HOW, as precisely as possible : - Type of water use, - Period of the year, - Additional volumes that can be abstracted, - Beneficiaries.	YES. Utilize treated effluent for groundwater augmentation in Ezousa Aquifer, which is a coastal aquifer. The coastal area has an intense agricultural activity and also supports the main urban centers that attract a growing number of tourists. Type of water use: Annual water demands are decomposed into two categories: irrigation purposes (mainly citrus cultivation), which consume approximately 17 million cubic meters, and tourism activities (including golf activities), which use around 3 million cubic meters. Period of the year: The tourism in Cyprus is mainly active during the summer period (from April to October)., while most water demands for the cultivation of citrus emerge between the end of winter-beginning of Spring (February-March). As a result, the usage of the recovered water from the aquifer from end-users is distributed along the whole year. On average, highest rates occur during the summer period (around 60% of the annual amount of recovered water). Additional volumes that can be abstracted: Since the construction of Kannaviou dam in 2005, the amount of water that flows in Ezousa river has been dramatically reduced. As a result, it can not be used as an alternative source of water abstraction. On the other hand, the water stored in the dams is released for irrigation purposes, part of which is mixed with the water recovered from the aquifer. Beneficiaries: According to Cyprus Agricultural Payments Organization (CAPO), there are around 820 persons (personal communication, WDD 2020) whose main work is agriculture that are currently using recovered water for irrigation purposes, while two companies are buying recovered water from the Water Development
B. Does the MAR scheme contributes to mitigate flood?	
If yes, please describe HOW, as precisely as possible : - Type of water source, - Period of the year, - Volume that can be infiltrated, - Beneficiaries.	NO. Cyprus suffers from water scarcity due to semi-arid conditions that prevail almost the entire time period. Consequently, no important storm-waters are emerging and thus no need to mitigate floods is present.
C. Does the MAR scheme contributes to support Groundwater Dependent Ecosystems (GDE)?	
If yes, please describe HOW, as precisely as possible : - Type of GDE, - Period of the year, - Additional flow in GDE expected from MAR, - Benefits provided by an additional flow, - Beneficiaries.	NO. Based on internal reports provided by the WWD (2003), no aquatic ecosystems of high value are present in the proximity of MAR facilities.
D. Does the MAR scheme contribute to provide other benefits to society?	
If yes, please describe HOW, as precisely as possible : - Type of benefits, - Beneficiaries.	YES. Ezousa aquifer is located at a coastal region that encounters excessive periods of low rainfall rates and high evaporation rates, thus exhibiting risks associated with seawater intrusion and large fluctuations on the groundwater levels. MAR scheme is expected to contribute to the mitigation of these effects, as pointed out in existing works 2, thus hindering the deterioration of the quality of the extracted water and thus avoiding the need to buy water from other sources or usage additional treatment processes.

STEP 2: Description of the risks associated to the MAR scheme		
Risk 1	Description	Groundwater levels and salinity. The hydrological conditions of the area are unique due to the construction of the Kannaviou dam in 2005 that resulted in a significant reduction of the natural recharge of the Ezousa aquifer and a lowering of the water table levels of the aquifer to a certain degree1. In addition, it was found that groundwater levels show large fluctuations .
	Potential impacts on expected benefits described in STEP 1	Mitigation of these risks can be achieved through MAR through the maintenance of a certain thickness of the unsaturated zone to ensure maximum removal of several quantities such as micro-organisms. In addition, proper monitoring of the MAR regarding the extraction rates and artificial recharge could minimize the combined effect on the freshwater-saltwater interface and prevent saltwater intrusion in the coastal aquifer.
	Potential management actions and associated costs	It is recommended to adjust basin recharge depending on seasonal water levels through the use of in-situ real-time observation system, as the one proposed in SMART-Control project. This choice is desirable for a number of reasons, such as: the replacement of costly, manual monitoring (sampling, laboratory analysis), the significant reduction of indirect costs caused by system's failure due to environmental and technical risks by the faster response time and tools offered by the project; and increased efficiency of the system leading to long-term economic (and environmental) gains. Thus, the extraction rates and artificial recharge could be coordinated to minimize their combined effect on the freshwater-saltwater interface and prevent saltwater intrusion in the coastal aquifer. A reduction of the financial cost can be achieved by mitigating the salinization effects, since it avoids the need to either consider additional water treatment or purchase water from more expensive sources, such as desalination.
Risk 2	Description	Pathogens. In the maximal risks assessment regarding Ezousa MAR (WP2-deliverable of the project), hazards to human health associated to pathogens are considered high because of elevated concentrations of pathogens in the source water and uncertainties about the performance of the treatment train. Except from E.Coli, measurements regarding other indicators or pathogens (e.g. rotavirus, cryptosporidium) in MAR influenced groundwater and treated wastewater after chlorination disinfection are missing.
	Potential impacts on expected benefits described in STEP 1	High levels of these parameters in the recovered water are recognized as a significant crop health issue. High concentrations of pathogens in the recovered water lead to potential clients (farmers) looking for other options (e.g. desalination water etc). Thus, pathogens can have a major impact on the expected benefits (water quality, cheap prices), since the majority of the recovered water is used for irrigation purposes, as mentioned in STEP 1.
	Potential management actions and associated costs	Improve the water monitoring by increasing the sampling frequency and by providing measurements for parameters that are currently not measured (e.g. rotavirus, cryptosporidium). This way, more efficient strategies can be designed in order to reduce the financial costs, thus reducing the need to either buy water from other sources, such as desalination. More specific, proper monitoring can be used to minimize the costs associated with the design of more efficient treatment processes, such as technical pre-treatment at the Waste-Water Treatment Plant (WWTP) and the soil-aquifer passage. Other preventive measures can involve reducing exposure through preventive measures on-site (e.g. controlling public access during irrigation with recovered water).
Risk 3	Description	Turbidity and particulates and organic chemicals (pharmaceuticals, pesticides). The public health and environmental risks associated with turbidity in relation to managed aquifer recharge include: • reduced disinfection performance, leading to increased risk from microbial pathogens • increased risk of transporting a range of contaminants that can sorb to particles • reduced permeability due to clogging (operational risk) Turbidity has not been monitored in the MAR project. Thus, the risk assessment of turbidity and particulates in Ezousa aquifer has been classified as unknown (uncertain risk) and requires further investigations. Similarly, measurements regarding organic chemicals, such as pharmaceuticals, are absent from the database of WDD. Consequently, hazards associated with these parameters are uncertain, thus further investigations are required.
	Potential impacts on expected benefits described in STEP 1	As in the previous cases, the concentration of these parameters have significant impact on water quality, thus making the potential clients to search for alternative options.
	Potential management actions and associated costs	Measurements regarding these parameters should be obtained in order to quantify the associated risks. Furthermore, frequent measurements of relevant quantities, such as Total Suspended Solids (TSS), should be conducted. For that purpose, consumables should be purchased, while skilled stuff should be hired to conduct the required water quality analyses.

STEP 3: Definition of two monitoring situations	
A. The "base case" situation	
Describe as precisely as possible the "base case" situation	The Ezousas aquifer characteristics, in particular its heterogeneity, high sulphate content from the gypsum dissolution, and limited size and depth, make it unsuitable as a potable water source. Hence, the recharge system was designed solely for crop irrigation use. In brief, the full-scale scheme at Ezousas, Cyprus (CYP) infiltrates tertiary treated wastewater through ponds to mitigate saltwater intrusion and increase the freshwater availability for irrigation. The recharge network consists of 23 infiltration ponds organized in groups of two to six basins . The infiltration area of each pond is approximately 2000 m^2 and 1.5 m below ground surface. Controlled abstraction (about 3 Mm ^3 annually) takes place at the lower reaches of the aquifer downstream, thus providing a semi-closed system for the detailed analysis of groundwater quality dynamics. Mixed groundwater (treated effluent and native groundwater) is extracted from several wells which are located in the area, together with native groundwater. These extractions are performed manually in order to investigate the evolution of groundwater composition in Ezousa project. Groundwater and reclaimed waste-water are collected three times per year since 2003 to analyze water quality parameters (BOD5, COD), biological parameters (Coliforms, Escherichia coli, Intestinal Coliforms, Bacteriophages), physico-chemical parameters (pH, Conductivity, Total hardness), anions and cations, Total Phosphorous (TP), heavy metals (Ni, Cd, Cr, Cu, Zn, Pb, Hg, Co, V, Fe, Ba) and metalloids (As, Se, B). In addition, toxicity tests are carried out (MTX EC20, MTX EC50, Daphnia EC50). Pesticide and insecticide residuals in groundwater and waste-water are also identified.
B. The "SMART-Control" situation	
Describe as precisely as possible the "SMART-Control" situation, in comparison with the "base case". Describe differences between 2 situations. Describe the type of additional costs.	The main outcome of SMART-Control will be the development of an innovative web-based open source platform including modelling, monitoring and risk assessment tools to improve the management and operation of MAR facilities and reduce the associated risks. By the development of open source and web-based tools in combination with real-time monitoring, monitoring at MAR facilities can be improved. For that purpose, in-situ real-time observation system will be installed in Ezousa site. Particularly, five sensors have been purchased from UIT company for measuring electric conductivity, temperature and relative pressure (groundwater levels). The installation of these sensors is on progress, and will provide automatic measurements in a weekly base, compared to the three times per year sampling that is currently the status. The data will be transmitted through the telemetry system of the sensors to the web-based platform, and will be used for different purposes (risk assessment, future predictions etc), thus enabling the up-to-date diagnostic for operators, regulators and water managers.
C. The ideal "SMART-Control" situation	
Describe as precisely as possible what would be an ideal "SMART-Control" situation, in comparison with the "base case". Describe differences between 2 situations. Describe the type of additional costs.	An ideal "SMART-Control" scenario would be to acquire online sensors that could measure not only electric conductivity, temperature and groundwater levels (as in the "SMART-Control" scenario) but additional ones. In particular, sensors that can measure various operational and water quality parameters including infiltration water volume, microbial content, chemical oxygen demand, nitrate, spectral adsorption coefficient, total suspended solids and dissolved organic carbon. These parameters encompass the most common operational, chemical and biological parameters that influence the risk at MAR facilities depending on the individual system setup.

STEP 4: Expected impact from SMART-Control on decision making	
A. Impacts on decision making regarding potential risks	
Will SMART-Control make it possible to better manage risks identified in STEP 2? If yes, which ones? How will it improve the decision making process? Increases the probability of taking the "right" decision? changes in the type of actions undertaken? economic implications?	SMART-Control approach (web-based tools and in-situ real-time observation system) can provide an efficient control of the recharge and recovery processes through simulation-based optimization and control, which will allow water operators to optimize the performance of MAR systems while satisfying economic and environmental constraints. The web-based platform is expected to provide various tools that can impact decision making regarding potential risks. As stated in the SMART-Control proposal, the first tool (T1) aims at initial risk assessment with the evaluation of risks and remediation measures which will be published in guidelines. The second tool (T2) will be used as a guided instrument to evaluate subsurface removal processes of pathogens. In addition, real-time monitoring data will be utilized for up-to-date optimisation and management simulations based on the numerical modelling scheme of the MAR system (T3). With the help of the prediction and advanced management tool (T4), upcoming changes regarding climate change and urban development can be incorporated into the modelling framework. Based on the above considerations, the owners/operators/regulators of Ezousa MAR site will have a strong economic benefit and improved decision making abilities from the project, which can be expressed in three components: a) the replacement of costly, manual monitoring (sampling, laboratory analysis) with automatic and real-time, sensor-based monitoring and risk control mechanisms, at some of the sites followed by real-time web-based modelling and scenario analysis; b) the significant reduction of indirect costs caused by system's failure due to environmental and technical risks by the faster response time and tools offered by the project; and c) increased efficiency of the system leading to long-term economic (and environmental) gains;
B. Other impacts	
What other types of impacts do you think SMART-Control may have on your study area?	The project will also contribute to increasing the public awareness on environmentally sound technologies and help educate different stakeholder groups about the advantages of MAR for sustainable water resources management. These gains are difficult to monetize at this stage but the investment in environmental education has in general a high long-term return rate.