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Climate Proof Fresh Water Supply in Coastal Areas and Deltas in Europe

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In the near future, climate change will likely increase pressures on transition zones such as deltas and coastal areas (IPCC, 2013). This special issue focuses on how to "climate proof" these zones with special concerns for the stresses stemming from droughts and salinization. Coastal zones and Deltas are under pressure worldwide. High water demand in these regions put pressure on the availability of freshwater resources and on coastal ecosystems. This leads to problems like water shortage, overexploitation of groundwater resources, saltwater intrusion, and degradation of wetlands. Economic growth, population increase, and climate change may potentially intensify these problems. This, therefore, is of strategic importance for Europe, which has a long coastline where many human activities are concentrated. Coastal aquifer development is often intensive and prone to induce salinization because of seawater intrusion, up-coning of deep saline water, and residual salinity in aquitards (Custodio 2010). Severity and frequency of droughts appear to have increased in the southern European countries. Minimum river flows are projected to decrease significantly not only in southern and southeastern Europe, but also in many other parts of the continent, especially in summer (EEA 2012). The Mediterranean region is particularly stressed (e.g. Giorgi 2006), due to the combined effect of rising sea levels, increased water demand due to global warming, and reduced aquifer recharge.

In this special issue, local impacts and responses to the challenges described above are discussed in seven papers with case studies from the Netherlands, Spain, Portugal and Greece.

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These papers are functional in

- representing and demonstrating a wide range of tools to assess risk of fresh water shortage under climate change at both local (Stofberg et al., 2016) and regional scale (Stigter et al., 2015, Giannikopouloua et al., 2015, and Iglesias et al., 2015),
- providing practical examples of how to systematically compare different adaptation strategies (Giannikopouloua et al. 2015) and socio-economic development scenarios (Stigter et al., 2015).
- exploring novel methods to develop resilient, robust and flexible adaptation plans (Thissen et al., 2015) to account for a range of future developments (Stigter et al., 2015)
- and showing that adoption of new technologies such as presented by Zuurbier et al., 2016 and inventoried by Iglesias et al.. Iglesias et al., 2015 depend mostly on the risk perception and the confidence in these technologies (Veraart et al., 2016), which in turn is influenced by demonstrated success in terms of reliability and the costs-benefits ratio (Veraart et al., 2016 and Zuurbier et al., 2016)

Veraart et al. (2016) evaluate the socio-economic factors that determine the wider use of adaptation measures at farm level in a few pilot studies in the Southwestern part of the Netherlands. Water availability during the agricultural growing season is expected to decrease because of an expected increase in freshwater demands and a changing climate and is expected to affect agricultural production. A survey among farmers was used to analyze drought risk perception and willingness to invest in new innovative technologies for water buffering. The survey was complemented by feasibility studies at three pilot locations. The main insights of the paper are, *i)* that farmers in the area are not well-informed about actual drought risk figures, *ii)* that the survey respondents were pessimistic about the wider implementation of the investigated technologies but that confidence in innovative measures increased amongst participants during the pilots and *iii)* that reliability of the freshwater supply and supportive legislation are the most decisive socio-economic factors for a future investment in additional freshwater supply for farmers in this region. Furthermore, the study showed that farm type and crop choices had a significant influence on the benefits of the technologies.

Stigter et al. (Stigter et al. 2015) present a combined assessment of the potential impacts from climate change (CC) and socioeconomic development (SED) on the most important aquifer in the south of Portugal. The goal is to understand how CC and SED affect the currently large pressures from water consuming and contaminating activities, predominantly agriculture. The novelty of the study lies in the development of SED scenarios using combination of bottom-up and top-down methods in a collaborative way with farmers and institutional stakeholders in the water sector. Groundwater use was quantified for each scenario. Together with the recharge scenarios, they were used to model their individual and joint impacts on groundwater levels and discharge rates into a coastal estuary. The study clearly reveals that the desired scenario of growth and modernization of agriculture is unsustainable and would call for considerable adaptation efforts. The results thus reveal that CC in the region will dynamically interact with economic factors, and going one step beyond, CC could be directly integrated as a constraint in the development of SED scenarios. In the authors' view the method presented contributes in an encouraging manner to a more holistic and trans disciplinary approach to water management, by allowing a more plausible identification of what (and if) adaptation measures are needed.

Iglesias et al. (2015) present another illustrative case for the Mediterranean area in which traditional agricultural practice, in this case rice production in coastal wetlands is threatened as freshwater supply is deteriorating at an unprecedented rate. The authors explore flexible adaptation options to climate change in the Doñana wetlands in Spain. Several policy options for the improvement of agricultural water management were derived from stakeholder views framed according to the local environmental, social and policy context. Results suggest that perception on the potential role of new water infrastructure and farming subsidies dominates the view of local communities. The choices of the stakeholders were simulated with an agro-hydrologicalmodel toquantify the effectsin terms of additional water availability for the rice farming. The paper shows that the in this way quantitative information provided during the study shaped the final adaptation options developed.

Giannikopouloua et al. (2015) propose a comprehensive method for an economic risk-based assessment and prioritization of long-term drought mitigation options in order to support decision making for drought planning. The assessment combines water balance modeling, hazard analysis, and risk and cost effectiveness analysis. The method is applied to the Greek island of Syros, a drought-prone area with recurring water scarcity problems due to agriculture and domestic water use. The proposed approach allows an improved understanding of drought-related risks by following a probabilistic analysis of drought impacts under different adaptation scenarios. Six adaptation strategies are compared in terms of contribution to future drought risk reduction using three criteria: risk, vulnerability and benefit-cost ratio. In contrast to the study by Stigter et al. (2015), *Giannikopoulou* et al. focus on the comparative risk assessment of adaptation options rather than on impacts under future uncertainties. In doing so they show the power of a systematic risk-based assessment of mitigation options coupled to the economic system in supporting decision makers.

Zuurbier et al. (2016) evaluate concrete innovative subsurface water technologies (SWT) that can provide solutions to manage freshwater resources in the subsurface. This is done by either actively increasing the amount of stored subsurface water or by protecting fresh water wells against salinization. The innovations are built upon existing techniques such as Aquifer Storage and Retrieval (ASR) but provide the users with much more control of their fresh water buffer under challenging circumstance like in salinizing deltas. By means of extensive field pilots and model exercises it is shown that the SWT can be used to deal with hydrogeological problems like seawater intrusion, upconing, and bubble drift during ASR and have significant economic benefits. At the same time these new technologies are sporadically applied to date. The authors argue that prolonged SWT testing in the current pilots, replication of SWT in other areas worldwide, and the development of technical and non-technical support tools are required to facilitate potential end-users in investment decision making and SWT implementation.

Stofberg et al., 2016 provide an extensive overview of analytical modeling tools to simulate and quantify *t*he dynamics of fresh water lenses and its effects on the root zone of crops or the natural vegetation. These tools help appraising the hazard of fresh water lenses disappearing from the Dutch coastal regions. The analytical models also give a basis to identify where the lenses may disappear periodically and in which coastal areas this risk is largest. The results obtained and the procedure followed by Stofberg et al. may assist in water management decisions and choosing prioritization strategies leading to a secure/robust fresh water supply on a national to regional scale. The methodologies presented are also relevant and may be adapted to other European regions where coastal polders and dune systems are present as, for example, in France, Spain and the Adriatic Italian coast.

Thissen et al. (2015) stress the need to take into account the fact that the future is highly uncertain and present three different approaches to fresh water supply planning under uncertainty in case studies in the Netherlands: a resilience approach, oriented to (re) designing fresh water systems in such a way that they will be less vulnerable, resp. Will be able to recover easily from future disturbances; a system robustness approach, oriented to quantitative assessment of system performance for various system configurations (adaptation options) under a range of external disturbances, and an exploratory modeling approach, developed to explore policy effectiveness and system operation under a very wide set of assumptions about future conditions. The examples shown are still rather conceptual and will need further operationalization. Some useful suggestions are however given how and under what circumstances to use the various methods. For example the presented resilience approach is recommended in an early stage of assessing a wide set of stakeholder options while the system robustness approach is recommended for quantitative analysis of one particular climate stressor. For all methods the outcome is however strongly dependent on whose perspective is guiding the scientific assessment and who is and is not responsible for adaptation.

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Evaluation of Socio-Economic Factors that Determine Adoption of Climate Compatible Freshwater Supply Measures at Farm Level: a Case Study in the Southwest Netherlands

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Abstract The availability of freshwater resources in soil and groundwater bodies in the southwestern part of The Netherlands is expected to decrease during the agricultural growing season because of an expected increase of freshwater demands and a changing climate. This expected shortage of fresh water might negatively affect agricultural production. To cope with this problem, three pilots were initiated aimed at increasing freshwater supply at farm-level. The objective of this paper is to evaluate the socio-economic factors that determine the wider use of the measures investigated in these pilots. Therefore, the results of a feasibility study and a survey about drought risks were compared. The survey indicates that respondents do not make distinction between a dry and extremely dry year in their estimation of the return period. The results of a feasibility study illustrate that confidence and the level of common understanding regarding the reliability of these innovative measures has increased amongst project participants since 2012. The survey respondents were less optimistic about the wider implementation of the investigated technologies. A reliable freshwater supply and supportive legislation are the most decisive socio-economic factors for a future investment in additional freshwater supply for farmers in this region. Both studies illustrate that the impact of additional freshwater supply on farm economics strongly depends on farm type and crop cultivation plan. These insights may support the wider use of these innovations and may help to improve agro-hydrological models.

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1 Introduction

Under average climatic conditions, freshwater supply for Dutch agriculture is excellent. A large part of Dutch agricultural areas can be supplied with water from the rivers (Fig. 1). However, in situations with a low river discharge and a high precipitation deficit, it is possible that the freshwater supply cannot meet agricultural freshwater demand during the growing season. This is particularly true for the rain-fed agricultural areas in the southwestern part of the Netherlands (Fig. 1) that have no access to river water. These agricultural areas, situated below sea level, are also sensitive to salt water intrusion (Cominelli et al. 2013; De Louw 2013; De Louw et al. 2011; Van Bakel et al. 2009).

The Netherlands usually has a precipitation deficit in summer (average 100 mm) and a precipitation surplus in winter. In the coastal zone, the precipitation deficit in spring and early summer is usually larger than in the rest of the country, whereas the situation is reversed in late summer and autumn (Van Minnen and Ligtvoet 2012). The annual cumulative maximum precipitation deficit occurs during the summer half-year from April to September (Beersma and Buishand 2004).

In the southwest of the Netherlands there are about 5500–6000 farms, of which 50 % perform arable farming, 12 % horticulture and 6 % greenhouse horticulture (CBS & LEI 2014). In 2012, total turnover amounted to some 1.3 billion euro (Visser & van Tuinen 2012).

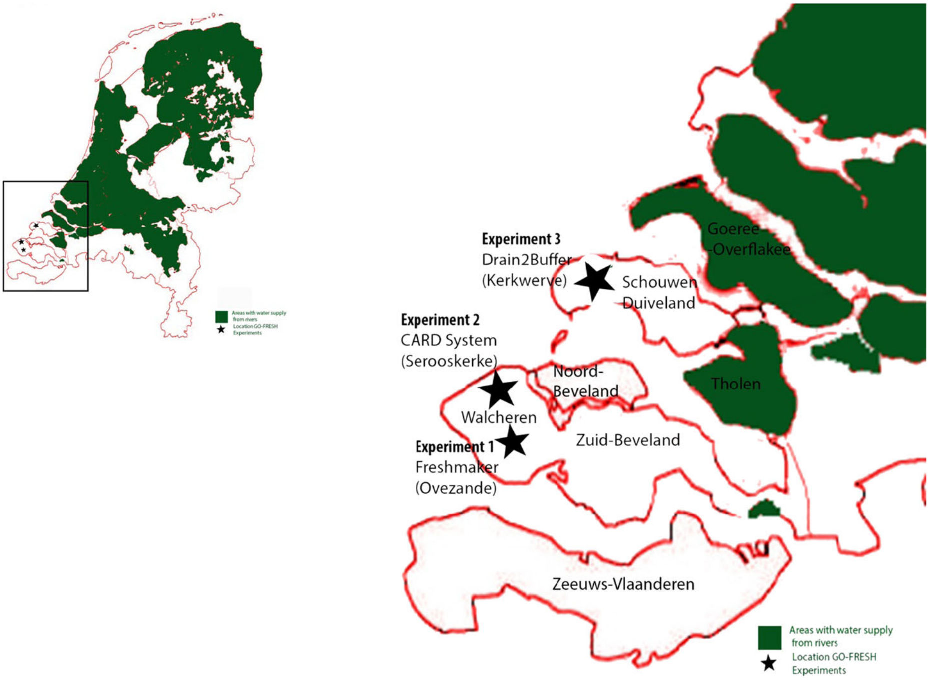

Fig. 1 Freshwater supply areas in the Netherlands (Van Minnen and Ligtvoet 2012). The white areas are dependent on precipitation and groundwater resources and/or artificial water supply (Zeeuws-Vlaanderen). The black stars represent the GO-FRESH experiments

The probability of agricultural yield reduction and loss of farm income due to water shortage and salinization in these rain-fed areas is therefore larger than the probability in other regions with an external fresh water supply from rivers. The availability of freshwater resources in soil and groundwater bodies will most likely decrease in southwest Netherlands due to prospective climate change and increasing water demand (Oude Essink et al. 2010).

Other reasons to improve freshwater supply at the farm-level, in this part of the Netherlands, are the expected impact of climate change (Kabat et al. 2009) and of the partial recovery of estuarine dynamics in this region (Hommes et al. 2009; Vinke-de Kruijf et al. 2010).

In practice, the application of a technology to improve freshwater supply at a farm depends on its socio-economic feasibility and the behaviour of the farmer. Within the research program ‘Knowledge for Climate’ (Jeuken Jeuken et al. 2012a; Oude Essink et al. 2014) these aspects were investigated in two projects:

The GO-FRESH project, which stands for Geo-hydrological Opportunities Fresh Water Supply consists of three pilots (2011–2014) with new technologies to improve freshwater supply at farm level (Table 1).

Moreover, the project also contains a so-called feasibility study with the objective to identify and to select socio-economic factors that determine the feasibility of the technologies applied in the pilots. It concerns technologies that buffer winter precipitation surplus in soil and groundwater bodies to be used in summer. By applying this technology, farms become better equipped to cope with precipitation deficits in summer. In each pilot, drainage, infiltration and abstraction technologies, known from geo-hydrological and agricultural engineering, are combined. The pilots are currently still in an experimental stage. The GO-FRESH project participants have worked together for three years (2011–2014).

Within the project ‘Balancing supply and demand of freshwater’, a survey was conducted in the southwest of the Netherlands to elicit farmers ‘risk perceptions and adaptive behaviour to drought (van Duinen et al. 2014; Van Duinen et al. 2015). The survey analyses the attitude of potential users of the new technologies with respect to the feasibility of drought mitigation measures over time at a certain moment (Spring 2013). The survey was conducted amongst

Table 1 *Description of the three GO-FRESH experiments*

Experiment 1 (Freshmaker): This technology is based upon aquifer storage and recovery (ASR) which involves injection and recovery of freshwater in aquifers via vertical abstraction wells. Although ASR is a proven technology(Pyne 2005), the technique is not yet often used in aquifers in a brackish to saline environment as exemplified in this experiment at a fruit orchard in Ovezande (Zuurbier et al. 2014a; Zuurbier et al. 2014b).

Experiment 2 (**CARD system**, *Controlled Artificial Recharge and Drainage system*) concerns storage and infiltration of freshwater in creek deposits with controlled drainage systems at two farms in Serooskerke (horticulture and arable farming). Also, controlled drainage systems and sub-irrigation are a proven technology (Madramootoo et al. 2007; Stuyt and Dierickx 2006) but have never been used to infiltrate fresh water into a saline groundwater environment (Pauw et al. 2015).

Experiment 3 (Drains2buffer) involves increasing shallow rainwater lenses with controlled drainage and has been applied at a farm in Schouwen-Duiveland, Kerkwerve (arable farming). The rainwater storage capacity of the subsurface is increased by drainage of brackish to saline groundwater. This is achieved by positioning the drainage pipes deeper and closer to each other as compared to conventional drainage designs (Oude Essink et al. 2014). The technology is also applied in the North of the Netherlands within the project Spaarwater (ACACIA Water 2014; Velstra et al. 2011).

agricultural entrepreneurs in the same region were the pilots were initiated (southwest Netherlands).

This paper focuses on socio-economic feasibility. Results of both studies are compared in order to assess how experts, farmers and policy makers evaluate environmental, socioeconomic, and behavioural factors that determine the wider use of water supply technologies at farm level.

2 Theoretical Framework

2.1 Adoption of Technologies

New technologies spread gradually, reflecting heterogeneity among potential adopters, processes of learning, technological improvement and socio-economic conditions (Rogers 2003; Vreugdenhil et al. 2012). Several studies stemming from various scientific disciplines (Bouma et al. 2011; Kiparsky et al. 2013; Ortt et al. 2008) highlight the importance of economic, behavioural, institutional, and social factors in the adoption of innovations in various sectors, including the water management (Nji and Fonteh 2002; Vreugdenhil et al. 2010a; Vreugdenhil et al. 2010b; Vreugdenhil et al. 2012) and climate adaptation science (Bolson and Broad 2013; Zilberman et al. 2012).

Adaptation to climate change can be defined in many ways (Fankhauser and Schmidt-Traub 2011; International Panel on Climate Change (IPCC) 2007; Nelson et al. 2007. We choose a definition suggested by Zilberman et al. (2012) where adaptation is defined as a response of economic agents and societies to environmental (climate adaptation) or political and socio-economic changes. Given the inherent uncertainties (Swart et al. 2009), decision making at farm level about adaptation strategies could be defined as a risk management strategy.

Application of micro-economic theory to study the adoption of farm technology, suggests that expected costs and benefits as well as risk aversion are important drivers of farmers' decision-making when facing risks (Just and Zilberman 1983; Liu 2013; Serra et al. 2008; van Duinen et al. 2014).

Typically, these studies assume perfectly rational decision-making in which agents form expectations based on perfect information on the probabilities and potential damages related to extreme weather conditions.

While economic factors are important, it becomes increasingly recognized that decision-making in a risk context is seldomly perfectly rational and that behavioural factors such as risk perception along with perceived costs, benefits and self-efficacy affect individual adaptive decision-making (Dang et al. 2014; Gebrehiwot and van der Veen 2015; Grothmann and Patt 2005; Liu 2013; Pidgeon and Fischhoff 2011; Schwarz and Ernst 2009). Research shows, for example, that farmers' drought risk perceptions are biased due to drought risk experience, perceived behavioural control and social networks (Tang et al. 2013; Van Duinen et al. 2015; Wheeler et al. 2013). Biased risk perceptions could give rise to risky behaviour or excessively protective behaviour.

Due to these behavioural factors and imperfect knowledge, farmers, water managers and the developers of a technology might perceive the socio-economic feasibility of an innovative technology differently (De Boer et al. 2010). Also, differences in perceptions regarding crop yield reduction risks may play a role in choices of farmers (Lavee 2010; van Duinen et al. 2012) regarding investments in local freshwater supply technologies. Biases in the perceptions of risks (De Boer et al. 2010), costs (Klostermann et al. 2013) and uncertainties about the effectiveness of measures to improve freshwater supply (Lavee 2010), may hamper the adoption and diffusion of these technologies.

3 Research Approach

Results from the feasibility and survey studies are combined and compared. Both studies tried to assess attitudes towards innovations in fresh water supply at the farm-level in the south-western Netherlands in view of climate change, in absence of sufficient empirical data on hydrological efficiciency and crop yield of the applied technologies. The quantification of some of the socio-economic factors were meant to discuss the impact of assumptions. It was not the objective to compare the feasibility of the three technologies.

As the study subject and its context are similar, a case study approach (Flyvbjerg 2006; Yin 2009; Yin 2012) is chosen to synthesize the results. It has to be taken into account that the studies were conducted in different ways.

4 Approach Feasibility Study

The feasibility study was conducted between 2011 and 2014 and included active membership (Adler and Adler 1987; Atkinson and Hammersley 1994) within a project team of about 20 people that consisted of technical experts, farmers, civil servants and some students (Table 2).

4.1 Selection of Feasibility Criteria

A wide array of criteria can be typified as relevant for the evaluation of the socio-economic feasibility of the investigated technologies. The criteria were identified through discussions with the project participants (Table 2) in workshops and interviews (Oude Essink et al. 2014).

Table 2 *actors directly involved in the experiments*

Funding bodies / regional authorities	Technical Experts	Target group for the innovation	Knowledge transfer / socio-economic conditions
Province of Zeeland	Deltares	Meeuwse Trading	HZ University of Applied Sciences
STOWA (Acronym for Foundation for Applied Water Research, founded by Dutch Water boards)	KWR Water	Fruit Cultivation firm (user technology 1)	ZLTO (Dutch agricultural interests association)
Water Board Scheldestromen	ACACIA Water	Arable farmer (user echnology 2)	Alterra
Foundation “Knowledge for Climate”		Horticulture (user technology 2)	
Municipality Schouwen-Duiveland		Arable farmer (user technology 3)	
ZLTO (Dutch agricultural interests association)			

All selected criteria were evaluated in a qualitative way. In addition, for all three experiments, the criteria directly related to the profitability at farm level were evaluated quantitatively.

4.2 Assessment of Costs and Benefits of the Application of a Technology at Farm Level

For each technology (CARD, Drain2buffer, FRESHMAKER), the expected net revenue of additional fresh water supply were estimated for two scenarios (Table 3). In the first scenario, the crop production plan has remained unchanged, while in the second scenario the crop production plan also has been altered to include more profitable crops. In the examples of arable farming, sugar beets were replaced by cauliflower. At the fruit company, on 25 % of the plots apples were replaced by pears (Table 3).

The estimated net revenue reflects the difference between the scenario and the reference situation, i.e. the situation without additional freshwater supply and baseline crop production plan. In the calculations no distinction is made between crop yield reduction caused by drought or by salinity. It is assumed that water nuisance damage is similar and minimized in all scenarios. Moreover (expected) long-term developments on the agricultural market and dynamics in market prices are not taken into account.

The applied farm sizes were the actual farm sizes where the experiments were conducted the applied crop production plans (arable farm 1, fruit farm) are representative for arable farming and fruit cultivation in this area in the Netherlands. The crop production plan of the farm in the DRAIN2BUFFER experiment was not applied because it included crops for which the required data were not available (spinach seed, grass seed).

4.3 Assumptions to Address Agro-Hydrological Uncertainties

It was assumed that application of a technology results in an additional freshwater supply of 100 mm, available for irrigation (FRESHMAKER, CARD) or as soil moisture (DRAINS2BUFFER). This irrigation gift quantity is representative for an average (moderately) dry year (Table 4). It is assumed that the three technologies have an equal and modest hydrological performance.

Table 3 *Farm properties used in the calculations*

Farm properties	Fruit farm	Arable farm 1 (Sanderse)	Arable farm 2 (Van den Hoek)
Applied technology	FRESMAKER	CARD	DRAIN2BUFFER
Farm size (ha)	15	25	75
Scenario 1: additional freshwater supply	75 % Elstar Apples, 25 % Conference Pears	Potatoes (25 %), unions (25 %), sugar beets (25 %), winter wheat (25 %)	
Scenario 2: Additional freshwater supply and an altered crop production plan	50 % Elstar Apples, 50 % Conference Pears	Potatoes (25 %), unions (25 %), winter wheat (25 % and 25 % cauliflower	

Table 4 *Characteristics of drought years that are used in national hydrological studies in the Netherlands* (*Klijn* et al. 2010)

	Precipitation deficit	Return period (as used in Dutch models) (Klijn et al. 2010; Klijn et al. 2011)	Relative yield reduction (as used in Dutch models) (Jeuken et al. 2012)	Irrigation gift (as used in Dutch models) (Massop et al. 2013; Stuyt et al. 2005)
Average dry year (1967)	151	2.5	6 %	100
Moderately dry year (1996)	199	6.7	?	?
Dry year (1949)	220	10	10 %	144
Extremely dry year (1976)	360	100	24 %	>200

4.4 Yield calculations: arable farms

For the reference situation (without additional freshwater supply), the figures of the gross production and the gross revenue per hectare for a specific crop were based upon the average yields (kg) and average prices (€/kg, VAT included) in the period 2007–2011 in the Netherlands (PPO Wageningen UR 2012). The gross revenue per hectare was calculated by subtracting material costs (fertilizers, pesticides, energy use, etc.) and the costs of hired labour from the gross production multiplied by the weighted average price/kg (Table 5). The gross revenue is the reward for the input of capital, land and (the farmers own) labour.

With respect to the supply of additional fresh water, it is assumed that, for all selected crops, a supply of 100 mm water increases the yield between 6 % and 10 % as compared to the reference situation (in the current Dutch climatic conditions). The assumed sensitivity to drought, therefore, is relatively small. Among the most drought-sensitive crops are summer vegetables, leafy vegetables, flower bulbs, fruit and tree crops. The potential gross yield of these crops might decrease by 9 to 38 % due to drought stress (Brouwer and Huinink 2002; Stuyt et al. 2005).

Table 5 Estimated *gross revenue per hectare of the crops within the crop rotation plans as used in the scenario's regarding* (*additional*) *water supply and changes in crop rotation*

	No additional water supply	With additional water supply			
Assumed yield increase	0 %	6 %	10 %	16 %	22 %
Source: (PPO Wageningen UR 2012)				(Heijerman-Peppelman and Roelofs 2010)	
	Gross revenue (€ *ha*$^{-1}$)				
Potatoes (consumption)	4011	4277	4573		
Winter wheat	1147	1112	1198		
Cauliflower	5216	5541	5893		
Sugar beet	1729	1770	1912		
Sowing union	3801	4050	4346		
Elstar apple	1444			2379	
Conference pear	7329				10,972

The difference between the reference situation and the situation with additional freshwater supply (scenario 1) and/or changed production plan (scenario 2), represents drought damage for up to a moderate dry year (Table 4).

4.5 Yield calculations: fruit firms

The difference between the measured averages of the 5-year physical yields (Heijerman-Peppelman and Roelofs 2010) of Elstar Apples (16 %) and Conference Pears (22 %) with and without irrigation was used to estimate the effect of an additional freshwater supply of 100 mm (Table 5). The net revenue of additional freshwater supply was calculated for the situation in which fruit trees are fully established and at full production. Apples and pears need respectively 4 and 6 years to achieve full production (Table 5) (Kipp 1992).

Cost calculations (*fruit and arable farming*)

The investment costs were estimated from the costs incurred during the construction of the experimental sites. The technical lifetime for all techniques used is set at 15 years in order to assess the annual depreciation.

Annual maintenance, energy and legislation costs are an important uncertainty, as the evaluated techniques have not yet been applied at a large scale. Estimations were made based upon a recent inventory of costs within the Netherlands (Tolk 2013) and cost estimations that were made during the course of the experiments by involved actors.

4.6 Net Revenue

In both cases the net revenue is determined as the product of the gross revenue for each crop and the corresponding crop surfaces minus the annual costs of the innovation. The annual costs of an innovation consist of the investment, maintenance and legislation costs. The costs of water supply (i.e. the use of the innovation) are accounted for in the yield calculations.

At present, the uncertainties in the costs and benefits for these three new technologies are still too large to calculate a net present value in a meaningful way with a discount rate. The cost calculations take into account an average inflation of 2.5 % over the entire lifespan of the investment.

5 Research Approach Survey Study

To elicit farmers' perceptions of drought risks and attitudes towards adaptive measures, a survey was conducted among 1474 members of a Dutch agricultural organization (division South, ZLTO) during January and February of 2013. TNS-NIPO, a professional organization in the Netherlands specializing in data collection using questionnaires (TNS-NIPO 2014), supported the survey design, web-application, and communication with respondents.

Some of the survey results (Van Duinen et al. 2015) are further explored to examine how the results agree with or differ from the experiences in the GO-FRESH project.

The survey was pre-tested in 12 interviews. After the pre-test, redundant questions were removed and unclear questions were reformulated. Survey requests and reminders were sent by email and by mail (Goeree Overflakkee) with the invitation to participate (online or by post). The 1474 survey requests, elicited 142 replies (response rate 9 %) (Van Duinen et al. 2015).

With small samples, response bias may pose a danger. To check the representativeness of the sample, age, education, farm size, farm type and access to an external water supply of the respondents were compared to those of the population in general using data from CBS Statistics Netherlands.

On average, farmers in the sample were slightly younger and better educated than the overall population they were thought to represent, but the differences were found to be small (Van Duinen et al. 2015). In the survey, arable farmers (81 % compared to 70 %) and those growing fruit and flowers were over-represented compared to farmers growing grass and corn (12 % compared to 26 % of the actual population). Consequently, the response rate was higher for those farms that are more susceptible for drought.

6 Feasibility Study: Results and Discussion

Table 6 illustrates the socio-economic factors, which were considered to be important for the feasibility by the GO-FRESH participants.

6.1 Discussion of Hydrological Performance

All participants involved (Table 2) were convinced that the hydrological performance of additional freshwater supply at the farm level is an important criterion for the adoption of the three studied technologies at a larger scale. The actors use the same indicator (additional freshwater supply expressed in m^3 or mm).

In the initial phase, regional authorities had doubts about the hydrological performance of the three experiments. This was because of their experiences with previous comparable experiments (Projectgroep Zoetwateronderzoek 1986; Van Meerten 1986; Vermaas 1987) with disappointing results. However, during the implementation of the results of the experiments, the farmers, researchers and policy makers involved became more convinced that the technologies are promising, despite uncertainties regarding their hydrological performance.

Field measurements also indicate that a significant and promising amount of freshwater was buffered in the subsurface in all three experiments (Table 7). This is also partly explained by the high winter precipitation surplus of 2013 (345 mm). Follow-up research (2015–2016) is scheduled for all 3 experiments in order to assess how the technologies perform under different weather conditions.

To implement the CARD-system, a 7 ha area was used and the development of the freshwater lens below this farm concerned (25 ha) and the neighbouring farm (11 ha) was monitored from May 2013 to May 2014. The application of the technology is beneficial to the increase of the size of the entire freshwater lens under both farms. Both farms have facilities (deep drains) to extract (irrigation) water from the lens.

The models applied predicted a total volumetric increase of the freshwater lens of about 190,000 m^3 after 10 years (Pauw et al. 2015). This implicates that after 1–2 years enough water is present in the sub-surface for 100 mm irrigation gift as assumed in the feasibility study.

For the Freshmaker technology, model calculations showed that after 2 years it becomes possible to annually recover 4200 m^3 from the subsurface (Zuurbier et al. 2014a). For this specific fruit farm in Ovezande the additional freshwater supply created is sufficient for a

Table 6 Overview of identified socio-economic factors within the GO-FRESH project team

	Involved Technical Experts	Involved Farmers & Drainage constructors	Regional authorities in water management & policy
Hydrological performance (additional water m^3 for irrigation)	Important, assumed to be significant, quantification is subject of research	Important, promising	Important, but also an uncertainty
Reliability & risk reduction	- Minimizing drought & salt damage risks - climate proof	- reliable water supply - climate proof	- Food security - Self-sufficient Freshwater supply - climate proof
Legislation	Minimize complexity	Minimize complexity	Necessary, but complexity is acknowledged.
Farm economics	- cost-benefit analysis at farm level (Δ€ ha^{-1} $yr.^{-1}$) - Revenue analysis (Δ€ ha-1 yr.-1) - Cost effectiveness (€ m^{-3}) - Investment return (yr)	Cost effectiveness (€ m^{-3})	cost-benefit analysis for agricultural sector (Δ€ ha^{-1} $yr.^{-1}$)
Ease of use	Not mentioned	Important	Not mentioned
Regional Environmental Impact	Water quality	What legislation permits	Water quality Ecology
Regional Economic Impact	Cost-benefit analysis for agricultural sector	Competitive advantages / co-operative freshwater supply	Fair distribution of cost & benefits of water supply

Table 7 Hydrological performance in the three pilot areas

	Irrigation requirement in a moderate dry year (100 mm)	Estimated hydrological performance	Development time of subsurface water buffer
CARD System Serooskerke (25 ha) (Pauw et al. 2015)	25.000 m3	190,000 M^3 Recharge after 10 years	10 years
Drains2Buffer Kerkwerve (75 ha) (Oude Essink et al. 2014)	75.000 m3	300,000 M^3	4–5 years
FRESHMAKER Ovezande Fruit Farm (15 ha)(Zuurbier et al. 2014a)	15.000 m^3	1700–3000 m^3 successfully infiltrated and recovered for irrigation in one season.	1 season

moderate dry summer. At first glance the additional water supply (4000 m3) does not meet the water demand (15,000 m3). However, in addition to sub surface storage (Freshmaker), this farm has a water basin (4500 m3). Rainwater is collected in winter. In case of water scarcity in spring or summer the basin can be re-filled with surface water, provided that the salinity is not too high. In case the salinity of the surface water is too high (summer), the basin can be re-filled with the additional water from the Freshmaker. In this specific example, the feasibility of the Freshwater technology benefitted from the presence of surface water and a water basin.

For the DRAIN2BUFFER technology, the first field measurements show that the drainage system performs better than the old drainage system. However, it was not yet possible to determine whether the freshwater lens in the field had increased significantly. Model calculations indicate that a maximum equilibrium of the freshwater lens can be reached in 4–5 years (Oude Essink et al. 2014). If the technology would be applied to the surface area of the farm, it would result in an increase of 300.000 m^3 freshwater. In theory, this will be sufficient to present an irrigation gift of 100 mm in the growing season in a moderate dry summer.

6.2 Reliability & Risk Reduction

The technical experts involved frequently used the reduction of drought and salt damage risks as an argument to apply the technologies. The farmers involved on the other hand, stressed the importance of reliability of freshwater supply. Only secondly, drought or salt damage risks were mentioned by the farmers. The farmers also asked the experts for guarantees on the hydrological performance of the technologies.

6.3 Legislation

The current legislation aims to reduce the environmental impact of large-scale withdrawals and infiltration of fresh water on the supplies of drinking water. All GO-FRESH participants agree that current legislation is not suited for small-scale applications of the three experiments.

Different regional authorities are in charge of the implementation (water board, municipality, province), while national authorities are responsible for the formulation of the quality standards for the water to be infiltrated. The regional authorities are cautious granting licenses in this early stage of technology development because the environmental impact of large-scale application at more farms in a region is unknown to them.

The level of juridical complexity is different for each technology. The use of the Freshmaker, for example, requires 5 licences for construction (bore holes), infiltration, withdrawal, discharge of brackish water into surface water and withdrawal of freshwater for irrigation. In addition, water quality monitoring is required for infiltration of freshwater and discharges of brackish groundwater into surface water. The application of the CARD and Drains2Buffer require less legislation and associated costs (Zuurbier et al. 2015).

Licenses include water quality standards and limits regarding the volume that is infiltrated or extracted. Monitoring activities are costs for the farmer. Permissions are an agreement between water manager and a farmer that a certain activity is allowed (no costs involved).

6.4 Farm Economics

All actors involved agree that the application of the technologies should, in the end, result in a benefit for the agricultural firm involved. However, different socio-economic indicators are used to assess the added value. Socio-economic indicators mentioned are the net revenue for farmers (Δ€ ha^{-1} yr.$^{-1}$) based upon the enumeration of costs and benefits at farm level, cost effectiveness (€ m^{-3}) and the investment return time (years). There was no agreement about what indicator to use preferentially. Although identical terms were used for the identified indicators, sometimes for the participants definitions implicitly are slightly different. For example, the cost-effectiveness of various technologies has been often discussed without information about the hydrological performance of each of the three technologies.

Table 8 presents the calculated economic indicators for the hypothetical firms with arable farming, horticulture and fruit cultivation for different scenarios regarding technology use and crop choice.

Table 8 Economic impacts of additional freshwater supply with applied new technologies (scenario 1) and changed crop rotation (scenario 2)

Socio-economic indicators	Fruit Farm (15 ha)	Arable farm (25 ha)	Arable farm (75 ha)
Applied technology	Aquifer storage & recovery (ASR) / Fresh maker	Storage in creek deposits	Storage in rainwater lenses
Investment costs (*euro*) (*derived from pilot costs*)	56,250	50,000	187,500
Annual costs technology* (euro)	6050–12.200	6500–7400	16,600–16,800
Annual cost/ha technology (€ *ha-*^{1})	400–800	260–300	220–225
Scenario 1: additional freshwater supply (technology use)			
Net revenue farmer ($\Delta\ 10^3$ € $ha^{-1}\ yr.^{-1}$)		−0.10 – 0.17 (6 %)	−0.1 (6 %)
	0.8–1.2	0.03–0.07 (10 %)	0.1 (10 %)
Scenario 2: additional freshwater supply and changed crop rotation			
Net revenue farmer ($\Delta\ 10^3$ € $ha^{-1}\ yr.^{-1}$)		0.07–0.08 (6 %)	0.9 (6 %)
	3.0–3.4	1.0–1.1 (10 %)	1.1 (10 %)

*Based upon a technical lifetime of 15 years

6.5 Discussion of Addressed Cost Indicators

The calculated cost indicators for the DRAIN2BUFFER and CARD are within the same range as mentioned in other studies (50–500 € ha^{-1}), while the estimated costs for Freshmaker application are relatively low compared to other studies (700–2400 € ha^{-1}) (Tolk 2013). Maintenance, energy use and legislation costs remain important uncertainties.

Differences in assumptions about investment costs have a low impact on the calculation of the net revenue because they are spread out over a 15 year period in the annual costs (depreciation). It should also be taken into account that farmers will compare the annual costs of additional freshwater supply with other investment options that may increase or maintain yield or farm income, such as crop management, pest management or harvest technologies (Kanellopoulos et al. 2014; Schaap et al. 2013).

6.6 Discussion of Net Revenues in Arable Farming

The results indicate that the application of additional fresh water supply (scenario 1) mitigates drought damage (net revenue ≈ 0) in moderate dry years, given the selected crop production plans for arable farming. At the fruit farm, additional the freshwater supply results into a modest revenue increase.

Scenario 2 illustrates that the net revenue of additional water supply can increase when the crop cultivation plan is simultaneously adapted towards more profitable crops for both type of farms. It should be noted that the design of the crop production plan does not only depend on freshwater availability. For example, pears are also very susceptible to pests and diseases. This risk also has an effect on the decision of a farmer regarding his crop production plan choice.

6.7 Ease of Use

The participating farmers and ZLTO expressed that the ease of use is an important factor when deciding whether to apply a certain technology or not. More experience is needed before concise statements can be made for a larger group of farmers.

6.8 Regional Environmental Impact

Water quality standards for groundwater and surface water are recognized criteria by technical experts, farmers and policy makers, as reflected in existent monitoring protocols for water supply and storage (Table 8). In particular, this is true for the Freshmaker project, where it was also subject of research. The Province of Zeeland also stressed the importance of ecological and landscape impacts when the technologies are applied at larger scale.

6.9 Regional Economic Impact

The application of the techniques can increase competitiveness of the agricultural sector in the southwestern Netherlands. However, additional freshwater supplies may also boost freshwater demand at regional level with implications for other water users. The distribution of costs was also brought up as a point of concern. If one farm invests in freshwater storage, the neighbouring farms may profit without sharing costs. Therefore a regulated freshwater supply with cost sharing via farm co-operations was also considered. This may accelerate the adoption of these technologies and reduce the legislation costs (cost sharing).

7 The Survey: Results and Discussion

7.1 Drought Risk Perceptions about Yield Reductions in a Dry and very Dry Year

The survey contained two questions that were designed to reveal farmers' drought risk perceptions. Respondents were asked to give a quantitative estimate of the return period (Fig. 2) and farm income reduction (Fig. 3) for a dry year and an extreme dry year.

Figure 2 shows that respondents did not make a distinction between a dry and extremely dry year in their estimation of the return period. For both meteorological conditions similar estimations were given that ranged between 2 and 15 years (Fig. 3). In hydrological studies (Table 4), a difference of a factor of 10 is assumed regarding years that are characteristic for the return period for a dry and a very dry year, respectively. This assumption is based upon time series analysis of climate data. It can be concluded that respondents tended to overestimate the probability of an extremely dry summer.

The survey respondents estimated an average production loss ranging from 750 euro per ha (arable farmers) up to 3500 euro per ha (fruit farms) in a very dry year (Fig. 3). The average income was ±3000–6000 € ha^{-1} (arable farming) and 15,000–19,000 € ha^{-1} (fruit) (LEI Wageningen UR 2014).

On average, farmers expect to suffer approximately €39,000 damage in a dry year compared to €78,000 in an extremely dry year. The average annual turnover of the respondents is

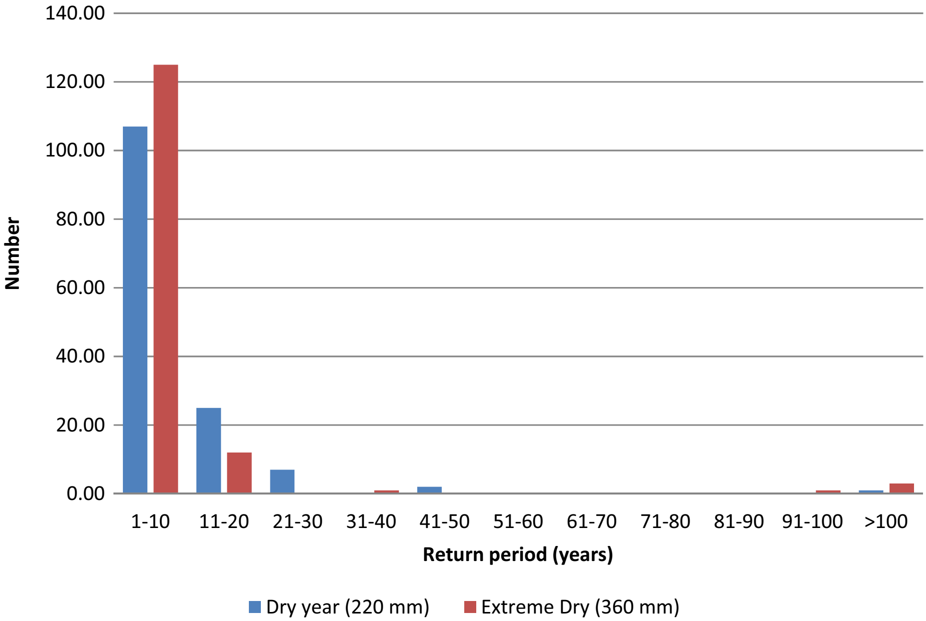

Fig. 2 Frequency distribution of farmers' estimation of the return time of a dry year and an extreme dry year (perceived probabilities)

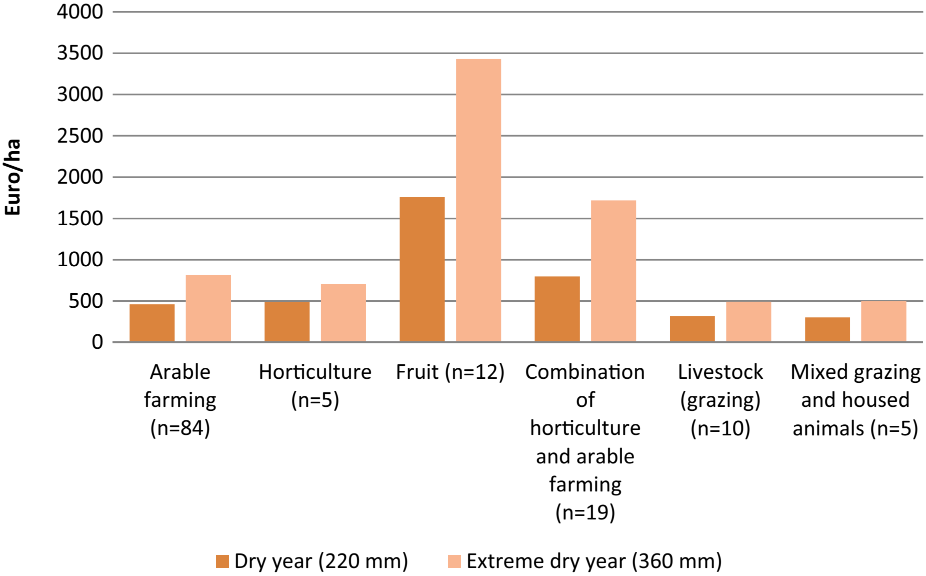

Fig. 3 Estimation of perceived damage by farmers in a dry and extremely dry year (expressed in euro ha^{-1} for different farm types

in the order of €200,000 to €250,000. Consequently, income losses amount to some 16–20 % in a dry year and 30–40 % in an extremely dry year.

7.2 Estimated Income Losses in Period 2003–2012

Respondents were also asked to estimate income losses as a result of drought for each year from 2003 to 2012 (Table 9).

There seems no correlation between annual cumulative summer deficit (April–September) and the estimated average production loss by the respondents (Table 9). An alternative

Table 9 Annual summer deficit in growing season in the Netherlands (Source: Royal Netherlands Meteorological Institute (KNMI)) and average estimated production loss in survey

year	Summer deficit (KNMI)	# resp.	Avg est. production loss	Sd
2003	227 mm	24	18.0	7.0
2004	12 mm	10	15.0	8.4
2005	52 mm	8	13.8	8.7
2006	117 mm	32	19.2	11.5
2007	0 mm	11	17.1	8.4
2008	109 mm	11	12.4	7.0
2009	197 mm	19	17.1	12.9
2010	45 mm	30	19.5	10.8
2011	17 mm	43	16.5	12.0
2012	13 mm	11	11.5	8.8

indicator for drought is the standardised drought indicator (SPI) (McKee et al. 1993). The SPI is the deviation of the amount of precipitation from the mean for a specified time period.

In Fig. 4 the monthly SPI values are presented for the period 2000–2014 from the KNMI weather station in Vlissingen that is situated in the neighbourhood of where the experiments are performed. The mean and standard deviation were derived from the data for the 1962–2014 period.

In 2003, 2006, 2009 and 2011, spring (March–May) was dry (Fig. 4). In these years the number of respondents that reported production loss nearly doubled. However, the average perceived yield reduction (± 18 %) did not differ significantly compared to other years.

Based on the cumulative summer deficit of 200 mm, 2009 can be typified as a 'moderately dry year'. About 19 respondents reported drought damage. This is a low response rate compared to years with similar or higher summer deficits (Table 9). The SPI time series (Fig. 4) indicate a mild drought ($0 < \text{SPI} < -1$) in the beginning of the growing season (March–June), while in July and August severe to extreme drought was measured ($-1.5 < \text{SPI} < -3$). The low number of farmers that reported drought damage despite a summer deficit of 200 mm is therefore probably explained by the fact that mostly fruit growers experienced drought damage in late summer. Most arable farmers within this sample experienced little or no drought damage in spring 2009.

The year 2011 (cumulative summer deficit =11 mm) can be classified as an average dry/wet year. Intuitively, one would expect a low number of respondents that report drought damage. Surprisingly, however, the response rate was high (43 respondents). The SPI-time series indicate a period of severe drought ($-1.5 < \text{SPI} < -2$) in the first part of growing season (March–May).

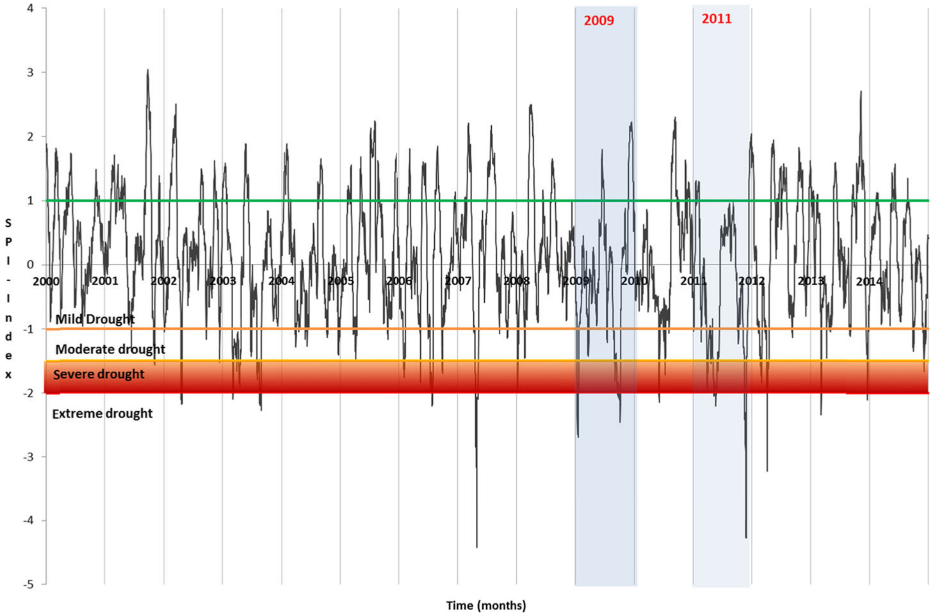

Fig. 4 SPI time series for the Weather station at Vlissingen in the period 2000–2014 (Alterra et al. 2015; Wesseling et al. 2011)

7.3 Attitudes towards the Innovative Measures

In the survey, famers indicated their level of familiarity with the adaptation measures, including the three studied GO-FRESH technologies, by multiple choices with six options (Fig. 5).

On a 7-point scale (1 = low; 7 = high). the farmers were asked to indicate the effectiveness and the costs of each the two measures. Based on these answers, a cost-effectiveness (CE)-score was calculated for each of the three measures. This is the ratio between perceived effectiveness and perceived costs. The value of the CE lies between 1/7 and 7.

7.4 Aquifer storage and recovery (FRESHMAKER)

About 50 % of the farmers are not aware of the existence of this measure. Approximately 40 % of the respondents conclude that this measure is not applicable to their farm (Fig. 5). The CE-ratio is below 1 for the majority of the respondents, indicating that they perceive the costs to be higher than the effectiveness of the measures. Perceptions were not found to differ between arable farming, fruit cultivation and horticulture.

7.5 Storage and infiltration of freshwater in creek deposits (CARD SYSTEM)

Of the respondents, 85 % was aware of the possibility to store and infiltrate fresh water in creek deposits (Fig. 5). The majority of farmers indicate that this measure is not applicable to their farm, probably because they are not located in the vicinity of a creek or sand ridge. The measure is perceived to be more cost-effective than FRESHMAKER and DRAIN2BUFFER. The cost-effectiveness ratio (CE) is above 1 for the majority of the respondents.

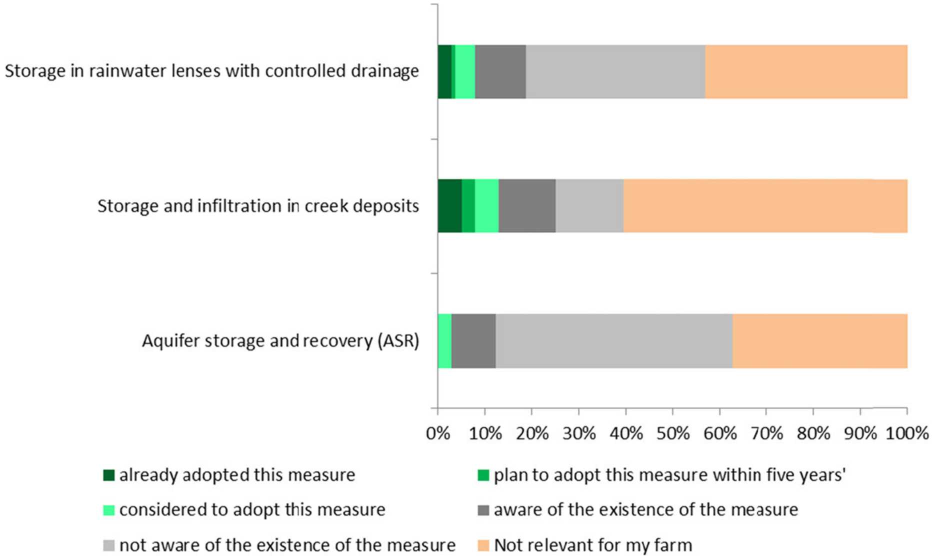

Fig. 5 Indicated level of familiarity for Aquifer storage and recovery (FRESHMAKER), Storage and infiltration of freshwater in creek deposits (CARD SYSTEM) and Freshwater storage in rainwater lenses with controlled drainage (DRAIN2BUFFER) (n = 139)

7.6 Freshwater storage in rainwater lenses with controlled drainage (DRAIN2BUFFER)

A large part of the farm sample is unfamiliar with this type of measure and thinks it is not applicable to their farm (Fig. 5). Furthermore, the perceived cost-effectiveness of this type of measure is low (<1).

8 Conclusions

The feasibility study and the survey were compared to analyse how experts, farmers and policy makers evaluate environmental, socioeconomic and behavioural factors that determine the wider use of climate compatible water supply technologies at farm level.

For the participants involved in the feasibility study and the respondents of the survey, it was difficult to quantify yield reduction risks in terms of probability, expected yield reduction and causes of yield reduction. This also applies to the involved scientists.

The respondents did not make a distinction in terms of drought damage between ‘dry’ or ‘moderately dry years’. In contrast to agro-hydrological models, in the period 2003–2012 the estimated average yearly drought damage (12–17 %) was more or less similar among respondents. The number of respondents reporting drought damage is a more reliable indicator of agricultural drought impact than the cumulative precipitation deficit, in particular when it is combined with the standardized precipitation index (SPI).

Furthermore, the survey reveals that farmers do not make a significant distinction between the probability of occurrence of a dry and extremely dry year. The survey respondents overestimate the risks of an extremely dry year by a factor 10.

These observations illustrate differences in understanding between the indicated drought damage risks by farmers compared to the used risk values in water management and research.

In the feasibility study it appeared to be difficult to select a single economic indicator for cost(−effectivenes) all involved actors agreed upon (low level of common understanding). In the survey ‘costs’ and ‘effectiveness’ were assessed separately in qualitative terms. This approach avoids this discussion and it is recommended to use this approach in feasibility studies.

The costs, and hence the cost-effectiveness, depend also on the existing water supply facilities at farm level. It is therefore difficult to identify generic cost estimates in both approaches. For example, if farms already have a controlled drainage system in place, the investment costs to apply CARD and DRAINS2BUFFER will be lower compared to the presented examples. On the other hand, within the pilot with the CARD system, costs were also reduced because the controlled drainage system was designed for two farms.

In the pilot with the FRESHMAKER, cost savings were possible because a sufficiently large water basin was present at the location studied. However, not all companies in this region have a water basin with the desired capacity. It is therefore recommended to add uncertainty ranges to cost estimates in feasibility studies in combination with cost saving opportunities.

The calculated CE ratios for the three technologies were low (<1) because most survey respondents were unfamiliar with the technologies in contrast to the farmers that participated in the GO-FRESH experiments. The level of common understanding of and confidence in the technical and socio-economic feasibility increased amongst the farmers, policy makers and experts that were involved in GO-FRESH. However, for farmers reliable freshwater supply and supportive legislation are the most decisive socio-economic criteria for a future investment.

Both the survey and the feasibility study illustrate that a positive impact of additional freshwater supply on the net revenue of an agricultural farm strongly depends on the type of farm (fruit, arable farming, and horticulture) and the crop cultivation plan. This insight offers opportunities to increase the positive impact of additional freshwater supply by simultaneously adapting the crop cultivation plan.

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Combined Assessment of Climate Change and Socio-Economic Development as Drivers of Freshwater Availability in the South of Portugal

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Abstract A combined assessment of the potential impacts from climate change (CC) and socio-economic development (SED) on water resources is presented for the most important aquifer in the south of Portugal. The goal is to understand how CC and SED affect the currently large pressures from water consuming and contaminating activities, predominantly agriculture. Short-term (2020–2050) and long-term (2070–2100) CC scenarios were developed and used to build aquifer recharge and crop water demand scenarios, using different methods to account for uncertainty. SED scenarios were developed using bottom-up and top-down methods, and discussed at workshops with farmers and institutional stakeholders in the water sector. Groundwater use was quantified for each scenario. Together with the recharge scenarios, these were run through a calibrated groundwater flow model, to study their individual and joint impacts on groundwater levels and discharge rates into a coastal estuary. Recharge scenarios show clear negative long-term trends and short-term increase in temporal variability of recharge, though short-term model uncertainties are higher. SED scenario 1 (SED1), predicting intensification and decline of small farms, considered the most likely by all workshop participants, shows a large drop in agricultural area and water demand. SED2, a most desired scenario by farmers, foresees growth and modernization of agriculture, but proves unsustainable in combination with predicted CC without efficient adaptation measures. The results thus reveal that CC in the region will dynamically interact with economic factors, and going one step beyond, CC could be directly integrated as a constraint in the development of SED scenarios. Exercises involving the integration of CC and SED regionally based scenarios,

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constructed in both bottom-up and top- down fashion and discussed in participatory contexts are still rarely used for adaptation, and specifically adaptation of agriculture to water scarcity. The joint analysis of CC and SED revealed challenging, as it involved the use of different methods across the border between natural and social sciences. In our view this method contributes in an encouraging manner to a more holistic and transdisciplinary water management, by allowing a more plausible identification of what (and if) adaptation measures are needed.

Keywords Climate change · Socio-economic development · Scenarios for water resources · Groundwater flow model · South Portugal

1 Introduction

Similar to other Mediterranean regions, freshwater availability in the south of Portugal is under increasing pressure from water consuming and contaminating activities. This threatens drinking water and irrigation supplies as well as the sustainability of wetlands that constitute groundwater dependent ecosystems (GDEs). In coastal aquifers overexploitation can lead to seawater intrusion. Climate change (CC) may aggravate such problems, particularly in the Mediterranean region (e.g. Giorgi 2006), due to the combined effect of rising sea levels, increased water demand due to global warming, and reduced aquifer recharge. Groundwater researchers have therefore started to integrate CC scenarios into their studies. These particularly try to predict the impact of changes in aquifer recharge on groundwater levels and discharge rates (e.g. Brouyère et al. 2004; Candela et al. 2009; Jackson et al. 2011; Stigter et al. 2014), and can also integrate sea level rise and water demand scenarios (Stigter et al. 2014).

Such studies, undoubtedly pertinent, generally ignore future changes in socio-economic development (SED) and the possible impacts this can have on freshwater supplies and demand (e.g. Holman et al. 2012). Scenarios continue to be constructed in ignorance of the local socio-economic and institutional context, and also ignore people’s cultural values, interests and needs (Kuruppu 2009). All these condition how resources are interpreted and utilised, and necessarily affect adaptation behaviours. According to Lorenzoni et al. (2000) “Socio-economic scenarios serve a particularly vital role in the assessment of adaptation and vulnerability because social change in the next century is likely to be as, if not more, profound than anything else brought about by CC…therefore it is at best simplistic, and at worst completely misguided to ignore the co-evolving dynamic development of social systems”. Complexity has increased, but realism too.

The lack of research regarding the regional interaction of CC scenarios with human systems (i.e. their socioeconomic and sociodemographic characteristics) and how this interaction will lead to effective adaptation has been recognized as an important gap of knowledge and one that inhibits adaptation.[1] Even less common (or virtually inexistent) are studies on CC adaptation combining climate and SED scenarios constructed and/or discussed in a participatory fashion (e.g. Harrison et al. 2013, 2015). Still, the interest of participatory foresight for

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[1] Although over the past two to three years there has been an increase in the discussion (in workshops, conferences, meetings, workgroups) about integrating SED scenarios with CC scenarios, to support adaptation decision by resource users and policy makers alike (Ebi et al. 2014), research actually carrying it out is, to our knowledge, still very scarce.

adaptation to CC is recognised by many (e.g. Berkhout et al. 2002; Eakin et al. 2007; Thompkins 2008; Rounsevell and Metzger 2010; Rinaudo et al. 2012; Wesche and Armitage 2013; Faysse et al. 2014). Participatory scenarios have demonstrated their utility in improving the uncertainty of CC models and their usefulness for adaptation, by generating critical self reflection and preparing the conditions for the change needed of adaptation. They also lay the ground for an easier, more consensual and more effective experience of adaptation by increasing social learning and social capital and incorporating different epistemologies (Bennett and Zurek 2006).

The scarcity of literature is not surprising as the integration of SED and CC data in scenarios is a daunting task. The reasons are multiple. SED scenarios are difficult to predict as they are co-evolving systems (Norgaard 1994) which have important feedback relationships with CC, particularly on a global scale (e.g. Nakićenović and Swart 2000). In addition, the time frames for SED and CC scenario analysis are quite different. Climate modellers prefer discussing the future 100 years from now, whereas socio-economic researchers using participated foresight methodologies, are mainly concerned with what happens in the following two to three decades, as looking further ahead inhibits the motivation and engagement of stakeholders (Roncoli 2006). Furthermore, the combination of SED and CC scenarios involves a combination of methods, expert-based vs. participatory and qualitative vs. quantitative, which remain problematic. CC scenarios are expert-based and typically articulated though quantitative models while SED scenarios are more methodologically heterogeneous and include qualitative components (Berkhout et al. 2002). In addition, the collaboration between disciplines from natural and social sciences in a truly collaborative endeavour still encounters many difficulties (Lowe and Phillipson 2009; Klein 2010; Varanda and Bento 2012). However, research engaging both the natural and the social sciences is seen as a necessary condition for an improved understanding of global changes affecting human societies (e.g. UNESCO 2010). Last but not least, CC may not even be a key issue for actors in the economy and governance of regional territories (Faysse et al. 2014), clearly a factor inhibiting participatory methodologies aiming at inducing adaptation.

For all the above-mentioned reasons, and notwithstanding the global studies on CC - SED interactions (e.g. Parry et al. 2007), there are important gaps in the literature concerning the integration of regional CC scenarios with SED scenarios, constructed and validated together (i.e. in participatory contexts) with those who will need to implement the adaptation measures. This paper wishes to take a step in filling this gap. Regional integrated studies of the expected evolution of SED and CC are essential in order to assess the individual and combined pressure they might exert on freshwater resources in the near and more distant future. Water resource adaptation policies must reflect the interdependencies between the climate and socio-economic systems, and users and policy makers need to be able to understand and visualise these interdependencies. Here a series of integrated CC and SED scenarios are produced, demonstrating the individual and joint impact on freshwater (groundwater) availability and demand, using a method that combines the information from future climate scenarios with a series of pictures about the social, economic and environmental elements affecting water availability at a regional scale. We thereby intend to illustrate: 1) the added value of integrating SED and CC scenarios as a means to deeper understanding of future societal responses to the unfolding impacts of CC; 2) the relevance of adding bottom-up approaches which add local texture and a valuable input to more top-down accounts of climate impacts. The method we propose should be looked upon, in this stage, as an heuristic tool that eventually, following further improvement and empirical testing, could constitute a useful decision making tool.

In the current study SED and CC scenarios were developed for the largest aquifer system in the south of Portugal in the scope of two transnational projects. Short-term (2020–2050) and long-term (2070–2100) CC scenarios were developed for the study site and used to build aquifer recharge scenarios based on soil water balance calculation methods. SED scenarios were developed using a combination of methods and then presented in workshops to the farmers and to other stakeholders, including the Water Basin Authority and the Regional Agricultural Administration, among others, in order to obtain feedback regarding which scenarios they found the most probable and the most desirable. For each scenario the evolution of water consumption is evaluated. The potential individual and joint effects of CC and SED on the quantitative status of the aquifer are illustrated by integrating several scenarios in a calibrated groundwater flow model of the aquifer.

2 Methods

2.1 Study Area

The study area is located in the Central Algarve, the southern most province of Portugal, as shown in Fig. 1. It is characterized by a Mediterranean climate, with dry and warm summers and mild wet winters. The climate normals (i.e. 30-year arithmetic means) for temperature and rainfall for 1980–2010 are respectively 17.5 °C and 739 mm (Stigter et al. 2014). Water resources are available both through surface water reservoirs and groundwater aquifers (Fig. 1), and both sources are used for public supply, tourism and irrigation. Public supply depended exclusively on groundwater until 2000, and was then substituted entirely by surface water from the reservoirs. The large drought of 2005 revealed the limitations of a single source supply (Stigter et al. 2009) and paved the road towards a conjunctive use and management of multiple water sources for public supply (Vieira et al. 2011), ideally leading towards integration within the more complex concept of integrated water resource management.

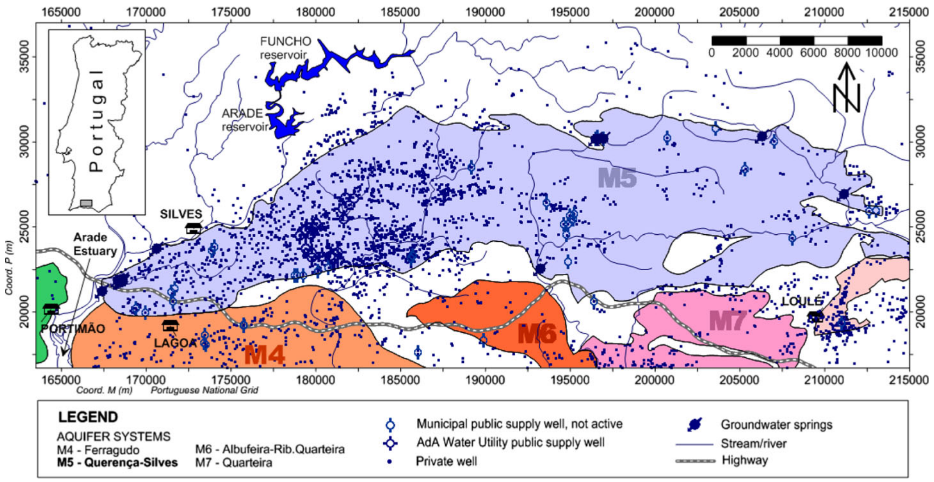

Fig. 1 Location and characterisation of water use and availability in the study area

The main aquifer of the region is built up of karstified carbonate rock, covering an E-W elongated area of 318 km^2 (Fig. 1) and known as the Querença-Silves aquifer. It is the most important groundwater reservoir in South Portugal (Monteiro et al. 2006; Stigter et al. 2009). Its mean annual recharge has been calculated to be 100 million m^3 (100 hm^3), of which currently 30 % is exploited for irrigation and 10 % for urban water supply (Stigter et al. 2009). In dry years pumping is more intense, and because of reduced recharge the pressure on the aquifer rises dramatically. The lowest groundwater levels were observed in 2005, but the levels were high enough to avoid the drying out of springs or the intrusion of seawater into the aquifer (Stigter et al. 2009; Hugman et al. 2012). Groundwater flows mainly towards the west, where it discharges into the Arade estuary (Fig. 1), largely through (partly subestuarine) springs that feed freshwater dependent wetlands (Silva et al. 2012). Surface-groundwater ecotones also occur at the many other springs that characterize the system.

Land use is dominated by irrigated citrus culture in the western sector overlying the aquifer, whereas extensive dry farming (olive, carob, almond and fig trees) occupies the eastern sector. The average farm size is 9 ha. Larger farms (generally above 20 ha) specialize in citrus production, and small farms (from 1 to 9 ha) specialize in market garden crops. Both types of farms also grow almond, olive, and carob trees. Almost all irrigated farmland uses drip irrigation. Water resources management in the region is currently framed within the River Basin Management Plan, developed for the region in compliance with the EU Water Framework Directive, and with the environmental goals to reach good quantitative, qualitative and ecological status.

2.2 Socio-Economic Development Scenarios and the Participatory Workshops

The main goal of socio-economic development (SED) scenarios is to function as a foresight tool helping decision-makers to explore the uncertainty associated with future developments. Foresight is a multi-disciplinary approach which is helpful to assess the consequences of the various strategic choices available. In this specific case we focused on agriculture and its impact on water use. The methodological approach was inspired by the emerging literature on scenario planning and participatory foresight for water resources management (Van der Helm 2003; Hatzilacou et al. 2007).

Participatory approaches are required to understand vulnerability and adaptation options from the perspective of those affected by socio-ecological change. They combine and integrate different types of knowledge to enhance understanding about regional change and its implication and allow a change of focus towards problem oriented and reflexive processes (e.g. Wesche and Armitage 2013; Hagemeier-Klose et al. 2014). This participatory component was deemed very important, as the content of the futures conceived and of the discussion these entail, had to make sense to the very people that will have to enact key adaptive responses to changes in the climate within the next decades.

These workshops followed a deliberative model (Fung 2006) in which participants deliberate after having been given access to information that was transparent, contrasting and as complete as possible. A key feature of our approach, given that the workshops were organized in a research context, was to encourage the expression of various pictures of the future, and to facilitate the mutual discovery of differing points of view concerning the future development of agriculture, and the associated water demands. The goal of these discussion sessions was not to reach consensus or decision making, hence all the information transmitted by the researchers in the workshops was presented not as revealing the "truth", but as to motivate the criticism and the confrontation with farmers' experience. The posture adopted by the team was thus exploratory and not normative. Such an approach results in scenarios that are "plausible examples of what could happen under particular assumptions and conditions [and are] contrasted against one another to provide a tool for thinking about the relationships between choices, dynamics and alternative futures" (Peterson et al. 2003).

The choice of the time horizon for the SED scenarios was based on the need to create common ground between the time frame of climate models and the one that actors generally use to plan and make decisions (Faysse et al. 2014). Typically, this common ground ranges from 25 years (e.g. Patel et al. 2007) to 50 years (e.g. Eakin et al. 2007) from the present. In the current study 2030 was used as time horizon in SED scenarios workshops.

Construction of the SED scenarios was based on a diversity of sources of information, both bottom-up and top-down. The importance of including a bottom-up (or participatory) approach is well recognised, especially when dealing with groundwater resources (e.g. Faysse et al. 2014). Incorporating local experience and knowledge fosters the development of adaptation strategies in the context of local conditions that may not be clearly evident to, or understood by, outsiders and may result in more reasonable, effective and lower cost adaptation behaviours.

The top-down sources of information used were: (i) pre-existing scenarios defined at national and European levels (e.g. European Commission scenarios, regional plans for rural development) and (ii) statistical information describing recent trends in local agriculture and regional economic development (e.g. regional plans for rural development, statistical yearbook of the Algarve). The bottom-up sources of information were: (iii) the identification of factors of change made through a specific workshop with experts in water and agriculture, both from academia and regional administration (the pre-test workshop for the research project had the objective of gathering visions of the future for agriculture of the Algarve); (iv) individual visions of the future expressed by farmers during interviews (a total of 30 interviews); v) visions of the future expressed by diverse stakeholders such as directors of agricultural cooperatives, of tourism associations, of local environmental associations, staff from the regional directorates of agriculture, river basin authority and water services company (total 40 interviews), and (vi) a previous workshop with the farmers that discussed a diagnosis of the current agricultural situation in the Algarve region and its drivers of change; a tripartite format was employed around positive aspects, negative aspects and aspects in need of change in the agriculture of the region, with the main objective to create a starting point enabling posterior discussion about climate and water, allowing the identification of local evolution factors constructed by the farmers themselves.

Four, mainly qualitative, scenarios were constructed to describe future evolution of the region, in a global context, with a specific focus on agricultural production at the 2030 time horizon and with storylines based on four main dimensions: global economic context and agricultural market, economy and territory in the Algarve, agricultural sector, and use of water resources. The storylines were built based on driving forces that influence the outcome of events. It has been said that there is no right way to develop scenarios. In our case we identified relevant external factors (those that cannot be acted upon by the regional actors that participate in the scenario discussion), which are macro-economic, political and social factors (such as European water policy, agricultural policy, international commerce, demographic changes) as well as factors relevant for the development of the Algarve which may be linked to water use (such as tourism development and demography of the region). Relevant internal factors included aspects that farmers can act upon such as investing in agricultural land, the cultures they grow, their water use, etc..

Scenario workshops can be implemented in very different ways depending on the objective, the types of participants and time and resources available. In our research, we clearly chose to pre-construct scenarios. This option seemed pertinent as the farmers didn't have experience in participatory events or in the exercise of foresight.

These developed SED scenarios were subsequently pre-tested next to the farmers and institutional actors in the water and agricultural sector and its storylines adapted therein. These scenarios were then the starting points for discussion, which participants were asked to challenge, deconstruct, criticize, and adapt according to their views. These discussions were tape-recorded to allow detailed analysis of the views expressed by participants through complete transcription of the discourses.

For the workshops with farmers two groups were created, distinguishing farmers between the eastern and western part of the area covering the Querença-Silves aquifer. This distinction also reflected differences in the type of farming systems (small-scale farms producing mostly rain-fed market garden and traditional dry farming crops in the east, versus medium-scale farms specialised in irrigated citrus production in the west). The composition of the groups assured representativeness, including farmers from different geographical areas, age groups, crop types and farm size. An additional workshop, carried out with institutional stakeholders, included very experienced researchers, public officers and members of associations in the fields of hydrology, agriculture and tourism. Further information on the group compositions and characteristics is provided by Faysse et al. (2014).

Given the high complexity of carrying out such participatory workshops, related for instance with the difficulty of envisioning the future and understanding the SED scenarios, and particularly for farmers, the lack of experience in holding such discussions and their overall low formal education, the research team took special care in the materials presented, such as posters and written flyers, as demonstrated in Fig. 2, which were supported by an oral presentation. Other aspects that were taken into attention, in order for communication to flow easily among all, was the style of facilitation (e.g. neutrality, creation of mutual trust), the location of the workshops (geography, the neutrality of the place and its pleasantness were taken into consideration), as well as a dinner invitation. All these created an informal space that was much valued by everyone, and created an ambiance of trustworthiness among all.

After all SED scenarios had been discussed, the participants were invited to prepare individual rankings of the four scenarios according to their probability and desirability. We should note that farmers had difficulties in using scenarios as a basis for discussion of future evolution. The ability to think in the long term outside today's norm is not a trivial matter.[2] Another difficulty has been to direct the discussion away from the assumptions related to external macro-economic evolution (e.g. reform of the common agricultural policy, increase of energy and international transportation costs, change in consumer demand, etc.). The instructions given to workshop participants were to consider these assumptions as granted, and only discuss the consequences and possible adaptation at the local level, which was not straightforward and required some persistence from the facilitators. The voting process was not straightforward either and we were just able to collect information on the expression of the main tendencies.

2.3 Development of Climate and Recharge Scenarios

Stigter et al. (2014) provide a detailed overview of how the scenarios for climate change (CC) and aquifer recharge were created. Three available downscaled Regional Climate Models

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[2] This ability to explore the future was progressively developed during the project (which in itself was the accomplishment of the social learning objectives of this project).

Cenário 1

Concorrência e declínio das pequenas explorações

Liberalização e concorrência internacional

Preços Baixos

Turismo

Desaparecimento das pequenas explorações

Sobrevivência dos mais fortes

Cenário 2

Aposta regional na modernização da agricultura

Política regional dinâmica

Incentivos para o sector agrícola

Incentivos à investigação

Avanços técnicos

Novas variedades – melhor rendimento

Promoção da produção nacional

Incentivos à formação + apoio técnico

Agro-empresários

Tecnologia

Produção organizada

Mais rendimento

Promoção da qualidade

Comercialização organizada

Restrições ao uso da água – manifestações de agricultores

Fig. 2 Illustration of posters used in workshops presenting SED scenarios 1 and 2 (in Portuguese)

(RCM) from the ENSEMBLES project (Van der Linden and Mitchell 2009) were used, using the balanced A1b CO_2 emission scenario. Although many more RCM runs exist, the choice of the three models at the time of the research project was based on the fact that they covered all the study areas from Southern Europe and Northern Africa, on a 25×25 km resolution. In addition, when comparing the modelled climate data for these three models to other climate model data covering the Central Algarve (unpublished data), they were found to cover the range of uncertainty very well. The modelled temperature (T) and precipitation (P) data were bias corrected using a reference (control) period of available observations, namely 1980–2010. Bias correction involved two different approaches: i) calculation of anomalies, and ii) monthly linear regressions between observed and modelled data (Stigter et al. 2014).

The resulting bias-corrected data were used to obtain predictions of P and T for two future climate normal (30-year) periods, 2020–2050 and 2069–2099, and subsequently to calculate recharge for these periods using two soil water budget methods: i) Thornthwaite-Mather, and ii) Penman-Grindley (Stigter et al. 2014). These methods were applied sequentially for each month, and calibrated using previous calculations of recharge (Stigter et al. 2009). The problem of underestimating recharge, which often occurs when using a monthly time step (e.g. Dripps and Bradbury 2007), was accounted for by allotting 20 % of rainfall as direct groundwater recharge (concentrated runoff/recharge caused by extreme rainfall, without recharging soil water deficits) before performing the remaining balance calculations. The 20 % value was selected after a comparison of recharge calculations made using daily and monthly meteorological data for Portugal (Stigter et al. 2014). The methods were calibrated for (part of) the historical reference period using previous calculations of recharge (Stigter et al. 2009), including the FAO dual crop coefficient method (Allen et al. 1998), recently applied by Oliveira et al. (2008). Besides scenarios for total recharge, the impacts of global warming on crop water demand and consequently groundwater withdrawals for irrigation were also quantified, by performing simplified calculations on the evolution of the potential evapotranspiration (ET). More specifically, present and future groundwater irrigation needs were simulated using the ET deficit, i.e. estimating the current and future differences between actual ET without applying irrigation and the potential ET of the crop indicating water demand. This difference therefore needs to be fulfilled by irrigation. It was further assumed that there is no change in crop type, growth cycle, irrigated area or irrigation efficiency (Stigter et al. 2014).

2.4 Groundwater Flow Model

Numerical simulation models for groundwater flow in the Querença-Silves aquifer have been performed and improved over the past decade (e.g. Monteiro et al. 2006; Stigter et al. 2009; Hugman et al. 2012). In short, the FEFLOW (Koskinen et al. 1996) software was used to build horizontal and vertical 2D domain models, of which the horizontal model was used for the scenario analysis in the current study. As the aquifer is of karstic nature, a single continuum equivalent porous model was used for the representation of the flow domain, which is valid when modeling hydraulic heads and flow volumetrics on a regional scale (Scanlon et al. 2003). Boundary conditions for the model were defined as constant head along the Arade estuary in the west (Fig. 1) and no-flow for the remaining part (for more details see Stigter et al. (2014)). Integration of recharge and abstraction volumes, including public and private wells, was performed as described by Stigter et al. (2009). The model was calibrated for 2001–2006 and validated for 2006–2010, based on hydraulic head data from national monitoring networks and implemented project-specific monitoring surveys. Transmissivity (T) was optimized through inverse calibration, whereas the storage coefficient (S) was calibrated by trial-and-error using available piezometric data (additional information provided by Hugman et al. (2012)). Following parameterisation and calibration procedures, the SED and CC scenarios were integrated into the model, in steady-state and transient simulations, to study their individual and joint impacts on water levels and discharge rates into the coastal estuary.

3 Results and Discussion

3.1 Socio-Economic Development

The scenarios that resulted from the methodology employed and described above, are characterized in Table 1, which also includes the corresponding change in water demand, considered to be supplied by groundwater in this case. Parameters such as changing land use or demography were also considered in the SED scenario discussion and development. The

Table 1 Description of the SED scenarios

	Global economic context and agricultural market	Economy and territory in Algarve	Agricultural sector	Use of water resources
SED1: Intensive agriculture, decline of small farms	World economy highly liberalized; Algarve's agriculture faces strong competition and agriculture's income has reduced in the last decades. Europe's economic stagnation leads consumer to search for low price rather than quality.	Development of tourism (main economic sector) contributes to decrease of farmland, including in the interior of Algarve (Barrocal area).	Farmland decreased substantially, small properties vanish. Some highly competitive farms compete at international level, some of which have Spanish owners. Citrus is still the main production, but indigenous trees occupy a similar size surface.	Large decrease in irrigation needs; public supply stable, with some increase in tourism sector (golf courses). Globally, water consumption decreases.
SED2: Growth and modernization of agriculture	EU Agriculture policy is transferred to regions, and Algarve like other EU regions receives financial support. Strong marketing increases population preferences for regional products. The consumer values the health and environmental benefits of regional products.	Tourism declining due to strong competition from other destinations. The region reacts with an ambitious strategy to revitalise agriculture. External competition is high, but the improved competitiveness in citrus production, carob trees and other indigenous cultures compensates for it.	Ambitious policies; strong financial investments, including in professional training and agricultural research; land restructuring supported by the regional government; improvements in the management, logistics and marketing. Farms decrease in number and are larger and more intensive. Citrus production is still the strongest, but carob trees increase considerably.	Water use reaches levels never attained before, leading to groundwater overexploitation. Conflicts of use are frequent and restriction of use takes place in less rainy years. Some farmers who do not respect the maximum extraction allowed are taken to court. Overexploitation caused sea water intrusion. Water quality becomes a concern too.
SED3: Dual agriculture competitive capacity and patrimony	Two types of agriculture coexist and are politically supported in Europe: i) highly competitive and intensive producing cheap low quality products; ii) subsidized and dedicated to high quality products (largest area). Small exploitations and indigenous cultures are valued.	Policies to attract senior immigration from northern Europe are taken seriously. These new consumers with high purchasing power improve the local economy; tourism increases dynamism and expands to Algarve's interior. New regional circuits, linked to agriculture, are created.	Two types of farms: highly efficient large properties and small farms living of subsidies, growing indigenous cultures. Citrus is still the largest production, but it decreases. Smaller citrus(tangerine) and carob increase their production.	Remains stable for agriculture, but population increase has led to a small increase in public supply. In dry years water management is challenging, and restrictions to water exploitation are introduced, although not always followed by farmers. The tourism sector often complains about this situation.

Table 1 (continued)

	Global economic context and agricultural market	Economy and territory in Algarve	Agricultural sector	Use of water resources
SED4: Sustainable development, agriculture of high environmental performance	Environmental and health issues have become a priority for agricultural policies and consumer. Intensive production is banished. European institutions invest in research dedicated to biological agriculture and water saving technologies. Severe controls were imposed to safeguard the environment and public health. A raise of consciousness, concerning the health and environmental perils of intensive agriculture, and global commercialization, drove this change of culture.	Total restructuring of agriculture in line with sustainability concerns. Emphasis on local production. Decline in international tourism, due to both a concern about the carbon footprint and the increase of the price of oil. Fast train does not yet reach Portugal as easily as other European countries. Population density remains stable with a slight increase in the interior region, due to a new generation that values rural development.	Use of land remains similar and the form of production becomes more sustainable. A new Agricultural Institute - state funded- is training young farmers in biological agriculture and water saving technologies. Research focused on citrus production has allowed its reconversion to biological agriculture. Exports have increased to Spain – facing a water shortage crisis- and Europe, where the brand “Laranja do Algarve” is highly appreciated.	Water consumption remains stable or decreases somewhat. Highly efficient irrigation is used. Water quality also improved. As a result there are no conflicts concerning water usage.

impact of demography changes on water consumption as compared to irrigation water use were not considered significant, as only a fraction of public water supply comes from groundwater. Large surface reservoirs supply most of the water to the urban areas. Increasing groundwater use for public supply in the future could have some impact, but was not considered in any scenario. Land use changes with regard to agriculture, i.e. increase or decrease in cropped area or crop type, were contemplated in the scenarios, as shown in Table 1, and reflect themselves in predicted changes in water use for each scenario. SED Scenario 1 (SED1, intensive agriculture, decline of small farms) has resulted in a significant reduction in irrigated land and crop water demand (only 8 hm^3). The duplication in irrigated land in SED2 (Growth and modernization of agriculture) has resulted in an additional 30 hm^3 (million m^3) demand for irrigation (based on known irrigation quantities and not considering the potential effect of global warming on crop water demand (Stigter et al. 2014)). SED3 (dual agriculture competitive capacity and patrimony) and SED4 (sustainable development, agriculture of high environmental performance) have distinct characteristics. The corresponding changes in water demand for agriculture were considered to be small.

The discussion of SED scenarios was meant to transport farmers into the future and have them discuss, explore and choose what futures were more probable and more desirable, in spite of the trade-offs each contained. As we said above, this discussion was not simple for farmers (neither for some institutional actors), as scenarios contained much information that goes beyond their daily concerns, and it forced them into an imagination effort they were not used to. Still through a facilitation adapted to the participants – which were well known to researchers from interviews and a previous workshop – and with the use of simple to read and comprehend materials, a constructive dialogue entailed. The voting process was not easily controlled by researchers, but strong tendencies were detected as to identify SED1 as the most probable (it is the continuation of an existing trend) and least desirable scenario (no one wants the decline of small farms). SED2 was the least probable (together with SED4), as farmers have had for long the feeling of being abandoned by policy makers, and did not believe that strong investments in agriculture would ever happen. Concerning desirability the voting process is not clear. Still, the discussion was lively and evolved around issues such as the quantity vs. the quality of the products (quality preferred), and the quantity vs. quality of water (quality being the main concern). SED3, which was the most neutral scenario, did not motivate participants to express a vote. SED4, which entailed the greatest change away from the norm, was considered by all as the least probable, and the least desirable by farmers, but the most desirable by institutional actors. This can be explained by the fact that producing less than technically possible in order to protect the environment is a relatively new thought in agriculture (Ondersteijn et al. 2002), and farmers fear that more optimized water saving and fertilization techniques may affect their economic situation. In fact, unbalanced fertilization is a major problem worldwide, including the study area, even if it is currently still masked by high recharge providing a high dilution potential to the studied aquifer system (Stigter et al. 2011).

3.2 Climate Change

Figure 3 presents the projected changes in rainfall (P) vs. temperature (T) for 2020–2050 (2035) and 2069–2099 (2085). The effect of global warming is clear, reflecting itself in an average rise in T of 1.3 and 3.4 °C for respectively the short-term and long-term future in the study area of South Portugal. This points to higher evaporative demands (higher PET) as well. Regarding P, the large uncertainty in short-term predictions is well reflected in the plot, with

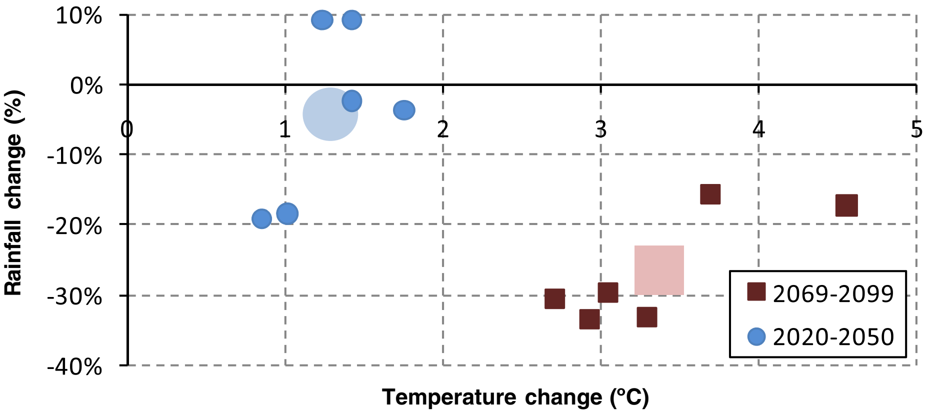

Fig. 3 Predicted changes in rainfall vs. temperature change, for three climate model runs (CNRM, C4IRCA and ICTP) and two bias correction methods (anomalies and regression). The *two larger* and *lighter symbols* represent the ensemble means for the two periods

some scenarios predicting a slight increase. The ensemble mean shows a 4 % decrease in P for 2035, and a 27 % decrease for 2085 (ensembles have been used to handle CC scenario uncertainty in previous studies, see e.g. Wetherald and Manabe (2002), and Nohara et al. (2006)). In other words, there is significant higher uncertainty regarding the trend of rainfall in the near future, whereas in the long-term all scenarios agree on a strong reduction in P. This phenomenon will reflect itself on the predicted evolution of aquifer recharge under CC, as will be discussed below. It is in agreement with the general trend of prediction uncertainty at the global and local scale with regard to internal variability and climate model characteristics (e.g. Hawkins and Sutton 2009), which tend to decrease with time (partly due to the averaging out of different weather paths). On the other hand, the uncertainty of SED and CO_2 emission scenarios tend to increase with time. Despite the larger short-term uncertainty regarding the average change of rainfall, there is a consensus among the models regarding the increase in the frequency of very dry and very wet years, as revealed by the model ensemble statistics (Stigter et al. 2014), and with important consequences for freshwater availability.

3.3 Integration of SED and CC Scenarios

The calculated effect of CC on recharge is shown in Fig. 4, where predicted mean annual recharge values are compared to the four SED-related water demand scenarios described in Table 1, for 2035 and 2085. One could argue that performing the combined study on CC and SED for the distant future is irrelevant due to the high uncertainty related to SED, or the feedback mechanisms that exist between SED and CC, regarding greenhouse gas emission and water demand/availability scenarios. Notwithstanding, the long-term predictions are believed to be illustrative for CC trends and how they may interfere with SED scenarios, and therefore integrating the two is considered an interesting though assumingly heuristic exercise.

The white symbols in Fig. 4 represent the quantification of the SED scenarios, ignoring CC. As previously discussed, SED2 has resulted in a 30 hm^3 increase in crop water demand, SED1 sees irrigation needs drop significantly to 8 hm^3, whereas SED3 and SED4 (SED3_4 in Fig. 4) are considered to have a negligible effect on water demand, therefore set to 0. Hence,

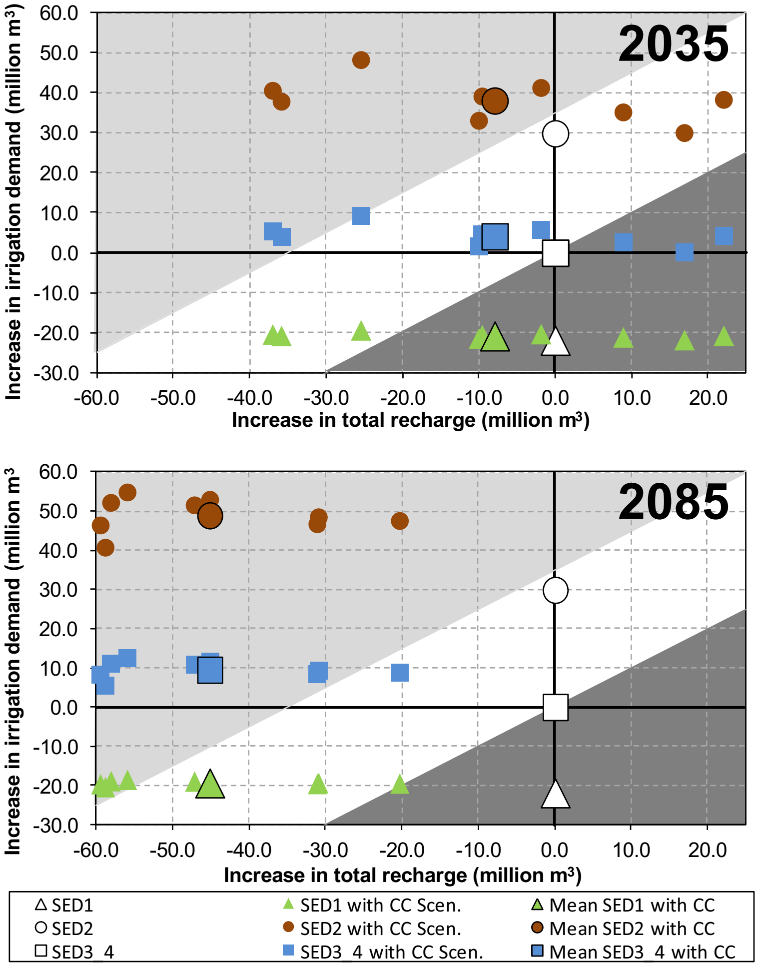

Fig. 4 Increase in irrigation demand and total recharge for 2035 and 2085, for SED and CC scenarios; *light-shaded* area indicates critical state beyond sustainability (Hugman et al. 2012); *dark-shaded* area represents an increase in water availability with respect to present state

combining CC with SED scenarios for the latter two is equivalent to considering the exclusive impact of CC, represented by the squared symbols in the plots.

For 2035 the scatter among these values is evident, with both predicted increases and decreases in recharge, and reflects uncertainty inherent in different combinations of climate model runs, bias correction and recharge calculation methods. Notwithstanding, the ensemble mean depicts an 8 hm^3 (around 8 %) decrease in recharge. Moreover, all but one CC scenario predict an increase in irrigation demand, solely due to higher evaporative demands. As a result, three of these scenarios plot near or beyond the border where groundwater abstractions become unsustainable (Fig. 4), according to criteria defined by Hugman et al. (2012). The latter are based on negative groundwater heads in the summer season, causing the cessation of groundwater discharge into the estuary and intrusion of seawater into the aquifer. In 2085 all but one CC scenario are located in the field of unsustainability.

As a consequence of the large reduction in water use, none of the SED1-CC combinations plot in the critical zone for 2035, and many indicate an increase in water availability (Fig. 4). This result is supported by the discussion had in participatory workshops, in which this is considered a highly probable scenario for participants, but one that goes against their will, as they unanimously condemn the decline of agricultural activity (this constitutes food for thought for farmers and policymakers alike). The situation is different in the 2085 horizon, due to a large predicted decrease in recharge. It must be noted that the indicated drop in irrigation demand for SED1 may be excessive, since properties are expected to increase in size and in part compensate for the decline of small areas. On the other hand, farming techniques are considered to improve, increasing water use efficiency.

The combination of SED2, where a large expansion of irrigated land is expected, with the CC scenarios, results in the largest predicted increase in pressure on the available water resources, despite the persisting scatter in the data. In fact, without considering CC the SED2 scenario already plots very near the limit of unsustainability. The combination with the ensemble mean CC results causes a shift in the diagram beyond the limit of sustainable aquifer exploitation. Most of the SED2-CC combinations are located far beyond this limit. The predicted increase in crop water demand due to increased evapotranspiration is also most pronounced in this scenario.

For 2085 the impacts on aquifer exploitation are further enhanced. In addition, the scatter within the results is significantly reduced, similar to what occurs with the other SED-CC combinations in 2085 and reflecting the decreased level of internal and model uncertainty of the climate model predictions (Hawkins and Sutton 2009). The impacts on the average yearly groundwater levels in 2035 of an increased groundwater use in SED2 and, in combination, the predicted average decrease in recharge due to CC, is shown in Fig. 5. The maps are the results of integrating the SED2 and ensemble mean CC results in the steady-state groundwater flow model. It is interesting to observe the pronounced difference between the impacts of the SED2 scenario with and without CC in the eastern sector of the aquifer. When CC is ignored, the decrease in groundwater head in the east is relatively modest and constant, between 4 and 6 m, resulting from the increased withdrawals that are largely concentrated in the west (Fig. 1). A reduction in recharge however affects the entire area and particularly the eastern area, where recharge is highest, and therefore results in much more pronounced drops in groundwater levels, mostly between 10 and 20 m, and exceeding these values towards the northeast. This could have significant consequences for farmers living in this area and also for groundwater dependent river ecosystems that exist in the region. The numerical model simulated a similar overall lowering of groundwater levels (results not shown) if a significant part of the intensively irrigated agriculture would shift towards the east, leading to the installation of many deep groundwater wells in this sector of the aquifer. Given the more mountainous characteristics of the terrain, the deeper groundwater level and the lower transmissivity of the aquifer, this is unlikely to occur.

Besides average changes, it is important to look at seasonal changes and the occurrence of extreme events. Figure 6 show transient simulations of groundwater discharge into the estuary for two CC scenarios, one of them combined with SED2. There are large differences between the two CC scenarios, particularly up to 2050. Similar results were found by Brouyère et al. (2004) in the Geer basin in Belgium and by Jackson et al. (2011) in an important chalk aquifer in central-southern England. Despite these differences, both CC scenarios show pronounced seasonal and interannual variations, with the alternation of dry periods (zero or negative outflow, indicating seawater intrusion) and wet extremes (marked by high discharge rates).

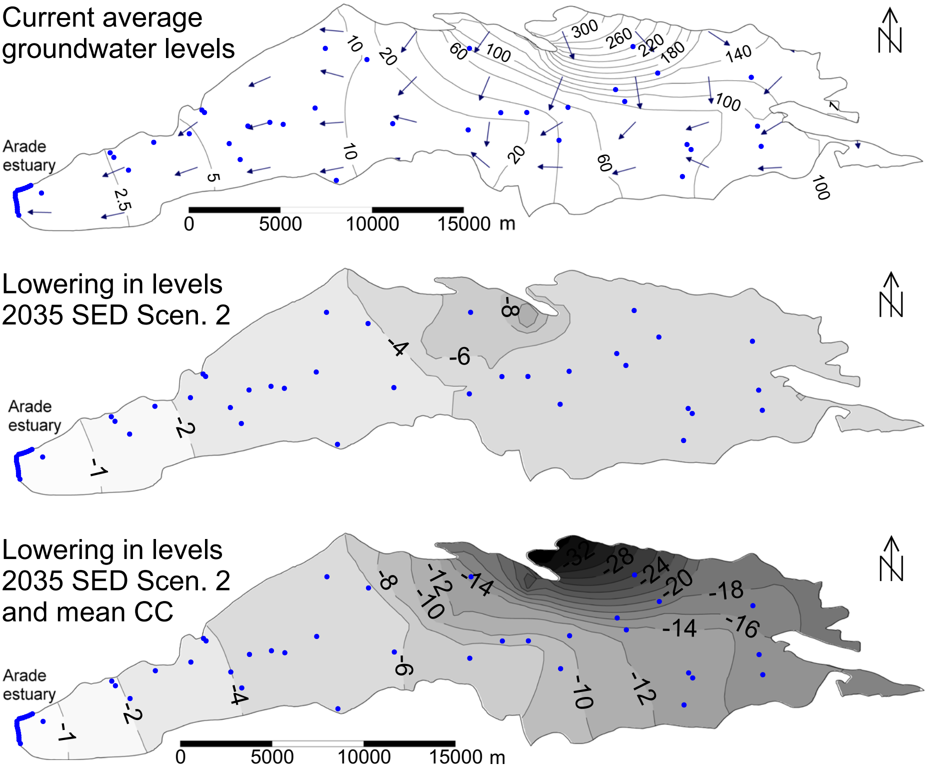

Fig. 5 Average groundwater levels (m above mean sea level) in the aquifer: current situation (*top*), predicted lowering in 2035 with SED2 (*middle*), and lowering due to the combination of SED2 with mean CC (*bottom*); *blue dots* are monitoring wells, *blue line* boundary condition at estuary, *arrows* indicate direction of groundwater flow

Towards the end of the century, extreme events continue to occur, but mean annual discharge levels into the estuary drop significantly, dampening the extremes. Moreover, the discrepancy

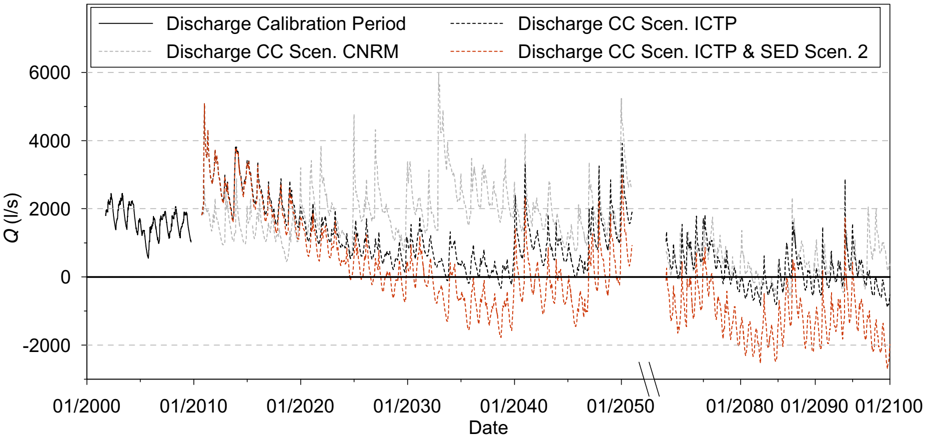

Fig. 6 Evolution of groundwater discharge into the estuary for two CC scenarios, and one combined CC-SED2 scenario

between the predicted groundwater discharges resulting from the integration of the different climate model runs, also decreases significantly. This is in agreement with results from a study by Goderniaux et al. (2011) in the Geer basin in Belgium, including six RCMs and 30 equiprobable scenarios, which showed that despite consistently large confidence intervals around projected groundwater levels, the climate change signal becomes stronger than that of natural climate variability by 2085.

The combination of the more pessimistic CC scenario with SED2 reveals high rates of seawater intrusion and wetland desiccation in many years and almost continuously towards the end of the century. It is clear from the foregoing that, despite existing uncertainties, the combination of SED2 and CC is not sustainable in a non-adaptive framework. In other words, agriculture as a driver of Algarve's development, and the reinforcement of policies conducting to it, may only be possible if adequate and efficient measures regarding CC adaptation are implemented in the area. These results must naturally be weighed against the results of the participatory workshops, if these are to be used for decision making. For instance, the worrisome trend in terms of water use depicted here by SED2 is attenuated by the results of the participatory workshop, as this scenario is considered the least probable by all participants: nobody envisions that agriculture will receive strong policy support. Notwithstanding, an important outcome of this research is that, should there be a change in policy, it needs to contemplate measures promoting freshwater resource sustainability. On the other hand, the optimistic future drawn through SED4 is probably too optimistic, as SED4 is not only the least desired scenario for farmers (but most desired by institutional actors) who disagree with the shift towards organic farming, but also considered the most unlikely by all. It is not believed that such paradigm change, and its environmental and public health concerns, will be on the European policy agenda.

Such measures can aim at water availability, for instance by enhancing (artificially) groundwater recharge and storage, by protecting preferential infiltration and recharge areas, or by promoting the use of alternative water sources such as treated wastewater for irrigation. Protecting recharge areas in some cases means avoiding the transformation of natural into agricultural land. This is an example, among others, of how SED and adaptation measures are interrelated and can be conflicting. Another concern pertains to the difficulties involved in implementing possible adaptation measures, for different reasons, from technical feasibility to social acceptance. In the Algarve the reuse of treated wastewater for irrigation of golf courses is an example of a planned measure, debated for over a decade, that has currently still not been implemented.

The conflicts related to adaptation and the difficulties of implementation of adaptation measures may be diminished with the increase of participatory processes in the whole process of adaptation. One of the research projects that formed the context for this paper clearly revealed that when transparent, credible and complete information is given away, and everyone's viewpoints, interests and difficulties are discussed openly, social learning is produced and divergent interests more easily reach common ground. In a subsequent workshop presenting the information concerning CC and the impact on agriculture, farmers were able to creatively come up with both technical and economic solutions for adapting their agricultural practices. They envisaged a change towards a more sustainable agriculture, with a greater dedication towards investment in indigenous species (given professional training and incentives). They mentioned the need and the viability of constructing small reservoirs, and they recognised the need for greater cooperation amongst them. All these findings result from a process of learning that was not predictable from the first gatherings at the initial stages of the research project.

4 Conclusions

The integration of SED scenarios, designed and discussed in a participatory manner, with CC scenarios provides a more complete picture of possible future changes in water resources, then when based exclusively on climate models. Our results reveal that CC in the region will dynamically interact with economic factors and may force a restructuring of ways of living. Although much uncertainty remains regarding the projected paths of future climate, particularly on regional scales and short-term horizons, the more frequent occurrence of extreme events in the short-term future, as well as the long-term trends in water availability will encourage no-regret strategies such as water saving techniques and the search for alternative water sources. We believe that a "mixed-methods" approach, combining qualitative and quantitative methodologies from both the social and natural sciences, can provide the best answers. The methodology here presented is to be looked upon as a heuristic tool, which given further developments may illuminate policy making. In our view, exercises such as this one of envisioning different paths for the SED of the region, through participatory events, are needed for citizens and policy makers to take action. For an increasingly realistic assessment of the impact of CC and the adaptation measures it entails, it will be necessary to consider the co-evolution of CC and the socioeconomic system.

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Towards Adaptation to Climate Change: Water for Rice in the Coastal Wetlands of Doñana, Southern Spain

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Abstract Rice production in coastal wetlands provides critical ecosystem services that range from flood control to wildlife habitat. In the Iberian Peninsula rice was introduced in the 10th Century. Today Iberian rice accounts for about one quarter of the total rice production of the European Union, almost exclusively cultivated in the coastal wetlands of Spain, with permanent flooding. The intensive water management required to produce rice stands at a crucial point since freshwater supply is deteriorating at an unprecedented rate. Here we explore flexible adaptation options to climate change in the Doñana wetlands - a world heritage and biodiversity site - from two points of view: What are the policy options for agricultural water management in view of climate change? How can informed stakeholders contribute to better adaptation? The first question is addressed by simulating water availability to farmers with the WAAPA model under a range of adaptation policy options derived from the view of the local communities. The second question was addressed by means of participatory research. Adaptation options are framed according to the local environmental, social and policy context. Results suggest that perception on the potential role of new water infrastructure and farming subsidies dominates the view of local communities. The choices of the stakeholders that could be simulated with the hydrological model, were quantified in terms of additional water availability for the rice farming, therefore providing a quantitative measure to the qualitative solutions. Information provided during the study shaped the final adaptation options developed. Our research contributes to the definition of sustainable rice production in Europe.

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1 Introduction

The Europe 2020 strategy promotes the development of a greener, more environmentally friendly economy for the European Union countries. The European Environment Agency (EEA, 2012) supports the idea that healthy and resilient coastal ecosystems may provide services needed for this green economy whilst maintaining human well being. However, the challenge remains in defining how to move towards sustainability in practical terms. Coastal wetlands provide a challenging example that combines the economic interests of rice producers, the policy interests of rural development policies, and the environmental interests of water conservation policies.

The Doñana region is a coastal wetland in the Guadalquivir River Basin District of Southern Spain, where water is shared among the natural and the artificial wetland. The recent high temperature and drought episodes are influencing the view of local communities about the need for adaptation in the Doñana natural ecosystems and agricultural systems (De Stefano et al. 2014). The water district is already under environmental pressure (Willaarts et al. 2014; EEA 2012), the coastal vulnerability to sea level rise is high (Ramieri et al. 2011; Ojeda et al. 2009), and the potential increase of irrigation demand is very high (Iglesias et al., 2012).

Drought episodes of the past 50 years in the Sothern Europe aggravate the structural water deficit in the Doñana coastal wetland and the policy strategies undertaken have been capable to deal with extreme situations, but ineffective to solve the conflict among users, especially with the environment (Iglesias et al. 2008a; Iglesias et al., 2008b). Further, the water competition and conflicts will be increased due to a major pressure on freshwater resources as a result of climate change impacts, increased population, pollution problems from agriculture intensification and fragmented and uncoordinated adaptation policy strategies (Iglesias 2009). There is a need of reaching a balance among equity, economic security and the environment by flexible adaptation options that may deal with the increasing pressure on freshwater resources and in turn reduce the conflict among users in the case study region.

The local actors' views need to be considered for designing environmental policies since they may reveal a great deal of helpful information to approach possible adaptation pathways closer to the reality (Picketts et al., 2013). For instance, Sánchez et al. (2014a) found by public consultation that the main drivers to encourage the adoption of new mitigation and adaptation measures by Spanish farmers were pro-environmental concerns, financial incentives and access to technical advice. Furthermore, García-Llorente et al. (2011) found by public consultation in Doñana that the environmental policy strategies should be aimed to increase education programs regarding conservation policies specially addressed to male ageing population with lower education levels.

Several hundred studies have made significant efforts to find climate change adaptation measures (IPCC, 2014) and many in Doñana are contributing to the definition of strategies that can be agreed among the local actors (De Stefano et al. 2014), among the environmental policy design (Martín-López et al. 2011) and among the economic choices (Berbel et al., 2011). This paper aims to address the social and environmental challenges for adaptation of the Doñana coastal wetland. We combine two sources of information to explore flexible adaptation options for the rice farming and the natural ecosystem. First, we define the magnitude of the impacts and the effects of policy by modelling the river basin system. Second, we conduct a participatory data collection process to inform on the social challenge.

The study is organised in five sections. The next Section presents the methods and data; Section 3 provides an estimation of water availability under climate change and the effect of water policy scenarios; Section 4 analyses and discuses adaptation from the view of local communities. Section 5 concludes.

2 Methods and Data

2.1 Study Area

The Doñana coastal wetland is recognised of international importance and declared as a Ramsar Wetland, UNESCO World Heritage Site and Biosphere Reserve for being one of the richest natural ecosystems in Europe (García Novo and Marín Cabrera, 2006). The coastal wetland of Doñana is located in the lower part of the Guadalquivir River District (Southern Spain) on the Atlantic coast of Andalusia, the protected area cover an area of over 121,600 ha under the protection status of Doñana Natural Park and in the eastern side is also located the largest rice (*Oryza sativa L.*) farming area of the country (ca. 36,000 ha) (Fig. 1). There are a population of nearly 213,839 inhabitants in the Doñana area, whose activities are mainly addressed to agriculture and tourism and in turn the wetland provides key ecological services such as a stepping-stone in the migration route for birds and waterfowl, a home to many

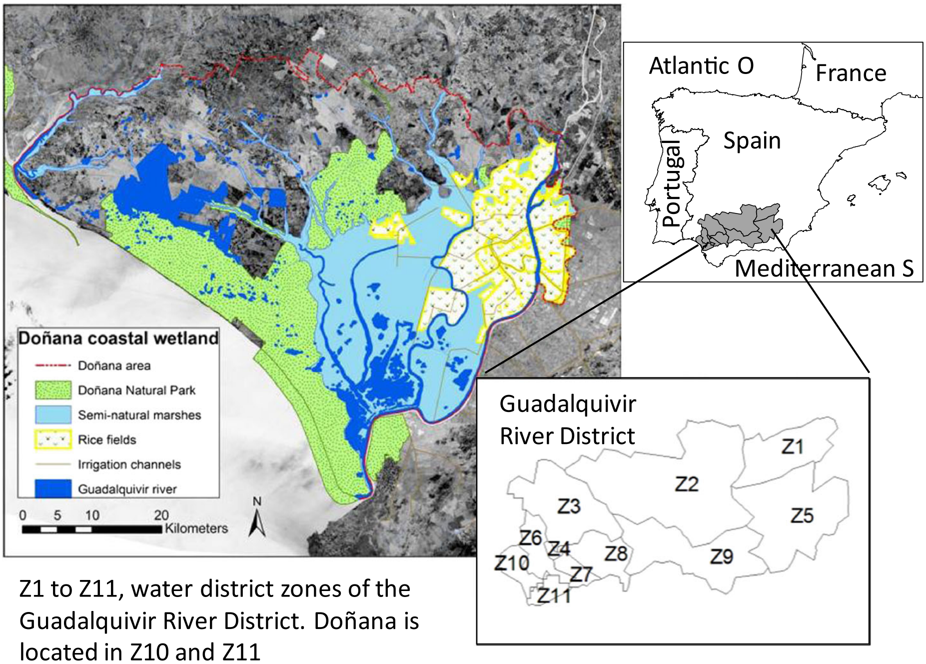

Fig. 1 Geographical location of the Doñana coastal wetland and the Guadalquivir River Basin District

endemic and threatened species, regulation of the local hydrologic cycle and provision of landscape services (Martín-López et al., 2011).

The Guadalquivir River District with around 650 km of length and 57.527 km^2 of area, amounts 7.022 hm^3/year in average of renewable water resources from which 4,007.73 hm^3/year are used mainly for agriculture (87 %), domestic use (11 %), industrial use (1 %) and energy (1 %) (CHG 2013). Rice farming is the main source of income for the local population but as well is one of the most water intensive crops of the river basin (De Stefano et al. 2014). Rice farming occupies the 4.2 % of the irrigated area and requires over 10,400 m^3/ha/year of water to achieve yields between 9 and 10 t/ha, it accounts a total of 366 hm^3/year, the 14.3 % of the annual regulated water resources of the river basin (CHG 2013). The irrigation system for the rice cultivation consist in taking water directly from the Guadalquivir River and flooding the fields until 20 cm of water, depending on the crop needs for each development stage, throughout channels. The semiarid conditions and the salinity of soils make difficult the cultivation of many other crops in the rice area. The flooding irrigation system allows tolerable levels of oxygen, temperature and salinity for growing the rice (maximum concentration of 2 g/l of salt in the water) whilst avoids the emergence of a saline crust in the top soil (Aguilar 2010). Further, the sea intrusion increases largely the salinity of the water in the estuary and the Guadalquivir Basin Authority has to provide for dam releases upstream from the rice area to improve the quality of irrigation water.

So far, rice farmers in Doñana received approximately 1,670 €/ha as public subsidies (within the framework of the CAP, Regulation EC/1782/2003) and if they met the integrated production commitment that includes a group of best management practices, they also received 398 €/ha (Regulation EC/1257/1999). Currently, rice farmers will have to meet the measures included into the CAP greening to perceive the equal subsidies. Thus rice production can be considered profitable for farmers since the average cost of producing rice in Doñana is over 1,496€/ha (reduced due to a highly mechanized agricultural system and higher education training of farm managers that implement precision agricultural methods) and rice price usually ranges between 2,000–2,200€/ha on average (Aguilar, 2010).

The Doñana coastal wetland is a complex socio-ecological system where the rice production and the wetland ecosystem show a great dependence on water and climate and any change of these factors may alter the state of the environment and local livelihood security.

2.2 Framework

Our methodological framework combined two information sources to explore flexible adaptation options for the rice farming and the natural ecosystem in the coastal wetlands of Doñana (Fig. 2): First, the WAAPA model is used to estimate the effect of exposure to climate change and of different adaptation policy options in water availability, providing information on the environmental challenge. Second, semi-structured interviews and an expert panel, inform on the view of local communities on climate change risk and adaptation measures to rice production and the wetland, providing information on the social challenge.

Climate change is clearly defined in the WAAPA model, since it is an input for the simulations. The climate change scenarios for 2071–2010 are explained below. Although these climate scenarios are also presented to the stakeholders, it is inevitable that these scenarios are compared to the perceived current and past water scarcity and climate variability. It is important to notice that water scarcity is a permanent fact in the area and climate scenarios intensify the scarcity level.

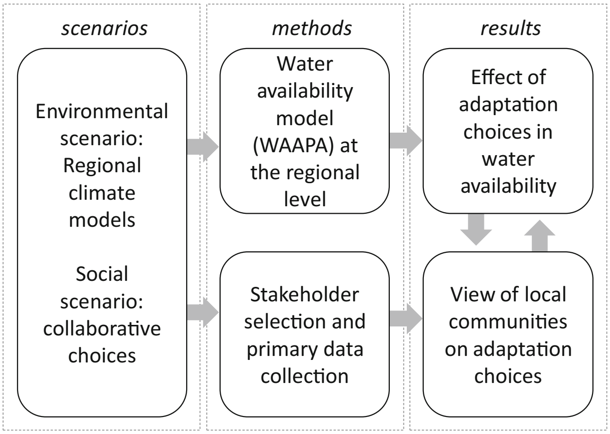

Fig. 2 Methodological framework

2.3 Modelling Water Availability and Policy Scenarios

The effect of climate change and policy on water availability for irrigation and for the natural ecosystem was estimated with the WAAPA model (Garrote et al. 2011; Garrote et al. 2015). The quantitative analysis provided support for the selection of adaptation policy options that inform local stakeholders.

The WAAPA model (Water Availability and Adaptation Policy Analysis) calculates Maximum Potential Water Withdrawal (MPWW), defined as the maximum water demand that could be provided at a given point in the river network with the available water infrastructure (i.e., reservoirs, dams and water transfers), satisfying management and environmental constraints. MPWW is associated to a given demand type, which implies a minimum required reliability and certain seasonal variation. In all cases urban supply is associated to population and has higher priority than irrigation. Water for ecosystems has also a higher priority than irrigation: The amount of water allocated for ecological flows is defined in each sub-district following the specification of the national regulation on hydrological planning.

Model architecture is summarized as follows: (a) Satisfaction of the environmental flow requirement in every reservoir with the available inflow. Environmental flows are passed to downstream reservoirs and added to their inflows. (b) Computation of evaporation in every reservoir and reduction of available storage accordingly. (c) Increment of storage with the remaining inflow, if any. Computation of excess storage (storage above maximum capacity) in every reservoir. (d) Satisfaction of demands ordered by priority, if possible. Use of excess storage first, then available storage starting from higher priority reservoirs. (e) If excess storage remains in any reservoir, computation of uncontrolled spills.

The MPWW analysis was applied to estimate the exposure of the Guadalquivir sub-districts to climate change. The comparison between the MPWW for irrigation in the control and in the climate change scenario provides a proxy variable to estimate exposure to climate change. In this study we consider that urban demand is fixed, because it is linked to population, which in the region under analysis is not expected to change significantly in the next 50 years (OECD 2012). Water for ecosystems is estimated following the environmental flow requirements specified in the national regulation, which establishes a range between the 5 and 15 % quantiles of the marginal distribution of monthly flows in current natural conditions. The central value, 10 %, was adopted and it was considered constant. According to climate change projections, this assumption may be perceived as conservative, since streamflow is expected to decrease sharply in the region, but it may underestimate or overestimate future ecosystem water demand depending on future land use and environmental regulations.

Water policy scenarios are constructed aiming to maintain adequate reliability for urban, ecosystem and irrigation demands. The effect of the adaptation effort is estimated from the difference between water availability for irrigation in the control and in the climate change scenario. This is based on the assumption that in the control period irrigation demand is similar to MPWW for irrigation. The assumption is well grounded for the study region, a water scarcity Mediterranean region, where water resources are developed (i.e., infrastructure and management) to satisfy existing demands. The larger the difference between current and future water availabilities for irrigation, the greater the adaptation policy effort required to compensate for climate change though adaptation.

The effect of policy scenarios here is calculated as the increase in future water availability resulting from the implementation of each policy. This study considers four adaptation policy scenarios aiming to reduce the irrigation demand that would be required in the climate change scenario in order to restore the same level of performance that is observed in the control scenario. Demand reduction is not the only policy alternative to reach the objective of adequately supplying the multiple demands of water in the area. In addition to demand reduction, this study considers four adaptation policy measures. Policy option 1 (urban policy) implies to improve urban water use efficiency and reach the target of 175 l/person/day supplied in urban areas. Currently this amount is 300 l/person/day, a value that is considered too high. Concrete examples for implementing this policy could be re-use of urban water or improvement of water technical efficiency within cities (supply management policy), imposed reduction of water per capita use (demand management policy), or water rights exchange programs (supply management policy). The data on urban water use of 300 l/pd is the reference value adopted in the Hydrological Plan of the Guadalquivir River Basin District in time horizon 2015 (taken as “current” scenario) (CHG 2013). The value of 175 l/pd is taken as a target value estimated from the water supply systems in Spain that currently show the smallest per-capita consumption reported (value 195 l/p.d in the Consorcio de Aguas de Tarragona, plus a further 10 % increase in efficiency) (CHE 2014).

Adaptation Policy 2 implies a reduction of the environmental flow requirements (from the 10 to 5 % quantile of the marginal monthly distribution of runoff). This assumption is clearly challenged within the current strategy for water management, but it is included here to illustrate the trade-off between water for the artificial wetland and for the natural wetland for the discussion among local actors. Adaptation Policy 3 implies to use the storage available in hydro-power dams for regulating water for irrigation. Finally, Adaptation Policy 4 is reached by improving the overall water management of the system by expanding the network of water interconnections and applying water resources systems optimization models.

In this study, climate change scenarios are derived from Regional Climate Models (RCM) driven by two greenhouse gas emission scenarios. The use of RCMs is an important tool for evaluating water management under future climate change scenarios (Varis et al. 2004). Nonetheless, it is well known that the output of the RCMs cannot be used directly if there is no procedure that eliminates the existing bias (Sharma et al. 2007). For this reason, in order to analyse the effect of climate change on water availability for irrigation in a regulated system, here we generate climate change projections based on the bias-corrected runoff alternatives (following Gonzalez-Zeas et al. 2012). We use two emission scenarios (A1B and E1, to represent the uncertainty derived from greenhouse emissions policies) and two regional climate models to represent the uncertainty derived from model choice). Climate change input for the WAAPA model was monthly time series of streamflow data obtained from the results of the ENSEMBLES project in two climate scenarios (Table 1). The transient runs (1950–2100) were split in two periods: control climate (1960–1990, Oct 1961 to Sep 1991) and future climate (2070–2100, Oct 2069 to Sep 2099).

2.4 Criteria for Selecting Stakeholders and Sample Size

Since the mid 1980s there is a growing awareness that the stakeholder may be crucial for effective change and adoption of innovation (Freeman 1984; Eden and Ackermann 1998; Bryson 2004). The fundamental principle is that there are a number of people, organisations and groups, who are critical to the adaptation viability and success. There has been a great deal written in the stakeholder literature on the definition of who or what is a stakeholder. There are numerous definitions of stakeholders; here we consider that stakeholders are groups of individuals with power to directly affect the adaptation future either by supporting or constraining actions (adapting the business definition of Eden and Ackermann (1998) to the adaptation objectives) and recognise that the stakeholders' views will change depending on the specific issue that is being addressed (see Cummings and Doh 2000; Glicken 2000). Following these concepts, we selected stakeholders in two steps: (1) Identification of the groups who have the potential to affect or may be affected by adaptation policies; and (2) Analysis of their power or influence in the adaptation decision in an influence vs interest map (Eden and Ackermann 1998).

Power versus interest grids typically help determine which players' interests and power bases must be taken into account in order to address the problem or issue at hand. As result we grouped the stakeholders in a matrix with four categories (Fig. 3). First, the critical players are the farmers, since they have high influence and high interest. Second, the context setters are the policy makers, which have high power but lower interest. Third, the significant players are the environmental groups, which have high interest and lower power. Finally, the citizens' group includes the less significant players, with lower interest and lower power. Recognising the importance citizens' opinion for setting values in adaptation, we assumed that the expert scientist group could represent an aggregated view of the population (see below). This assumption is clearly flawed, but may be valid in the absence of data derived from a large survey, that is completely out of the scope of this study. Therefore the views of the expert panel

Table 1 Climate change scenarios used as input to the WAAPA obtained from the ENSEMBLES project

Scenario name in this study	Global model	Regional model	Resolution and time frame	ENSEMBLES file	Socio economic assumptions (*)
CRNM A1B	ARPEGE	RM5.1	25×25 km, 1950–2100	CNRM-RM5.1_SCN_ ARPEGE_MM_25km_ 1950-2100_mrro.nc	A1B
KNMI A1B	ECHAM5-r3	RACMO2	25×25 km, 1950-2100	KNMI-RACMO2_A1B_ ECHAM5-r3_ MM_25km_mrro.nc	A1B

(*) See Nakicenovic et al. 2000

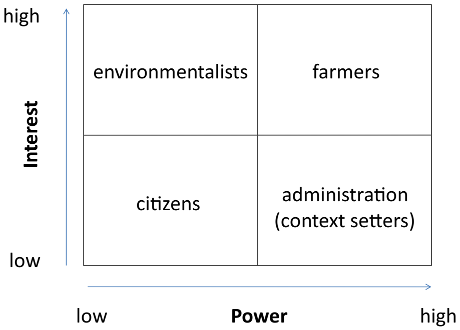

Fig. 3 Criteria for selecting stakeholder groups, adapted from the theoretical power versus interest grid of Eden and Ackermann (1998)

are not formally considered in the study; the reason to include this group in the description is to communicate the research process.

Once the groups were defined, deciding who should be involved is a key strategic choice. In general, people should be involved if they have information that cannot be gained otherwise, or if their participation is necessary to assure successful implementation of adaptation strategies. These two aspects, together the available volunteer participants, guided the selection of stakeholders for the one-to-one long interviews (see Appendix 1).

In all groups, the number of available volunteer participants was very low, limiting the potential sample size. This raises the question of the representation of the sample. In relation to the representation, it is recognised good results can be achieved with just a few interviews, as data become saturated, and data analysis indicates that all themes can reach saturation, meaning additional participants would likely not have added to the depth or breadth of parent responses (Sandelowski 1995a, 1995b; Carlsen and Glenton 2011).

In this study area, the position of the farmers is extremely well defined, since all want to maintain or increase the water supply for rice cultivation. Over 90 % of rice farmers in Doñana belong to farmer associations (i.e., Farmer Association body, such as Farmers Advisory Services, Irrigation Communities, Cooperatives or Rice Farming Federations and Unions; see Aguilar 2010). These services include only private members with a technical profile or experienced farmers, and do not include representatives of the local or regional administration. The rice farmer associations provide services to manage irrigation, to the processing of rice after harvest and to facilitate the marketing to the farmers. They also offer technical advice and legislative information, including regular supervision and follow-up of the rice fields and production. The high level of association between rice farmers makes them a strong lobby with very uniform interests. For the interviews we selected members from the five organisations that represent 90 % of the farmers, with the aim of providing the representation of the rice farmers in the area as accurate as possible. The Administration body refers to the public service organization which has control on water resources policy, water management and irrigation planning in the Guadalquivir River Basin District. It includes the River Basin Authorities and public officials, with almost absolutely uniform view on the possible solutions facing climate change. The environmentalist body is a lobby group representing the environmental rights and the nature welfare of the Doñana coastal wetland by strategic actions in water management and new regulations; this group has a uniform voice since the 1960s claiming more water for the natural wetland.

2.5 Primary Data Collection

Primary data on observed impacts in the coastal wetland and possible adjustments in view of climate change was collected by means of two qualitative social research methods used in sequence: semi-structured interviews and an expert panel. These are sampling techniques commonly used in policy research (Martín-López et al., 2011; Harrell and Bradley 2009; Ingram and Morris 2007).

Semi-structured interviews were conducted with a standardized guideline to ensure that the researcher covers the material and with an open framework with some discretion about the order in which questions were asked. This sampling method is adequate when the objective is to look deeply into a topic and to understand thoroughly the answers provided (Harrell and Bradley 2009). The interviewer provided information about climate change impacts on water resources in the Guadalquivir River Basin District (included in the Results section) and received information about the observed changes in the coastal wetland and potential adjustments of current water management that affects rice production and the natural ecosystem. In particular, the interview aimed to identify the flexible adaptation measures that could be effective from the social and environmental points of view. A guideline to the interviews was prepared in advance (Appendix 1), however the interviews resulted in additional discussion topics that contribute to understand the barriers to implement the potential technical measures.

The semi-structured interviews aim to obtain specific qualitative information about observed climate impacts and possible adjustments from a sample of the population. The main advantage of the method is that it encourages two-way communication, those being interviewed can ask questions to the interviewer, provides arguments for answers, and encourages discussion on sensitive issues. The main limitations are derived from the small sample size and the lack of trust that the interviewed may have about the confidentiality of the responses.

The expert panel assisted in the formalisation of the research questions derived from the semi-structured interviews. The interview survey was conducted during 31 January, 1 and 2 February 2012. To supply a broad outline on observed climate impacts and possible adjustments, eleven key participants from relevant sectors of the coastal wetland were encouraged to give their input (Table 2). The requirements for the participants' selection were: i) to be working on activities related to the rice production and the natural ecosystem during the last decade; ii) to have an extensive knowledge about the rice productive sector and to have regular contact with the rice farmers; ii) to have an extensive knowledge about the welfare of the wetland and the natural ecosystem functioning; and iii) to be informed on the water management requirements to cope successfully with the rice production and the natural ecosystem.

The resulting information of the consulting process was also used to inform local stakeholders of the rice farming area by organizing two workshops about the local climate change risk and adaptation with a total of 51 participants (De Stefano et al. 2014).

2.6 Limitations of the Methodology

There are some major limitations of our methodology, derived from the modelling approach and from the consultation process.

The simulation of water availability under climate and policy changes with the WAAPA models have major sources of uncertainty and limitations. The streamflow were derived from

Table 2 Description of the public consulting conducted in terms of type of consultancy, number of participants and structure of the sample

Type of consultancy	Date and venue	Number of participants	Type of participants
Semi structured individual interviews to local actors	31 January to 2 February, 2012 in Doñana area	11	Farmer Association (5), Administration (3), Environmentalists (3)
Expert panel to experts / scientists	20 April of 2012 in Madrid	3	Research scientists in Hydrology (1), Agriculture (1) and Economics (1)

the output of regional climate models that include a very crude representation of the hydrological cycle, demands are estimated using globally available data as proxy variables. This is fully explained in Garrote et al. (2015). In addition changes in land use consistent with the climate scenario projections have not been included in the simulations, since the aim was to simulate policy choices for the current wetland system.

A major limitation is derived from the consultation process. Although the three groups of participants selected are reasonably in line with adaptation in the case study, the interview sample is quite small and it is not necessarily representative of all the communities and organizations involved. The study did not address the full range of stakeholders which affect or are affected by climate change adaptation. Here the groups included are likely to have a potential interest and influence in the decision making process of an adaptation strategy, but some actors may be missing due to the limitations in the sample size. A derived shortcoming of the consulting process arises from the current level of conflict between stakeholders having different views on water management. This may have resulted in some degree of mistrust on the confidentiality of their responses. In addition, the consulting process applied in this study only included qualitative information, resulting in difficult comparison among responses and limited in capturing variability among the respondents. The open questions of the semi-structured interviews did not provide enough information for a quantitative analysis. Thus, we identified a portfolio of adaptation options for water resources management rather than seeking consensus on the more cost effective option or priority that could be derived from more quantitative data. Further research is needed in order to incorporate the local knowledge into climate change adaptation local plans and in the wider policy context.

Despite these uncertainties and limitations, the results obtained show a qualitative picture for future water availability in the Guadalquivir basin under a choice of adaptation policy options derived from the consultation. Our findings advance the knowledge of differing climate change strategies at local scale by providing increased comprehension of the stakeholders oppose or support to adaptation options which could be used to incorporate in local adaptation plans.

3 Water Availability and Potential Policy Choices

Climate change jeopardizes the equilibrium of water resources in the Guadalquivir water district and the impacts will vary as a result of local regulation capacity (Fig. 3). The difference between runoff and water availability is defined by the effect of storage. Reservoir regulation is one of the most important water resources management policies in water-scarcity areas and has generated significant impacts. Existing reservoirs are being subjected to intense multi-objective demands on limited resources (i.e., water supply, flood control, hydropower, navigation, fish and wild life conservation, recreation, and water quality by assimilating waste effluents.)

These scenarios of water availability (Fig. 3) demonstrate that in water scarcity regions, water availability is likely to be one of the great future challenges. Defining future water availability under different adaptation policy options is therefore a basic step for water policy formulation.

Reductions of water runoff and increased variability, resulting from exposure to climate change, will lead to significant decreases in the water availability (Fig. 3). This clearly demands for adaptation policy measures. Here we only consider impositions of demand restrictions since regulatory capacity is already at a maximum in the river district. This is particularly true in the case of irrigation water demand scenarios since it is reasonable to assume that, without changes in policy, land use or technology, projected irrigation demand in the basin will be higher than present irrigation demand even if farmers apply efficient management practices and adjust cropping systems to the new climate. Moreover, when policy and technology remain constant, it has been shown that agricultural water demand will increase in all scenarios in the region (Iglesias et al., 2007, Iglesias 2009). The main drivers of this irrigation demand increase are the decrease in effective rainfall and increase in potential evapotranspiration (due to higher temperature and changes of other meteorological variables).

4 The View of Local Communities: Main Risks and Local Adaptation Options

Here we present the results of the consulting process (with key local actors and the experts) focusing on a) how the accelerated state of climate change is already affecting the rice production and the natural ecosystem and b) what are the main conflicts and the potential opportunities for societal consensus on local adaptation options.

The results were first generalized into appropriate categories using the topics included in the interview guideline in Appendix 1 and expanded in Appendix 2. The categorization was conducted by the primary researcher, and then assessed and verified by other researchers and the experts. Table 3 synthesizes the interviews results. The local actors' views fell into the following categories: (1) risks derived from changes in the climate and degree of social concern on them and (2) local adaptation options according to the identified risks. In this second category, we characterise the: current implementation level per adaptation option identified; acceptance (green) or rejection (red) of the local adaptation options by farmers associations; acceptance (green) or rejection (red) of the local adaptation options by environmentalists; and support for (green) or rejection of (red) the local adaptation options from the administration. The white cells make reference to "no opinion" answers.

The first category describes stakeholders' perception on the risks derived from changes in the climate and the degree of social concern to them. The results of the interviews suggest that that the major risks in the case study area are water scarcity, salinity problems in water and soils, and to a lesser extent increased invasive species and pests and decreased rice yields and quality. Most respondents' perceptions stemmed from the scarcity of water as the main risk to be concerned. A possible reason why water scarcity is perceived to be the most important risk is the fact that it can easily lead to fall of productivity and rice yield reductions and in turn

Table 3 Summary of the view of local actors on climate change risks and adaptation options

Risk derived from changes in the climate / Degree of social concern	Local adaptation option	Current implementation level$^{(1)}$	Acceptability to farmer associations	Acceptability to environmentalists	Support from the administration
	I. Technological measures to face the risk				
Increased water scarcity /High	Water recirculation and reutilization within the paddy rice	M	🟩	🟩	
	Increase the technical efficiency of the irrigation systems	L	🟩	🟩	
	Installation of flow meters	L		🟩	
	Laser levelling	H	🟩	🟩	🟩
	Additional water infrastructure	n.a.	🟩	🟥	🟥
Increased water salinity /High	Water releases from upstream reservoirs	M	🟩	🟥	
	New pipeline to bring in the water directly upstream from the salt water intrusion	n.a.	🟩	🟥	🟥
Increased soil salinity /High	Flooding irrigation systems to wash soils	H	🟩	🟥	
	Organic production (good farming practices)	L	🟥	🟩	
Increased invasive species and pests /Medium	Integrated production (inputs use efficiency)	H	🟩		🟩
Decreased rice yield and quality /Low	New longer cycle rice varieties	L	🟥	🟩	🟥
	New rice varieties adapted to water and heat stress	L	🟥	🟩	🟥
	II. Organizational measures to face the risk				
All risks /High	Reduction of the available cultivated surface	L	🟥	🟩	
	Crop diversification and diversification to others activities (e.g. aquaculture, agro-tourism)	L	🟥	🟩	🟥
	Anticipating local and regional water shortages	L	🟩	🟩	🟥
	Increase monitoring and information on water use and availability at local level	L	🟩	🟩	
	Setting of irrigation turns	M	🟩	🟩	
	III. Governance measures to face the risk				
All risks /High	Actions at the basin level leading flexible adaptation strategies to climate change	L	🟥	🟩	
	Improve transparency and public participation to encourage agro-environmental awareness	L	🟥	🟩	🟩
	Increase scientific research, field studies, dissemination	M	🟩	🟩	
	Improve coordination between institutions, data sharing	L	🟩	🟩	🟩
	Encourage a long-term perspective in water management	L		🟩	🟩
	Implement good practices defined in the WFD	M		🟩	🟩
	Increase in farmers training and technical advice	M	🟩	🟩	🟩
	Supplemental transfer water from the Guadiana new riverbed	n.a.	🟩	🟥	🟥

(1) *L* Low implementation level, *M* Medium implementation level, *H* High implementation level, *n.a.* not available

provoke biodiversity losses. The foresee sea level rise projections in the coastal wetland are expected to worsen the water quality in the lower part of the Guadalquivir River Basin, the case study area, due to larger marine intrusion (IPCC 2014; Ramieri et al. 2011; Ojeda et al. 2009). An increased relative water scarcity, together with higher levels of salinity, makes rise conflicts and competition among users over the allocation of water (Rijsberman 2006).

The literature review and the findings of this study suggest that higher temperatures are also expected to change water demands and have direct physical effects on the plant growth and development (IPCC 2013, Hanak and Lund 2012). Pulido-Calvo et al. (2012) found that in dry periods a mean temperature increase of 1 °C in low altitude locations of the Guadalquivir River Basin will result in a mean increase of 12 % in the irrigation demand on outflows. Rice is particularly sensitive to heat stress and may suffer serious damages during the anthesis to maximum temperatures above 37 °C and especially when it is exposed to water stress during the entire flowering stage (Sánchez et al. 2014b). Although the expected mid and long-term scenarios of high temperatures are not recognize as a relevant risk by responses of farmer associations, they are already changing the rice growing calendar and introducing new varieties which are more tolerant to heat stress and longer cycle rice varieties (e.g., J-sendra 155 or Puntal 145).

In a qualitative way, the farmer associations responses reflected that farmers in the Doñana coastal wetland: (i) are likely more concerned about the present than about the future; (ii) are very aware of the damage of current climate extremes in rice production and the natural ecosystem, although they do not entirely recognise that the intensification of current extremes may be a consequence of the climate change; (iii) probably do not perceive increased climate variability as a risk to be concerned in the long-term, since they have a shot-term view more addressed to profit-driven principles than to those related to climate change; and (iv) are likely more concerned about severe droughts or salinity since they have faced these events over the years. Rice farmers have demonstrated to have good adaptation capacities to current and past extreme events, but they do not seem to be particularly open to innovation for the forthcoming risks linked to climate change.

Forming the second category, the respondents provided a broad spectrum of local adaptation options for the rice production to face the identified risk. We organize them into three main groups: technological, organizational and governance measures. The following categories are related to the current implementation level of the options, farmer associations and environmentalists' acceptability and administration support per option.

Different points of views about the adaptation options were stated depending on the type of participants. Almost half of adaptation options included in Table 3 confront farmer associations and environmentalists' views, since the options may not be fully corresponding to their own interests and goals. Farmer associations try to promote technological and governance measures that involve options to build new water infrastructures (e.g., a pipeline to bring in the water directly upstream from the salt water intrusion) or increase the water supply to the rice crops (e.g., water releases from upstream reservoirs or supplemental transfer water from the Guadiana new riverbed). So far, environmentalists and administration have null acceptance and support from those options that may result in higher economic costs and environmental impact of new infrastructures. In the perception of the farmer associations, measures that may imply lower yields (organic production, rice varieties adapted to climate change) or reductions of the cultivated area should not be accepted. However, Pulido-Calvo et al. (2012) results supported that the current water deficit in the Guadalquivir River Basin may inevitably lead to reductions in irrigated areas. Environmentalists agree with this projection, but the administration seems not willingness to support the change of management or activity.

Technological measures to increase water efficiency at the field level were most likely to be accepted for both farmer associations and environmentalists. For instance, water recirculation and reutilization within the paddy rice or increased technical efficiency of the irrigation systems. Other technological options that have already proven benefits to the rice production and are widely implemented in the area (laser levelling and integrated production) were also fully supported by the administration. Rice farming in the Doñana wetland is characterized to be a highly mechanized agricultural system with qualified labour that uses precision agricultural methods (Aguilar 2010; De Stefano et al. 2014).

Organizational measures related to water management were positively perceived by the farmer associations and environmentalists. Their responses reflected that there is a lack of local monitoring and information on water availability and use. The provision of accurate, accessible and useful water information at different scales is essential to deal with reductions in water availability (Wei et al. 2011). Reed et al. (2006) reported that including thresholds information about the risks at local scale, even when they are difficult to identify, they can further improve the value of monitoring in managed ecosystems. In the perceptions of the two groups, farmer associations and environmentalists, there is also a need of anticipating management options to local water shortages. Once problems have arisen, reactive management efforts can be more costly than anticipating management to reduce risk by actions to enhance the resilience of the river basin (Palmer et al. 2008). Proactive management efforts may include among others: management plans to the risk of water scarcity at the farm level, on-farm reservoirs, improvements in water use efficiency (Iglesias et al. 2007) and, the establishment of water markets to negotiate water between water users and in turn encouraging the reallocation of water rights to restore freshwater ecosystem health (Garrick et al. 2009; Rey et al. 2014). The high number of “no opinion” answers obtained within the category of “administration support” to technological or organizational options is striking. It suggests to some extent a limited commitment to measures addressed at farm or local scale on this topic. Most of questions concerning to governance options were perceived to be supported by the administration, since it directly fall in their scope of action.

Governance measures included options addressed to improve the coordination between institutions. The critical importance of institutional good governance has been previously established as a requirement for the regional adaptation capacity by preceding research (Berrang-Ford et al. 2014; Hanak and Lund 2012; Iglesias 2009). Increase scientific research, farmer training and technical advice were governance options perceived positively by all the groups. Finally, a lack of confidence in the truth or efficacy of governance measures addressed to climate change strategies and environmental awareness is often referred in the farmer associations’ responses. These results prove that climate change and environment can be concepts which are not be easily grasped, and tends to be something that is less tangible to farmers. Experts also pointed out the need of encouraging the farmers’ long-term views by climate change advisement and capacity building.

Overall, the results from the consulting process stressed the difficult to find adaptation options which are concurrent for the farmer associations, environmentalists and administration preferences. The spectrum of potential adaptation options in the case study can be represent from two end points, the purely environmental one (eco-centric perspective addressed to reduce impacts on the Guadalquivir River resources and the conservation of natural ecosystems), and the fully agricultural (technocratic perspective addressed to ensure rice yields and productivity) (Figs. 4 and 5). If possible, policy makers and researchers should try to encourage more flexible adaptation options or those located in the middle of the spectrum where environmental and agricultural profit-driven preferences are closer. The international competition in a globalized sector together with the new environmental requirements from

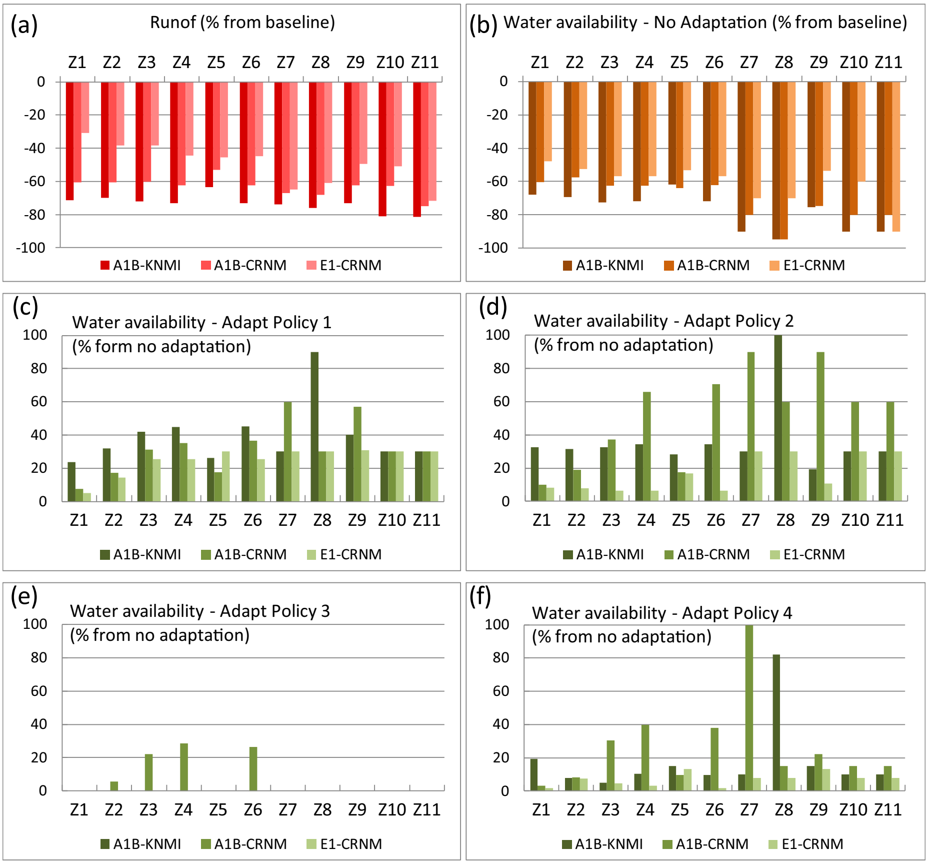

Fig. 4 Effect of climate change scenario (2070–2100) with respect to control run (1960–1990) for the RCM models forced with two emission scenarios in the Guadalquivir water district. (**a**) Per unit reduction of runoff; (**b**) water availability for irrigation with current policy; (**c**) water availability for irrigation with improved water policy in urban areas; (**d**) water availability for irrigation with water reduced allocation for environmental uses; (**e**) water availability for irrigation with hydropower reservoir water conservations; (**f**) water availability for irrigation with improved the overall water management of the system by water interconnections

CAP might bring more pressure, raising the current conflicts between water users in the area (De Stefano et al. 2014). The portfolio of adaptation options and initiatives will probably fail if policy makers and advisors do not empower and inform local actors (Jones 2010). Additionally, there is a need of adaptation options that in turn are able to mitigate climate change by having less favourable energy implications (Hanak and Lund 2012).

5 Potential Policy Interventions based on the Interrelation of the two Results

The interrelation of the qualitative and quantitative components of the study is a challenge. Our approach to interrelation is summarised in Table 4 and includes three steps. The first step is the characterisation of water shortages under climate change by the WAAPA model. This diagnostic step is a quantification of the potential water availability changes in the basin and in

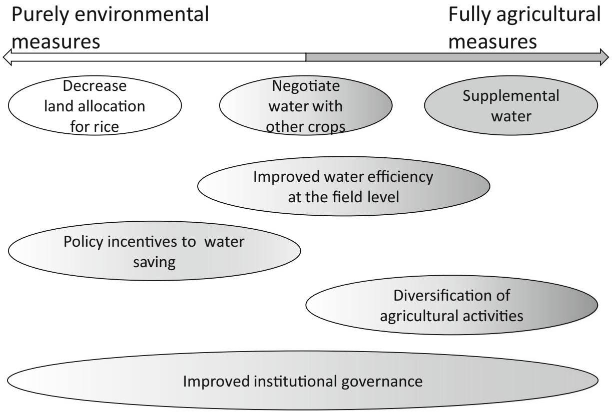

Fig. 5 The spectrum of potential adaptation options to climate change for the case study

Doñana, in particular. The broader scale is necessary, since the changes at the local level - and the potential solutions - depend on the changes in the basin. The simulations of water availability changes in all sub-basins range from −45 to −93 % of current water availability.

The second step explores the choices of stakeholders. The complete stakeholder views on adaptation measures are a consequence of their recurrent exposure to water limitations under the current climate. The range of options identified include agronomic, water management, and governance measures. The measures related to water management are then selected to provide an quantitative estimation on their effectiveness with the WAAPA model in the third step.

The approach links perceptions on the potential effect of the measure with a quantification by means of a water policy model. We focus on options that presented a high degree of disagreement among the stakeholders groups (Table 3). The application of the WAAPA model to these choices helped clarify the objective effect of the options. Furthermore, the WAAPA model was also used to simulate policy options that could be implemented in other sectors, e.g., urban or ecosystems, since these choices could bring a quantitative perspective to compare the local community choices.

The Adaptation Policy 1 addressed to improve water urban use could reach major improvements of water availability for irrigation and in turn avoid reduced water for environmental use by adaptation policy 2. The use of additional water infrastructure for irrigation (e.g., from hydropower reservoirs) was performed by the adaptation policy 3. The simulations showed that the effect for improving water availability of policy 3 was not significant. Adaptation options to improve the water managements by interconnections (a new pipeline connecting upstream water bodies to the rice fields, additional releases from upstream reservoirs or transfer of water) were endorsed into adaptation policy 4. The adoption of policy 4 was specially controversy between stakeholders in their acceptance, however the simulations clearly showed improvement of less than 20 % except in a few sub-basins and scenarios.

6 Conclusions

Policy is deeply involved in the water sector. Usually, policy development is based on an historical analysis of water demand and supply. It is therefore a challenge to develop policies that respond to an

Table 4 Integration of stakeholder choices and potential policy choices

Diagnostic water shortages from model WAAPA and stakeholder views First step	Choices of the stakeholders that can be simulated with WAAPA[a] Second step	Adaptation policy simulated with WAAPA[b] Third step	Quantitative evaluation of the effect on water availability[2]
Water shortages simulated in all sub-basin ranging between −45 and −93 % of current water availability	• Flexible actions at the basin levels (trade-offs with environmental and urban efficiency options)	Adaptation policy 1 and Adaptation policy 2	Overall the largest effect on water availability in most of sub-basins and scenarios
	• Use of additional water infrastructure for irrigation (hydropower reservoirs to be use also for irrigation)	Adaptation policy 3	Overall no effect for improving water availability except for very small positive effects in for only one climate change scenario
	• New pipeline connecting upstream water bodies to the rice fields • Additional releases from upstream reservoirs • Transfer of water	Adaptation policy 4	Overall improvement of projected impacts less than 20 % except in a few sub-basins and scenarios

[a] Included here only the options that can be simulated by WAAPA mode, additional information presented in Table 3

[b] Additional information and quantification in all sub-basins presented in Fig. 3

uncertain future. Indeed, science-policy integration is one of the most complex challenges that the scientific and policy making communities face since it involves knowledge sharing and ex-change among a wide range of disciplines and actors (Quevauviller et al. 2005). Despite these challenges, it is possible to achieve this goal and there are success stories throughout the world.

In this study we have attempted to face part of this challenge by presenting an approach that assesses how people – water policy and local actors – may influence water in the costal wetland under climate change. Together – policy and stakeholder choices – may be useful in singling out areas for moving towards adaptation and dialogue. This information may be used to implement and develop policy.

We recognise that the data needs for developing such a decision-making tool are complex and may be hard to satisfy; nevertheless, the conceptual steps that are presented remain valid and may be undertaken at a simplified level. Moreover, since the kinds of policy decisions being considered are at a local level it is likely that the availability of data will be greater.

Qualitative information from participatory research can be of great value in climate change adaptation and policy making when is combined with other tools or models to generate quantitative information (van Aalst et al. 2008). Recent researches have combined both methods to assess and identify climate change risk and adaptation options with valuable results on the adoption of a local adaptation strategy (Picketts et al. 2013; Cohen et al. 2006). Tisdell (2010) evaluated the implications of different water policy options in a semiarid area of Australia by modelling and found that the most cost effective option was a reduction of the water allocation to entitlement holders in order to increase water available for environmental use. Similarly to our study, Cohen et al. (2006) identified, by combining computer-based models and participatory research in the Okanagan Basin (Canada), a portfolio of adaptation options for water resources management rather than seeking consensus on the "best" option or process. Méndez et al. (2012) explored the historical records of the Doñana case study to develop a tailored action research program and provide specific policy-relevant recommendations for water resources management and wetland conservation. They conclude that there is a need of flexible and adaptive institutional regimes, social research and public participation, and improved monitoring and mechanisms for information exchange among others, which seem to be quite concurrent with our findings. Palomo et al. (2011) also carried out a participative process to analyze the current and the future situation in the Doñana wetland. They stressed the scarcity of water as the biggest problem and proposed consensual management strategies that include coordinated local plans and increased professional training. Participatory research can help to advance adaptation planning since knowing and doing is linked through action (Moser and Elkstrom 2011; Picketts et al. 2013).

Climate change is a global challenge with increasing severe consequences at the local level. In the Lower Guadalquivir River Basin District, existing water conflicts between the rice farming and the natural ecosystem are expected to be intensified in the future due to projected scenarios of water availability reduction and higher temperatures. This study aims to identify flexible climate change adaptation options in the Doñana coastal wetlands by simulating water availability to farmers with the WAAPA model and by engaging informed stakeholders in the assessment process. The combination of both methodologies approaches the potential adaptation options to the local environmental, social and policy context.

Results suggest that perception on new water infrastructure and farming subsidies dominates the decision process. Information provided during the study shaped the final adaptation options developed. Our research contributes to the definition of sustainable water management for rice production, livelihood support and the environment.

Results from the consulting process showed how the accelerated state of climate change is already affecting the rice production and the natural ecosystem in the Doñana wetland and what are the main conflicts and agreements on adaptation options under water availability reductions. The water scarcity and the water quality deterioration were perceived by all the informants as the major risks for the good functioning of both the rice farming and the natural ecosystem. Rice farmers do not recognize higher temperatures as a risk to be concerned, but they are already changing the rice growing calendar and introducing new varieties which are more tolerant to heat stress. The rice farming is a highly mechanized and organized agricultural system and rice farmers have a high education level. However, they seem to have a shot-term view of risks and they do not necessarily link them to climate change. Reductions of water availability together with the large water need to irrigate the rice fields and to control the water salinity will raise the current conflict between water users from different economic activities and the natural ecosystem conservation.

There is a shared perception on the need of new and diverse local initiatives to face the increasing water scarcity and salinity risk. The decision making processes of adaptation options is variable according to the stakeholder views. Farmers Association decisions are mainly dominated by technological and profit-driven principles with preference on new water infrastructure and farming subsidies. The lack of generational renewal by the decreasing number of young farmers and the new environmental requirements from CAP can bring more pressure on local farmers' price support. Environmentalists showed reluctance to those options which may result in higher economic costs and environmental impacts due to new infrastructures. Environmentalists and administration actors supported the reduction of rice cultivated area as an effective adaptation option. All the actors and the experts emphasized the important role that could play improved institutional governance and the need of encouraging the farmers' long-term views by climate change advisement and capacity building.

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Appendix 1. Guidelines for the Interviews

Objective of the Research

Coastal systems in the North-east Atlantic Ocean are expected to experience adverse impacts due to projected sea-level rise and climate change. There is a need to improve the planning by assessment of coastal vulnerability and flexible adaptation from the local scale and engage widely with relevant stakeholders.

The main goal of this research is to assess the climate change risk and what are the potential adaptation options in the Doñana coastal wetlands, a world heritage and biodiversity site with an intensive agricultural activity under scarcity conditions. We aimed to contribute to adaptation plans development in the case study region including the participation of informed stakeholders. The research was completed within the Spanish Biodiversity Foundation project of Adaptation in Doñana, implemented and coordinated by WWF-Spain.

Methodology

The interviews aimed to draw a broad outline of the case study's vulnerability based on the expertise and knowledge of local actors and develop a range of flexible adaptation options according to the local environmental, social and policy context.

The interview survey was conducted across different days in February 2012 and eleven key participants from relevant sectors of the coastal wetland were encouraged to give their input. The requirements for the participants' selection were: i) to be working on activities related to the rice production and the natural ecosystem during the last decade; ii) to have an extensive knowledge about the rice productive sector and to have regular contact with the rice farmers; ii) to have an extensive knowledge about the welfare of the wetland and the natural ecosystem functioning; and iii) to be informed on the water management requirements to cope successfully with the rice production and the natural ecosystem.

Interview Questions

Type of question	Selected interview question
Introduction	Q1: Name Q2: Background and experience in the region Q3: Employment status
Perception of climate change risks/impacts for the rice farming and the natural ecosystem	Q4: Do you feel that the Doñana socio-environmental system has changed due to climate variability or extreme events (droughts, heat waves, rainfall distributions) over the last 20 years? (E.g. severe droughts of 1979/80, 1991/95 or 2004/05)? Q5: Have you noticed changes in the yields or the growing cycle (shortening/ lengthening) of rice crops in the wetland? Q6: Have you noticed changes in the presence or occurrence of pests, weeds and diseases? Q7: Have you noticed changes in the management (e.g., operations, irrigation, use of fertilizers/sprays) of rice crops? Q8: Have you noticed river hydro morphological alterations or changes in the water availability and quality (e.g., salinity of water) in the region? Q9: Have you noticed changes in the distribution of natural vegetation and wildlife? Q10: What factor do you consider as the most harmful for the rice farming and the natural ecosystem in the region?
Perception of flexible adaptation options for the rice farming and the natural ecosystem	Q11: What measures have been implemented to tackle climate variability and climate change? Q12: What strategies have been implemented to ensure water availability? Q13: What importance do you consider that may have strategies to increase water savings? Q14: What adaptation options do you consider the most effective for the rice farming and the natural ecosystem in the region? Q15: What are the main drivers and tools to undertake these adaptation measures and strategies? Q16: What are the main barriers to the implementation of climate change adaptation options in the region?
Other comments	Q17: Are there any other issues that you consider important in relation to the climate change risks and adaptation which have not tried yet in this interview?

Appendix 2. Summary of the Responses of the Interviews

Identification of risks and adaptation options	Farmer association (5)	Administration (3)	Environmentalists (3)
Main risk for the artificial rice wetland	Decreased water availability	Decreased water availability	Decreased water availability
	Increased water salinity	Increased water salinity	Increased water salinity
	Higher temperatures	Higher temperatures	
		Reductions of water stored	
		Heavy rains and higher deposits appearance	
Most effective adaptation, overall	Changes of water management	Water saving	Energy and water savings
	Modernization of irrigation systems	Increased scientific research, field studies and transferring	Increased scientific research, field studies and farmers training
	Water recirculation and reutilization within the paddy	Improved coordination between institutions, aggregated of the information and dissemination	Strategies to conserve biodiversity and ensure the provision of ecosystem services
	New dams construction and other water infrastructures	Improved monitoring and information on water use	Regulations from WFD and the Hydrologic Plan of the Guadalquivir River Basin
		Reduction of the cultivated areas located closer to the sea	Long-term climate change strategies and agreements
		Increased the technical efficiency of the irrigation systems	Increased dissemination, public participation and environmental awareness raising
		Local climate change actions	Organic agriculture
		Dikes construction to contain marine intrusion	
Responsible for implementing adaptation	Administration; rice farming unions and cooperatives	Administration; Rice farming unions and cooperatives; Research groups to facilitate	Administration; Rice farming unions and cooperatives; Research groups to facilitate
Barriers to implement adaptation	The lack of clear actions	Rice farming conservative traditions	Rice farming conservative traditions
	Larger reductions of inputs (water, fertilizers, sprays)	The difficult for generational renewal and change due to aging farmers' population	The difficult for generational renewal and change due to aging farmers' population
	Marine intrusion during drought periods	Farmers' short-term perception of risks and profit-driven principles	Farmers' short-term perception of risks and profit-driven principles
	New CAP environmental requirements	The lack of interest of rice farmers in climate change issues and debates	The lack of interest of rice farmers in climate change issues and debates

	Energy prices	Easy crop management, all the operations are subcontracted	Low labour needs and high water comsuption
	Lower yields and quality crops	High subsidies dependence	The lack of environmental awareness
	Irrigation water costs	Clay soils, risks of floods	New CAP environmental requirements
	Extremely competitive and highly volatile price sector	The unstable equilibrium of the Doñana system	The lack of accurate irrigation water measures (flow meters)
Risks related to water scarcity	Water availability reductions	Water availability reductions	Water availability reductions
	Turbidity, muddy water	Turbidity, muddy water	Water stored reductions
	Cumulative impacts in the Guadalquivir River Basin affect the rice fields		Cumulative impacts in the Guadalquivir River Basin affect the rice fields
	Erosion problems		
Adaptation to increased water scarcity	Changes of water management	Changes of water management	Changes of water management
	Modernization of irrigation systems	Modernization of irrigation systems	Water saving strategies
	Water recirculation and reutilization within the paddy	Water recirculation and reutilization within the paddy	Water recirculation and reutilization within the paddy
	Laser levelling	Installation of flow meters	Modernization of irrigation systems avoiding new water infrastructures with environmental impact
	New dams construction and other water infrastructures		Efficient solutions for both the rice farming and the natural ecosystem
	Setting of irrigation turns		Long-term agreements on water and climate change management (water markets, water use allocation permits)
	Increased farmers training, technical advice and scientific information		Actions at the basin level leading flexible adaptation strategies to climate change
	New rice varieties adapted to water and heat stress		Regulations from WFD and the Hydrologic Plan of the Guadalquivir River Basin
	Installation of flow meters		
	Reduced energy costs		
Perception of the importance of water saving	High	High	High

Risk related to increased salinity	Increased soil salinity	Increased soil salinity	Increased soil salinity
	Increased salinity in the aquifer	Increased salinity in the aquifer	Increased salinity in the aquifer
			Biodiversity losses
Adaptation to increased salinity	Dam water releases upstream from the rice area	Dam water releases upstream from the rice area	Dam water releases upstream from the rice area
	Flooding irrigation systems to wash soils		Organic production (good farming practices)
	New pipeline to bring in the water directly upstream from the salt water intrusion		
Risk related to increased invasive species, pests and diseases	Ineffectiveness of current plant protection products		Biodiversity losses
Adaptation to increased invasive species, pests and diseases	Integrated production	Integrated production	Integrated production
Risk related to decreased rice productivity and quality	Reduction of the rice cultivated areas	Reduction of the rice cultivated areas	Reduction of the rice cultivated areas
	Lower income		
Adaptation to decreased productivity and quality	Changes of the management (integrated production)	Changes of the management (integrated production)	Changes of the management (integrated production)
	New longer cycle rice varieties (J-sendra de 155 or Puntal 145)	Improved commercialization	New varieties but not including those GMOs
	Modernization and innovative technical measures	Farmers training and environmental awareness raising	Farmers training and environmental awareness raising
			Improved the product processed to be exported (organic products)

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Risk-Based Assessment of Drought Mitigation Options: the Case of Syros Island, Greece

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Abstract Drought-related risk estimation is widely acknowledged as a tool towards enhancing drought preparedness and minimizing impacts on people, the economy and the environment. In this paper a method is proposed for the risk-based assessment and prioritisation of long-term drought mitigation options in order to support decision making for drought planning. The assessment combines water balance modelling, hazard analysis, and risk and cost effectiveness analysis. The proposed approach allows an improved understanding of drought-related risks by following a probabilistic analysis of drought impacts under different mitigation options. The method is applied in a drought-prone area with water scarcity problems, the Greek island of Syros. The assessment focuses on agriculture and domestic water use, the two main water using sectors in the island. Six mitigation options are cross-compared in terms of contribution to future drought risk reduction using three criteria: risk, vulnerability and benefit-cost ratio. The results validate the use of risk-based assessment of mitigation options as a valuable tool for improved drought management.

Keywords Drought risk · Vulnerability · Impact mitigation · Syros Island

1 Introduction

Drought management entails a series of actions and measures taken to assess drought hazard and mitigate its impacts on economic activities, the society and the environment. It includes four main components (UN/ISDR 2009): (i) policy development and governance, (ii) enhancement of drought awareness and knowledge, (iii) risk analysis, assessment and early warning, and (iv) selection of mitigation and preparedness measures. The overall procedure aims at introducing drought risk-related issues to stakeholders and

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decision makers and at selecting suitable options for minimizing drought impacts (Hayes et al. 2004; Rossi et al. 2008).

The shift from the traditional reactive management approach to the proactive, risk-based development of drought management plans has been fostered (Fontaine and Steinemann 2009; Rossi et al. 2007, 2008; Wilhite et al. 2000) as a means to support decision making for investing in drought mitigation (Wilhite et al. 2007). Risk, typically expressed as a function of hazard and vulnerability (UNDP 2011), serves as a measure of anticipated consequences and can indicate an improvement (or not) after the implementation of a mitigation option. In addition, traditional cost-benefit analysis could be used to support the selection of the appropriate measures (Dziegielewski 2003; Rossi et al. 2005).

Specifically in water supply systems, risk assessment includes an analysis of water demands that cannot be fully met due to drought and the estimation of associated impacts (Cubillo and Garrote 2008; Rossi and Cancelliere 2013). Risk management, referring to the processes and measures for dealing with drought and minimizing risk to an acceptable level, can be supported by simulation to assess the contribution of measures to impact mitigation (Karavitis 1999; Querner and van Lanen 2001). Simulations are performed for a long-term horizon, setting the current state as the initial conditions for the system (Cancelliere et al. 2009).

This paper presents an approach for the assessment of long-term mitigation options in water supply systems, using drought risk and vulnerability, in addition to cost-benefit analysis, as the evaluation criteria. The approach combines hazard analysis, water balance modelling and risk analysis to assess options for future drought risk reduction and enables the probabilistic estimation of losses. The method is illustrated through its application in Syros Island, Greece.

2 Risk-Based Assessment of Drought Mitigation Options

A process for the risk-based assessment of drought mitigation options is proposed, which involves three steps (Fig. 1), starting from future hazard analysis and concluding with a comparative analysis of potential mitigation options:

1. First step: Risk identification. Drought conditions are analysed in terms of magnitude (severity), duration and frequency (probability of occurrence and return period), on the basis of climate projections;
2. Second step: Risk assessment regarding anticipated impacts. Impacts are quantified in monetary terms, for the different drought severity levels, and then aggregated to estimate the total risk of economic losses;
3. Third step: Risk management, through measures for dealing with drought and minimizing risk to an acceptable level. Water balance modelling is used to assess the effect of measures on drought mitigation, whereas measures are compared and ranked on the basis of three criteria: risk, vulnerability and cost-benefit ratio.

2.1 Step 1: Drought Risk Identification

The Standardized Precipitation Index (SPI), introduced by McKee et al. (1993), is used for analysing future meteorological droughts. SPI is a generally accepted indicator (Stagge et al. 2015), commonly used for monitoring drought conditions (e.g. European Drought

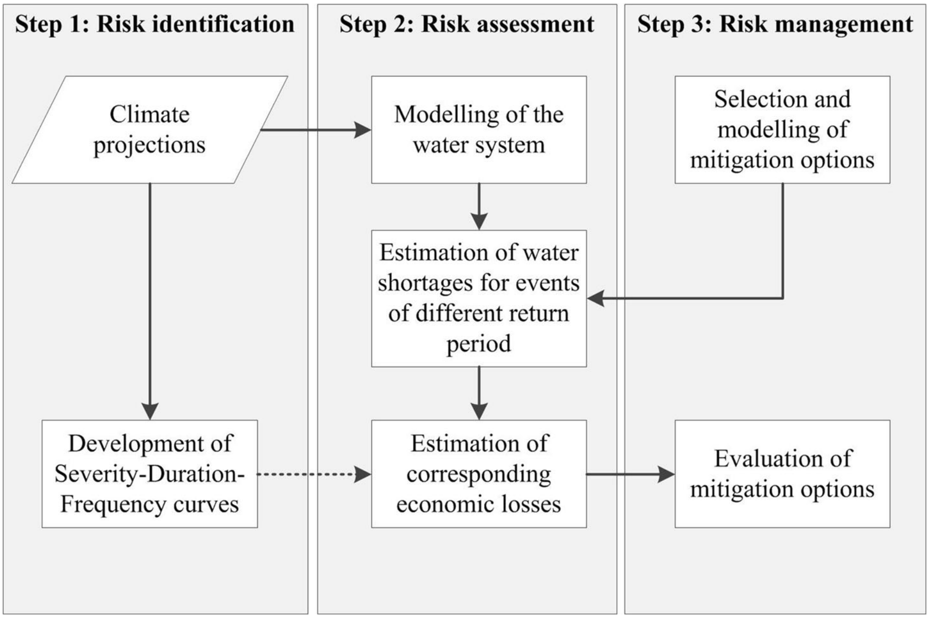

Fig. 1 The process for the risk-based assessment of drought mitigation options

Observatory, USA Drought monitor). Its wide applicability is attributed to (i) the limited data requirements (only precipitation data are required), (ii) the simplicity in its calculation (Hayes et al. 1999), and (iii) the ability to describe drought at different time scales (Tsakiris and Vangelis 2004; Mishra and Desai 2006; Cacciamani et al. 2007; Belayneh et al. 2014). A time series of future monthly SPI values is derived using precipitation data from climate projections, to assess future droughts and their properties using Severity-Duration-Frequency (SDF) curves. Negative SPI values describe drought conditions and the accumulative sum of these values defines severity. A statistical test is performed to find the probability density function that best represents the drought severity variable. Statistical information used in the subsequent steps is: (i) the return period of events of different duration, and (ii) the corresponding probability of occurrence.

2.2 Step 2: Risk Assessment

The analysis of the relationship between impacts and drought characteristics follows. The impact variable is selected according to the sector examined (Todisco et al. 2012), whereas its quantification is supported by water balance modelling to estimate water availability for each sector/activity. In this context the drought impacts can be expressed by the following generic formula:

$$\textit{Drought Economic Impact}_s = \mathrm{DEI}\left(\mathrm{DI}_{T,D}, Q_s, I_s\right) \tag{1}$$

Where: DI refers to the drought intensity of events of different return period T (yrs) and duration D (months); Q_s (m^3) corresponds to water availability (or deficit) estimated for the specific sector (s) from the water balance model; and I_s to any other parameters that specify the economic impacts of drought for the specific sector.

Several approaches have been developed for risk assessment (Pliefke et al. 2007); in this work, risk (R) is defined as the probability of occurrence of economic loss (Iglesias et al. 2009) and is expressed as a function of the probability (p) of occurrence of a drought event with a given return period and the economic losses associated with this event (Eq. 2):

$$R_D = \sum_T p_{D,T} \bullet DEI_{D,T} \tag{2}$$

Where: $p_{D,T}$ is the probability of occurrence of a drought event of a given return period and duration and $DEI_{D,T}$ (€) is the associated economic impact.

Impact studies are mainly focused on the agricultural sector (e.g. Li et al. 2009; Wu et al. 2004) and domestic water supply (e.g. Jinno 1995; Merabtene et al. 2002; Shahid and Behrawan 2008), which are mainly affected by droughts. The main direct drought impacts are crop yield reduction and water deficit respectively. An equation similar to Eq. 1 can be derived by analysing impacts without the application of any new mitigation options.

2.2.1 Economic Losses in Agriculture

Drought impacts in agriculture refer to the reduction of farm income due to crop yield reduction. The estimation of the yield of irrigated crops and effective rainfall is based on Smith and Steduto (2012) and the Hellenic Ministry of Development (2008) respectively:

$$\frac{y}{y_o} = 1 - k_y \bullet \left(1 - \frac{R' + U}{ET_m}\right) \tag{3}$$

$$R' = \max \left\{ \begin{array}{l} 0, \text{ if } R - \left(a + \frac{R}{8}\right) < 0 \\ R - \left(a + \frac{R}{8}\right) \end{array} \right\} \tag{4}$$

Where, y_o is the maximum crop yield for the area (t/ha), y the actual crop yield (t/ha), ET_m the actual evapontraspiration (mm) calculated as a function of potential evapotranspiration using the Blaney-Criddle method (Blaney and Criddle 1950, 1962; Papazafeiriou 1999), k_y the crop response factor, R' and R is the effective and actual rainfall (mm), respectively, U the water delivered for irrigation (output of water balance modelling, m^3) and a coefficient with values ranging from 10 (for lowland areas, close to the sea) to 20.

The economic losses in agriculture ($DEI_{a,DI}$) are defined as the difference between the net economic benefit for crop (c) yield averages and the actual yields under drought conditions, as in Eq. 5:

$$DEI_{a,DI} = \sum_c \Delta y_c \bullet AC_c \bullet PP_c \tag{5}$$

Where, Δy_c is the crop yield reduction due to drought compared to the long-term average of crop yield (t/ha), AC_c the crop area (ha; no change in cultivated area assumed) and PP_c the product price (€/t, no change in market prices assumed).

Total economic losses for the affected system can be estimated for different crops that are characterized by different crop response factors, k_y.

2.2.2 Economic Losses in Domestic Use

The domestic water deficit is estimated by the water balance model on the basis of background information for water consumption per capita, population in the region and water availability. The economic impacts of drought on the domestic sector ($DEI_{u,DI}$) are estimated on the basis of the cost of using an alternative water resource to cover the water deficit, as in Eq. 6:

$$DEI_{u,DI} = Q_u \bullet PW \tag{6}$$

Where, Q_u is the water deficit (m^3) and PW the price of alternative water resource of adequate quality (€/m^3, no change in prices assumed).

2.3 Step 3: Risk Management

The final step involves the assessment of drought mitigation options in terms of risk, vulnerability, and benefit to cost ratio. Risk is estimated for drought events of different return period, both for the baseline conditions (without mitigation) and the alternative states (with mitigation options).

Vulnerability is recognized as a complex concept with more than twenty-five definitions that explore methods for its systematic assessment (Birkmann 2006). In this work, vulnerability is expressed through the magnitude of losses and takes a value between zero (0) and one (1) indicating minimum to high vulnerability to drought, respectively (Tsakiris 2009). The following equation expresses the vulnerability of the system (V), after applying each mitigation option (the vulnerability of a system prior to the implementation of an option is assumed to be equal to 1):

$$V_{D,T,o} = \frac{DEI_{D,T,o}}{DEI_{D,T,b}} \tag{7}$$

Where, (o) refers to drought mitigation options and (b) refers to baseline conditions.

Benefit to cost (B/C) is defined as the ratio of risk reduction, due to the implementation of an option, and the associated cost of implementation, respectively to the lifetime of it, as given in Eq. 8:

$$B/C = \frac{\sum_D R_{T,b} - \sum_D R_{T,o}}{C_o} \tag{8}$$

3 The Case of Syros Island, Greece

3.1 Background Information

Syros Island is located in the Greek Cyclades complex (Fig. 2). It has a typical Mediterranean climate, with relatively low annual precipitation values. Based on 40 years of observation (1970–2010, Hellenic National Meteorological Service), mean annual precipitation is 293 mm, with very little to no precipitation during summer (4 % of annual precipitation occurs during June and September, long-term average), and mean annual potential evapotranspiration is 1675 mm (calculated using the Blaney-Criddle method). Total run-off is estimated at 3.7 hm^3/yr, whereas infiltration corresponds to 2.56 hm^3/yr (Hellenic Ministry of Development 2008) the majority of which is lost to the sea. The main economic activities in the island include agriculture, tourism, commerce and shipping. Syros faces water scarcity problems that mainly affect agriculture, as domestic water demand is mostly covered by desalination plants. The current desalination capacity equals 8340 m^3/day (thirteen reverse osmosis units with individual capacity ranging from 250 m^3/day to 2000 m^3/day) and the units operate on a daily basis using electrical energy, which is produced in the autonomous grid operated in the island by the local Public Power Corporation plant. Groundwater is primarily used for irrigation, and for domestic use only in some agglomerations, resulting into conflicts over groundwater use during drought periods.

Droughts are rather frequent (mainly mild, meteorological, events) in the Cyclades, corresponding to 45 % of the time for the period 1955–2005 (Tigkas 2008). The sectors mostly affected by drought in the past were agriculture and the urban sector, with significant water deficits. A crisis management approach has been followed so far, involving either restrictions in water supply or emergency water hauling from other areas and especially the Greek mainland. Traditional practices to cope with drought include water storage in cisterns (at the household and farm level), cultivation of local crop varieties that do not require water (e.g. melon, tomato), and land terracing as a means to reduce runoff.

The proposed methodology was implemented in Syros Island, to examine the contribution of long-term mitigation options to drought risk reduction. The aim was to analyse drought risk due to climate (change) conditions and the implementation of alternative mitigation measures, given that there is no change in the socio-economic system (i.e. population size, water use per capita, total cultivated area, crop pattern). The emphasis is on the proposed step-wise framework for assessing drought mitigation measures and not on the analysis of climate change and its effects on sectoral aspects, such as for example crop growing season or productivity. In this regard, results are illustrative of the process followed and its outcomes and should be considered with caution regarding the uncertainty involved in climate projections and future socio-economic conditions.

3.2 Results

The analysis for Syros Island covers the 2011–2050 period, with 2011 representing the baseline state for Syros. A water balance model was set up for the island, using the Water Evaluation and Planning (WEAP) software tool developed by the Stockholm Environment Institute (SEI). The model was based on the work undertaken by the Ministry of Development (2008) for developing a water management study for the island. The model was updated after consultation with local stakeholders to better represent water demand and supply nodes, their links, and their current status. Climate projections (output of the HIRHAM5 model forced by the ECHAM5 GCM for the A1B IPCC scenario) from the EU FP7 WASSERMed project (Pizzigalli et al. 2011) were used to assess drought conditions, water demand and availability in the future. Data for setting the water balance model were provided by the Hellenic Statistical Authority (2007 agricultural census, population census for 2001 and 2011, tourism statistics for the period 2005–2010), the water management study of the Hellenic Ministry of Development (e.g. per capita consumption, irrigation efficiency), the Municipal Enterprise of Water Supply and Sewerage of Syros (e.g. network losses, desalination capacity), Local Farmer

Fig. 2 Location of Syros Island, Greece

Associations (e.g. water demand for irrigation, demand coverage from water stored in cisterns), and Mpezes (2001; capacity of groundwater bodies).

For each Step of the analysis, indicative results are presented.

3.2.1 Drought Risk Identification

The SPI-12 index was calculated for the 2011–2050 period (Fig. 3a). Drought duration, in this work, is defined as the consecutive months with SPI-12 negative values, whereas the corresponding severity (magnitude) was the sum of the SPI-12 values for the whole drought duration. Events were classified according to their duration into five classes (1, 2, 11–13, 20–24, >25 months), to distinguish between short and prolonged events. Severity-duration-frequency (SDF) curves were developed to estimate the return period of drought events of different severity. A statistical test was performed to select the probability function that best fits the SPI data and the Gumbel Max distribution was found to be the best for the drought frequency analysis (Fig. 3b), in line with the results from similar analyses for Greece (Dalezios et al. 2000). The corresponding probability of occurrence was estimated at 28 %, 17 %, 22 %, 22 % and 11 % respectively for each one of the above duration classes. Dry spells of up to 2 months and events of 1 to 2 years duration show almost the same probability of occurrence.

3.2.2 Drought Risk Assessment

Impacts were estimated for the agricultural and domestic sectors using Eq. 3 to 6. The estimation of economic losses in agriculture was based on the existing crop pattern, classified into arable crops, vegetables, citrus, olives and grapes. The total cultivated area was assumed constant in the time period of analysis, as well as product prices, in order to examine only drought effects on water availability for irrigation and thus crop productivity. The values of crop-related parameters were obtained from the FAO Irrigation and Drainage Paper no. 66 (Smith and Steduto 2012). For the urban sector, desalination was considered to be the alternative water source for covering water deficit.

Economic losses in agriculture and the domestic sector were calculated for each drought event of given duration and return period. Figure 4 presents an example of total estimated monetary losses (sum for the two sectors) in Syros for the baseline case (no mitigation actions), due to future drought events of more than 1 year duration (accounting for almost 50 % of drought events). No economic losses were estimated for drought events of 1 month duration, whereas the losses for 2 months duration are relatively low compared to those estimated for prolonged drought events (<10 % of losses of events of the same return period and longer

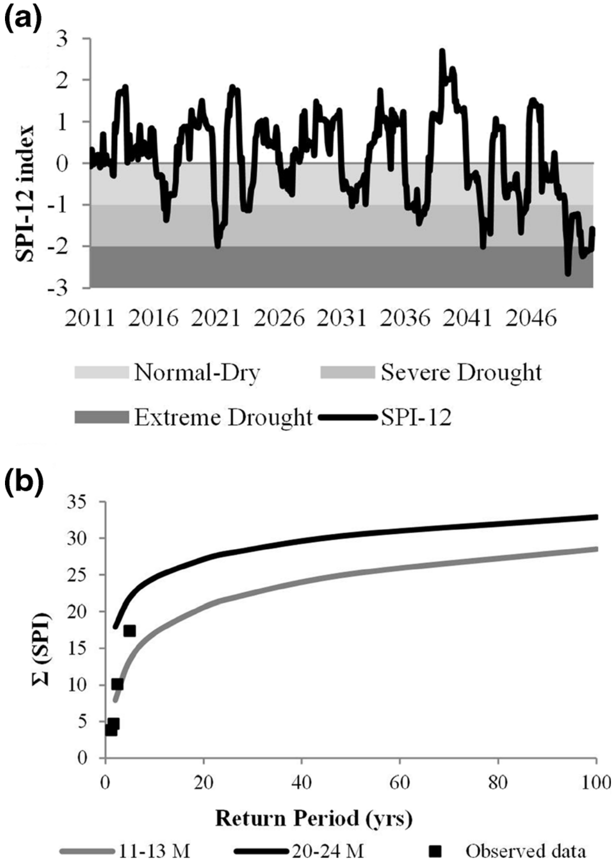

Fig. 3 **a** SPI-12 for the period 2011–2050, **b** SDF for events of one and 2 years duration

duration). Economic losses in the domestic sector account for 2 to 9 % of total losses, indicating that emphasis should be placed on mitigating impacts on the agricultural sector.

3.2.3 Drought Risk Management in Syros

Modelled drought mitigation options include: (i) Rainwater harvesting in cisterns for domestic use (up to 10 % coverage of demand), (ii) Rainwater harvesting in cisterns for irrigation (up to 25 % coverage of demand), (iii) Direct wastewater reuse for irrigation, (iv) Increase of desalination capacity to meet peak water demand, (v) Artificial aquifer recharge (wastewater reuse for groundwater recharge), and (vi) Crop substitution to more drought resilient ones (e.g. soya). For each option, the water delivered for irrigation and the deficit of the domestic use, as estimated by the water balance model, were used for calculating economic losses during drought (Fig. 5). All options contribute to the reduction of total economic losses as a result of increased water availability, with rainwater harvesting having the lowest contribution, and crop substitution the highest. Water storage in cisterns cannot support mitigation, particularly during prolonged events, as cisterns cannot be (re)filled. Even though the increase of desalination capacity increases water availability in the urban sector, significant water deficits are still estimated by the water balance model for agriculture (which is mainly supplied with groundwater) and consequently total economic losses remain high. Wastewater reuse also appears to be an effective option in mitigating drought impacts, particularly in the agricultural sector. Direct reuse has a higher effect on minimizing losses, as all the available reclaimed water is directly used for irrigation. On the contrary, in the case of aquifer recharge, a portion of the volume stored in groundwater reservoirs is also used by the domestic sector and its availability is restricted by the extraction rates of the existing drills.

On the basis of estimated economic losses for each mitigation option, total risk (Fig. 6) and vulnerability (Fig. 7) are significantly reduced for five out of six options. Given that risk

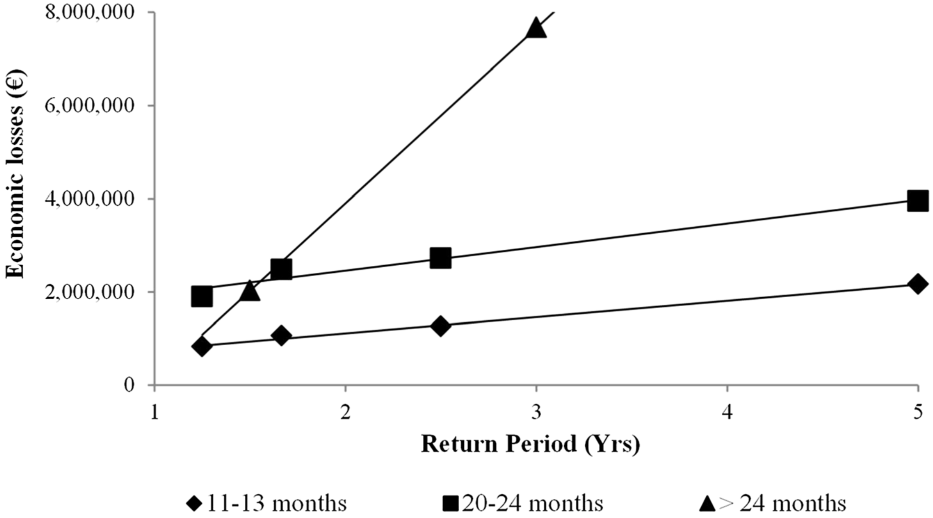

Fig. 4 Economic losses for a drought event of over 1 year duration as a function of return period (agriculture and domestic sectors)

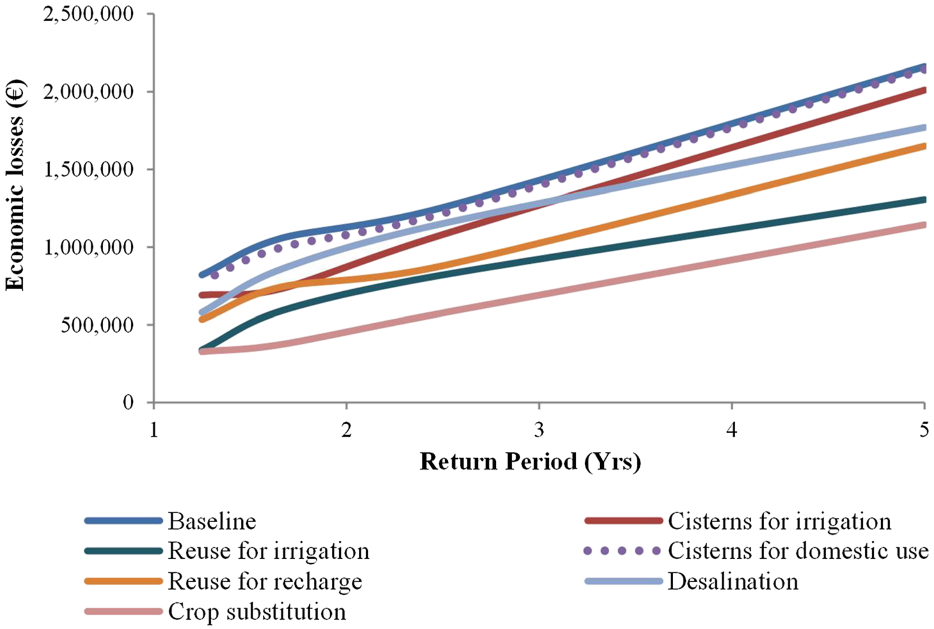

Fig. 5 Economic losses for a drought event of 1 year duration as a function of return period (agriculture and domestic sectors) with and without the implementation of mitigation options

expresses the probability of occurrence of economic losses, the contribution of each option to the reduction of risk in Fig. 6 follows the same pattern as in Fig. 5. Table 1 presents the contribution of options in risk and vulnerability reduction in the domestic and agricultural

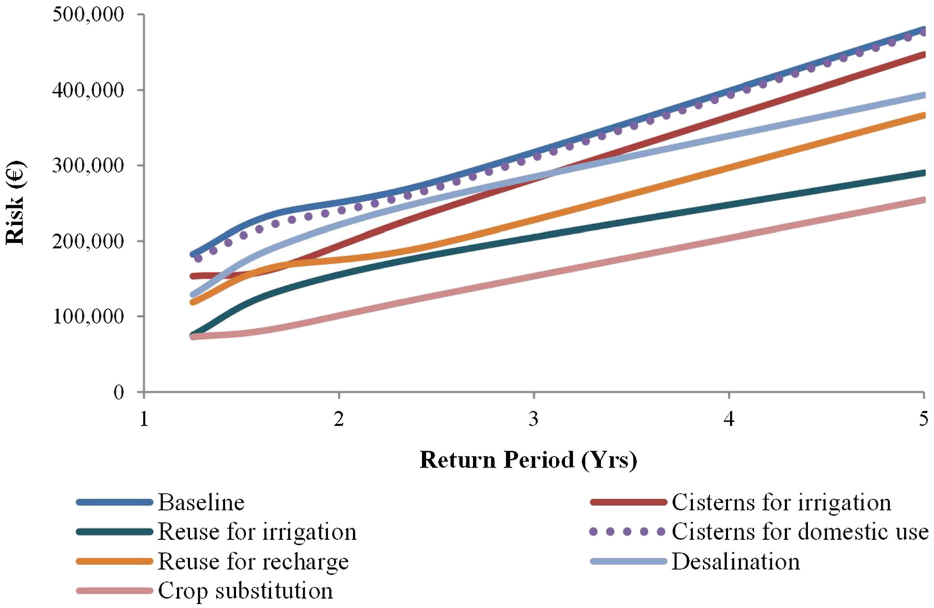

Fig. 6 Risk estimated for a drought event of 1 year duration as a function of return period

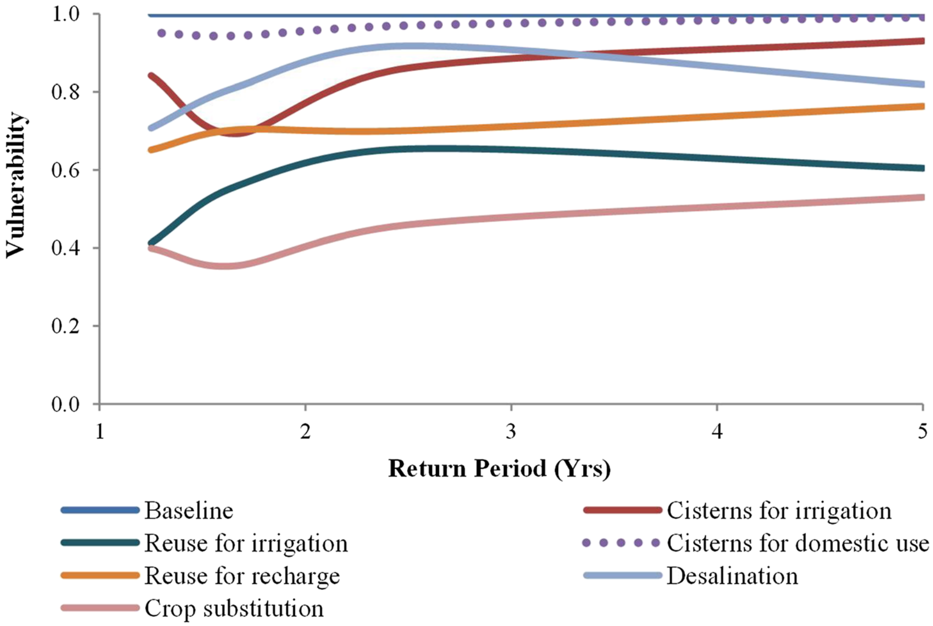

Fig. 7 Vulnerability estimated for a drought event of 1 year duration as a function of return period

sectors separately. Direct wastewater reuse for irrigation reduces risk and vulnerability both in agriculture and domestic sector (Table 1), as water irrigation needs are fully met, the demand for groundwater is reduced and there is more water available for domestic use (for those agglomerations in the island supplied with water from groundwater sources). Increase of desalination capacity to meet water demand also eliminates water deficit in the urban sector and thus significantly reduces vulnerability to drought. Crop substitution appears to be the best option for agriculture, as the cultivation of more drought resilient crop minimizes economic losses. Considering total risk and vulnerability, crop substitution and direct wastewater reuse are the two options that minimize impacts.

Table 1 Cross-comparison of options for a drought event of 5 years return period

Option	Risk of losses (M€)		Vulnerability		Capital cost	
	Agriculture	Domestic use	Agriculture	Domestic use	€/m^3	Annualised (€; 40 years depreciation period & 5 % rate)
Baseline (no options)	0.45	0.02	1.00	1.00	–	–
Cisterns for irrigation	0.42	0.02	0.93	1.00	100	323,444
Reuse for irrigation	0.29	0.00	0.63	0.00	935	61,432
Cisterns for domestic use	0.45	0.02	0.99	0.94	100	79,841
Reuse for groundwater recharge	0.35	0.02	0.76	0.81	1168	94,722
Desalination	0.39	0.00	0.86	0.00	1100	32,956
Crop substitution	0.24	0.01	0.52	0.64	–	2,158,281

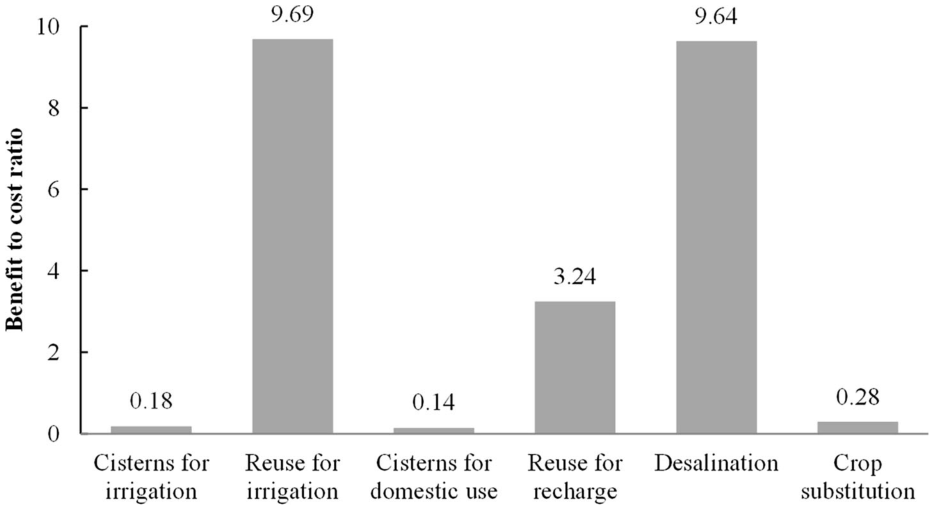

Fig. 8 Benefit to cost ratio for each drought mitigation option

The B/C ratio (Fig. 8), for the options examined, was estimated considering the total risk of all possible drought events with a 5-year return period, not just the events with 11–13 months duration. Cost (Table 1) involves the implementation costs of each option (capital and O&M costs), with the exception of the crop substitution option, in which case cost corresponds to the net economic output foregone by the farmers (permanent crop substitution assumed). The unit cost for investment, operation and maintenance of wastewater reuse facilities was obtained from the study of Gonzalez-Serrano et al. (2005). The options with higher benefit to cost ratio are wastewater reuse for irrigation and increase of desalination plant capacity. Even though crop substitution is estimated to be the best option in minimizing losses in case of drought, the annual cost for farmers as a result of the permanent change in crops (from current crop pattern to more drought resilient crops) is extremely high and thus this option has a very low B/C ratio. Reuse for recharge is estimated also to have a low B/C ratio, as the implementation cost and the drought-related economic losses are higher than those of direct reuse. Low-cost options, such as rainwater harvesting, do not significantly minimize total risk and vulnerability and thus can only be used as supplementary to other drought mitigation options, supporting mitigation in drought events of low duration (<2 months).

4 Summary and Conclusions

The proposed framework addresses the evaluation and selection of long-term drought mitigation options using a risk-based approach. As socio-economic damages from drought cannot be accurately forecasted, the estimation of risk can support decision making for long-term preparedness, particularly under the framework of uncertainty related to climate projections. The process encompasses drought hazard analysis, drought impact assessment and risk management, and provides an objective tool for the comparison and evaluation of options, facilitating drought management efforts.

SPI has been selected due to its usefulness for planning and decision-making and limited data requirements. However, the approach is straightforward and other drought (single or composite) indices can be used instead to better represent either drought intensity in a region or drought impacts on a specific sector (e.g. agriculture). The same also applies for the estimation of other parameters. Depending primarily on data availability, more sophisticated (or data intensive) methods can be applied for estimating for example irrigation-related parameters (e.g. evapotranspiration, effective rainfall). In this work, it was selected to illustrate the methodology using easily applicable calculation methods, in order to stress that risk-based assessments can still be performed in cases with limited data availability.

Results have been illustrated for the case of events of a 5-year return period. Similar analysis for events of different return periods provides the range of future drought-related risks. The contribution of each option to the mitigation of impacts and risk reduction could thus be assessed for alternative "drought conditions", and drought planning could be oriented towards minimizing total risk or risk associated to drought events of specific characteristics. In addition, the assessment of total and sectoral risks could guide individual mitigation efforts along with the overall drought planning.

Risk and vulnerability are by definition interrelated concepts and therefore provide the same results in terms of option ranking. The use of an additional economic criterion in the analysis (benefit to cost ratio) enhances the selection process. However, further criteria should be used to account for the social-related component of drought management, as the social acceptability of an option could affect its adoption or rejection. In addition, the acceptable level of drought risk is a social and political decision that reflects region-specific priorities and values.

For the case of Syros Island, results from hazard analysis show that drought episodes with duration longer than 1 year account for almost 50 % of events. Emphasis should thus be placed on managing prolonged events through the appropriate mix of short-term and long-term measures. However, a similar analysis is recommended (i) using climate projections from other models and IPCC scenarios, to deal with uncertainty in climate projections and have a more complete view of the anticipated future drought conditions, and (ii) incorporating scenario analysis to account for social characteristics (e.g. population growth) and sectoral development policies. Furthermore, the analysis indicated that a long-term strategy for drought-risk reduction should consider wastewater reuse. The Joint Ministerial Decree 145116/11 (GG B' 354/2011) sets the standards, measures and processes for wastewater reuse and could guide a more detailed analysis of the reuse potential in Syros.

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How Subsurface Water Technologies (SWT) can Provide Robust, Effective, and Cost-Efficient Solutions for Freshwater Management in Coastal Zones

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Abstract Freshwater resources in coastal zones are limited while demands are high, resulting in problems like seasonal water shortage, overexploitation of freshwater aquifers, and seawater intrusion. Three subsurface water technologies (SWT) that can provide robust, effective, and cost-efficient solutions to manage freshwater resources in the subsurface are evaluated using groundwater modelling and validation at field-scale: (1) ASR-coastal to store freshwater surpluses in confined brackish-saline aquifers for recovery in times of demand, (2) the Freshkeeper to counteract salinization of well fields by interception and desalination of upconing brackish groundwater, and (3) the Freshmaker to combine ASR and Freshkeeper to enlarge the volume of natural freshwater lenses for later abstraction. The evaluation indicates that SWT can be used in various hydrogeological settings for various hydrogeological problems like seawater intrusion, upconing, and bubble drift during ASR and have significant economic benefits. Although only sporadically applied to date, we foresee that SWT will stimulate (cost-)efficient and sustainable exploitation of various freshwater sources (like groundwater, rainwater, treated waste water, surface water) in coastal zones. Prolonged SWT testing in the current pilots, replication of SWT in other areas worldwide, and the development of technical and non-technical support tools are required to facilitate potential end-users in investment decision making and SWT implementation.

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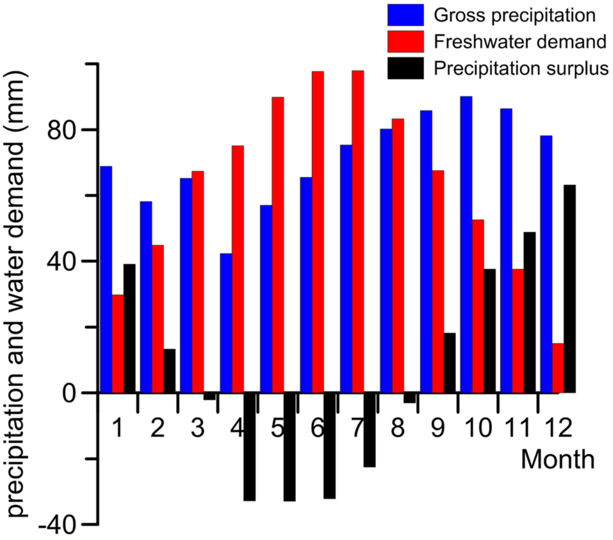
Keywords Aquifer storage and recovery · Coastal aquifers · Freshwater · Salinization · Seasonal water shortage · Subsurface water technologies

1 Introduction

Coastal zones are the most densely populated, productive, and economically dominant regions of the world. About half of the world's population lives within 200 km of a coastline (United Nations 2010), and while this produces many economic benefits, the associated high water demand puts tremendous pressure on the freshwater resources and the coastal ecosystems. This leads to problems like seasonal water shortage (Fig. 1), overexploitation of groundwater resources, saltwater intrusion, and disappearance of wetlands. Further economic growth, population increase, and climate change will intensify these problems, ultimately blocking the sustainable development of coastal zones in industrial, emerging, and developing countries (European Commission 2012). In 2015, water crises were identified as the main global risk in terms of impact (World Economic Forum 2015).

Traditionally, aboveground solutions are sought for these problems, such as construction of reservoirs or saltwater desalination. However, the subsurface may provide more robust, effective, sustainable, and cost-efficient freshwater management solutions due to a better water conservation and limited space requirements aboveground. For instance, the concept of subsurface storage and/or treatment known as managed aquifer recharge (MAR) is increasingly applied worldwide for water storage and treatment (Dillon et al. 2010). In coastal zones, however, the abstraction of (stored) freshwater is generally hampered by saline groundwater, causing early salinization of simple abstraction wells due to buoyancy effects and upconing (Oude Essink 2001; Ward et al. 2009). This makes traditional well configurations vulnerable to salinization and thus application of MAR often inefficient. The same holds for exploitation of fresh groundwater lenses formed by natural recharge, which is difficult due to upconing of

Fig. 1 Illustration of average freshwater availability and demand in a coastal area: mean gross monthly precipitation (1980–2010), estimated monthly water demand of an intensive greenhouse horticulture area (Greenport Westland-Oostland) in the Province of Zuid-Holland in The Netherlands (Paalman et al. 2012), and resulting freshwater surplus/deficit. Source: Zuurbier et al. (2013)



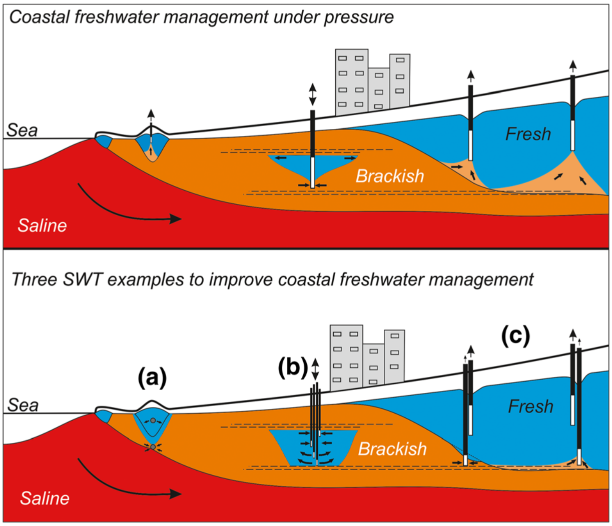


Fig. 2 Three examples of subsurface water technologies to overcome common freshwater issues in coastal aquifers, field-tested in the last 5 years. **a** = Freshmaker (horizontal wells to infiltrate in and recover from shallow freshwater lenses), **b** = ASR-coastal (deep injection, shallow recovery in brackish aquifers), **c** = Freshkeeper (interception of upconing brackish groundwater)

deeper saltwater (Fig. 2). The challenge is, therefore, to optimize the management of natural freshwater sources in the subsurface for drinking and irrigation water, thereby creating a valuable ecosystem service in coastal zones.

In the past decade, a set of practical tools and concepts that may have the ability to improve freshwater management in coastal-zone aquifers was proposed to solve irrigation and drinking water shortages in The Netherlands. The common feature of these subsurface water technologies (SWT) is to protect, enlarge, and utilize fresh groundwater resources in coastal zones through advanced groundwater management (Fig. 2). Sophisticated and dedicated new well designs, configurations, and management strategies were designed to obtain maximum control over the water resources, and go far beyond the levels of control provided by standard water management techniques. The aim of this study is to report and evaluate the efficiency of three SWT examples (summarized in Table 1) recently applied in the Netherlands, and explore their potential for solving typical freshwater management problems in other coastal zones worldwide. In a first step, the most relevant outcomes of three recently extensively studied SWT

Table 1 Typical characteristics of the different subsurface water technologies (SWT) discussed

SWT	Aim	Target conditions	Artificial recharge	Saltwater interception	Well type	Water treatment
ASR-coastal	Temporal storage	Brackish aquifers	yes	no	MPPW	Pre-treatment
Freshkeeper	Protect wellfields	Stratified groundwater quality	no	yes	PP, MPPW	Optional post-treatment
Freshmaker	Temporal storage	Freshwater lenses	yes	yes	HDDW	Pre-treatment

MPPW multiple partially penetrating wells; *PP* partially penetrating well; *HDDW* horizontal directional drilled well examples for freshwater management were presented. Secondly, common freshwater management problems in coastal areas were identified in scientific literature. Finally, the ability of SWT to counteract these typical coastal freshwater management problems was analysed and discussed.

2 Materials and Methods

2.1 Field-Testing of Subsurface Water Technologies (SWT)

2.1.1 ASR-Coastal

Aquifer storage and recovery (ASR) of freshwater using wells in coastal zones may not recover sufficient freshwater to meet the demands due to the mentioned losses by buoyancy effects. With ASR-coastal, multiple partially penetrating wells in a single borehole (MPPW, Fig. 3) are introduced, enabling injection at the base of the aquifer and recovery at the top. An ASR-coastal system with MPPW was successfully applied in a Dutch coastal greenhouse horticulture area (Nootdorp, Province of Zuid-Holland, 12 km from the North Sea coast) and reported by Zuurbier et al. (2014). Here, a brackish (chloride concentration: 150–1100 mg/l) aquifer at 13–41 m below sea level and confined by clay layers was targeted for ASR. The operation of the ASR system, the injected and recovered water quality, and the water quality changes in the aquifer were extensively monitored (Fig. 4) to provide the data to set up a calibrated, density-dependent groundwater transport model (SEAWAT; Langevin et al. 2007) and use this to compare the performance of this advanced configuration with a 'conventional' ASR configuration (Zuurbier et al. 2014). The ASR-system was monitored from January 2012 untill September 2013.

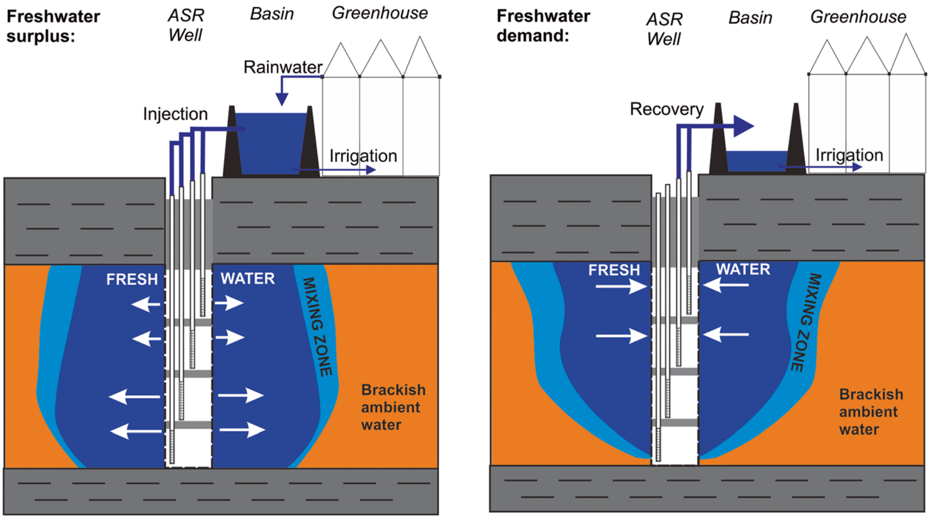


Fig. 3 Use of multiple partially penetrating wells (MPPW) for improvement of freshwater recovery of coastal ASR systems storing rainwater harvested from greenhouse roofs

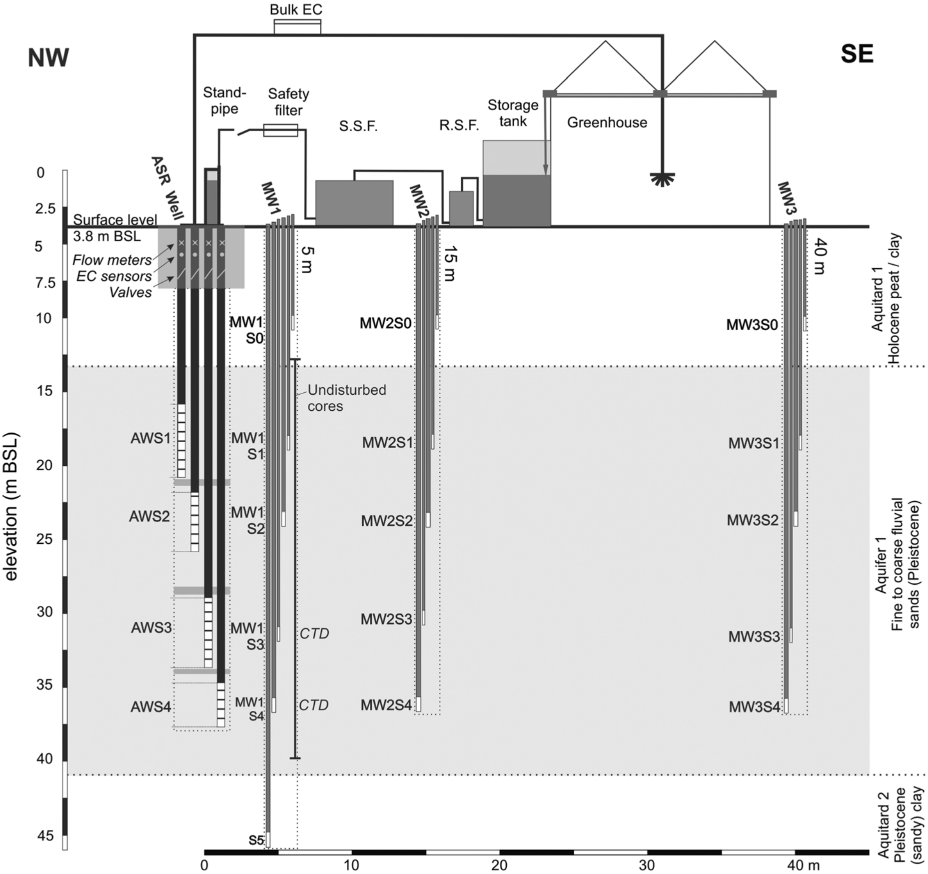


Fig. 4 Cross-section of the Nootdorp ASR system as presented in Zuurbier et al. (2014). Water from the greenhouse is first pre-treated by rapid sand filtration (R.S.F.) and slow sand filtration (S.S.F) and then injected mainly by deeper wells in the aquifer, whereas recovery occurs from the shallow wells

2.1.2 Freshkeeper

The Freshkeeper (Fig. 5) aims to safeguard the water supply from abstraction wells at risk of salinization. The concept follows a three-step approach: (1) intercept upconing brackish groundwater by abstracting freshwater from the top of the aquifer, while pumping intruding brackish water from the lower part of the aquifer; (2) use the intercepted brackish water as an additional water source by desalination through reverse osmosis; and (3) dispose of the RO membrane concentrate by deep-well injection into a confined, more saline aquifer. This 3-way approach was successfully applied in a pilot conducted at the Noardburgum well field (Province of Friesland, The Netherlands) by Vitens Water Supply (Oosterhof et al. 2013), at a well field that was abandoned in 1993 because of salinization. Shallow fresh and deeper brackish groundwater were extracted within a multiple partially penetrating well equipped with two separate well screens, at a rate of 50 m^3/h each. The focus of this pilot was on the management of the freshwater-brackish water interface and the injectivity of the RO-concentrate.

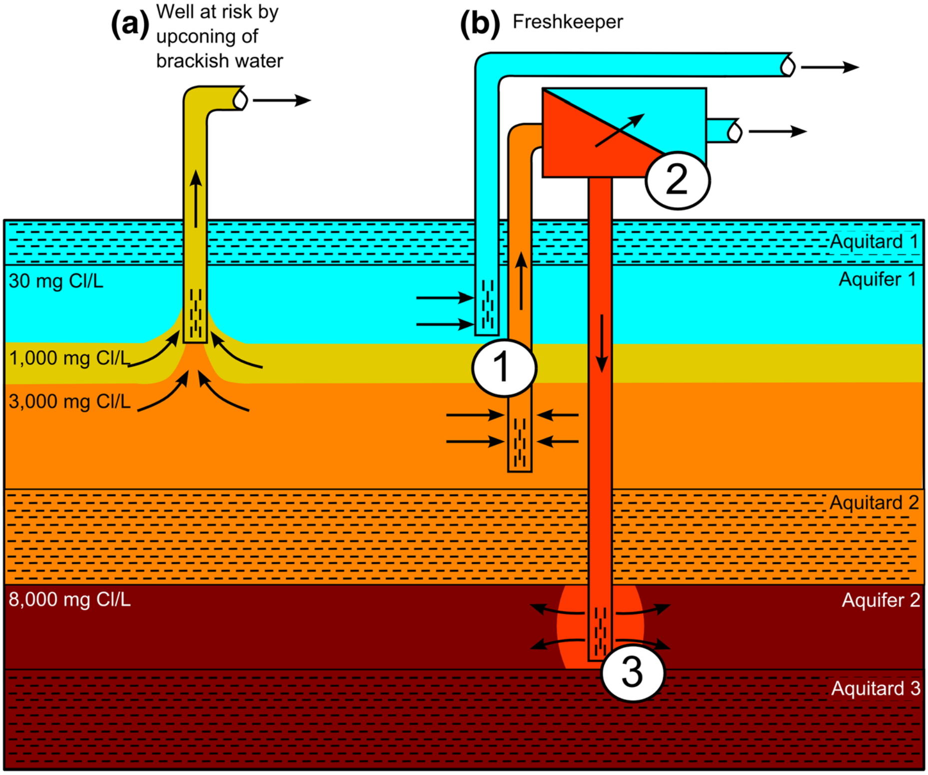


Fig. 5 Water well prone to salinization (**a**) and the Freshkeeper solution (**b**)

2.1.3 Freshmaker

It was reasoned that ASR-coastal is inefficient when target aquifers are shallow, saline, and unconfined because of severe buoyancy effects and the risk of unwanted hydrological effects. The Freshmaker technology therefore combines the ASR and Freshkeeper concepts with the use of recently developed horizontal directional drilled wells (HDDWs; Cirkel et al. 2010). With this HDDW-technology, long horizontal wells can be installed at any desired depth in shallow coastal aquifers. The horizontal wells allow for the depth-controlled injection and recovery of large volumes of freshwater and was named the ‘Freshmaker’. A shallow HDDW (the actual ‘ASR well’) is used for artificial recharge and recovery of freshwater surpluses, while buoyancy effects and upconing of saline water are prevented by the use of a deep interception HDDW (Fig. 6). The injected freshwater enlarges the natural freshwater lens along the HDDWs in periods with a freshwater surplus, and this stored water is available for recovery in periods of demand. The first Freshmaker was installed in 2013 in the coastal Province of Zeeland to supply a local fruit grower with irrigation water in Ovezande. Its efficiency was evaluated by 2-D groundwater transport modelling (using SEAWAT) and subsequently using geophysical field measurements (EM-39 borehole logging; McNeill et al. 1990), EC-sensors, and hydrochemical analyses during operation of the Ovezande field pilot. For more information on the modelling approach, the reader is referred to Zuurbier et al. (2015).

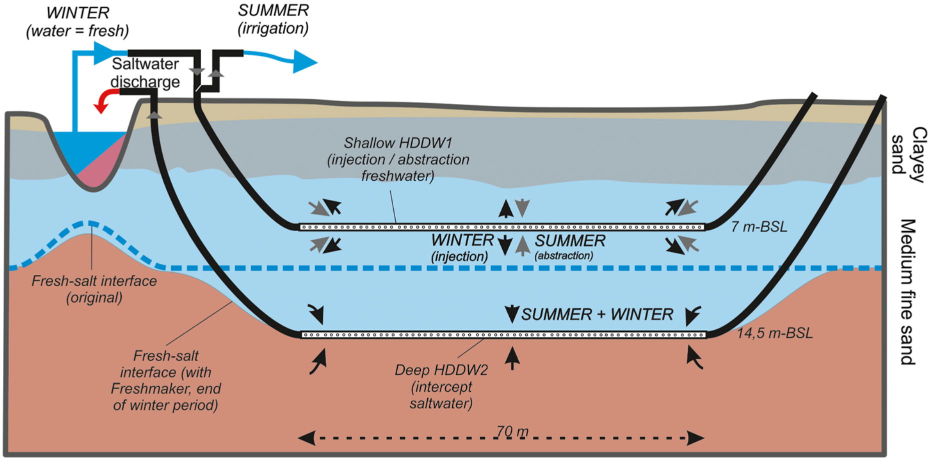


Fig. 6 Use of the Freshmaker principle to enlarge freshwater lenses. Side-view at the HDDWs. Set-up as installed at the Ovezande field-trial. m-BSL = meters below sea-level

2.2 Broader Evaluation of the Efficiency of Subsurface Water Technologies (SWT) to Improve Freshwater Management

In order to explore the (broader) applicability of SWT for freshwater management in coastal zones, its efficiency to solve five common hydrogeological problems in these areas was assessed:

- *Brackish water upconing* (Reilly and Goodman 1987): resorting from shallow abstraction from a stratified aquifer (i.e., freshwater overlying brackish/saline water);
- *Seawater intrusion* (*SWI;* Werner et al. (2013): 'the landward incursion of seawater' via the subsurface;
- *Bubble drift during aquifer storage and recovery* (Ward et al. 2009): 'injected freshwater trying to "float" upwards through the aquifer while the denser native groundwater sinks down and inwards, contaminating the well at the bottom';
- *Thin target aquifer for abstraction / storage*: this may imply a low yield per well, requiring placement of expensive well galleries with many wells and pumps;
- *Saline seepage in deep polder areas* (de Louw et al. 2010): with ongoing land subsidence, sea-level rise, and occasionally (former) peat excavations, saline seepage is a increasing problem in delta areas as it causes salinization of inland surface waters.

3 Results

3.1 Field-Testing of Subsurface Water Technologies (SWT)

3.1.1 ASR-Coastal

The Nootdorp field trial obtained satisfying results, with more than 40 % of the injected freshwater (13,700 m^3) recovered practically unmixed in the first cycle in 2012. A calibrated SEAWAT model was able to reproduce this performance, and predicted even better performance in subsequent cycles, with recovery efficiencies approaching almost 60 % (Fig. 7). This proved to be more than sufficient to guarantee freshwater availability for the greenhouse, even during long periods of drought. Alternatively, without the advanced MPPW set-up, less than 20 % was found recoverable by conventional ASR wells, according to the SEAWAT model (Zuurbier et al. 2014), which would have led to frequent freshwater shortages throughout the summer season. Compared to a situation without buoyancy effects, however, the recovery will always be lower as the formation of a stable, protecting mixing zone is absent in the lower half of the aquifer. The estimated cost price for water supplied by this ASR concept is 0.17 to 1.58 €/m^3 (Zuurbier et al. 2012), depending on the scale and recovery efficiency achieved. This makes the concept competitive with less-sustainable, alternative water sources in the area (drinking water, desalinated water: ~1 €/m^3).

3.1.2 Freshkeeper

At the Noardburgum field site, the abstracted freshwater as well as the brackish abstraction water freshened upon dual zone Freshkeeper abstraction. Chloride concentrations of the abstracted fresh and brackish water decreased in the first months of the pilot, from 45 to 35 and 1000 to 600 mg/L, respectively. Freshening not only occurred in the near surrounding of the abstracting well screens, but also in observation wells at greater distance (Fig. 8). Only the observation well screen just above the confining clay layer did not show any freshening; chloride concentrations remained stable there due to the lateral inflow of brackish groundwater.

While the goal was to stabilize the fresh-brackish water interface, the chosen operation (fresh and brackish water abstraction rates of 50 m^3/h) even provoked downconing of brackish water, which was confirmed by SEAWAT modelling (Van der Valk 2011). In the same study,

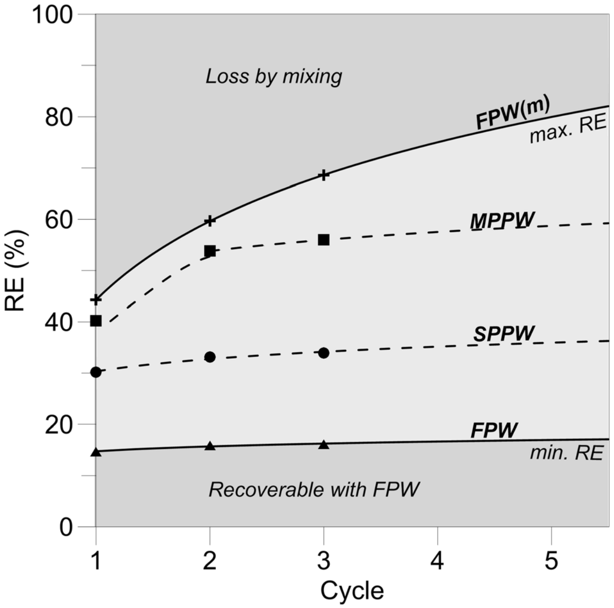


Fig. 7 Modelled RE per cycle versus cycle number for four scenarios. FPW (m) = scenario with only mixing and a fully penetrating ASR well, but no buoyancy. The other scenarios take into account mixing, seepage, and buoyancy for multiple partially penetrating wells (MPPW), a single partially penetrating well in the upper half of the aquifer (SPPW), and a fully penetrating well (FPW). Cycles 1-3 were modelled, cycle 4 and 5 were extrapolated from the modelled cycles. Data from: Zuurbier et al. (2014)

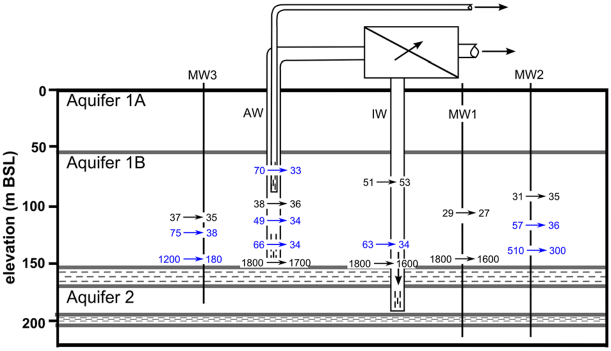


Fig. 8 Changes in chloride concentrations (in mg/l) in the source aquifer, after 8 months of simultaneous abstraction of fresh and brackish groundwater. In blue: freshening; in black: no change in chloride. AW = dual zone Freshkeeper abstraction well; IW = RO concentrate injection well; MW = monitoring well. m BSL = meters below sea-level

SEAWAT modelling suggested that the brackish water abstraction rate can be lowered to 16 m^3/h to keep chloride concentrations in the abstracted freshwater well constant at 45 mg/L.

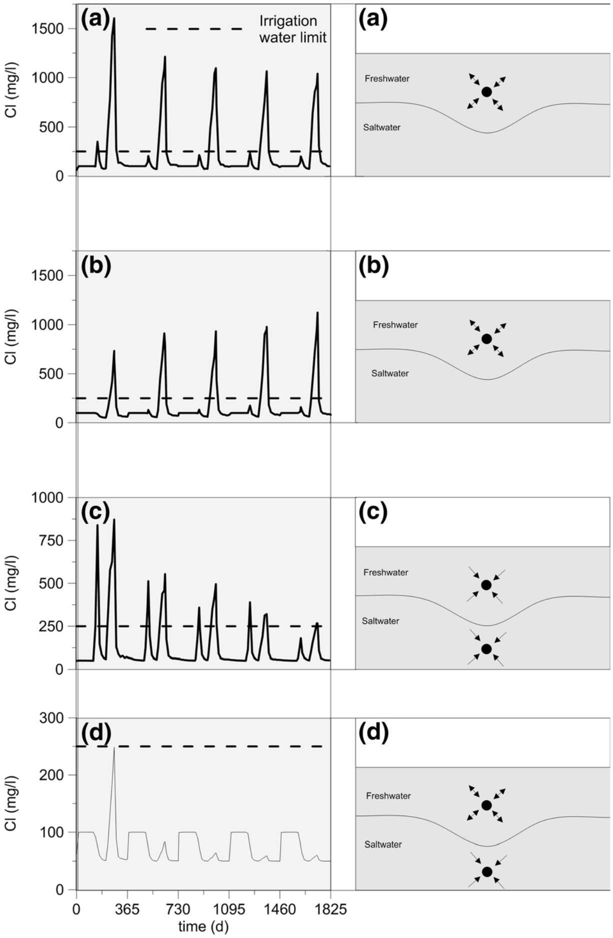
A reverse osmosis recovery level of 70 % was attained, which was accompanied by a waste stream of 30 % containing the dissolved solids from the brackish groundwater and requiring re-injection. Although anti-scalants were not applied in the brackish water desalination process, clogging was not observed during injection of the RO concentrate in a deeper, unconsolidated, sandy aquifer. Production of calcite precipitates was not observed, which was explained by the high iron(II) levels in the feed water, inhibiting calcite precipitation (Wolthek et al. 2012). In a parallel concentrate injection experiment conducted at Zevenbergen, the Netherlands (Brabant Water Water Supply), calcite precipitation caused injection well clogging, which was later prevented by dosing CO_2 to the concentrate.

Following the successful pilot, Vitens Water Supply sees opportunities to apply the Freshkeeper at full-scale and to reopen the abandoned well field. A circular setup of six Freshkeeper wells appears to be the most effective in preventing salinization of the wells and of the central part of the well field (Van der Valk 2011). In this study, the fresh to brackish abstraction ratio was more than 3:1, i.e. for every 3 m^3 of fresh water less than 1 m^3 of brackish water needs to be abstracted. Using a RO recovery of 50 %, this would result in a yearly, sustainable production of 3 Mm^3 of drinking water (abstracted fresh water and RO permeate), while 0.43 Mm^3 concentrate is to be disposed of by deep-well injection (Oosterhof et al. 2013).

3.1.3 Freshmaker

Model Results SEAWAT modelling results suggest that the modelled Freshmaker at Ovezande should be able to keep the targeted freshwater volume of 4200 m^3 available for abstraction during at least 6 months (Zuurbier et al. 2015). In the simulation, the deepest HDDW was actively intercepting saline groundwater to lower and stabilize the freshwater-saltwater interface. The modelled chloride concentrations in the abstracted water at the shallowest HDDW (HDDW1), used for injection and recovery of freshwater, indicated that injected surface water will be abstracted in spring. Abstracted water will be mainly native groundwater from the natural freshwater lens in late summers, which is mixed with upconing saltwater at the end of Cycle 1 (Fig. 9; Scenario D). In Cycle 2–5 this simulated upconing was limited and did not impose a

Fig. 9 Modelled chloride concentrations at the upper HDDW for upon yearly injection and abstraction of 4500 m^3 of freshwater without the interception of saline groundwater by a deep HDDW (**a**), same as (**a**), but after 1 year without recovery (**b**), with interception of deep saline groundwater but without injection (**c**), and with a complete Freshmaker (**d**). Source: Zuurbier et al. (2015)



risk for the salinity of the abstracted water. The simulation results show the upper part of the aquifer will gradually freshen, which will result in a decrease in saline seepage towards a local water course and eventually even local infiltration via the water course during freshwater recovery.

Significantly less freshwater was found to be attainable when only a shallow single HDDW is used (Scenario A), even when excessive infiltration was applied to form a ‘buffer zone’ of unrecovered infiltration water (Scenario B). The maximum chloride concentration for irrigation water would be exceeded after abstraction of a volume which was ~50 % of the injected volume. When a Freshmaker was installed, but no water was injected (like a Freshkeeper, Scenario C), a satisfying volume of freshwater could be abstracted from Cycle 5 onwards, due to the almost continuous interception of saltwater by the deep HDDW (HDDW2). This indicates that active injection of freshwater at this location (having a natural recharge of approximately 0.75 mm/d) is not a requirement for the abstraction of a same volume of freshwater, and that continuous interception of saltwater preceding freshwater abstraction can be sufficient.

Field Results The Freshmaker Ovezande field pilot is being executed since 2013. In Cycle 1 (June – September 2013), 1700 m^3 was injected and a same freshwater volume was successfully abstracted. In Cycle 2 (November 2013 – September 2014) 4450 m^3 was injected, and 4.400 m^3 of freshwater was abstracted by September 2014. The geophysical EM-39 measurements show that the Freshmaker indeed enlarged the freshwater lens during injection (3 to 4 m, Fig. 10), kept the freshwater at its place during storage (Cycle 1 and 2), and is able to recover a freshwater volume equal to the injected volume. The estimated cost-price for the water supplied by the Freshmaker is 0.35 €/m^3, which is less than the local alternative (piped water: 0.70 €/m^3).

3.2 Broader Evaluation of the Efficiency of Subsurface Water Technologies (SWT) to Improve Freshwater Management

Based on the outcomes and insights of the SWT field and modelling studies, the applicability of SWT to solve common hydrogeological problems and improve freshwater supply in coastal zones was evaluated. The outcomes are summarized in Table 2 and discussed below.

- *Brackish water upconing*: this process can be delayed by ASR-coastal, but full elimination cannot be guaranteed as upconing may still occur during recovery, especially when storage periods are long and deeper water is saline, which is similar to scenario A and B of the Freshmaker in Section 3.1.3. When brackish water is not desalinated or discharged from the groundwater system but only re-injected, upconing may also still threaten shallow abstraction wells in the Freshkeeper case, as recently demonstrated by Alam and Olsthoorn (2014). The Freshkeeper and Freshmaker in their presented form (injecting membrane concentrate in a deeper confined aquifer or discharging abstracted saltwater to sea) can sufficiently eliminate upconing, as demonstrated by field monitoring (Section 3.1.2) and model scenarios C and D (Section 4.1.3). For both the Freshkeeper and Freshmaker it is

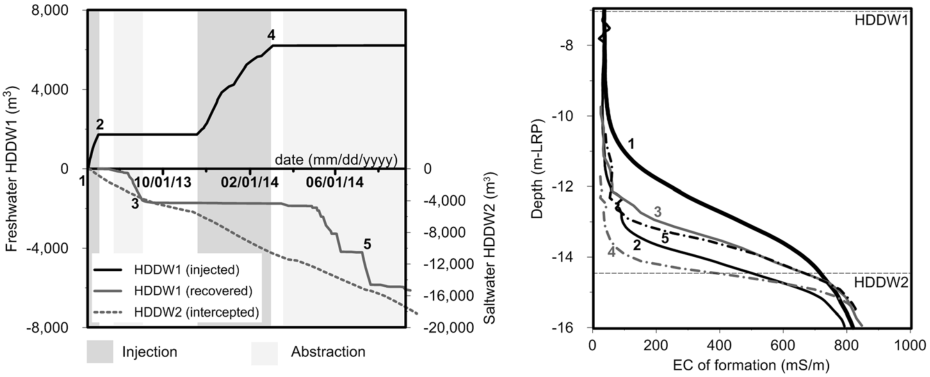


Fig. 10 Pumping by the Freshmaker (positive = injection, negative = abstraction). Changes in the electrical conductivity of the formation in the target aquifer measured by EM-39 demonstrating freshening (EC decrease) and salinization (EC increase) at the centre of the Freshmaker (halfway the HDDW well screens). Black arrows indicate the shift of the freshwater-saltwater interface over time. *m-LRP* = meters below local reference point, which is at approximately 0.4 m above sea-level. *Numbers* 1–5 indicate the moments at which EM-39 recordings were performed

Table 2 Evaluation of the efficiency of SWT concepts to counteract common hydrogeological problems

Hydrological problem	ASR-coastal	Freshkeeper	Freshmaker
Brackish water upconing	+/-	+	+
Seawater intrusion	+/-	+	+
Bubble drift during ASR	+/-	+/-	+
Thin target aquifer for abstraction / storage	-	-	+
Saline seepage	+/-	+	+

+: Counteracting the hydrological problem

+/-: May counteract when boundary conditions are met

-: No positive effect, or even negative effect

required that freshwater abstraction rates and saltwater interception rates are coupled: overabstraction of freshwater during limited interception of saltwater will result in upconing;

- *Seawater intrusion*: ASR-coastal may only prevent saltwater intrusion if the net injection exceeds the saltwater intrusion, making it a freshwater hydraulic barrier (e.g. Luyun et al. 2011; Mahesha 1996), with deep injection at the optimal aquifer interval (Abarca et al. 2006). One may expect, however, that the Freshkeeper and the Freshmaker can even prevent saltwater intrusion, provided that the well placement and their abstraction rates are such that the entire intruding saltwater wedge is intercepted and disposed of or desalinated. This was confirmed using density-dependent transport modelling in combination with an optimization model (Abd-Elhamid and Javadi 2011), which indicated that coupled interception and abstraction (ADR: abstraction, desalination, recharge) can then be considered most (cost-) efficient;
- *Bubble drift during aquifer storage and recovery*: ASR-coastal can reduce the freshwater during ASR, but it was shown by Zuurbier et al. (2014) that it will not lead to 100 % recovery of injected freshwater. Like for conventional ASR: the more saline the aquifer is, the lower the recovery efficiency will be. A Freshkeeper may help to recover a larger part of injected freshwater during ASR, but will also not make the system render 100 % recovery of injected freshwater (Van Ginkel et al. 2014). The Freshmaker concept appeared able to recover a volume equal to the injected freshwater volume in a saline environment (without depleting the natural freshwater lens), given that an existing freshwater lens is enlarged and natural recharge is occurring;
- *Thin target aquifer for abstraction / storage*: ASR-coastal and the Freshkeeper will be hard to apply in thin aquifers. However, the use of HDDWs in the Freshmaker case may make thin aquifers viable for abstraction/storage, since a single, high-capacity well is feasible. Approriate design of the HDDW (length, diameter, pumping rates, amongst others) is however crucial to attain a uniform distribution of the abstraction along the HDDW screen (Sun and Zhan 2006; Wang et al. 2014). At the Freshmaker trial, this was ensured by the relatively limited length of the HDDWs (70 m) and confirmed by the observed lowering of the freshwater-saltwater interface along full length the wells;
- *Saline seepage in deep polders*: ASR-coastal may freshen the diffusive seepage component sourced by shallow groundwater in the upper aquifer, but is less effective in counteracting seepage of deeper, saline groundwater via boils, which can be the largest salt contributor in polder areas (de Louw et al. 2010). The Freshkeeper concept was

previously suggested as a suitable technique to counteract saline seepage (Olsthoorn 2008; Stuyfzand and Raat 2010), although it was considered unviable when all abstracted water is directly re-injected in deeper aquifers (De Louw et al. 2007) because of hydrological effects in the surrounding areas and the required high pumping rates. This underlines that disposal or concentration of the abstracted brackish water is desirable. The Freshmaker can decrease the saline seepage in polder areas based on the modelling performed for the Ovezande field pilot (Section 3.1.3). The current set-up does not contribute to a reduction in salt load to the local surface water system, as the intercepted saltwater is disposed of at a local water course here,. Disposal of intercepted brackish-saline groundwater and membrane concentrate is therefore expected to be a key element in coastal freshwater management.

4 Discussion: Current State of Subsurface Water Technologies (SWT)

4.1 The Efficiency and Economics of the Demonstrated SWT

The presented subsurface water technologies (SWT) highlight a recent trend in hydrological engineering driven by new drilling techniques, water treatment, and automation of water supply facilities using sophisticated programming and sensors. The SWT-examples (ASR-coastal, Freshkeeper, and Freshmaker) show that despite the increasing complexity, these technologies can realize a significant increase in freshwater availability in coastal areas for a competitive cost price.

SWT will not fully overcome all the mentioned hydrological problems in all coastal zones, but can generally improve freshwater production, or as found in this study: a reduction of freshwater losses during storage of several tens of percents or the complete prevention of freshwater upconing. This has economical relevance. For instance, the greenhouse owner's water demand at the Nootdorp ASR-coastal field site requires an average recovery efficiency of approximately 40 % of the injected water. It was demonstrated that this was not feasible with a conventional ASR well (<20 %) or a shallow partially penetrating well (<35 %). The use of a MPPW at this site (with only minor additional costs for PVC pipelines, standpipes, and valves) boosted the freshwater recovery up to more than the owner's demand (55 %). Instead of investing in more expensive and less sustainable freshwater sources (in this case: desalinated or piped water), there is now a valuable freshwater surplus that can be sold to neighbouring companies with a higher demand.

In the case of the Freshkeeper (Noardburgum) an entire well field was closed and replaced following salinization in 1993. SEAWAT modelling scenarios suggest that installation of only six Freshkeeper wells in a circular set-up is sufficient to prevent salinization of the entire well-field in future (Oosterhof et al. 2013; Van der Valk 2011). Since Vitens Water Supply was looking for additional drinking water in this region, this is a cost-reducing outcome. A recent study has shown the potentials of Freshkeeper to abate salinization problems in Florida (USA), and to guarantee the long-term drinking water supply there (Ross et al. 2014). In the Florida case, a Freshkeeper was found economically much more feasible than alternative water supply options such as full-scale brackish water reverse osmosis. The exact economic benefits of SWT for other cases may vary and likewise for normal MAR-techniques, they are often hard to assess a priori due to feasibility uncertainties and the chance of under-performance (Arshad et al. 2014; Maliva 2014). However, the SWT ability to counteract reductions in freshwater production resulting from unsuitable aquifer conditions will mitigate the increase of operational expenditures, potentially compensating for higher capital expenditures.

4.2 Other SWT Examples

SWT are not limited to the field test examples presented in this paper. For instance, Van Ginkel et al. (2014) proposed an elegant concept to store freshwater in an Egyptian saline aquifer by combining freshwater storage with saltwater abstraction from below the injected freshwater, which has similarities with and can further improve the ASR-coastal concept. Alam and Olsthoorn (2014) proposed to discharge a part of the intercepted brackish water by deep Punjab scavenger wells to achieve a net freshening effect (comparable to elements of both the Freshkeeper and the Freshmaker). In 2013, the Baton Rouge Water Co. (U.S.A.) has installed a brackish water scavenger well that, similar to the Noardburgum Freshkeeper, should prevent brackish water upconing to the overlying freshwater production wells. The pumped brackish water is disposed of to the Mississippi river (Tsai 2011). Olsthoorn (2008) and Stuyfzand and Raat (2010) proposed a Freshkeeper at a polder scale, using the abstracted brackish water for drinking water production and simultaneously solving various environmental problems caused by upward seepage of nutrient-rich brackish groundwater at the same time. However, no Freshkeeper is currently operating for this purpose.

4.3 Wider Scope of Application

The SWT development and studies mentioned above suggest that although the field-tested SWT are all situated in the Netherlands, they potentially have a much wider scope of application. This is underlined by the evaluation of the SWT in this study, which shows SWT can be used to reduce or overcome very common hydrological problems in coastal zones, which are amplified by an expected exacerbation of saltwater intrusion in coastal zones by sea-level rise and changes in both recharge and evaporation due to global climate change (Oude Essink et al. 2010), which will require a more enhanced management of coastal aquifers (Werner et al. 2013). SWT fulfills the demand for more advanced management tools to deal with coastal groundwater salinization and the demand for increased freshwater storage.

Elements of the SWT discussed in this paper may also be combined. For instance, a Freshkeeper was recently added to a new field ASR-coastal system to protect shallow recovery wells and produced additional freshwater via RO-treatment. In this field pilot, clogging of the RO-membranes is monitored with large interest, since these receive a feedwater, which is a mixture of infiltrated fresh, oxic rainwater with saline, anoxic groundwater. In general, abstracted water quality is a relevant aspect when RO-treatment is involved in SWT since the chemical and physical (suspended fines, temperature) quality of water used for RO, which is abstracted close to the freshwater–saltwater transitions may vary significantly over time due to freshening, salinization, and changes in redox conditions, especially upon artificial infiltration of fresh, oxic water. Membrane selection and prevention of membrane clogging are, therefore, critical aspects when desalination via RO is incorporated in the selected SWT.

It should be noted that all current SWT examples are being tested in sandy aquifers in The Netherlands, which are dominated by intergranular flow. However, limestone aquifers are also frequently found in coastal zones, and are targeted for freshwater supply worldwide. Transport processes may differ significantly in such aquifers due to dual-porosity (Bibby

1981). This can lead to underperforming ASR-systems due to early salinization via preferential flow paths (e.g., Maliva and Missimer 2010; Missimer et al. 2002; Pyne 2005). In the same way, this may reduce the effectiveness of SWT, since flow patterns are less predictable and preferential flow paths may hamper for instance the interception of brackish-saline water by the Freshkeeper and the Freshmaker.

Disposal of concentrate produced upon desalination as applied in the Freshkeeper example may be another obstacle, as this is often not allowed on surface waters or sewage systems. Re-injection in deeper aquifers on the other hand may induce (local) groundwater salinization and is therefore under discussion. Important prerequisites for this disposal are often the salinity of the receiving aquifer and the required separation of abstraction and injection well screens by aquitards because local salinization and short-circuiting must be prevented. Since desalination in combination with deep disposal of concentrate does not directly add an additional salt mass to the groundwater system, it may be more relevant to evaluate the regional consequences of this net abstraction of H_2O from the groundwater body. A key question is then if this net abstraction is compensated by either intrusion of more saline groundwater (negative) or by recharge of freshwater (naturally or artificially). The latter is often the case when inland brackish or saline groundwater originates from former transgressions in coastal zones that are currently recharged by freshwater, while seawater intrusion is generally limited to areas close to the shore.

4.4 The Future of SWT

SWT provide a coupled solution of a natural ecosystem service with a technological approach that allows for an enhanced protection and utilization of the freshwater resources in coastal areas. The SWT described in this paper have all been developed within public-private partnerships of innovators in the water market. SWT are gaining more-and-more interest from early adopters in the Netherlands. Following the pilot described in this paper, authorities in western Netherlands now consider ASR-Coastal as an important tool serving their regional water governance, and are stimulating greenhouse owners to increase their water self-supportiveness by applying this technique. Recently, a group of farmers in southwest Netherlands have inquired for a Freshmaker feasibility study to improve the irrigation water supply in their orchards. Vitens Water Supply in the North of the country just started a follow-up Freshkeeper pilot study that should be the final step towards full-scale application in the near future.

Despite the growing interest for SWT, further uptake inside and outside The Netherlands is slowed down by a number of non-technical barriers, including a lack of: (1) demonstration of long-term viability, (2) an analysis of their hydrological effects in their surroundings, (3) knowledge of new technologies and the ability to construct and operate them, (4) capabilities upon making investment decisions, and (5) inherent conservatism due to a lacking *local* track-record of successful implementation of SWT. As a consequence, more expensive and potentially unsustainable but proven technologies are chosen for freshwater management, such as seawater desalination or restrictions on water delivery. We plea for prolonged SWT testing in the current pilots, replication of SWT pilots in other areas worldwide, and the development of technical and non-technical support tools that can facilitate potential end-users in investment decision making and SWT implementation. Such an approach will accelerate acceptance and implementation of subsurface water technologies as robust answers to freshwater resources challenges in coastal areas.

5 Conclusions

Balancing freshwater availability and demand is a major challenge in especially coastal areas. Subsurface water technologies (SWT) have transformed from idea to proven-technology in the past decade to better manage subsurface freshwater volumes. Both groundwater transport modelling and extensive field operation and monitoring of three SWT examples (ASR-coastal, Freshkeeper, Freshmaker) underline that SWT can be used to protect, enlarge, and utilize fresh groundwater resources in coastal zones for use in times of demand. For this reason, coastal aquifers that have been considered to be or have become unsuitable for freshwater supply or storage have thus become ‘instruments’ for coastal freshwater management. Local natural freshwater sources such as rainwater can be utilized this way without claiming large areas aboveground and reduce the need for other less sustainable sources of freshwater. SWT can also combine innovations in drilling techniques, information and communications technology (ICT) and online sensoring, and water treatment to counteract very common coastal hydrological problems like saltwater upconing, seawater intrusion, and ASR bubble drift. SWT is not necessarily a freshwater management panacea for every hydrogeological setting, but the required (increase of) water supply may become technically and economically feasibile by SWT. Prolonged SWT testing in the current pilots, replication of SWT in other areas worldwide, and the development of technical and non-technical support tools are required to facilitate potential end-users in investment decision making and SWT implementation. Such an approach will accelerate acceptance of subsurface water technologies as robust answers to freshwater management challenges in coastal zones.

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Fresh Water Lens Persistence and Root Zone Salinization Hazard Under Temperate Climate

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Abstract In low lying deltaic areas in temperate climates, groundwater can be brackish to saline at shallow depth, even with a yearly rainfall excess. For primary production in horticulture, agriculture, and terrestrial nature areas, the fresh water availability may be restricted to so-called fresh water lenses: relatively thin pockets of fresh groundwater floating on top of saline groundwater. The persistence of such fresh water lenses, as well as the quantity and quality of surface water is expected to be under pressure due to climate change, as summer droughts may intensify in North-West Europe. Better understanding through modelling of these fresh water resources may help anticipate the impact of salinity on primary production. We use a simple model to determine in which circumstances fresh water lenses may disappear during summer droughts, as that could give rise to enhanced root zone salinity. With a more involved combination of expert judgement and numerical simulations, it is possible to give an appraisal of the hazard that fresh water lenses disappear for the Dutch coastal regions. For such situations, we derive an analytical tool for anticipating the resulting salinization of the root zone, which agrees well with numerical simulations. The provided tools give a basis to quantify which lenses are in hazard of disappearing periodically, as well as an impression in which coastal areas this hazard is largest. Accordingly, these results and the followed procedure may assist water management decisions and prioritization strategies leading to a secure/robust fresh water supply on a national to regional scale.

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Keywords Salinity · Simple model · Fresh water lens · Root zone salinization

1 Introduction

Soil and groundwater salinity have long been recognized as major problems for crop production worldwide (Maas and Hoffman 1977; Tanji and Kielen 2002; Rozema and Flowers 2008). Whereas it may be most pressing in semi-arid regions (Allison (1964) mentions one third of agricultural land in arid and semi-arid regions), in temperate regions, salinity may cause problems as well (De Louw et al. 2013; Vandenbohede et al. 2014). Commonly, this is due to elevated salinity by seawater intrusion via groundwater or surface water, but it may also be significant by salt spray near the coast or by de-icing roads (Thunqvist 2004). Due to climate change, the area that may be salt affected can increase. For temperate regions, particularly more frequent droughts may enhance salt stress in the growing season (KNMI 2014).

Plants exposed to elevated salinity may experience different forms of stress. Due to the high osmotic value of saline solutions, soil water may become less available for plants to accommodate their transpiration and primary production (de Wit 1958; Maas and Hoffman 1977) in a similar way as drought. However, it is also well known that salts (e.g. involving Na^+, Cl^-) may be toxic for plants, or that toxic components such as boron (B) and selenium (Se) become more bio-available under saline conditions. In addition, induced nutrient deficiency has been well documented, e.g. for iron and nitrate (Schinas and Rowell 1977; Grattan and Grieve 1992). Salt tolerance has been investigated much for agricultural crops, both in field and greenhouse conditions, and particularly for the case that salts enter the root zone. Different plant species have different salt tolerances and strategies to deal with salinity (Parida and Das 2005; Munns and Tester 2008).

Because of the long awareness of the impact of salinity on primary production, research of salt affected soils has a long tradition. Two main routes for salts entering the root zone are (i) capillary rise from brackish to saline groundwater leading to primary salinization, and (ii) salt spray and irrigation causing secondary salinization (Szabolcs 1989). For the case of secondary salinization, an important model concept has been developed, called the Leaching Requirement (Richards et al. 1954) and that is aimed at preventing too large salt concentrations in the root zone.

For temperate regions, where annual precipitation is usually sufficient for plant transpiration demands, infiltrating water can meet upward seeping groundwater, if the soil surface is close to the drainage level. In that case, the so-called fresh water lenses that develop on top of brackish or saline groundwater in coastal areas may become rather thin (Eeman et al. 2011; De Louw et al. 2011). If these lenses temporarily disappear in summer, this may lead to saline capillary rise water, that salinizes the root zone.

Avoiding, mitigating or adapting to the adverse effects of groundwater salinity is possible if we recognize in which cases salts accumulate in the root zone. In this paper, we consider the hazard of root zone salinization due to depletion of fresh water lenses, as in that case, capillary rise of saline water to the root zone commences. We provide relatively simple tools that differ with respect to their data demand, to appraise this hazard.

2 Fresh Water Lens Persistence

In low lying regions with shallow saline groundwater, such as in deltaic areas or small islands, saline water may enter the root zone due to capillary upward flow of groundwater. In case the annual rainfall is sufficient, precious fresh water lenses may develop preventing the underlying saline groundwater to reach the root zone via capillary rise. Experimental evidence of fresh water lenses on saline groundwater has been provided for different continents, e.g. De Louw et al. (2011), Fetter (1972), Underwood et al. (1992), even for inland areas of Australia (Jolly et al. 1998; Cendón et al. 2010), Oman (Young et al. 2004) and Hungary (Szabolcs 1989; Toth 2008). Whether or not a fresh water lens protects primary production from salt induced yield depressions will depend on the persistence of such lenses in temperate climates in the dry season (often summer).

Fresh water lenses resemble large fresh water volumes in coastal dune areas (Martinez and Psuty 2008) and analytical solutions have been found for different assumptions regarding e.g. the outflow zone at the dunes' perifery, or whether or not the salt underlying water is flowing, assuming a sharp fresh/salt interface (Badon-Ghijben 1888; Herzberg 1901; Van Der Veer 1977; Maas 2007). Investigating fresh water lenses in low-lying flat coastal regions, Eeman et al. (2011) revealed that the analytical solution provided by Maas (2007) is in close agreement with their numerical modelling using the model SUTRA-3D. The solution of Maas is given by:

$$\sqrt{\frac{Z^2}{(L^2+Z^2)}} = \left[-\frac{S}{P} + \sqrt{\left(\frac{S}{P}\right)^2 + 4\left(1+\frac{S}{P}+R\right)}\right] \Big/ \left[2\left(1+\frac{S}{P}+R\right)\right] \qquad (1)$$

where S is upward seepage rate [LT^{-1}], P is mean net precipitation or infiltration rate [LT^{-1}], R is the Rayleigh number ($R=\kappa g\Delta\rho/(\mu P)$ with intrinsic permeability κ [L^2], gravity acceleration g [LT^{-2}], density difference $\Delta\rho$ [$\mathrm{M/L}^3$], and dynamic viscosity μ [$\mathrm{ML}^{-1}\mathrm{T}^{-1}$], L is the half spacing [L] between two drains or ditches, i.e., the distance from drain or ditch to hydrological divide, and Z is the largest thickness of the lens at the hydrological divide. For such a lens, the volume V_M [L^3] is equal to

$$V_M = \frac{1}{4}\pi LZ \qquad (2)$$

The impact for upward seepage S in (1) is a crucial one, as it is a major force that counters the development of a full Badon-Ghijben-Herzberg (BGH) lens that complies with Archimedes' law. Especially this occurs for low lying areas in e.g. delta regions, as in Dutch polders (De Louw et al. 2011, 2013) or the Po delta, Italy (Vandenbohede et al. 2014). In the absence of such seepage, other (simpler) solutions are available that are outside the scope of this paper, as here we are focusing on lowland areas with upward saline seepage rather than coastal dunes, where groundwater flow is predominantly downward and BGH lens thicknesses of tens of meters can develop.

For the case that the groundwater densities of the lens and the underlying groundwater are equal, the solution follows directly from (1) by setting the Rayleigh number equal to zero, giving for the right hand side $(1+S/P)^{-1}$. Such a situation is often found in topographically higher areas with upwelling fresh groundwater as in stream valleys (Cirkel et al. 2014). Then, lens thickness thicker than those for sea water salinity circumstances are found. From (1), we then obtain for any value of R, an expression for Z:

$$Z = \surd\left(L^2\left[\frac{F^2}{1-F^2}\right]\right);\ F = \left\{-m + \sqrt{m^2+4r}\right\}/2r;\ m = \frac{S}{P};\ r = 1+m+R \qquad (3)$$

Impressions of lens properties are given for different parameter combinations in Fig. 1 for a seepage/recharge ratio $S/P = 1$, and a permeability $\kappa = 10^{-12}$ m^2 which is equivalent to a hydraulic conductivity of about 1 m/day ($K = \kappa\rho g/\mu$). Lens thickness Z is proportional to the half distance between drains or ditches L and increases as the water density $\Delta\rho$ differences between lens and groundwater become smaller in agreement with a BGH lens.

Recognizing that both the lens thickness and the mixing zone thickness are important for the risk that brackish water from the mixing zone moves up by capillary rise into the root zone,

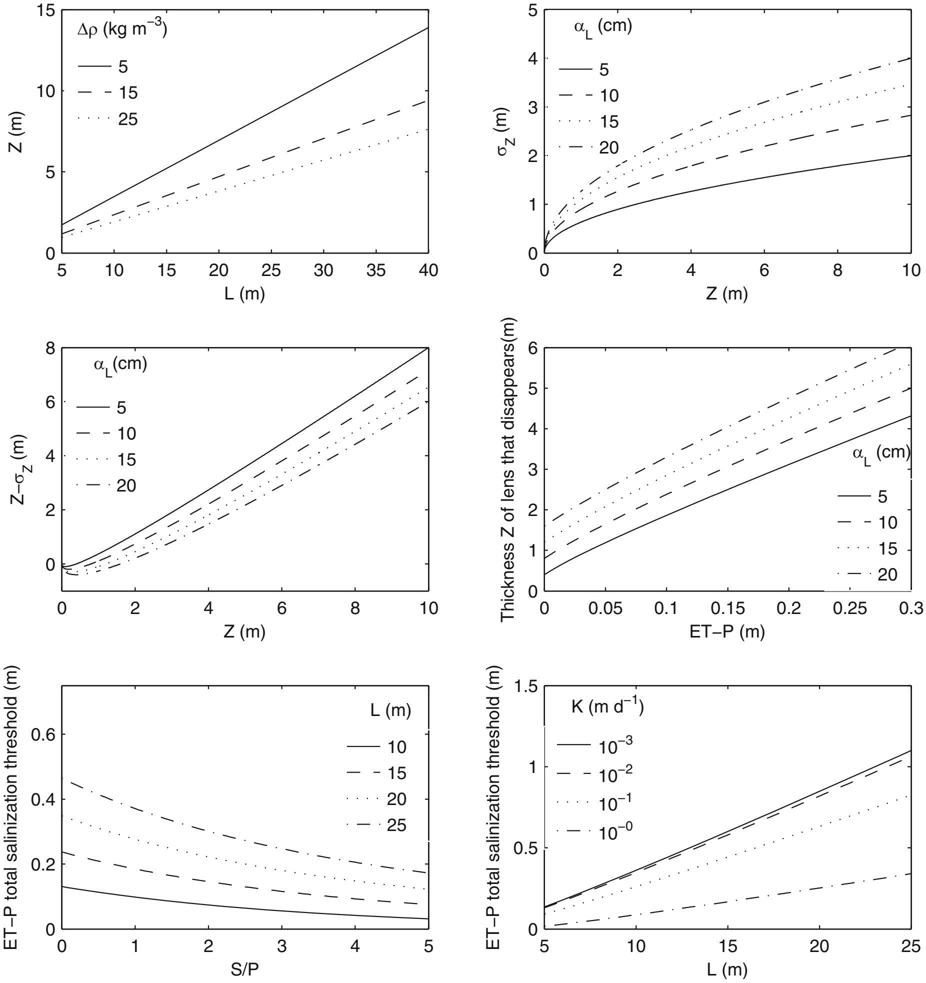

Fig. 1 Lens properties as a function of system parameters: **a** Lens thickness Z as a function of half spacing between drains or ditches L for several water density $\Delta\rho$ differences between lens and groundwater, seepage/recharge ratio S/P = 1, $\kappa = 10^{-12}$ m^2. **b** Mixing zone thickness σ_Z as a function of lens thickness for different longitudinal dispersivity values α_L. **c** Thickness of fresh water zone Z-σ_Z as a function of Z for different longitudinal dispersivity values. **d** Thickness of lens Z that may disappear as a function of rainfall deficit ET-P for different longitudinal dispersivity values, specific yield $s_y = 0.1$. **e** Threshold rainfall/precipitation deficit at which the total fresh water zone disappears as a function of seepage/recharge ratio for different half distances between ditches, a density difference as found in Dutch coastal subsoils of $\Delta\rho = 15$ kg m^{-3}, $\kappa = 10^{-12}$ m^2, $\alpha_L = 0.1$ m, $s_y = 0.1$. **f** Threshold rainfall deficit at which the total fresh water zone disappears as a function of half distance between ditches, for different values of hydraulic conductivity, S/P = 1, $\Delta\rho = 15$ kg m^{-3}, $\alpha_L = 0.1$ m, $s_y = 0.1$

an alternative to numerically estimating the critical mixing zone thickness is appealing. Based on the analysis of Cirkel et al. (2015) this thickness can be estimated easily. We consider a lens of thickness Z where half of the mixing zone is situated in the lens, and the other half is in the saline groundwater below the lens.

This half thickness (σ_Z) can also be represented by the variance or second central spatial moment of vertical salt concentration change

$$\sigma_z^2 = 2\alpha_L\langle|v_z|\rangle t \tag{4}$$

In (4), α_L is the longitudinal dispersivity [L^2] and in view of recent insights by Eeman et al. (2012) and Cirkel et al. (2015), we may interpret $\langle|v_z|\rangle t$ as the total distance that the mixing zone travels during one year (lens growing in winter, diminishing in summer). If the lens disappears at the end of each drought period and the fluctuation of the mixing zone is sinusoidal, the amplitude of vertical transition zone position is equal to $Az = Z$. This leads to $\langle|v_z|\rangle = 4A_z f$ where f is the seasonal frequency. We then obtain from (4)

$$\sigma_z = \sqrt{8\alpha_L A_z} = \sqrt{8\alpha_L Z} \tag{5}$$

In Fig. 1b we show how σ_Z increases as a function of lens thickness if the longitudinal dispersivity α_L increases. As these figures show, for relatively thin lenses, their thickness can be of the same order of magnitude as that of the mixing zone, which means that the water lens contains significant amounts of salts. This is also seen from the thickness of fresh water zone, when the mixing zone thickness within the lens, σ_Z, is subtracted from the lens thickness Z. In Fig. 1c, Z-σ_Z is shown as a function of Z and for different longitudinal dispersivities. For thin lenses, the lens may become brackish throughout, as is implied by the negative values of Z-σ_Z. This was also found by field measurements in the south-western Dutch delta which showed that almost all rainwater lenses lacked truly fresh water (De Louw et al. 2011). Since the lens thickness represents a volume of water, it is possible to assess for which thicknesses of the lens it will disappear as a function of rainfall deficit *ET-P*, longitudinal dispersivity α_L, and specific yield s_y (taken to be 0.1). For the Netherlands, a cumulative rainfall deficit of 200 mm is not uncommon, hence, lenses of 3–4 m thickness may disappear to such a degree, that brackish water can reach the root zone by capillary rise. With this in mind, we show in Fig. 1e, how the rainfall deficit for which the lens disappears will depend on the distance L between drain and middle of the field, and the ratio of seepage and recharge (*S*/*P*, see Eq. 1). It is clear, that for the chosen parameters and a reasonable rainfall deficit, this is mostly the case for small fields and relatively large seepage rates. Underlying reason is that stronger upward groundwater seepage (*S*) forces the interface between fresh and salt water upwards, i.e., leads to small Z-values. Such a combination may represent a wetland under native vegetation rather than an agricultural field. If, however, predictions for a substantial sea water level rise become true, this inevitably causes an increase in upward seepage (Oude Essink et al. 2010).

A factor that is somewhat hidden in the illustrations is the soil type. This can be illustrated with Fig. 1f that shows how the rainfall deficit, where the lens disappears, depends on both half spacing (L) and the soil hydraulic conductivity. Realistic values may be reached with high hydraulic conductivities or small L-values. In practice, ditch distances depend on the hydraulic conductivity of the soil, with smaller conductivities meaning smaller L-values, but also on desired drainage levels. In Fig. 2, the lenses are shown for a clayey and for a peaty soil. Despite its larger conductivity, fields in peat soil are often more densely drained, in order to more accurately fix groundwater levels. If groundwater levels were allowed to fall significantly in

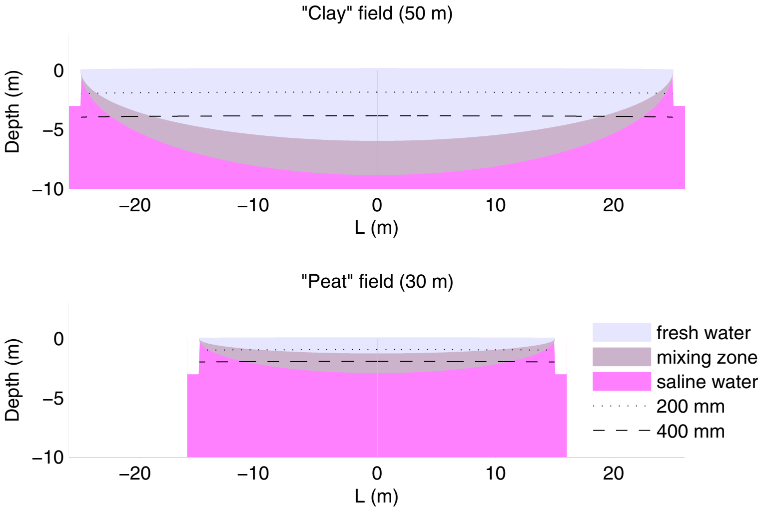

Fig. 2 Cross section of a fresh water lens in a large 'clay' field with low hydraulic conductivity (L = 25 m, K = 0.01 m d-1, $s_y = 0.1$) and a smaller 'peat' field with higher hydraulic conductivity (L = 15 m, K = 1 m d-1, $s_y = 0.2$) in a situation in which S/P = 2, $\Delta\rho = 15$ kg/m^3 and $\alpha_L = 0.12$ m. *Dotted lines* indicate which part may be depleted if the rainfall deficit increases to 200 and 400 mm. Percentage of the field that is depleted of fresh water due to rainfall deficit is 6 % (200 mm) and 25 % (400 mm) in the clay field and 38 % (200 mm) and 100 % (400 mm) in the peat field

peat, this might lead to mineralization of peat, irreversible consolidation and land subsidence. As Fig. 2 shows, good control of groundwater level by intense drainage results in a thin and vulnerable fresh water lens. In our calculations it has not been taken into account that soil type may affect net infiltration, as larger hydraulic conductivities favour a large net infiltration rate, hence thicker fresh water lenses (De Louw et al. 2011). This may mean that in practice, the total salinization threshold differences between different soil types are slightly smaller than represented in Fig. 1f.

With results as in Fig. 1, it is also easy to see what the risk is that a lens will disappear completely during a dry period if we consider climate change projections. In the next decades, the average rainfall deficit in summer may increase from 144 to 187 mm in 2050, with 10-year extremes of 288 mm (KNMI 2014). This implies that lenses with a thickness of 0.25 m/s_y = 2.5 m (for our default parameter values) may regularly disappear. A record dry year was 1976, in which the rainfall deficit grew to 360 mm, and for a specific yield of 0.1, even lenses of 3.6 m thick might disappear.

The approximations of Fig. 1 are somewhat crude, because under water and salt stress, plants will cease to transpire at the potential rate. At which concentrations salt stress occurs depends on both crop and genotype. Also regarding evaporation from the bare soil surface, it is unlikely to continue at maximum rate as drought sets in. Instead, a drying front may cause a rapid decline of evaporation as soil dries out. In addition, water that flows upward from the declining fresh water lens towards the root zone will take time to travel that distance. This time is important in view of the frequency with which significant rainfall occurs, as such showers may leach salt that is underway. In other words, characteristic times of rainfall and water travel times between saturated groundwater and root zone become important. This is even more so the case if cumulative effects over years can be anticipated, e.g. due to summers that become drier due to climate change. For instance, a rainfall deficit requires time to be balanced by a rainfall excess, yet during this time, discharge to drains and ditches continues to remove fresh water. Accordingly, the risk of a succession of different dry summers is probably a factor to be accounted for.

Although simplifications have been made on the reaction of fresh water lenses to erratic rainfall, this is not the case with regard to the impact of erratic rainfall on the fresh/salt mixing zone. High frequency variations of lens recharge may affect the thickness of the lens and therefore the value of Z, but these variations do not affect the validity of (4) and (5), as was demonstrated (Cirkel et al. 2014).

3 Regionalization of Fresh Water Persistence

The tools that were discussed in the previous section are based on analytical approximations that can be easily communicated. However, for management it is often attractive to present dependencies between environmental conditions and output of interest in the form of maps, as done by De Louw et al. (2011, 2013). With various numerical instruments, we made such a vulnerability map for regions with saline or brackish groundwater in The Netherlands.

The vulnerability map was inferred from the chloride concentration below the upper confining layer in the Netherlands (Oude Essink et al. 2010; De Lange et al. 2014). This data was retrieved from numerical models at the regional/national scale of the Netherlands (De Lange et al. 2014), with which future stresses were simulated. Comparing the results of this exercise with field data from for example De Louw et al. (2011) yielded acceptable results, except in the polder areas which used to be inland lakes and that were reclaimed relatively recently (i.e., later than 1800 AD). In these areas, this approach underestimated the thickness of the freshwater lenses. Therefore, a paleogeographical map (Vos 2015) was used to delineate these 'recently' reclaimed polders and to assign them to the 'Low' class. The year 2000 was compared with 2100, to indicate the effect of future stresses, such as land subsidence (Haasnoot et al. 1999), climate change and sea level rise.

Figure 3 shows the vulnerability of shallow fresh water lenses, for the current situation as well as for the situation in year 2100 AD. For the year 2100 AD, climate change impacts on the chloride concentration below the upper confining layer were implemented using results of national groundwater flow model simulating effects due to sea level rise, changes in precipitation patterns and autonomous salinization (Oude Essink et al. 2010; De Lange et al. 2014). Land subsidence was incorporated using the map of Haasnoot et al. (1999) in the expert judgement analysis. Because this approach is in some aspects fuzzy, the results of the final maps should be used with care. On the other hand, this exercise does show how with limited time but with distributed data used in numerical models, a reasonable indication of the vulnerability of fresh water lenses can be obtained. A profound advantage is also, that parameters that co-vary (e.g. L and K in Fig. 1f) are considered in their mutual dependency. Results as Fig. 3 can then be used by water authorities and policy makers as first-step decision information.

4 Modelling Root Zone

As is already apparent from the previous sections, changes of precipitation and evapotranspiration affect the salinity of the shallowest groundwater that may enter the root

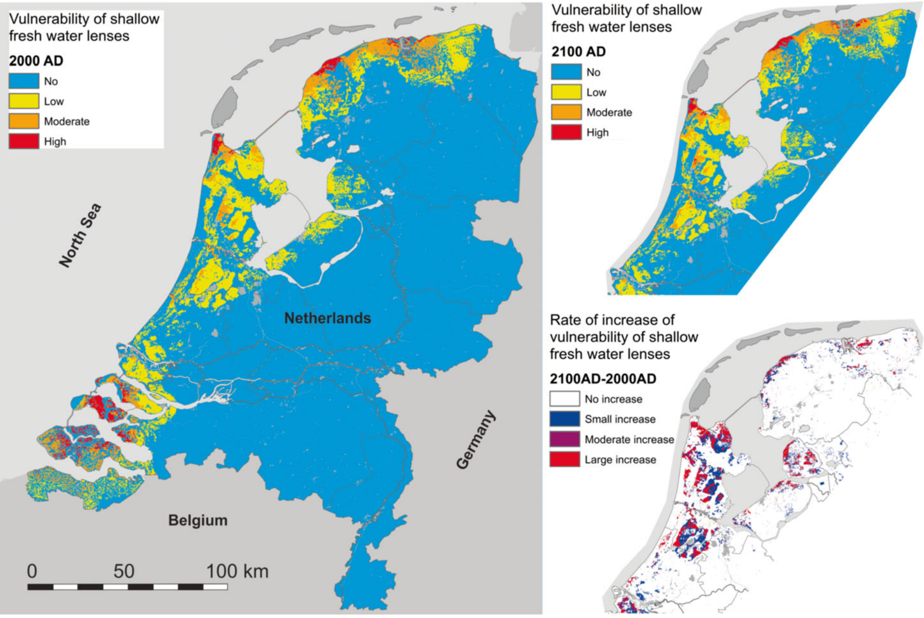

Fig. 3 Vulnerability of shallow fresh water lenses in the Dutch coastal zone, on 2000 AD and 2100 AD, as well as the rate of increase of the vulnerability of the fresh water lenses over this 2000 AD–2100 AD period, all based on a national numerical model and expert judgement. The vulnerability classes 'No', 'Low', 'Moderate', and 'High' correspond with chloride concentrations below the upper confining layer of $Cl^{-} = 0\ mg\ l^{-1}$, $0\ mg\ l^{-1} > Cl^{-} < 1000\ mg\ l^{-1}$, $1000\ mg\ l^{-1} > Cl^{-} < 5000\ mg\ l^{-1}$, and $Cl^{-} > 5000\ mg\ l^{-1}$

zone by capillary rise if fresh water lenses disappear temporarily. This may introduce salts into the root zone. Though salinity has been investigated already for a long time (Richards et al. 1954; Bresler et al. 1982), the impact of erratic weather has not often been the focus.

Practically, a major problem is that weather can be predicted in a statistical sense (mean temperature, long term average rainfall), but actual weather may differ significantly from the average behaviour and is hardly predictable. It is nearly impossible to predict whether a year will be average, or dry or wet. However, for e.g. farmers and water managers, this type of information is crucial. For practice, it is important to deal with erratic weather, as it affects e.g. primary production (yield) and it is necessary to recognize the risk of crop failure.

To model soil, which is implied in predicting, the basis is usually the Richards' equation (for unsaturated water flow, see e.g. Kuhlmann et al. 2012) and the convection dispersion or CDE equation for salt transport. Despite improving hardware and data availability, combining these equations with e.g. GCM modelling of climate change is still a challenge. This is much less the case with the popular, though simplified, root zone 'bucket' approach, in which the root zone is assumed to be a perfectly homogenized (ploughed) soil layer (Rodriguez-Iturbe and Porporato 2004).

Adopting this latter approach, taking into account the capillary upward flow from groundwater (Vervoort and van der Zee 2008), the salt balance has been solved for the long term by Shah et al. (2011). Recently, this numerical analysis has been extended towards sodicity, which considers the relative accumulation of sodium in soil to levels where it may induce soil structure degradation (Bresler et al. 1982; van der Zee et al. 2014). Although soil sodicity is a long term threat to sustainable soil use because it is poorly reversible, we will not address this process in detail in this paper, to avoid duplication with the recent analysis using the model SODIC by van der Zee et al. (2014).

Due to the irregular rainfall and seasonal evapotranspiration, the root zone has periods of drought and of wetness. During drought, capillary rise of groundwater may replenish the root zone, while during wet periods, root zone water above the field capacity may readily drain. For different conditions, Shah et al. (2011) investigated how salt accumulates in the root zone if the groundwater is somewhat brackish. Likewise, Suweis et al. (2010) considered the situation where salt spray supplies salts to the root zone.

To give an impression of the impact of weather on salinity, we simulated water and salt balances. To efficiently simulate the water and salt balances, we adopted the approach of Vervoort and van der Zee (2008) and Shah et al. (2011), where a root zone was considered at some distance above the water table. Though the Netherlands are characterized by sufficient rainfall of about 800 mm/y, net recharge has a distinct seasonal variation, as evapotranspiration is mainly concentrated in the summer period. On average, net groundwater recharge is less than 1 mm/d.

For Dutch conditions, it is quite well possible that groundwater at the water table is brackish, e.g. if fresh water lenses disappear in summer (De Louw et al. 2011, 2013). We considered a soil that initially is not saline. Due to alternation of rainfall and irrigation water entering the soil and of capillary rise of groundwater, the root zone will salinize to some degree. As demonstrated in earlier work (Suweis et al. 2010; Shah et al. 2011), this leads to irregular fluctuations of salt concentration (C) that builds up first and then stabilizes around a long term mean value. The resulting strongly erratic pattern of C as a function of time, is a direct consequence of the erratic pattern of rainfall, irrigation, and other water balance terms. Therefore, this pattern as such is not tractable to real prediction. In a first assessment, it may be sufficient to assess the mean concentration around which C will vary through time, for comparison with the crop's tolerance. Such a first assessment was already developed much earlier (Richards et al. 1954), for the case that salts originate from brackish irrigation water. As its main concept, it used the so-called leaching requirement (*LR*) given by

$$LR = \frac{D_{dw}}{D_{irr}} = \frac{\theta_{fc}}{\theta_{sp}} . \frac{C_{irr}}{C_e} \tag{6}$$

written in terms of concentrations, instead of electrical conductivity as often used. In Eq. (6), *D* is the quantity (in water layer thickness per year) of irrigation water applied ($_{\mathrm{irr}}$) and drainage water ($_{\mathrm{dw}}$), *C* refers to the concentration of salts in irrigation water and in the saturated paste of soil (subscript $_e$), and θ_{sp} and θ_{fc} are the volumetric water contents of the saturated paste and at field capacity (pF = 2.5), respectively, and correspond with the water contents at the point of liquefaction and above which water drains due to gravity (Richards et al. 1954). The principle is that if the tolerance of a crop for salt is designated as C_e, then the leaching requirement tells us how much irrigation water excess for drainage is needed, to keep concentrations in this soil at this tolerance threshold. *LR* is attractive, as it gives a simple and robust tool to predict salinity due to irrigation with water that contains some salts, in other words, it is simple tool to assess irrigation practise sustainability.

It is attractive to develop a similarly robust tool to predict salinity if salts originate from capillary upward flowing groundwater and erratic weather. Shah et al. (2011) investigated the long term salinity for a range of conditions, using the approach that has just been described. Using the same model SODIC, that was extended to account for sodicity, but for Dutch conditions, the long term average salt concentration was simulated numerically. It appeared that in its simplest form, if only groundwater is a source of salts, the long term root zone salinity can be estimated with

$$\langle C \rangle = \frac{\langle D_{cr} \rangle}{\langle D_{dw} \rangle} C_Z \tag{7}$$

where brackets < . > denote time-average, D_{cr} stands for capillary rise flux of groundwater, D_{dw} is the drainage water flux, and the phreatic groundwater concentration is C_z.

In many agricultural regions, besides precipitation, both groundwater and irrigation water are used for evapotranspiration. Therefore, we take the result of Shah et al. (2011) as a point of departure to consider the case where irrigation water has a distinct salt concentration C_{irr}, but also groundwater is (somewhat) saline. We consider a clayey soil covered with grass, with different groundwater levels below soil surface (Z_f) in the range 100 cm < Z_f < 250 cm and a root zone thickness of 25 cm. By using the reasoning that resulted in (7), we obtain in analogy the following result

$$\langle C \rangle = \frac{\langle D_{cr} \rangle \, C_Z + \langle D_{iw} \rangle \, C_{irr}}{\langle D_{dw} \rangle} \tag{8}$$

This expression, that ignores short term fluctuations, agrees quite well with numerical results, and only has a small systematic bias as can be seen from Fig. 4.

Figure 5 illustrates the long-time average salt concentrations under various Dutch conditions as calculated with Eq. 8, assuming capillary rise of (moderately) saline groundwater after (partial) disappearance of a fresh water lens. Average salt concentrations do not exceed groundwater concentrations due to dilution (precipitation surplus, Fig. 5a), although in practice, the concentrations would vary seasonally. The salinizing effects of capillary rise (during seasonal precipitation deficit, assuming no reduction of evapotranspiration) may be mitigated by irrigating with water that has a lower salt concentration than the average concentration that would have occurred without irrigation (Fig. 5b, d and e). Moreover, it should be noted that irrigation lead to decreased capillary rise as well, adding to the mitigating effect. If however, the concentration of irrigation water is equal to the

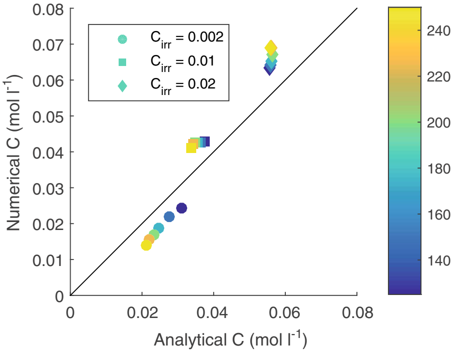

Fig. 4 Root zone salt concentrations as modelled numerically for a root zone model, and as determined with the approximation of Eq. (8), for different groundwater levels (Z_f in cm below surface) indicated by the colour bar to the right, and a temperate climate as in The Netherlands. Irrigation water salinity given by C_{irr} in mol l^{-1}, and groundwater salt concentration of 0.02 mol l^{-1}

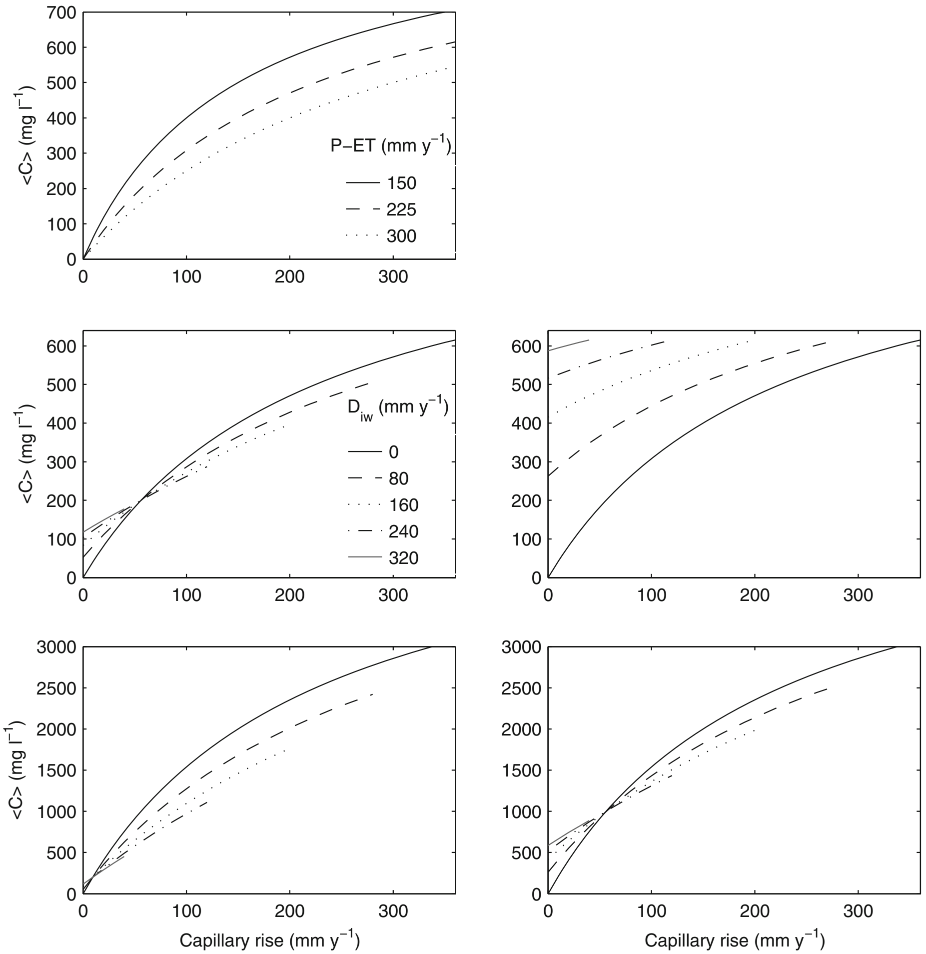

Fig. 5 Average salt concentrations as calculated by Eq. 8. Drainage (D_{dw}) is calculated as the sum of the precipitation surplus (P-ET), capillary rise (D_{cr}) and irrigation (D_{irr}). **a** The effect of precipitation surplus on the average salt concentration as a function of capillary rise, in a situation without irrigation and a groundwater chloride concentration of 1000 mg l^{-1}. **b–e** show the effect of irrigation on the average chloride concentration as a function of capillary rise. A precipitation surplus of 225 mm y^{-1} is assumed and the sum of irrigation and capillary rise is assumed to not exceed 360 mm y^{-1}. **b** Average chloride concentration with a groundwater salinity of 1000 mg l^{-1} Cl^- and irrigation water salinity of 200 mg l^{-1} Cl^-. **c** Average salt concentration with a groundwater salinity of 1000 mg l^{-1} Cl^- and irrigation water salinity of 1000 mg l^{-1} Cl^-. **d** Average salt concentration with a groundwater salinity of 5000 mg l^{-1} Cl^- and irrigation water salinity of 200 mg l^{-1} Cl^-. **e** Average salt concentration with a groundwater salinity of 5000 mg l^{-1} Cl^- and irrigation water salinity of 1000 mg l^{-1} Cl^-

groundwater salinity, irrigation leads to increased long-term average concentrations (Fig. 5c).

More refined predictions of long term root zone concentrations can be made, based on projected future rainfall intensities and evapotranspiration demand. At this moment, it is not yet clear whether such predictions have to account for the travel time of capillary upward moving water and salt, and the probability that saline water is leached before it reaches the root zone, by incidental rainfall showers.

5 Summary and Conclusions

In managing fresh water scarcity and salinity in the deltaic areas, which may grow in importance due to climate change and related sea level rise, modelling of the behaviour of shallow fresh water lenses in relation to increased root zone salinities is an important tool to help us anticipate possible chances in primary food production. To be of use, models have to be aligned with experimental results, i.e., be properly parameterized. A main issue is that a proper assessment must be made of how crops respond to salinity. Despite that this has been under investigation for decades, quite basic issues such as compensation behaviour of plants in dealing with drought and salt stress are still frontiers in our science (Javaux et al. 2008; Kuhlmann et al. 2012).

Despite the recognition of scientific gaps in knowledge, for managing our resources, a robust prediction of broad features may be sufficient these coming decades. An example is given by predicting the persistency of fresh water lenses in saline, shallow groundwater situations such as in deltaic areas. Numerical modelling by Eeman et al. (2011, 2012) revealed that analytical solutions of e.g. Maas (2007) describe the mean depth of the fresh/salt transition zone pretty well. With some approximations that are also founded on a good agreement with numerical simulations, we can judge also the thickness of the fresh water lens above the fresh/salt transition zone. In combination, this resulted in an assessment of the combination of factors for which fresh water lenses may disappear in drier summers as predicted for climate change on the European subcontinent. It appears that in practice, fresh water lenses have to be very thin or subject to large mixing at the interface to be threatened to disappear completely. However, near draining ditches or gullies, the risk may be larger as lens thickness decreases significantly in their vicinity.

Based on numerical models and available spatially distributed data from different sources, a relatively straightforward data assimilation is possible towards the vulnerability of fresh water lenses to temporarily disappear. Such an assessment was done for the Dutch coastal region, and this may provide a basis for later, more detailed predictions.

If the shallowest groundwater becomes brackish or saline, this can cause the root zone to become saline due to capillary rise of marginal water. With simulations that account for erratic aspects of weather, notably rainfall, it is possible to investigate the root zone salinity as a function of different factors such as vegetation or crop, root zone thickness, groundwater depth, and climate. Typically, this leads to a salt concentration that fluctuates much as a function of time. To predict which concentrations in root zone develop on the longer term, two very simple approximations (7) and (8) are presented that reproduce the main features obtained with detailed numerical simulations pretty well. Accordingly, the concept of Leaching Requirement, that has proven its use for practical soil water and salinity management during the last 7 decades, has been extended to more complex situations. However, despite the promise of the good agreement between numerical simulations and these approximations, it is necessary to confirm the applicability with experimental evidence. If that leads to favourable results, a very useful management tool is the result.

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Dealing with Uncertainties in Fresh Water Supply: Experiences in the Netherlands

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Abstract Developing fresh water supply strategies for the long term needs to take into account the fact that the future is deeply uncertain. Not only the extent of climate change and the extent and nature of its impacts are unknown, also socio-economic conditions may change in unpredictable ways, as well as social preferences. Often, it is not possible to find solid ground for estimating probabilities for the relevant range of imaginable possible future developments. Yet, some of these may have profound impacts and consequences for society which could be reduced by timely proactive adaptation. In response to these and similar challenges, various approaches, methods and techniques have been proposed and are being developed to specifically address long-term strategy development under so-called deep uncertainty. This paper, first, offers a brief overview of developments in the field of planning under (deep) uncertainty. Next, we illustrate application of three different approaches to fresh water provision planning under uncertainty in case studies in the Netherlands: a resilience approach, oriented to (re) designing fresh water systems in such a way that they will be less vulnerable, resp. will be able to recover easily from future disturbances; a robustness approach, oriented to

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quantitative assessment of system performance for various system configurations (adaptation options) under a range of external disturbances, and an exploratory modeling approach, developed to explore policy effectiveness and system operation under a very wide set of assumptions about future conditions.

Keywords Fresh water supply · Uncertainties · Adaptation · Resilience · Robustness

1 Uncertainties: New Challenges for Decision Making on Fresh Water Supply Systems

Decision making and planning for fresh water supply are challenging because of a number of different reasons: First, a variety of individual measures or tactics need to be considered at both the supply and the demand side, including regulation, adaptation of infrastructure elements, subsidies or fines, operational control and coordination, etc., and appropriate combinations of these need to be made in the process of policy design. Second, different scales need to be considered, such as the local, regional, national and river basin scales, each having their associated governmental bodies. Third, a range of sometimes conflicting interests needs to be considered. Fourth, various uncertainties come into play. Traditionally, ample attention has been given to natural climate variability, for which empirical data are available and probabilistic approaches can be used to estimate the likelihood and consequences of various climate scenario's, and to assess the effectiveness of alternative policies. It has been argued that under the rapidly changing global climate, the assumption of stationarity is no longer valid, meaning that historic return frequencies of extreme hydrological and weather conditions can no longer be relied on in water management: here the past is no longer the key to the future (Milly et al. 2008). Long-term decision making, involving, for example, decisions regarding water supply infrastructures having long lifetimes, brings a new class of important uncertainties. Climate change, itself being uncertain, may have significant – yet uncertain – impacts on precipitation and evaporation patterns, salt intrusion, salinization, and seasonal variation. In addition, a variety of uncertain but possible developments in land use and agricultural conditions, food markets, spatial developments, economic developments, future technology, and future societal values may also affect the future impacts and valuation of policies that have to be decided in the short term.

Partly but not exclusively triggered by the need to explore the impacts of climate change, during the last decade, the literature on dealing with various sorts of uncertainties has been developing rapidly (e.g., Maxim and Van der Sluijs 2011; Van Bree and Van der Sluijs 2014). Therefore, in this paper, we will first give a brief overview of some of the major developments in the uncertainty literature. Next, three examples are presented of application of one of the many approaches under development in the field of fresh water supply. We conclude with a few general observations on the state of the art, and recommendations for further work in the field.

2 Developments in Dealing with Uncertainties

Knowledge available for long-term policy making is unavoidably incomplete and often controversial. In the science-policy interface, strategic use of uncertainties seems to dominate: uncertainties are either downplayed to promote political decisions or they are overemphasized to prevent political action. Both are problematic and lead to policy strategies that are not fit for meeting the challenges posed by the uncertainties and complexities faced. While the scientific community has not ignored the problems of uncertainty, most efforts thus far have been associated with analysing and dealing with those uncertainties that can be described quantitatively (e.g., probabilistically, like in risk analysis), and with efforts at reducing uncertainties through additional research and/or refined modelling.

Not all uncertainties encountered in decision making can be quantified. In fact, unquantifiable uncertainties can sometimes be more relevant than the part where we do have enough knowledge to quantify uncertainty. Rather than using such unquantifiable uncertainties in a strategic way, or ignoring them, there is a growing consensus among scholars that deliberate policy strategies in the face of often irreducible uncertainties should be developed and implemented (Van der Sluijs et al 2008), and a wide variety of approaches and methods have emerged in the literature on the subject. As a result, the field is quite fragmented, and different key authors and groups have developed their own terminologies. A certain degree of conceptual confusion results, as approaches partially overlap, and different authors use the same terms in different ways. For example, approaches like ‘Adaptive Management’, ‘Adaptation Policy Framework’, and ‘Robust Decision making’ strongly (but not completely) overlap in their guiding principles.

Despite the fragmented character of the field, there seems to be a general agreement that different approaches are suitable under different degrees and types of uncertainty, that in real world situations often different types of uncertainty are present at the same time, and that combinations of approaches need to be fine-tuned to the characteristics of the situation. We will now briefly elaborate on these aspects.

2.1 Types and Levels of Uncertainty

In an attempt to harmonize diverse literatures in as far as they relate to model-based decision support, Walker et al. (2003) presented an uncertainty framework. The starting point for this framework is the distinction between an analyst’s perspective on uncertainty and a decision maker’s perspective on uncertainty (van Asselt 2000). The framework focuses on the analyst’s perspective on uncertainty. A central idea of this framework is that uncertainty is a multi-dimensional concept. Ironically, this framework in turn had its own variants, motivated by various perceived shortcomings of the original typology or perceived need to tailor it to a specific field of study. More recently, Kwakkel et al. (2011) presented a review of the variants and what motivated them, and presented a new framework that integrated and harmonized the variants. Both the original and the new framework categorize uncertainties by their location, nature, and level. The location dimension focuses on where the uncertainty is located. The nature dimension focuses on the character of the uncertainty, i.e., whether the uncertainty is knowledge-based, a direct consequence of inherent variability, or related to human interpretation (ambiguity) or human values now and in the future. The level dimension focuses on the severity of the uncertainty.

Each of the three dimensions is relevant when selecting an appropriate approach for handling the uncertainty. However, the level dimension plays the most important role. Broadly speaking, the level of uncertainty is the assignment of likelihood to things or events. In some cases the likelihood or plausibility of these things, events or situations can be expressed using numbers, but in other cases more imprecise labels are used, such as more likely, less likely, or equally likely. Overall, the level of uncertainty ranges from complete certainty to absolute ignorance. We define five intermediate levels of uncertainty: we speak of level 1 uncertainty, or recognized uncertainty, when one admits that one is not absolutely certain but when one is not willing to measure the degree of uncertainty in any explicit way (Hillier and Lieberman 2001). We speak of Level 2 uncertainty, or shallow uncertainty, when one is able to enumerate multiple possibilities and is able to provide probabilities. We speak of Level 3 uncertainty, or medium uncertainty, when one is able to enumerate multiple possibilities and able to rank order them in terms of perceived likelihood. However, how much more likely or unlikely one possibility is compared to another cannot be specified. We speak of Level 4 uncertainty, or deep uncertainty, when one is able to enumerate multiple possibilities without being able or willing to rank order the possibilities in terms of how likely or plausible they are judged to be. Finally, we speak of Level 5 uncertainty, or recognized ignorance when one is unable to enumerate multiple possibilities, while admitting the possibility of being surprised (Kwakkel et al. 2011). Table 1 summarizes the five levels.

2.2 A New Paradigm for Handling Uncertainty

Uncertainties pose a significant challenge to planning and decision making. The dominant approach in many fields has been to ignore the uncertainties, to quantify them into error margins, to try and reduce them, or to deal with only those uncertainties that can be easily quantified (Quade 1982; Dempsey et al. 1997; Marchau et al. 2009; Van Geenhuizen et al. 2007; van Geenhuizen and Thissen 2007; McDaniel and Driebe 2005). However, such approaches suffer from the problem that they focus on those uncertainties that are “among the least of our worries; their effects are swamped by uncertainties about the state of the world and human factors for which we know absolutely nothing about probability distributions and

Table 1 The five levels of uncertainty (adapted from Kwakkel et al. 2010b)

Level of Uncertainty	Description	Examples
Level 1 (recognized uncertainty)	Recognizing that one is not absolutely certain, without being able or willing to measure the uncertainty explicitly.	Performing a sensitivity analysis on a parameter in a model by changing its default value with some small fraction.
Level 2 (shallow uncertainty)	Being able to enumerate multiple alternatives and being able to provide probabilities (subjective or objective)	Being able to enumerate multiple possible futures or alternative model structures, and specify their probability of occurring
Level 3 (medium uncertainty)	Being able to enumerate multiple possibilities and being able to rank order the possibilities in terms of perceived likelihood. However, how much more likely or unlikely one alternative is compared to another cannot be specified	Being able to enumerate multiple possible futures or alternative model structures, and being able to judge them in terms of perceived likelihood
Level 4 (deep uncertainty)	Being able to enumerate multiple possibilities without being able to rank order the possibilities in terms of how likely or plausible they are judged to be	Being able to enumerate multiple possible futures or specify multiple alternative model structures, without being able to specify their likelihood
Level 5 (recognized ignorance)	Being unable to enumerate multiple possibilities, while admitting the possibility of being surprised	Keeping open the possibility of being wrong or being surprised

little more about the possible outcomes” (Quade 1982). Similarly, Goodwin and Wright (2010) (p. 355) demonstrate that “all the extant forecasting methods – including the use of expert judgment, statistical forecasting, Delphi and prediction markets – contain fundamental weaknesses.” And Popper et al. (2009) state that the traditional methods “all founder on the same shoals: an inability to grapple with the long-term’s multiplicity of plausible futures.” In response to this, various new planning approaches have been put forward (e.g., Lempert et al. 2003; Walker et al. 2001; de Neufville 2000, 2003; Dewar 2002; Dewar et al. 1993; Holling 1973; Lempert 2002). These approaches generally contain three types of elements:

- analytic methods and tools to capture and assess the (consequences of) uncertainties,
- specific action or policy strategies in light of irreducible uncertainties,
- specific, often participatory processes to involve stakeholders and decisionmakers

Analytic approaches (Swanson et al. 2010) generally emphasize the need for a more thorough integrated forward-looking analysis of the uncertainties through techniques such as exploratory modelling and analysis (Agusdinata 2008; Lempert et al. 2003), bounce casting (Kahan et al. 2004), and scenarios in various forms (Bradfield et al. 2005; Varum and Melo 2010).

The action or policy strategies can be divided in three partly overlapping categories: First, so-called top-down or robust strategies build on analytic approaches in order to assess the vulnerability of alternative strategies, and to select those policies that do well under a wide variety of possible futures. Second, so-called bottom-up, resilience-based strategies recognize the limited capability of analytic approaches for anticipating rare events, and focus on the system-to-be-governed or to-be-designed itself, and try to enhance the system’s inherent ability to cope with disturbances and its self-organizational capacity in a comprehensive way (e.g., Wardekker et al. 2010). Third, there is a growing interest in flexibility and adaptability in plans in which a strategic vision of the future is combined with short-term actions and a framework that can guide future actions (Albrechts 2004; Walker et al. 2001; Walker et al. 2013).

Together with a focus on involving stakeholders and decisionmakers in both the identification of uncertainties and the assessment of alternative strategies, these new approaches can be considered to form a new emerging paradigm for handling uncertainty differently. They are based on accepting the uncertainties, and focusing on the question what can best be done now, given that we don’t know what the future will bring.

For a more complete overview of concepts, approaches and methods, the reader is referred to recent review reports and articles (Dessai and Van der Sluijs 2007, 2011; Wardekker 2011; Walker et al 2013; Lourenço et al 2014a; van Bree and van der Sluijs 2014).

2.3 Applications in the Field of Fresh Water Supply

As explained above, fresh water supply planning faces a variety of uncertainties, part of which cannot adequately be dealt with in a (purely) probabilistic way. Recently, a number of example applications of the type of approaches mentioned above have been reported in the literature. For example, Groves, et al. (2007; 2012) have reported on a number of studies on fresh water supply in California and Colorado River, using the so-called ‘robust decisionmaking’ approach that is strongly based on analytical and computational techniques. Matrosov et al (2013a; 2013b) apply among others Robust Decision Making to a fresh water supply case in the United Kingdom. Groot et al. (2014) report, among other things, on several practical cases of water supply planning in Portugal, the UK, and Hungary. These studies mostly were related to dealing with uncertainties of the scenario-type, and used a combination of multiple methods such as expert elicitation, stakeholder involvement and model-based sensitivity analysis. The studies demonstrate, on the one hand, the complexity of the challenge, and, on the other, the relevance of more explicitly dealing with uncertainties, and ‘a shift towards a flexible, robust and no-regret approach’ (Groot et al. 2014, p 67). Lourenço et al. (2014b) also emphasize a preference for ‘options that contribute to enhance resilience and adaptive capacity’.

In another study in Hungary (Malatinszky et al. 2013), the focus was on climate adaptation strategies for wetlands and grasslands. The authors emphasize the importance and various benefits of stakeholder involvement in such processes, which include “enhanced awareness, willingness to taking action, inclusion of local knowledge, information exchange among affected parties, identification of win-win-solutions for land users and nature conservation, and building trust in authorities”.

Clearly, while there seems to be agreement on the general tendencies of preferred approaches, much remains to be developed and learned, both with respect to methods and tools and their potential and limitations in practical applications and with respect to what strategies fit what uncertainty situations.

In the following sections, we will therefore, in order to learn more about their applicability, illustrate the application of three novel but different approaches to two different real-world fresh water supply cases in The Netherlands. First, the resilience approach is applied to an area of peat grassland in the west of the Netherlands. Second, a system robustness approach is applied to a low-lying polder area mainly used for agricultural purposes. Third, an exploratory modeling approach is applied to the same case study area.

3 A Resilience Approach: the Venen-Vechtstreek Region

3.1 Resilience

Resilience is a concept that emerged in ecology research in the 1960s. It was used in relation to the stability of ecosystems in the face of a wide range of external perturbations: “the amount of disturbance that a system can absorb and still remain within the same state or domain of attraction” (Holling 1973; Walker and Salt 2006). The concept has since been adopted by various disciplines, ranging from engineering to psychology, disaster studies, and climate change adaptation. Walker et al (2004) define resilience in relation to ‘social-ecological systems’ as: “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks”. Resilience focusses on coping with disturbances and preventing collapse into a qualitatively different state, rather than predicting and preventing disturbances.

In relation to climate change adaptation, resilience can be understood as a bottom-up approach, which aims at strengthening the system, removing vulnerabilities, and enhancing the capacity to cope with and recover from climate change-related disturbances and surprises. The case-study examined the consequences of various proposed measures and developments on the climate-resilience of the freshwater systems in the Venen-Vechtstreek region. These measures are plans to manage the area in general and are not specifically proposed to adapt to climate change.

Resilience analysis can take several steps. The first step is to determine ‘resilience of what?’. This includes an overview of the area, the trends and challenges it faces, the way it is used, and the key characteristics and functions that make the system for what it is (i.e., if these are not retained, the system has shifted to a different state). The second step is to address the question of ‘resilience to what?’. In this study, an inventory of climate change impacts was made. The third step is to assess the resilience of the system, measures that will enhance resilience, or the resilience consequences of developments. This case study concerned the latter. We applied a set of ‘resilience principles’ describing different mechanisms by which systems can absorb disturbances and retain identity (Watt and Craig 1986; Barnett 2001; Wardekker et al. 2010):

- Homeostasis: multiple feedback loops counteract disturbances and stabilize the system.
- Omnivory: vulnerability is reduced by diversification of resources and means.
- High flux: a fast rate of movement of resources (e.g., information, money, expertise, goods for emergency relief, fuel) through the system ensures fast mobilization of these resources to enable coping with perturbations through for instance reduced feedback delay. If information is proactively and rapidly exchanged, parties can act on this faster when there is a problem.
- Flatness: the hierarchical levels relative to the base should not be top-heavy. Overly hierarchical systems are too inflexible and too slow to cope with surprise. The more hierarchical levels exists through which stabilizing feedback signals must operate, the lower the signal to noise ratio and the lower the speed of signal transmission, and thus of action to counteract the perturbation or remedy the damage.
- Buffering: essential capacities are over-dimensioned such that critical thresholds are less likely to be crossed.
- Redundancy: overlapping functions; if one fails, others can take over.

3.2 Case Study Area and Trends

The Venen-Vechtstreek region is an area of peat grassland in the west of the Netherlands. It is known for its wide views, cow-filled meadows, and long and narrow stretches of land separated by water (Fig. 1). The appearance of the region has changed little over the centuries. The case study focused on the specific area of Groot Wilnis – Vinkeveen. The region is part of a range of wetlands forming a ‘robust ecological corridor’ between areas protected under Natura 2000, the European ecological network of protected areas. The corridor is intended to provide a connection and shelter that allows animals and plants to migrate between nature areas. The area is situated at approximately 2.5 m below sea level and is artificially drained.

Due to the artificial drainage, peat comes into contact with oxygen and decomposes. Consequently, the area suffers from soil subsidence. The most sensitive parts of the area have seen subsidence of up to 12 mm per year. Agricultural areas suffer more subsidence than nature areas, due to higher levels of drainage, resulting in large local differences in water levels. The decomposing peat also releases nutrients into the surface water and greenhouse gasses into the atmosphere.

The area is valuable for both ecological and agricultural reasons. The area’s management covenant (Stichting Ontwikkeling De Venen 2010) specifies that the area should be preserved as an open landscape in which the dairy sector can continue to develop. Four key functions can be distinguished: fresh water supply, nature, agriculture, and recreation. Stakeholders aim to strengthen these functions, as well as to reduce the amount of soil subsidence. The functions

Fig. 1 Satellite view of the case-study area (source: Google Maps)

have different implications for the management of the area. Connecting them through integrated measures will be an important step in enhancing resilience.

Climate change will affect Dutch freshwater systems through increasing air and water temperatures, sea level rise, changes in seasonal river discharge, and changes in precipitation (PBL 2013). Average precipitation may either increase or decrease in summer, and increase in winter. For the study area, this may result in an increasing potential precipitation deficit during summer. Dry periods could negatively impact water availability and quality for fresh water supply as well as for nature and agriculture. Wet periods could result in flooding, negatively impacting all four functions. They could also exacerbate the current tension in water level requirements for agriculture (relatively low) and nature (relatively high), and enhance nutrient leaching from fields into surface water, negatively impacting nature. Temperature changes can impact various plants and animals. For 2050, a scenario study projects a moderate to high terrestrial drought risk, moderate risk of aquatic eutrophication, low risk of terrestrial eutrophication, and low to high risk of aquatic salinization (Verhoeven 2012). The high salinization risk occurred in a scenario with warm, dry summers, when brackish water from outside the area would be required to manage the water levels.

3.3 Analysis

A list was drafted including measures that are currently planned for managing the study area, based on the management covenant, other policy documents, and position papers of regional and national stakeholders. This list was supplemented with options that could contribute to the area's overall resilience. These supplementary options were collected through interviews with stakeholders and experts with experience concerning the study area. Options were categorized according to the key functions they contribute to: nature, agriculture, water quality, and recreation.

The research team performed an initial reflection on the resilience implications of the options, followed by a second set of interviews. These reflections were used in preparation of a workshop with stakeholders and experts on the area and on resilience: to select a subset of options to be discussed in the limited time available, and to seed the discussion. Workshop participants (*n* = 7; this number is adequate for an expert assessment; 6–12 is advisable, to cover relevant fields of expertise, but allowing for sufficient time for discussion; Knol et al. 2010) scored the shortlist of options on each of the resilience principles. They applied a five-point scale, ranging from strong decrease to strong increase of resilience. Aggregated 'resilience scores' were also generated. See Fig. 2.

Nearly all of the assessed options for nature improved resilience, according to the scores of most participants (occasionally, one or two participants disagreed). The participants expected the option 'marshland construction and capillarity' to perform particularly well. Agricultural options scored less well; half resulted in (slightly) reduced resilience. The option 'underwater drainage' did receive a good score. For both types of options, the range between individual aggregated scores was generally one to two points. Scores on separate resilience scores had similar ranges. They could on occasion diverge more strongly (up to scores of -2 to +2, cf. Fig. 2, although these were exceptions), but the interquartile ranges (25–75 percentiles of scores) were two points in most cases. The group size was sufficiently large that a single expert scoring notably different did not change the interquartile ranges.

The approach to assessing resilience applied in this case study provided a useful tool to scan a variety of options on a range of impacts for a range of stakeholders on their implications. It allows

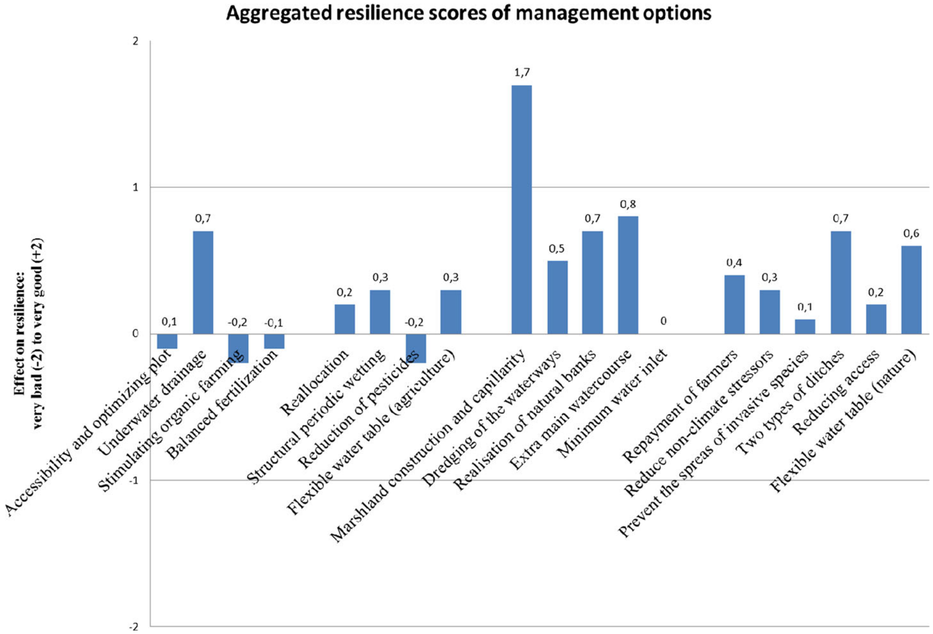


Fig. 2 Mean aggregated resilience scores. Options are arranged in four groups, from left to right: agriculture (planned and new) and nature (planned and new)

for a relatively quick evaluation of options and the inclusion of stakeholders and their perspectives. The approach was also easy to combine with other decision criteria in a multicriteria assessment, allowing for a broader evaluation of policy options. Preferably, this would include multiple workshops with a broader range of expertise amongst the participants. A downside is that the assessment takes place on an ordinal scale (categories, rather than full quantification) and does not examine spatial patterns. Also differences in opinion between participants scores will remain, even with extensive discussion. These require further investigation and may hint at deeper differences in opinion (uncertainty due to ambiguity; see e.g., Brugnach et al. 2008), or different ways in which an option can be implemented. The approach can be applied for a broad range of cases, and does not require extensive computing power or special software. It does require some insight in the system dynamics of the case study (among researchers and participants), as well as experience with participatory processes (among researchers). It is possible to scan a broader set of options with the research team only, and/or include a larger set of stakeholders by means of a survey. However, discussion with, and among, local stakeholders and experts remains important to analyze local resilience in a meaningful way.

We concluded that, considering that agriculture is a key function of the area, covering most of the land use, it would be advisable to pay attention to increasing resilience in agricultural developments. Scores on separate resilience principles (i.e., not aggregated into a single resilience score) showed that very few options increase flatness. Additionally, few agricultural options address redundancy.

4 A System Robustness Analysis: Case Rijnland

4.1 System Robustness

System robustness is a concept that originates from engineering and biology, where it refers to the ability of systems to maintain system characteristics when subjected to disturbances (Carlson and Doyle 2002; Stelling et al. 2004). For example, a road network is robust to incidents when the effect on traffic congestion is prevented and/or limited (Snelder et al. 2012). According to the Merriam-Webster dictionary, the term *robustness* indicates that systems or networks are capable of performing without failure under a wide range of conditions. In the context of flood and drought risk management, system robustness is defined as the ability of a socio-economic system to remain functioning under a range of disturbance magnitudes (Mens et al. 2011). The term disturbance refers to an external event resulting from climate variability, for example floods or droughts. The system for which robustness is assessed comprises biophysical as well as socio-economic aspects. For example, the robustness of a flood risk system does not only depend on the flood protection system, but also on the characteristics that determine the flood impact, and on the social and economic capacity to recover from these impacts. Failure of the system thus means that impacts are too large to recover from. Such impacts may be considered a catastrophe or a disaster. Likewise, a robust drought risk system is one that can resist frequent droughts (zero impact) and that can recover from socio-economic impacts of rare droughts (limited impact).

System robustness can be assessed by studying the so-called response curve: the relationship between disturbance and response, for example the relationship between precipitation deficit and crop yield deficit. Key aspects of the response curve for this application are:

- Resistance threshold: the smallest deficit causing yield deficit;
- Manageability: the severity of the yield deficit in comparison with a recovery threshold (i.e., the societally unacceptable level of yield deficit).

Manageability refers to how severe the impacts of a drought can become. Whether a response is considered severe depends on the social and economic capacity to recover from the response to a disturbance (see De Bruijn 2004). This capacity can be quantified by a recovery threshold, indicating the level of response from which it will be very difficult to recover. For example, when economic impacts of flooding exceed 5 % of the national GDP, it often means that aid is needed from other countries (5). Manageability indicates the extent to which the response stays far from the recovery threshold for the range of considered disturbance magnitudes.

4.2 Case Rijnland

Droughts occur as a natural temporary feature of the climate (AMS 2013), but it may have an effect on reservoir storage, groundwater resources and river discharges, thereby potentially causing socio-economic and environmental impacts. Climate change may cause a change in the frequency and severity of droughts. Many water resources studies focus on the impact of climate change on long-term average flows (Lehner et al. 2006), thereby analysing the average demand and supply balance in the long-term. However, even if water supply is sufficient to meet demand on average, droughts may cause a temporary shortage of water which may have far-reaching impacts on society. Insight is thus needed into the impact of potential drought events resulting from climate variability, now and in the future.

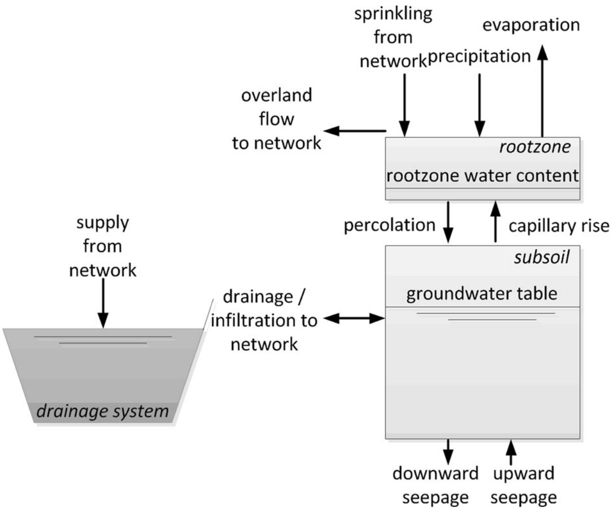
To understand how systems robustness analysis can aid in the management of drought risk systems, it was applied on a case: Rijnland polder areas (Mens and Klijn 2015; Mens et al. this issue). A drought risk system is a geographical area that depends on one or more water resource for several functions (e.g., drinking water supply, industry, nature and agriculture). Drought, in this case defined as a period of precipitation deficit (i.e., evapotranspiration is larger than precipitation), may cause water shortage with an impact on the area's functions. Precipitation deficit is thus considered the disturbance to the system.

The case study area, Rijnland, is a system of low-lying polders with agriculture (potatoes, horticulture, bulbs, flowers, dairy farming) as the main land use type. This is a mixture of rain-fed and irrigated agriculture. The water supply and drainage system consists of ditches, canals, lakes, and pumps and sluices. In winter, there is an excess of water that is drained and pumped out, and in summer fresh water is let into the surface water system from a nearby river (see also Mens et al. this issue). The inlet water is used for water level control, flushing for water quality management and water supply (irrigation, drinking water, industry). Water level control guarantees the stability of canal embankments, and flushing reduces the salinity in the canals and ditches, caused by seepage of saline groundwater. During an average summer, the total external fresh water inlet amounts 40 to 60 10^6 m^3. In a dry summer, this may increase to about 100 10^6 m^3 (Rijnland 2009). The analysis focuses on the impact of drought on agriculture.

4.3 Model

Figure 3 presents an overview of the model structure. The water demand module generates water demands for irrigation and water level control in rural areas and is a simple two layer grid-based groundwater model with a resolution of 250 by 250 m, taking into account a limited number of

Fig. 3 Diagram showing the basic structure of the model (adapted from Haasnoot et al. (2014))



land use and soil types. For each layer in each grid cell, the model calculates the water balance. First, the potential evaporation is calculated by multiplying the reference evaporation with a crop factor that is specified for each crop and 10-day period. The actual evaporation is a function of the potential evaporation, the moisture in the root zone, and the soil moisture suction (pF value). Lateral flow from groundwater to local surface water and vice versa is a function of groundwater depth relative to surface water level. Water flowing from the root zone to the subsoil (percolation) depends on the root depth, porosity, and precipitation. Capillary rise (flow from subsoil to root zone) is calculated as a function of the groundwater depth below the surface level and the root zone suction (Kabat and Beekma 1994; Oosterbaan 2001). The lower boundary condition of each plot is an annual seepage flux taken from results of the complex model for an average year. In case the root zone and subsoil are saturated, excess water is moved through surface runoff. In urban areas surface runoff is a function of the net precipitation and a runoff co- efficient of 0.8 (Urbonas and Roesner 1993). The water demand is determined from the difference between the actual and potential evaporation. The amount of water requested for maintaining the target water level in the local surface waters areas is derived from the net precipitation and the surface area of these waters. The grid cells are aggregated over a watershed area (called district).

The salt intrusion module simulates the salt concentration at the Gouda inlet depending on river discharge and sea level. This module is based on empirical correlation between the Rhine discharge at Lobith and salt concentrations in the lower river reaches calculated using a 1D hydraulic model (SOBEK) (van den Boogaard and van Velzen 2012).

$$Salt = 1700 + (90 - 1700) \times \frac{e^{Fact}}{1 + e^{Fact}}$$
$$Fact = \left(\frac{Q_{lobith} - 600}{2.211}\right)^{0.309}$$

where Q_{lobith} is the discharge at Lobith in cubic meter per second and *Salt* is the salt concentration at the Gouda inlet in milligram per liter. As discussed in Haasnoot et al. (2014), this relation will slightly underestimate the frequency of closure at Gouda.

The focus of this analysis is on the economic damages to agriculture due to drought. For this, we use Agricom (Mulder and Veldhuizen 2014) which is an agro-economic model to estimate agricultural yield losses due to water shortage, saline soil moisture and water excess. Drought is defined in terms of

$$E_{ratio} = \frac{ET_{act}}{ET_{pot}}$$

Where ET_{act} is the actual evatranspiration and ET_{pot} is the potential evapotranspiration. Given E_{ratio} and crop specific damage curves that take into account the growing season, the E_{ratio} is translated into a loss of yield in kilogram, which in turn is monetized. In our analysis, we calculate both the potential yield in Euro, assuming perfect conditions, and the actual yield in Euro's, allowing us to calculate the relative loss due to deficiencies in the system.

4.4 Results

The response curve of the reference situation is given in Fig. 4. Each point in the curve is a sample from climate variability according the current climate and according to the worst-case climate change scenario for 2100. Together they provide an indication of the range of drought magnitudes that may occur and the corresponding impact on agricultural yield deficit. The vertical range is explained by the timing of the precipitation deficit within the growing season. Some crops are more sensitive to drought in the beginning of the season, while others are more sensitive at the end of the season. Droughts with similar precipitation deficits may therefore occur, but when they differ in timing the impact will differ as well.

There are two lines drawn in the figure: one at 5 % yield deficit and one at 10 % yield deficit. Yield deficits below 5 % are considered not significant, because farmers take into account some level of business risk. The first point that exceeds this line (indicated with an arrow) indicates the *resistance threshold* at 250 mm precipitation deficit. The 10 % line is arbitrarily chosen to indicate the level of unacceptable yield deficit that must be avoided (recovery threshold). Only two of the 35 events exceed this 10 % line in the future climate.

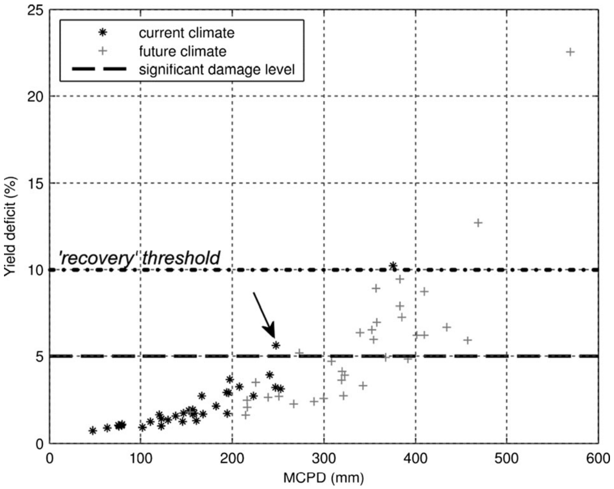


Fig. 4 Response curve of the Rijnland system: yield deficit as a function of maximum cumulative precipitation deficit (MCPD), the indicator for drought magnitude

When it is aimed to enhance the *manageability*, measures should be designed that reduce the impact for these events.

In practice, the location of both the 5 % and the 10 % line is a political choice. In fact, the real recovery threshold in this system will never be exceeded, since it can be expected that the area can still economically recover from 100 % yield deficit (see Mens et al. this issue). The Rijnland system can be considered robust to droughts, because the maximum simulated yield deficit does not exceed 25 % for a large range of precipitation deficits. This can be partly explained by the storage capacity as well as the diversity of crop types that vary in when they are most sensitive to water shortage (Mens et al. this issue).

4.5 Reflection

Although the model obviously is a limited representation of reality, it suffices for the purpose of the robustness analysis. Different model parameter assumptions could slightly change the resistance threshold, but the score on proportionality and manageability is not expected to change. Thus, the conclusion on how well the system is able to deal with a range of drought events is not affected by the choice of the model.

Two types of measures are often considered in a drought risk context: those that increase the water supply and those that reduce the water demand. In traditional decision making approaches, where supply reliability is the main decision criterion, both types of measures will increase the supply reliability. However, a high reliability does not inform about the consequences of low-probability drought events. Additional criteria are thus needed that assess measures on how they affect the system in terms of avoiding large societal and economic impacts due to droughts. The two robustness criteria, resistance threshold and manageability, seem to fulfil this need. More applications are needed to explore how different types of drought risk reduction measures score on the robustness criteria.

We believe that a robust system, that can deal well with frequent as well as rare events, will also be able to deal well with changed variability under a future climate (Watts et al. 2012). Knowledge or assumptions about the future climate variability are not needed to perform robustness analysis. However, climate change scenarios are helpful in determining the range of drought events for which the system's robustness is assessed.

5 An Exploratory Modeling Approach for Designing Adaptation Pathways

5.1 Adaptation Pathways

An emerging approach to the design of climate adaptation plans and strategies is adaptation pathways (Haasnoot et al. 2013; Wise et al. 2014). This approach combines two bodies of literature on planning under uncertainty: work on adaptive policymaking (Walker et al. 2001; Kwakkel et al. 2010; Hamarat et al. 2013) and work on adaptation tipping points and policy pathways (Kwadijk et al. 2010; Haasnoot et al. 2012; Offermans 2012). A plan is conceptualized as a series of actions taken over time. In order to come to a good plan, it is necessary to first identify candidate policy actions and their adaptation tipping points. An adaptation tipping point is the condition under which a given policy action no longer meets its objectives. The point in time at which this happens (the so-called sell-by-date) is scenario dependent. In light of an analysis of the sell-by dates of various policy actions, concatenations of options, or policy pathways, can be specified where a new policy option is activated once its predecessor is no longer able to meet the definition of success. Typically, there is a portfolio of pathways that decision-makers would like to keep open for the future. This adaptation map forms the basis for the plan. Figure 5 shows an example of such a map. For a more detailed elaboration on DAPP, see Haasnoot et al. (2013).

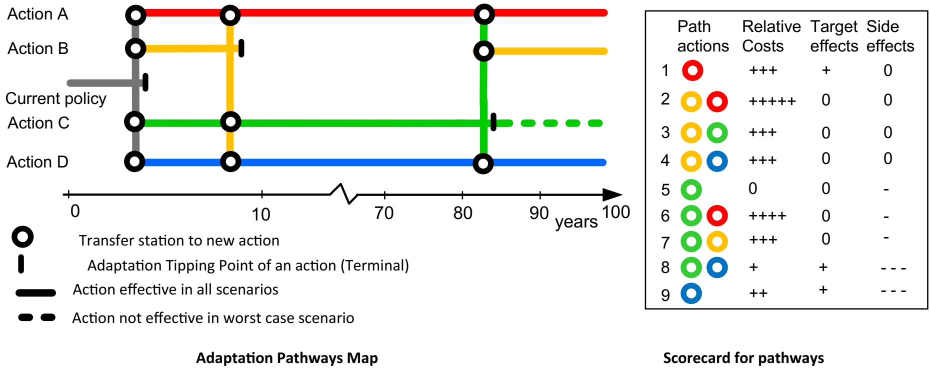
Model-based decision support for the design of adaptation pathways is challenging for a variety of reasons. There exist a wide variety of candidate policies that has to be considered. These policies might be sequenced in different ways, taking into account co-dependencies between the various options. Their assessment needs to explicitly take into account the dynamics over time, rather than some endpoint. The assessment also should cover the variety of outcomes of interest the different stakeholders involved in the decision-making care about. And last but not least, the assessment should cover the variety of irreducible uncertainties that exist and the performance of candidate pathways needs to be assessed over the full range of uncertain factors.

One approach that might be amendable to supporting the design of adaptation pathways is exploratory modeling. Weaver et al. (2013) have argued that adaptive planning requires an exploratory modeling approach. In exploratory modeling, modelers account for the various unresolvable uncertain factors by conducting series of computational experiments that systematically explore the consequences of alternative realizations of the various uncertain factors (Bankes et al. 2013). These computational experiments can be used also a test bed for candidate policies (Lempert et al. 2003).

5.2 The Case, the Model and the Associated Uncertain Factors

As case, we use the Rijnland case as described in section 4. We use the same model as used there with a few small changes. First, we adapted the model to account for the following uncertain factors:

- River runoff in the Rhine
- Rainfall



	Path actions	Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟠 🔴	+++++	0	0
3	🟠 🟢	+++	0	0
4	🟠 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟠	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Adaptation Pathways Map **Scorecard for pathways**

Fig. 5 An example of an Adaptation Pathways map (left) and a scorecard presenting the costs and benefits of the 9 possible pathways presented in the map. In the map, starting from the current situation, targets begin to be missed after 4 years. Following the grey lines of the current plan, one can see that there are four options. Actions A and D should be able to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first 4 years, a tipping point is reached within about 5 years; a shift to one of the other three actions will then be needed to achieve the targets (follow the *orange lines*). If Action C is chosen after the first 4 years, a shift to Action A, B, or D will be needed after approximately 85 years in the worst case scenario (follow the *solid green lines*). In all other scenarios, the targets will be achieved for the next 100 years (the *dashed green line*). The colors in the scorecard refer to the actions: A (*red*), B (*orange*), C (*green*), and D (*blue*)

- Land use
- Evatranspiration

For each of these sources of uncertainty we use transient scenarios (Haasnoot et al. 2014) to address them. So, rather than looking at the system in e.g., 2050, we consider the change over time from the current system to the state of the system in 2100. For river runoff, rainfall, and evapotranspiration we use different possible realizations of the climate scenarios W+ and G.. These are climate scnearios for the Netherlands and have been developed by the Dutch Royal metrological institute. W+ is an extreme warming scenario, while G represents a modest warming scenario (KNMI 2006). These realizations are the same as those used by Haasnoot et al. (2014), although here we only use the parts relevant to the case study area. We use 10 possible realizations of both scenarios. For land use, we use the land use as described in the four delta scenarios as developed in the Deltaprogram. These scenarios are labelled Warm, Pressure, Rest, and Steam. These delta scenarios combine the 2006 W+ and G climate scenarios (KNMI 2006) with socio-economic scenarios. Figure 6 shows the scenario logic for the scenarios. Maps were available for 2050 and 2100. We interpolated the maps in between. Given that we sum up over the region, a rather simple and crude interpolation has been used. Combining the different realizations with he delta scenarios gives 40 scenarios. To assess the role of changing land use, we include, in addition to the changing land use also a no change case, giving 60 scenarios in total (i.e., Warm, Pressure, Rest, Steam, No change W+, and no change G). Note that in the current results land use has some influence on water demand, but the irrigation maps do not evolve with land use.

5.3 Results

A variety of analyses have been carried out. As a first experiment, we explore how the system responds if water supply is deliberately closed. To this end we simulate two situations. In the first situation, we keep the water inlet at Gouda open at all time, in the other, we close the inlet at all times. We assessed the performance for both situations by analyzing the results for 5000 experiments. A boxplot for the loss of income of farmers due to reduced yields in both situations is shown in Fig. 7. So, this is the monetized loss of yield as explained near the end of section 4.3. As can be seen, there are a few more extreme cases in terms of income loss when

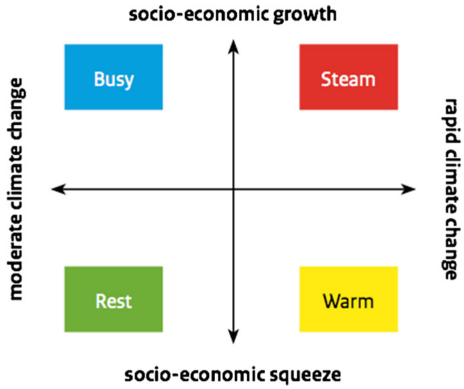


Fig. 6 The scenario logic of the delta scenarios (adapted from (Delta Programme 2012)

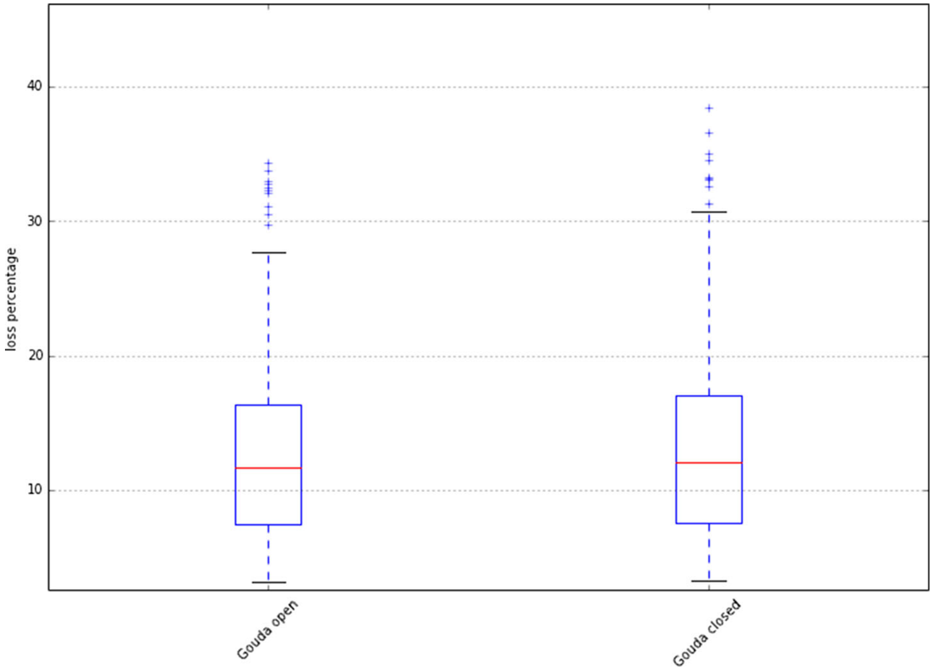


Fig. 7 Boxplot of percentage income loss for farmers due to a reduction in yields, comparing the situation where the fresh water inlet at Gouda is open at all times with the situation where the fresh water inlet at Gouda is closed at all times

the Gouda inlet is closed at all times. Still, the differences are quite small and it is relevant to investigate this further.

In order to understand why there is only a minor difference in income loss between the situation where the fresh water inlet at Gouda is always open, and the situation where the fresh water inlet at Gouda is always closed, we looked at the worst-case delta scenario. In this scenario, warm, the system experiences severe climate change, combined with substantial land use developments putting even more pressure on the system. We explored the behavior of the system for all ten possible realizations. The resulting water demands per decade are shown in Fig. 8.

In Fig. 8 we compare the water demand at a decade level for only those situations where Gouda is closed on the one hand, and for all decades on the other. As can be seen, during the decades during which the fresh water inlet at Gouda is closed, the water demand is quite small. In fact, the demand is below the supply available via the small scale water supply (5 cubic meter per second). As such, no severe water shortages occur. This suggests that decades with high demand for fresh water do not coincide with low runoff off of the Rhine. In light of this analysis, it appears that no future adaptation actions are necessary. There are a few caveats with this conclusion.

First, the relation used to calculate closure of Gouda is known to underestimate closures (Haasnoot et al. 2014). As such, a closer analysis on a different time scale might be needed. The current analysis uses decades, and it might be necessary to shift to a daily analysis to get a better insight into what is happening.

Second, the model does consider land use change. This land use change affects water demand. We have not translated the changes in land use into changes in the areas being irrigated. Doing so is possible. Ter Maat et al (2013), for example, introduce several additional assumptions regarding future irrigation demands, allowing the translation of land use change into changes in water demand.

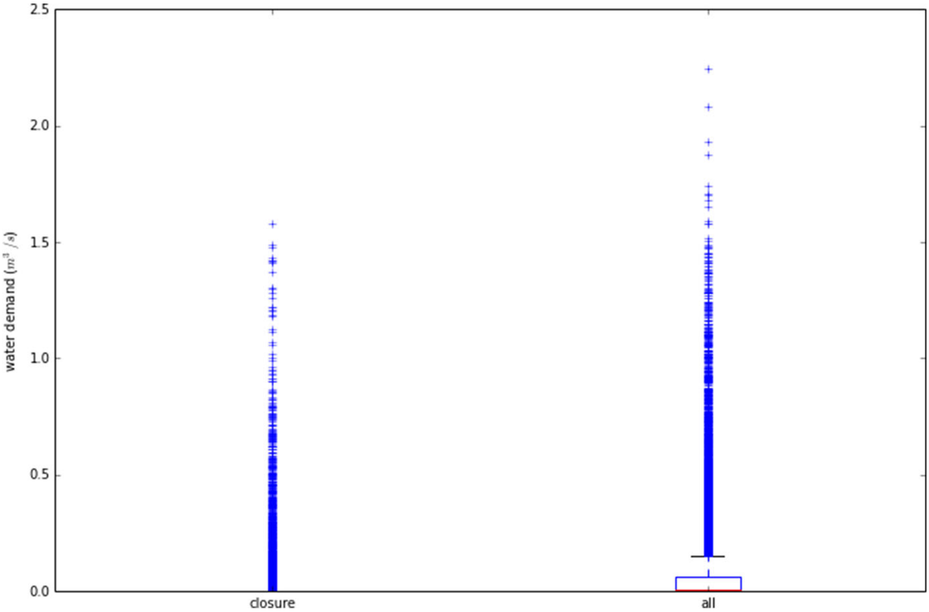


Fig. 8 Water demand per decade for the Warm scenario. The left hand boxplot contains the water demand when the fresh water inlet at Gouda is closed because of salt intrusion. The right hand boxplot contains all the decades irrespective of whether the fresh water inlet at Gouda is closed or not

We speculate that one of the reasons for the differences between the results reported here and those reported in ter Maat et al. (2013) are due to how changes in land use affect irrigation.

Third, it appears that the model at every time step resets the water levels to the norm height. Inspection of the source code of the model did not provide clarity as to where the water for this comes from. That is to say, it appears that a hidden assumption in the model is that that the full capacity of the KWA is available for maintaining water levels. Based on ter Maat et al. (2013), this assumption is questionable. If the model were modified such that the KWA is first used to maintain water levels, and only subsequently if possible for irrigation, it is plausible that there would be more severe fresh water shortages for irrigation. In turn, this would increase the income loss of farmers.

From a methodological point of view, the main conclusions of the analyses reported on are that it is possible to consider a wide range of different uncertainties simultaneously. Exploratory modeling offers an approach for systematically mapping out the consequences of various uncertainties. We also demonstrated that it is possible to do a variety of potentially useful further analyses on the exploratory modeling results. On the one hand, these analyses provide usefull information for policy-making. On the other hand, the analyses create new insight into the behavior of the models. Moreover, these kinds of analyses can also help in assessing the usefulness of models, since they stress test the model and clarify the domain over which the model provides meaningful results.

6 Conclusions and Discussion

Long term planning for fresh water supply faces a variety of sources and types of uncertainty, many of which cannot be adequately dealt with using probabilistic approaches. In response, a variety of complementary approaches has been proposed and developed to explicitly recognize and deal with these uncertainties. On the one hand, analytical methods are being developed to capture and assess uncertainties and their impacts, on the other, various action strategies are proposed in view of uncertainties, including approaches based on robustness, on resilience, and on flexibility and adaptation. We have illustrated the application of respectively a resilience approach, a robustness approach, and an exploratory modeling approach. Reflecting on these different approaches, we observe that the robustness approach requires quantification of uncertainties and computational analysis. The exploratory modeling approach builds on computational power and enables exploration of a broad set of possible assumptions about the future while relaxing requirements of probabilistic specification.

The resilience approach, on the other hand, is primarily qualitative. As a result, the effectiveness and efficiency of resilience options is difficult to assess in quantitative terms. But the resilience approach may, as illustrated, be more suitable for tailoring adaptation to local situations, and appeal to notions of stakeholder involvement and ownership, self-governance and self-reliance. In contrast to the robustness and exploratory modelling approach, the resilience approach can be used for those adaptation policy challenges where the state of scientific knowledge does not (yet) allow a sufficiently adequate form of quantification of impacts at the spatial and temporal scales that are pertinent to that particular adaptation policy challenge.

Application in the Venen-Vechtstreek case illustrates that the resilience approach enables involvement of multiple stakeholder perspectives and consideration of multiple societal reactions (that in turn can influence the effectiveness of the various management options) as well as a range of other criteria relevant to the decision making challenge such as costs and co-benefits of the management options. In our workshop, the co-benefits turned out to be crucial to obtain support for resilience-based climate adaptation measures from local stakeholders such as farmers. The approach is especially useful for a quick screening of management options.

The robustness approach focusses on a partial challenge around a single metric (vulnerability of the present fresh water system from the view point of the water manager only), but enables spatially explicit detail and quantitative assessment of societal costs and benefits often required in policy making contexts to justify interventions that affect various stakeholders in various ways.

In practical terms, the resilience approach is useful in the phase where long term management and adaptation strategies for a region are being designed in multiple stakeholder processes and considering multiple impacts on multiple sectors. Robustness analysis is more useful to assess specific issues (vulnerability to a specific impact for a specific sector), and fit for situations where the relevant set of future scenario's is known and quantifiable. As such the approaches can be highly complementary (see also Wardekker et al. 2010). Especially in cases where decisions on dimensioning of options is key, a combination of approaches can have added value: if a resilience based screening of options reveals the wish to create fresh water buffers in an area (buffering) or to increase the inlet of fresh water from outside the area (ominvory), then a specific robustness analysis can help to answer the questions how big the buffer should be or what is the required capacity of the extra fresh water inlet should be.

More generally speaking, in practical cases different types of uncertainties will play a role, and analyses and strategies at different levels will be needed. As a result, a tailored combination of different approaches may be the best way forward, combining more top-down measures with bottom-up approaches. Clearly, both the analytical approach and the choice of strategies will have to be tuned to the characteristics of the situation, and more research and experience are needed to increase our understanding of the advantages and disadvantages for various approaches, and how they relate to the various types of uncertainties.

Another lesson from the cases presented here is that the match between the choice of policy objectives (which possible impacts do we seek to reduce with the adaptation policies) and the choice of scope and system boundaries of the scientific assessment carried out to support that decision making process is crucial. Is the key concern in agricultural impacts the *physical* yield (in kg of crops per ha) or the *economic* yield (in monetary units per ha)? Should we focus on the robustness of water *supply* only (how can we maintain the fresh supply under future climates to meet the given future demand) or should we address the robustness of the *entire* fresh water system? In the latter case, adaptation of water *demand* to a reduced supply would also need to be considered in the scientific assessment. This relates to the question whose perspective should guide the scientific assessment and who is and is not deemed responsible for adaptation.

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