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Managing saltwater intrusion in coastal arid regions and its societal implications for agriculture

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Abstract. Coastal aquifers in arid and semiarid regions are particularly at risk due to intrusion of salty marine water. Since groundwater is predominantly used in irrigated agriculture, its excessive pumping – above the natural rate of replenishment – strengthen the intrusion process. Using this increasingly saline water for irrigation, leads to a destruction of valuable agricultural resources and the economic basis of farmers and their communities. The limitation of resources (water and soil) in these regions requires a societal adaptation and change in behaviour as well as the development of appropriate management strategies for a transition towards stable and sustainable future hydrosystem states. Besides a description of the system dynamics and the spatial consequences of adaptation on the resources availability, the contribution combines results of an empirical survey with stakeholders and physically based modelling of the groundwater-agriculture hydrosystem interactions. This includes an analysis of stakeholders' (farmers and decision makers) behaviour and opinions regarding several management interventions aiming on water demand and water resources management as well as the thinking of decision makers how farmers will behave. In this context, the technical counter measures to manage the saltwater intrusion by simulating different groundwater pumping strategies and scenarios are evaluated from the economic and social point of view and if the spatial variability of the aquifer's hydrogeology is taken into consideration. The study is exemplarily investigated for the south Batinah region in the Sultanate of Oman, which is affected by saltwater intrusion into a coastal aquifer system due to excessive groundwater withdrawal for irrigated agriculture.

1 Introduction

Sustainable water management strategies are required to meet future water demands considering the predicted changes e.g. for population growth and climate as well as the diverse availability of water resources worldwide (WWAP, 2015). Since environmental systems are intensively used by human interventions, societal, environmental, and economic aspects needs to consider for evaluating appropriate management options for regional development (see IWRM definition, GWP-TAC, 2000). As a prerequisite, fundamental knowledge about linkages and feedbacks of the various system components is needed to portray the complexity of systems and the outcome of future scenarios adequately (Montanari et al., 2013). This includes considering different sectors and resources with their relevant players and stakeholders (Hering and Ingold, 2012). Each of them having different interests and mostly contradicting objectives which have to be formulated in a multi-objective, multiple-decision maker water management problem. To handle this complexity for planning of water management options and actions participatory approaches are recommended following a systematic procedure based on an appropriate system of well-defined objectives, criteria and indicators for evaluating, discussing, and negotiating different water management options (Soncini-Sessa et al., 2007).

The contribution focuses on water management of coastal (semi-) arid regions, as an example of water a management problem under limited resources. Besides a description of the system dynamics and the spatial consequences of adap-

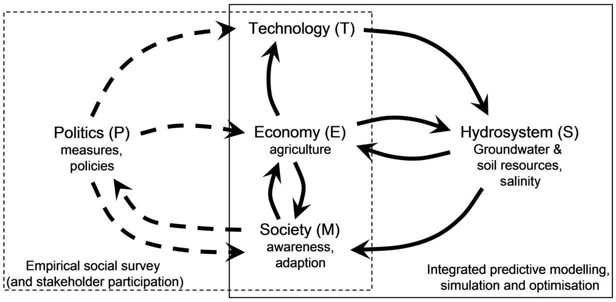

Figure 1. Schematic of system dynamics for managing saltwater intrusion in agricultural coastal plain.

tation on the resources availability, the contribution seeks to determine selected indicators for social, environmental and economic criteria in order to evaluate different water management options and policies. Results are obtained from empirical social surveys about stakeholders' behaviour and opinions on possible management interventions and an integrated predictive physically based modelling system of the groundwater-agriculture interactions. The study is exemplarily investigated for the south Batinah region in the Sultanate of Oman, which is affected by saltwater intrusion into a coastal aquifer system due to excessive groundwater withdrawal for irrigated agriculture.

2 Methods

2.1 Conceptualizing societal adjustment to saltwater intrusion

The principles of societal adaptation on saltwater intrusion are illustrated in Fig. 1. The linkages between the system components agricultural economy (E), hydrosystem (S), technology (T), society (M) and politics (P) are displayed by lines with arrows showing their direction. The adaptation as a consequence of saltwater intrusion is illustrated by solid lines. Due to an increased application of technology (T) for groundwater pumping as well as inefficient agricultural practices (E) from a society (M) showing less awareness about resources limitation, the groundwater-soil-hydrosystem (S) is damaged by salinity which feeds back to agriculture (E) by reduced crop yields and society (M) which loses its connection to water of good quality. Management feedbacks are illustrated by dashed lines. They are triggered by the request of the society (M) to politics (P), which may respond by different actions focusing/supporting on technology (T), agricultural practices (E), and society's behaviour (M), through e.g. technological countermeasures, agricultural incentives or education. The system components and their linkages are assessed and evaluated by different types of investigation and modelling (see rectangular boxes in Fig. 1). The responses of the system components on management interventions can be described by several criteria characterising the system states in the modelling system as well as the acceptance of interventions in the society represented by concerned stakeholders (e.g. decision maker (P), farmers (M)). Selected criteria as well as the methods of their determination are described in the following.

2.2 Integrated predictive modelling, simulation and optimisation

Physically based modelling of bio-physical processes is applied to portray the interactions between the agriculture and the groundwater-soil hydrosystem (S) and to obtain predictions of unknown future system states. Groundwater flow phenomena introduced by different geological units and water quality problems caused by saltwater intrusion are simulated using a density dependent transient groundwater model (Kolditz et al., 2012). Water abstraction in terms of water amount and quality (i.e. salinity of water) for agricultural production is realized by several vertical wells positioned at different distances from the sea to represent farm locations. The impact of management interventions represented by groundwater pumping schemes on the groundwater system is indicated by changes of salinity concentration s and water levels h on x_k observation points between the end t_n and the initial state t_1 of the simulation period. It is calculated by a sustainability index SI (Eq. 1), where a small value shows a high stability of the aquifer system.

$$\mathrm{SI}(t_n) = \sum_{k=1}^{\mathrm{end}} \frac{\mathrm{abs}\left(s(t_1, x_k) - s(t_n, x_k)\right)}{s_{\max}} + \sum_{k=1}^{\mathrm{end}} \frac{\mathrm{abs}\left(h(t_1, x_k) - h(t_n, x_k)\right)}{h_{\max}} \quad (1)$$

The adaption of the society (M) on the water quality is addressed by implementation of a moving inner boundary condition in the numerical density dependent groundwater model, which adjusts the locations for groundwater abstraction according to the position of the saltwater intrusion front controlled by thresholds of relative chloride concentration. The adaption process is performed for each management cycle within transient model simulations and allows for considering feedbacks with the society (M) by moving agricultural farms more inland or towards the sea if more fertile soils at the coast could be recovered.

The behaviour of agricultural farms and its economy (E) is simulated by a database of crop-water-production functions which is constructed by an extension of the OCCASION methodology (Schütze and Schmitz, 2010; Schütze et al., 2012) presented in Grundmann et al. (2012). It describes the relationship between the applied amount of water, its salinity and the produced yield for a given combination of crop/soil/climate under the assumption of optimal water application considering climate uncertainty. Assuming a rational behaviour of the farmers the Profit from agricultural

Table 1. Selected results of a social survey for potential management interventions.

Intervention measures	Farmers (mean)	DM's (mean)	Farmers (SD)	DM's (SD)	p value	Direction	System impacted
Introducing water quotas	3.47	1.88	1.391	1.023	0	D	E
Introducing water quotas with subsidies in form of equipments for modern irrigation systems	2.75	1.7	1.309	0.779	0	D	E, T
Use of treated wastewater for agricultural use, if it is available and the quality is acceptable	2.17	1.61	1.092	0.834	0.001	R	T
Encourage the farmer to reduce the withdrawal of groundwater by guidance and training	2.31	1.63	0.974	0.756	0	D	M
Implementation of centralized well fields which provides water in a good quality to farmers	2.42	2.27	1.193	1.162	0.458	R	T
Convince the farmer to change the type of crops to ones with lower crop water requirements	2.48	2.03	1.084	1.058	0.017	D	E
Encourage farmers to improve irrigation methods	2.02	1.45	0.968	0.61	0	D	T
Construction of more desalination plants for brackish and seawater for use in irrigation	2.14	3.09	1.082	1.311	0	R	T
Increase the effectiveness of water use by public awareness	1.55	1.46	0.561	0.636	0.424	D	M
Introduce water prices for pumped groundwater	3.92	2.48	1.276	1.133	0	D	E
Forming water managers groups	1.88	1.91	0.864	0.9	0.819	D	M, E
Stop all agricultural activities in the coastal zone	3.28	3.79	1.315	1.32	0.029	–	E, M
Leave the system as it is (No action)	4.09	4.19	1.205	1.305	0.649	R	–

production is calculated (Eq. 2), where CI_j and CP are fixed and variable costs for irrigated agriculture and groundwater pumping respectively, Pr_j the current prices for the cultivated crops $j = 1, \ldots, m$ which are produced from the acreage L_j for the cultivation period $i = 1, \ldots, n$, and Y_j the crop yield.

$$\mathrm{Profit} = \sum_{i=1}^{n} \left[\left(\sum_{j=1}^{m} \mathrm{Pr}_j Y_j(t_i) L(t_i) - \mathrm{CI}_j(t_i) \right) - \mathrm{CP}(t_i) \right] \quad (2)$$

Technology (T) is represented on the water abstraction side by different types of pumps having different economic and hydraulic behaviour (pump characteristic curves). On the water consumption side, different irrigation technologies are considered via their irrigation efficiencies and production costs.

The described simulator is used in a simulation–optimisation framework to find optimal solutions for water management considering contradicting objectives. Two main principles are applied to achieve a fast and reliable operation of the system: (1) customized tuned simulation-optimization based on surrogate models, which emulate the behaviour of the process models and (2) the decomposition of complex optimization problems into smaller, independently solved problems (Grundmann et al., 2014).

2.3 Analysis of stakeholder's behaviour and opinions

One of the most appropriate tools to explore the opinions of stakeholders in a domain is a social survey by distributing questionnaires and face to face interviews. After identification of relevant stakeholders e.g. water professionals, farmers from the study area and decision makers from different organizations, a pre-test survey is performed to collect stakeholder's ideas for possible management interventions. Afterwards questionnaires are designed and a social survey is performed to collect a combination of environmental, social and economic data as well as opinions regarding several management interventions from stakeholders. The obtained data are analysed statistically for each group separately by calculating primary statistic measures like mean and standard deviation. Applying these statistics on the list of management interventions indicates the degree of acceptance of an intervention by the group. Differences between opinions of groups are examined by an independent sample t test. If calculated p values are next to zero, significant differences between opinions of groups existing, which indicate a low implementation potential for the intervention measure from the social point of view (M, P).

3 Results and discussion

Selected results are presented for a study performed in the south Al-Batinah region of Oman. The region is affected by saltwater intrusion into an alluvial coastal aquifer system due to uncontrolled, excessive groundwater withdrawal for irrigated agriculture by numerous small scaled farms located in different distances from the sea. The marine saltwater intrusion process is ongoing since many years and led to a continuously increasing number of abandoned farms and a damage of valuable soil resources for agriculture.

A social survey was performed for collecting data and opinions from more than 130 stakeholders in the study area (Al-Khatri et al., 2014). Stakeholders were split into 2 groups; (1) farmers from the region and (2) decision makers and experts. Amongst other issues they were asked to rate several management options and interventions between 1 (strongly agree) and 5 (strongly disagree). Selected results for some interventions are presented in Table 1 by their mean, standard deviation (SD) and p values. Furthermore, it is indicated in the table if the management options and interventions either focus on water demand side (D) measures to reduce water consumption and use the resources more efficiently, or on water resources side (R) measures to increase the availability of water. Additionally, the system component (see Fig. 1) impacted by the measure is addressed. Results show that the need of improvement and implementing new management strategies is supported by all groups of stakeholders. In most cases, farmers are more likely to interventions of increasing water availability (R), while decision makers (DM's) were more likely to demand management (D). Opinions of farmers are mostly more diverse than DM's opinions shown by SD values. Results showing the functionality of the simulation-optimisation framework can be obtained from Grundmann et al. (2014).

4 Conclusion and outlook

The paper deals with a management problem under limited resources availability (water and soil) and quality, illustrated on the situation of arid coastal regions infected by marine saltwater intrusion and its implications on agriculture and society. A simulation-optimisation framework of bio-physical processes allows for multi-objective optimization of sustainable water resources and profitable agricultural management on farm and regional scale by providing optimal groundwater abstraction schemes and an appropriate choice of crop patterns regarding their salinity tolerance. Furthermore, trade-offs between contradicting objectives can be explored (Grundmann et al., 2013) and help to understand system behaviour and the impact of different management strategies on the society. Working with stakeholders by using empirical social surveys show the implementation potential of management interventions and foster a participatory process for supporting decision makers to take more informed decisions. Statistical analysis of stakeholder's responses helps to identify contradicting opinions between and within groups. Understanding the drivers behind these opinions offers the opportunity to trigger the acceptance of management interventions, which is part of our ongoing research. Due to complexity of processes and linkages in coastal systems there is no single solution which fits all constraints and requirements. Therefore, future work is focused on supporting management decisions by the development of indicators and criteria to evaluate management options preferably within a participatory stakeholder dialogue as well as to develop methods for identifying and scheduling appropriate combinations of measures considering different response times of system components.

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