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A practical planning software program for desalination in agriculture - SPARE:WATER^{opt}

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HIGHLIGHTS

- A novel tool for optimizing the use of desalinated water in irrigation agriculture
- Spatial (available land) and temporal (daily water supply) optimization of water utilization
- Balancing water supply and demand made possible using 97% of available water
- Gross margin is maximized by a cropping pattern dominated by cash crops using 77% of available water.
- Irrigation by seawater desalination can be economically feasible for cash crops.

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ABSTRACT

Water shortage limits agricultural production worldwide, and irrigation leads to a rapid depletion of water resources. Using desalinated water for irrigation reduces pressure on local resources but it is expensive. An economically viable utilization for using desalinated water in agriculture is only possible through the optimal planning and management of cropland and irrigation scheduling management. We developed a software program aiming to maximize the gross margin (GM) by optimizing cropping patterns using a site-specific crop water requirement model. We used the simplex algorithm under the boundary conditions of limited water (temporal scale) and available land (spatial scale). In a proof of concept, we tested the software for a desalination plant in Saudi Arabia that produces 60,000 m^3 day^{-1}. A cropping pattern for 4278 ha was derived that maximizes GM (92 Mio US\$ yr^{-1}) and uses most (97%) of the constant water supply to the plant. An optimal cropping pattern (4023 ha) solely maximizing GM yields a higher outcome (125 Mio US\$ yr^{-1}) and requires even less water for irrigation. This surplus water can be used for leaching soils or other purposes. Both cropping patterns are dominated by cucumber and tomatoes, covering the largest fractions of cropland at 74% and 88%, respectively.

1. Introduction

1.1. Agricultural development by desalination

A vast increase in food prices on the global market has been observed since 2003, and several reasons have been discussed, e.g., weather shocks, increasing oil prices and financial market speculation [1]. Prices for primary commodities, such as rice, wheat, soybean and maize, increased threefold or more until peaking in 2008. After that, the prices dropped again. Investments in agricultural research and development are helpful to prevent food prices from undergoing such severe increases [2]. Because many regions worldwide face an increasing unsustainable use of local

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water resources [3] and increasingly rely on foreign water resources to support their growing populations [4], alternative pathways must be developed to support agriculture with water because the current solutions are often closely associated with local water resource depletion [5,6]. The desalination of seawater provides such an alternative and may be helpful to partly counteract water scarcity [7]. In particular, comprehensive investments in large-scale desalination are needed to ensure a sustainable development as reported for the Gulf Cooperation Council countries (GCC) [8]. The question arises as to how available water resources from new investments, as well as existing ones, can be used optimally. The importance of modelling tools has been recently highlighted to solve such integrated problems regarding the energy, water and food nexus [9] and to ensure a sustainable use of desalinated seawater for agriculture [10]. In this study, a novel spatial decision support system (sDSS) is presented to optimize desalinated water use for agriculture. Because optimal agriculture management is important to successfully utilize desalinated water for irrigation [11], a particular emphasis is given to the factors of irrigation technology, salinity and crop salt tolerance, which have been reported to be major determinants for investigating the potential of agricultural production on the Arabian Peninsula [12]. It has been shown that irrigation technology has a high impact on the national water consumption [13] because changes in cropping pattern as well as the implementation of modern irrigation technology can reduce water consumption by up to 32% in Saudi Arabia [14].

1.2. Desalination technology and cost

Improved desalination techniques [15] may reshape agricultural production. The applicability of different desalination techniques to provide water for irrigation has been recently reviewed [11], and the authors stress the suitability of reverse osmosis (RO) for agriculture purposes. However, Shaffer et al. [16] highlight the potential of forward osmosis technology coupled with RO for agriculture purposes compared to the sole application of RO because of its better water quality at lower costs. Efforts have been made to use renewable energy for running plants, e.g., by photovoltaic power, wind power or solar energy, and the feasibility of the application of desalination with renewable energy has been discussed widely [17,18].

The costs for desalinated water are still high compared to the utilization of surface or groundwater for irrigation because the latter ones have no or only low prices in most countries. In most cases, only pumping costs are incurred. Generally, it is often unclear whether the cost for desalination includes capital and investment costs or the planned lifespan of the desalination plant [19–21], which makes difficult a general comparison of literature data on desalination costs. For example, the price for desalination using RO ranges between 0.5 and 1.2 US\$ m^{-3} [19], which is high compared to the water costs of 0.05 € m^{-3}, as reported for an irrigation district in Spain [22] using surface water resources for irrigation. The key question is as follows: how much are farmers willing to pay? Barron et al. [23] conducted a nationwide study in Australia based on various datasets of water availability, quality and economic aspects and stated that farmers a likely to spend no > 1.2 AU\$ m^{-3} (1.0 AU\$–0.7 US\$). In contrast, a water price between 0.14 and 0.35 US\$ m^{-3} has been reported for an irrigation district in Jordan [24]. Overall, desalinated water remains an expensive resource, and its consumption should be managed properly to avoid wasting precious water and to ensure an economically feasible utilization.

1.3. Optimization of water allocation

To optimize water resource use, different scales and factors must be considered, i.e., (i) the spatial allocation of water (e.g., between districts) [22,25,26], (ii) the crop selection and cropping patterns [26] and (iii) the timing of the crop irrigation schedule [27], in addition to the amount of available irrigation water. The optimization of cropping pattern is often conducted by coupled crop water economic optimization models, assuming a fixed water supply. The optimization is often performed in a hierarchical way, e.g., Garcia-Vila and Fereres [22] derived crop productivity functions for site-specific conditions with a dynamic crop model (AquaCrop [28,29]) under various supplies. These functions are then used in a second step in an economic model to optimize management. Reca et al. [30] used a three-step hierarchical system to optimize water use: on the field level for single crops, on the district level for cropping pattern and on a hydrological system scale for complete land cover. Pandey et al. [31] used the Cropwat model [32] in a three-phase approach to optimize the field level water use as well as the cropping pattern. Shanguuan et al. [33] applied in their hierarchical approach three layers with different objectives in order to maximize crop yields, the benefit of the cropping pattern and the benefit at the basin scale. The objective functions that are commonly optimized is the gross margin [22,25], the water use efficiency, or a combination of both. Others optimize the gross income, net income, irrigation water productivity or labour use [26], as well as crop yield [34]. Net farm income, minimization of waterlogging and minimization of groundwater depletion are listed in another review [35]. Most optimization approaches are restricted by limitations, e.g., maximum and minimum percentages for each crop to prevent optimization for favouring only high-value crops [25], land and water availability [31] and irrigation depth [30]. Such limitations are implemented by penalty functions [25] or limited parameter ranges as is often the case for cropping patterns [30].

Mathematical algorithms are used to solve the optimization problem. Four methods, i.e., linear, non-linear and dynamic programming and a genetic algorithm, have been recently discussed in the context of irrigation management optimization [35]. To solve nonlinear problems, simulated annealing (SA) comes into play. The simulated annealing approach has been recently reviewed for conjunctive water use management, and the practicability of combining optimization approaches and simulation models has been highlighted [36]. Brown et al. [37] used such a coupled approach to optimize irrigation scheduling using simulated annealing and the FarmWi\$e/APSIM model. They showed that pasture yields could be increased by 10% through optimal irrigation scheduling in Canterbury (New Zealand). In the case of multi-objective optimization problems, which are limited by several constraints, linear programming is an often-applied method. A popular linear programming optimization method is the simplex algorithm [38,39]. This algorithm enables an effective and straightforward implementation of boundary conditions, which is important in the case of planning land use under a limited water supply and other constraints. Sadeghi et al. [40] optimized the management of a watershed in Iran using the simplex method, showing that soil erosion could be reduced and the net benefits increased through the optimal planning of orchards, irrigation and dryland farming. Khare et al. [41] utilized an economic engineering optimization model based on the simplex algorithm. They derived optimal cropping patterns supplied by either surface or groundwater for a planned canal system in India. The results indicate potential water saving through inter-basin water trade. Chen et al. [42] applied the Conversion of Land Use and its Effects (iCLUE) program, which implements the simplex method for optimizing land-use pattern for an area in Northern China. The authors highlight the practicability of the proposed method to ensure ecological security at the regional scale.

1.4. Study objective

Countries experiencing food price shocks as observed in the last decade [1] require measures to increase resilience. This leads to the need for further investments in research and development in the agricultural sector [2]. As part of Saudi Arabia's strategy to cope with limited water resources, desalination is proposed as one measure to address water shortage [8]. Given that agriculture is the largest water-consuming sector in Saudi Arabia, constituting > 90% of the total water use [43], there is greater potential to improve irrigation management in order to make the best use of this expensive resource. Potential strategies to improve desalinated seawater use in agriculture include the spatial reallocation of crops, the diversification of cropping patterns and the optimization of water use over time