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STOCHASTIC OPTIMIZATION OF IRRIGATION SYSTEMS UNDER WATER RESOURCE CONSTRAINTS FROM PLOT TO REGIONAL SCALE USING DECOMPOSITION

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Summary. Many regions in the world which are used for agriculture are highly water stressed and water resources often overexploited. In this contribution a new stochastic simulation optimization framework for decision support for optimal planning and operation of water supply in irrigation is introduced. This consists of (i) a weather generator for simulating climate variability and regional impacts of climate change on the basis of IPCC scenarios; (ii) a tailor-made evolutionary optimization algorithm for optimal irrigation management with limited water supply; (iii) mechanistic models for simulating water transport and crop growth in a sound manner; and (iv) a kernel density estimator for estimating stochastic productivity, profit and demand functions by a nonparametric method. A decomposition solution strategy is developed which allows the use of numerical process models together with Monte Carlo simulations for a reliable estimation of higher quantiles of the minimum agricultural water demand of deficit irrigation strategies at plot and regional scale. As a result of several simulation/optimization runs within the framework stochastic crop-water production functions (SCWPF) for different crops are presented which can be used as a basic tool for assessing the impact of climate variability on the risk for the potential yield. In addition, microeconomic impacts of climate change and the vulnerability of the agro-ecological systems are discussed. Finally, an application to a real case problem in south Al-Batinah region in the Sultanate of Oman is presented where a coastal aquifer is affected by saltwater intrusion due to excessive groundwater withdrawal for irrigated agriculture.

1 INTRODUCTION

Arid and semi-arid areas that are intensively used for agriculture, are facing water shortage which is often intensified by an overexploitation of existing water resources. Accordingly, they show an increased sensitivity to water stress and a high vulnerability that can only be reduced by a highly efficient and foresighted water resource management practices. One way to achieve this objective is an improvement of water productivity (WP) which needs a good quantitative understanding of the relationship between irrigation practices and grain yield, i.e. crop water production function (CWPF). With this knowledge, the value of each unit of water applied to a field can be estimated and compared with alternative uses within and beyond the agricultural sector. Automated soil and plant-based sensing scheduling methods are one option for reducing watering volumes for full irrigation systems and, at the same time, increase WP. However, much greater sophistication is required if the objective is to improve the overall irrigation water productivity by applying a deficit irrigation strategy (DI)[1]. A relatively new technique with respect to increased water productivity is controlled deficit irrigation[2]. For deficit irrigation it is necessary to find an optimal irrigation schedule under which crops can sustain an acceptable degree of water deficit and yield reduction. To date, mostly open loop contol techniques are applied for providing optimal schedules which maximize yield. This optimization strategy is based on forecasts or scenarios generated by weather generators and simulations of the water balance and crop production of an irrigation system for a whole growing period in advance. Optimal open loop control leads in general to a mixed integer optimization problem which is difficult to solve, since the number of decision variables (i.e. the number of irrigations) is a priori unknown. For this reason, recent studies tend to simplify the optimization problem either by fixing the irrigation dates[3] or the irrigation intervals[4]. In addition, heuristic optimizing algorithms such as the Nelder-Mead simplex method[3] or simulated annealing[4] are used which, unfortunately, may fail in practice when: (a) local optimal solutions exist, or (b) the number of decision variables becomes too large, or (c) they require unreasonable computation power and time using brute-force approaches[5]. A recently developed evolutionary algorithm by[6] avoids the above disadvantages and reduces the computational effort for calculating optimal schedules considerably.

The optimal deficit irrigation strategies developed by[6] and others disregard the influence of the stochastic properties of the relevant climate factors (e.g. precipitation and temperature) and of the soil properties which limits their applicabilities. Recent studies[7,8] try to analyze possible impacts of climate variability and climate change on agriculture, based on process-based simulation models. Most of the published work deals with rainfed or non-irrigated sites or assume a full irrigation management. A few papers[8,9] focus on deficit irrigation systems and the impact of climate variability on crop water production functions (CWPF).

The objective of this study is to demonstrate how to apply an efficient scheduling algorithm for evaluating potential yield and corresponding risks in deficit irrigation strategies, i.e. generating stochastic crop water production functions (SCWPF) and derivatives such as stochastic productivity functions, profit functions and water demand functions. The new methods are already used as a building block for estimating water demand within a new Assessment-, Prognoses-, Planning- and Management tool (APPM) for the design and operation of multi-quality irrigation water supply systems in arid countries[10].

2 STOCHASTIC OPTIMIZATION FRAMEWORK

In the following we briefly present a methodology which allows for quantifying the impact of climatic variability on CWPF by a two-dimensional probability distribution, which is referred to as stochastic CWPF (SCWPF).

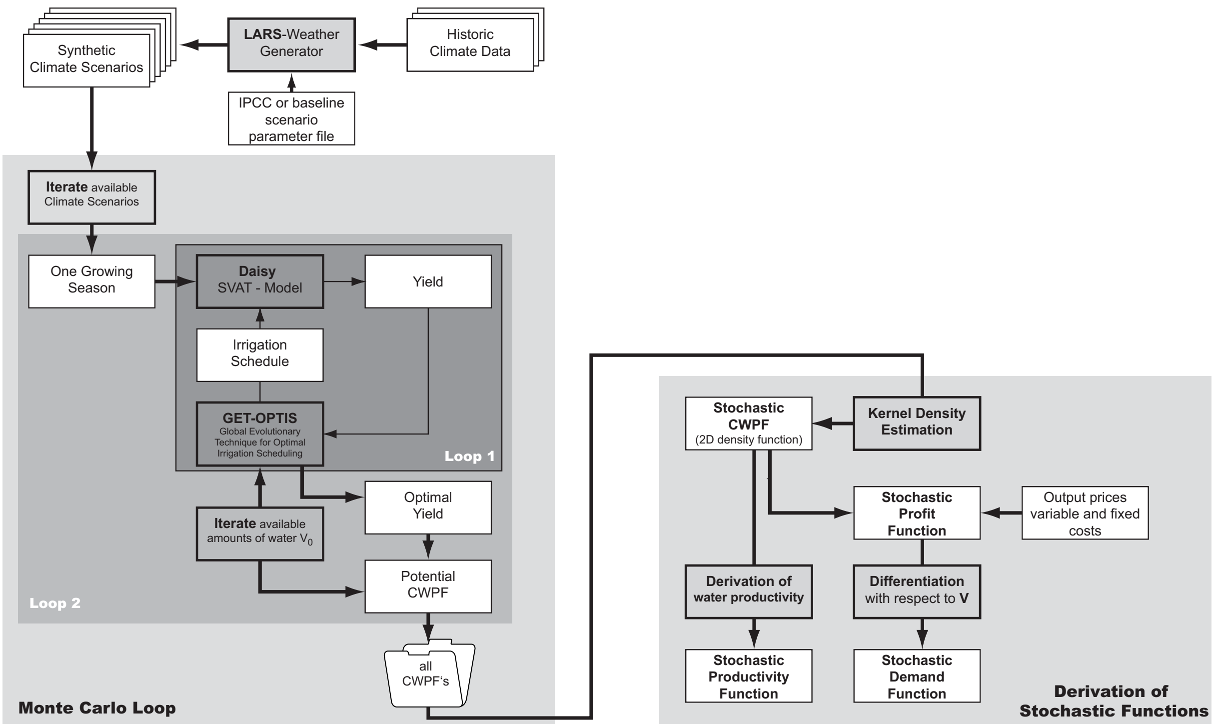

Figure 1: Generation of stochastic crop water production functions (SCWPF) and their derivatives

Generally, two components are necessary to generate reliable simulation-based CWPFs (see Fig. 1, loop 1): an irrigation scheduling optimizer and a simulator of plant growth and water transport. The objective of the most inner iteration loop is to maximize yield for a specific climate scenario and a given amount of water for irrigation during the growing season. With the second loop which iterates over a range of given water volumes, a complete CWPF can be constructed. The generated CWPF represents the maximum yields that can be achieved with a given amount of water and is referred to as the potential CWPF. The weather generator can be interpreted as a Monte Carlo sampler for providing site specific weather series with a desired number of scenarios. Thus, in the third loop the necessary amount of CWPFs is generated in order to accurately compute the statistical characteristics of the random sample of CWPFs in a non-parametric way, i.e. the resulting SCWPF is an empirical probability function. To be useful for Monte Carlo simulations, the irrigation scheduling optimizer and the simulation model should be highly efficient and effective in finding the global maximum yield in order to generate a SCWPF within an acceptable computation time. Finally, the generated empirical probability function SCWPF is converted into a continuously differentiable density function for the calculation of derivatives such as productivity, profit and demand function (see Fig. 2).

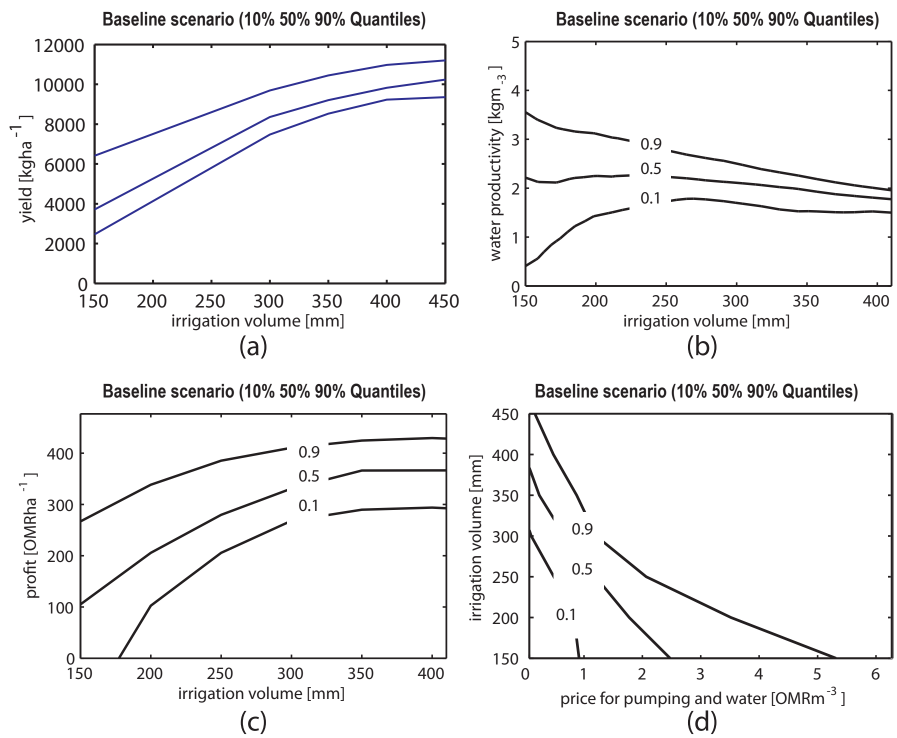

Figure 2: SCWPF (a), productivity (b), profit (c) and demand (d) functions for maize grown in Oman

3 DISCUSSION AND CONCLUSIONS

The generation of a SCWPF requires considerable computational effort. However, the proposed strategy for an application in water resources planning is to perform by far the majority of the computational effort during a first preparatory phase. During this phase a comprehensive database is established which contains the full range of SCWPF's - representing all the relevant combinations of crops, soils and climate scenarios (growing seasons and/or climate change scenarios) for a considered region or basin. On this basis it becomes possible to quickly access to potential yield or water demand data - including the corresponding probabilities and to combine it with spatial information in a GIS. Thus, an appropriate database of SCWPF's can help to evaluate and assess management, mitigation and adaption measures for ensuring food security through an analysis of multiple irrigation sites in a considered basin. Another potential application of SCWPF as a building block for estimating water demand is with the process of the design and operation of large multi-quality irrigation water supply systems. In arid countries, for example, these often have to consider interrelations between irrigation water salinity, leaching requirements and yield levels[11]. As the used crop model includes water and matter transport, a second type of SCWPF building block can simultaneously be used to estimate e.g. the contamination risk (nutrients and salt) of surface and subsurface water reservoirs in the vicinity of specific irrigation sites. The latter building block is a kind of stochastic damage function, and is it suitable for multi-criteria decision making for long term, sustainable water resources management at a larger scale.

In a preliminary application at a regional scale, a database of SCWPF's is successfully used for the optimal management of groundwater resources and agricultural water demand for a coastal plain in Oman[10]. There, it was shown that numerical process models at field scale can be incorporated into decision support systems for integrated and efficient management of water resources of large hydrological systems.

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