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Optimal irrigation scheduling under water quantity and quality constraints accounting for the stochastic character of regional weather patterns

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ABSTRACT

In arid countries both water scarcity and salinity represent the key factors which drastically limit crop yield in irrigated agriculture. In addition, relatively poor management practices with pretty low water productivity (WP) seriously aggravate the situation. In order to get "more crop per drop", i.e., to substantially improve water use efficiency, this thesis proposes the novel strategy NEMO (Nested Experimental, Modeling, and Optimization Strategy) for reliably evaluating an optimal irrigation schedule. The proposed methodology relies upon a close interaction between in-depth field investigations and physically based process modeling. It is tailored specifically to fit the requirements in resource-restricted regions.

Comprehensive field experiments, on site measurements as well as various laboratory analyses provide a representative database for characterizing the relevant environmental parameters as e.g. the soil properties at the considered location and the prevailing climate. A substantial part of the data obtained from the field experiments provided the input for the internationally recognized SVAT software DAISY[1] or APSIM[2], both physically based irrigation models which have already been successfully applied in arid regions. APSIM - which is used in the advanced parts of the study - includes not only a process based model for soil moisture transport but also a plant physiological model which describes the plant behavior under specific irrigation scenarios for a selected crop throughout a growing season.

The adaption of the irrigation model to local conditions and its preliminary parameterization firstly follows available guidelines and data for areas with similar climate and soil conditions. Reference data and deterministic weather data served to build up DAISY's basic model files. DAISY is then used within the framework of the custom made and problem oriented optimization software GET-OPTIS for evaluating the corresponding optimal irrigation schedule for a first preliminary series of experiments (IrrEx1). A second series of field experiments (IrrEx2) was accompanied by transient soil moisture measurements, which served for evaluating the soil hydraulic parameters, while the obtained yield was used for calibrating the plant physiological model of APSIM. Taking still into account the stochastic nature of weather phenomena, a stochastic optimization with GET-OPTIS was then applied not only for the traditional full irrigation but also for the most important deficit irrigation and the irrigation with saline water.

The obtained optimal irrigation schedules are subsequently used for a final series of rigorous irrigation experiments (IrrEx3) which specifically focused on: (1) full irrigation for high yields

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[1] DAISY (Hansen 2002) is a well-tested physically based 1D and 2D Soil-Vegetation-Atmosphere
[2] APSIM (The Agricultural Production Systems Simulator) is a modular modelling framework, been developed by the Agricultural Production Systems Research Unit in Australia (Keating et al. 2003).

with most economic water application, (2) deficit irrigation aiming at a maximum yield with only a limited amount of irrigation water, and (3) full irrigation with saline irrigation water for maximum yield.

At the harvesting time, the observed crop yield and the water productivity were compared - together with other plant characteristics - with the corresponding calculated values. The agreement between calculated and measured crop data was excellent.

All the field experiments have been performed following a parallel use of the common traditional FAO class A-Pan method and the novel NEMO technology. Based on the outcome of the field experiments, the NEMO applications demonstrated a striking superiority throughout all scenarios as compared to the FAO method as regards economic efficiency and sustainable use of irrigation water in both aspects water quantity and salt accumulation.

Contrary to common practice, the optimal NEMO irrigation schedule - which relies on stochastic weather data - has an extended validity. Together with the use of physical data and adequate process models, the developed methodology features a highly promising potential for generalizing the experimental findings for other, environmentally similar, regions. NEMO thus opens wide possibilities for a cost effective and sustainable long-term application to other arid or semi-arid areas.

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ABBREVIATIONS AND SYMBOLS LIST

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
APSIM	APSIM (The Agricultural Production Systems Simulator) is a modular modelling framework, has been developed by the Agricultural Production Systems Research Unit in Australia
CWP	Crop Water Productivity
CWPFs	Crop-Water Production Functions
DIS	Deficit irrigation schedule
ETo	Reference evapotranspiration [mm day^{-1}]
ETc	The actual crop evapotranspiration [mm day^{-1}]
FIS	Full irrigation schedule
GET-OPTIS	The Global Evolutionary Technique for OPTimal Irrigation Scheduling
IrrEx1	The first preparatory field experiment
IrrEx2	The experimental series 2
IrrEx3	The experimental series 3
K_c	Crop coefficient
MAF	Ministry of Agriculture and Fisheries, Sultanate of Oman
NEMO	Nested Experimental, Modeling, and Optimization Strategy
OCCASION	Optimal Climate Change Adaption Strategies for Irrigation
RMSE	Root Mean Square Error
SVAT	Soil-vegetation-atmosphere-transfer
SWIM	Soil Water Infiltration and Movement
WP	Water Productivity
WUE	Water Use Efficiency

1 CONFLICTING PRIORITIES IN IRRIGATED AGRICULTURE: GROWING FOOD DEMAND VERSUS INCREASING WATER SCARCITY

In arid and semi-arid countries, water is the limiting factor as regards food production. In such countries, agriculture is the major competitor for placing demands on available water. It can account in specific arid regions for about 90% of the total freshwater consumption (FAO 2012). In recent years an over abstraction of groundwater, the main water resource, has led to quantity decline and severe quality deterioration. In the GCC[3] countries, it has been estimated that by the year 2030 the water requirements will increase about two times in Bahrain, Oman and Qatar and three times in Kuwait, Saudi Arabia and UAE (El-Beltagy 2004).

In Oman, as an example of physical water scarcity[4], mostly all the agricultural production requires irrigation and it depletes the largest amount of fresh water. The employment of traditional irrigation methods[5] is the cause for a big loss of water in transferring and distributing water in irrigation channels and on field by flood irrigation; giving the plants more water than actually required. During the eighties and nineties, there was a great expansion in agriculture. An over abstraction of groundwater occurred in more extensive areas either by wells equipped with motors or by the drilling of deep wells (power driven) and by heavy pumping to irrigate new farms in the upstream areas. As a result, the aquifer became deficit because the recharge was less than the withdrawals. This led to the begin of sea water intrusion and a salinization process (secondary salinity) became very active and persistent (Hussain et al. 2006; Kacimov et al. 2009; Stanger 1985). Such examples of physical water scarcity - shown also in Fig. 1 - underline the importance and challenge for the development of a more sustainable management of irrigation systems.

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[3] Gulf Cooperation Council (GCC) is a political and economic alliance of six Middle Eastern countries—Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, Bahrain, and Oman.

[4] Physical water scarcity is the situation whereby natural water resources are close to or have exceeded sustainable limits, whereas Economic water scarcity is caused by human, institutional, political or financial restraints on the supply of water despite the fact that sufficient water for human needs would normally be locally available (UNESCO. 2012).

[5] In Oman, the traditional flood system remains the most common irrigation technique and accounts for about 80%. (FAO 2008).

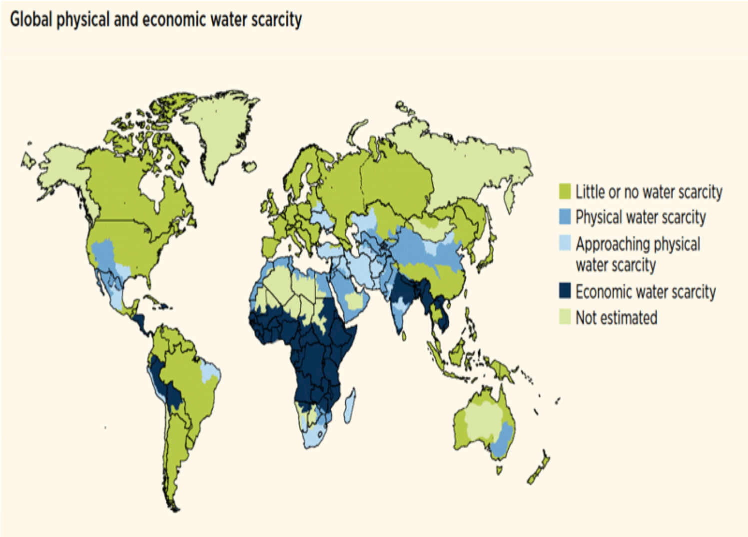

Fig. 1 Global physical and economic water scarcity (UNESCO. 2012)

In such water-limited environments, a new effective means for saving water and improving productivity of crops is the use of modern irrigation systems. These systems, mainly drip irrigation, will directly deliver water to the roots of individual plants. In order to increase the efficiency of these systems, an optimal design has to be combined with an optimal irrigation control that aims to reach a distribution of the soil water in the root zone with minimal losses due to deep percolation or surface runoff (Seidel 2012).

Modeling could be the adequate tool for conducting this optimization whereby a crop model and a hydrodynamic irrigation model would be closely linked. Subsequently, with the increased knowledge of the physical–chemical–biological interactions that occur in the soil-water-crop-atmosphere system - and the advent of high-speed computers - models have been developed that are able to take into account the dynamic interactions in any irrigation system (Letey and Feng 2007).

In spite of this, current practice for irrigation planning and control still employs simplistic modeling tools. It does not really allow for a physically sound consideration of the interacting water transport processes from the field entrance to the roots of the plants and down to the groundwater level (Schmitz and Wöhling 2007). For instance, the crop coefficients (K_c), with the ASCE[6] standardized reference evapotranspiration (ET_{ref}) method, were developed empirically and are not readily transferable to different growing conditions such as soil, elevation, climate and environmental factors (FAO 1998; Wahaibi 2011). The same is true, and even more so, for the calculation of the leaching requirements and timing when the applied water has a certain salt concentration. Mostly, simplistic steady-state approaches are used to estimate the additional amount of water for leaching (e.g. Rhoads 1974) which is

[6] (ASCE) is an acronym that stands for The Committee on Irrigation Water Requirements of the American Society of Civil Engineers.

based on achieving maximum yield and on assuming uniform distribution of salinity in the soil.

If water is limited, another problem is that even when sensor-based scheduling is used it is generally not foreseeable when a future irrigation will be required (Jones 2004; Seidel 2012). This is where simulation-based scheduling can help as it enables a sufficiently accurate prediction of future irrigation requirements (Schütze, de Paly, and Shamir 2012). The simulation-based scheduling could do this by using a physically based model to simulate the essential water transport processes together with mechanistic crop growth modeling for a realistic and predictive simulation of irrigation system. On this basis, the required irrigation control parameters can be calculated theoretically for all future irrigation events if the climate development is known in advance (Schütze and Schmitz 2010).

However, it is obviously the case that farmers need a simple, robust irrigation strategy which is straightforward to operate. Additionally, three main goals have to be achieved simultaneously: productivity, sustainability and simplicity. In this content, research gaps exist principally at the interfaces between irrigation engineering, experiments at research farms, model development and the practical application. Tools are required to realistically simulate irrigation systems and, at the same time, for finding an optimizing schedule which can fulfill these goals. Furthermore, when addressing these gaps, the complexity of the irrigation management under multiple water resource constraints by the use of different water quantity and quality should be considered in future research. In addition, comparative analyses within integrative approaches have also to be enabled.

This contribution proposes a novel strategy for optimal irrigation scheduling and control to improve crop yield under restricted water quantity and quality. It demonstrates its performance by rigorously monitored, comprehensive field experiments in the Sultanate of Oman. The new approach employs the physically based mechanistic APSIM-SWIM[7] model (Keating et al. 2003) for portraying the plant growth characteristics and a simulation based optimization within the new evolutionary algorithm for optimal irrigation scheduling of deficit irrigation systems GET-OPTIS[8] (Schütze and Schmitz 2010).

Key objectives of this research were:

- To develop a methodology that is based upon a close interaction between in-depth field investigations and physically based process modeling in order to successfully provide realistic optimal irrigation schedules.

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[7] APSIM (The Agricultural Production Systems Simulator) is a modular modelling framework, developed by the Agricultural Production Systems Research Unit in Australia and SWIM is an acronym that stands for Soil Water Infiltration and Movement.

[8] GET-OPTIS is an acronym that stands for The Global Evolutionary Technique for OPTimal Irrigation Scheduling.

- Evaluate the practical benefit of the simulation and optimization methodology for irrigation scheduling in arid climate under multiple water resources constraints (quantity and quality).
- To directly validate the optimized (deficit) irrigation schedules, with irrigation experiments using water with limitations in quantity and quality, and thereby to prove the overall potential of the new strategies which combine optimal irrigation and leaching management at the same time.
- To investigate a highly relevant irrigation phenomenon – namely, the salt accumulation in different soil depths as a consequence of different irrigation strategies.

In respect to these objectives, this thesis has the following structure. Firstly it highlights the overall problem of coping with water scarcity in irrigated agriculture. After discussing the task specific current research efforts, chapter 3 deals with the methods and approaches relevant for this thesis. Subsequently, the outline of the novel strategy for optimal irrigation schedules under water quantity and quality constraints is introduced and implemented using a series of sound and rigorously monitored field experiments. A discussion of the results followed by conclusions and an outlook complete the present research study.

2 CURRENT RESEARCH TO IMPROVE IRRIGATION EFFICIENCY

In the light of a fast growing population with the need for increasing food production, optimizing irrigation control and scheduling for achieving higher water use efficiency in agriculture is of mandatory importance. In general, this task requires a comprehensive conceptual framework with an adequate portrayal of the underlying physical and biological processes such as soil water extraction, transpiration, photosynthesis. This can provide not only a basis for analyzing the existing situation and evaluating the corresponding efficiencies but also paves the way for substantial improvements in irrigation management and thus in food production (Hsiao, Steduto, and Fereres 2007).

This chapter provides an overview of the interactions between experiments, simulation and optimization approaches for optimal irrigation scheduling and control as found in current literature.

2.1 Field experiments with full and deficit irrigation

Irrigation experiments in the field are rather expensive and time consuming. Nonetheless many research papers refer to experiments on a single field ((Aase and Pikul 2000); (Fereres and Soriano 2007); (Kang, Shi, and Zhang 2000); (Passioura and Angus 2010) and (Deng et al. 2006)). In all these contributions, the aim focused on improving irrigation efficiency exclusively based on the experimental outcome.

Efforts in order to obtain best irrigation management practices by using just field experiments were reported by Zwart & Bastiaanssen (2004). They investigated in a general review article 84 references with results of experiments not older than 25 years. The outcome showed that the range of Crop Water Productivity (CWP) of wheat, rice, cotton and maize exceeded in all the cases even those which were reported by FAO. Especially large ranges were obtained for example for cotton seed 0.41–0.95 kg m^{-3}; cotton lint 0.14–0.33 kg m^{-3} and maize 1.1–2.7 kg m^{-3}. One of the main reasons for this huge variability of CWP for the same crop refers to the influence of irrigation water management (e.g. (Oktem, Simsek, and Oktem 2003); (Kang et al. 2000); (Yazar, Sezen, and Gencel 2002)). Furthermore, the study stated that the problem with the standard ‘FAO33-approach’ is that the estimation of the maximum yield is too vague but should be used nonetheless in the absence of alternative expressions. Accordingly, full irrigation is apparently not a precise term and varies according to scheduling and given cultural practices.

Contrary to the commonly applied full irrigation, deficit irrigation practices gain more and more attention in irrigated agriculture. Many research papers and case studies convincingly demonstrated the potential of this irrigation strategy for not only increasing water productivity, but also the profit of the farmer (English and Raja 1996; Fereres and Soriano 2007; Hsiao et al. 2007; Pereira, Oweis, and Zairi 2002) Like full irrigation, also deficit irrigation practices have been researched extensively to quantify the effect on yield and to find optimum Crop Water Productivity (CWP) values. Zwart & Bastiaanssen (2004) found that adequate deficit irrigation strategies result in astonishingly high Crop Water Productivity values (CWP's).

Along these lines, the following experiment was conducted by the soil and water research center in Sultanate of Oman over two seasons in order to investigate the effects of applying different irrigation levels on muskmelon yields of a hybrid "Joyce F1" variety using a drip irrigation system (D.G.A.L.R. Dir. Soil and Water Research (Oman) 2008). More precisely, the experiment aimed at identifying a relationship between the different irrigation quantities and the corresponding yield parameters using a randomized block design with four treatments and four replicates. The investigation summarized that especially the irrigation management plays a mandatory role on Crop Water Productivity (CWP) and that different irrigation practice led to a big range of CWP's which seem to originate from the lack of an optimal irrigation schedule for a growing season with a given maximum water quantity.

Productivity improvements using deficit irrigation

In regions where irrigation water is a limiting factor, (Dağdelen et al. 2006) analyzed a great number of papers which focused on water use efficiency (WUE) and crop yield. For example, water use efficiency (WUE) values reported in Turkey, for corn Koksal and Kanber (1998); Yazar et al. (2002); Oktem et al. (2003) and for cotton Anaç et al. (1999); Ertek and Kanber (2001b), Yazar et al. (2002) were different than those of other researchers in other regions ((Howell et al. 1996); (Hunsaker et al., 1998), (Jin et al., 1999), (Kang et al. 2000) and (Roygard et al., 2002)).

Romero et al. (2010) investigated the effects of two regulated deficit-irrigation (RDI)[9] strategies pre- and postveraison[10] on soil-plant water relations. They analyzed the influence on leaf area development, cluster microclimate, yield and berry quality. The investigations were performed during two years in field-grown Monastrell grapevines under semiarid conditions in southeastern Spain. The study focused on finding significant relationships between physiological indicators and berry composition under regulated deficit irrigation. Furthermore, it aimed at identifying the threshold limits or vine-specific optimums of these

[9] Regulated deficit irrigation (RDI) means applying less than the full potential water requirement on vines with a drip irrigation system to achieve properly timed mild water stress. The results are improved wine quality and conservation of water and energy. (https://www.wineinstitute.org/files/DeficitIrregationMar2002.pdf)

[10] In viticulture (grape-growing), veraison is the onset of ripening. The term is originally French (véraison), but has been adopted into English use. The official definition of veraison is "change of color of the grape berries". (https://en.wikipedia.org/wiki/Veraison)

indicators during different phenological stages to maximize berry phenolic composition at harvest. They claim that they identified optimum physiological thresholds for several vine water indicators pre- and postveraison. Nonetheless, although the authors executed a very sophisticated analysis of the different stages of plant development, they ignored the fact that field experiments cannot account for all possible combinations of water stress or yield-affecting environmental conditions. Accordingly, a suitable estimation of efficient irrigation management close to optimal irrigation schedules for field experiments is relatively difficult. This raises doubts as to the validity of overall experimental findings to general water application practices. As well, the findings from a field experiment are severely restricted not only with regard to the applied irrigation management practices but especially depend to a similar extent to the soil hydraulic properties and other soil specifics.

Along these lines, the preceding experimental research efforts highlight the need for comprehensive observation records and rigorous monitoring in order to obtain a physically based characterization of the experimental environmental characteristics and specifics as a precondition to generalize their results via suitable process models.

2.2 Field experiments with slightly saline irrigation water and a specific focus on leaching

A serious drawback of mainly drip deficit irrigation is associated with the soil salinity problem (U.S. Salinity Laboratory Staff 1954); (FAO 2002); (Smedema and Shiati 2002). Soil salinity may arise not only from over irrigation but also from saline irrigation water (Duncan et al. 2008); (UNESCO. 2012).

In arid and semi-arid regions the use of saline water for irrigation is a common practice, even though it may cause a reduction in crop yield and lead to progressive soil salinization (Leite et al. 2015). Of the 270 million ha of irrigated land in the world, about 110 million ha (roughly 40%) is located in these regions of water scarcity. The other 60% of the irrigation is practised under more humid climatic conditions with the rainfall on an annual basis providing enough leaching to prevent the harmful accumulation of salts (Smedema and Shiati 2002).

Numerous field trials have demonstrated the effectiveness of leaching for salt removal as e.g. (Ahmed, Al-Rawahy, and Hussain 2010); (Rhoades and Suarez 1977); (Tomar et al. 2003); (Al-Harbi et al. n.d.). In these experimental trials, their investigations on optimal management practices were based on examining a number of treatments under a statistical experimental design. Using salinity soil samples - collected at different times during the experiment - and a number of plant and yield results from different plots, the experimental findings were obtained using statistical analysis. However, these experimental results are not only closely connected with the irrigation management but they heavily depend upon the local soil hydraulic properties and other soil specifics. Thus, applying these experimental findings to other locations and conditions will definitely lead to significant misinterpretation and inadequate conclusions because exclusive field experiments with their unique portrayal of the specific environmental constellations are not sufficient to explain the various phenomena and are not applicable for generalizing specific experimental results.

Combining Experiments on Full and Deficit Irrigation with Leaching methods

Plant response to salt and water stress may result in a response that is not necessarily equal or additive when the two stress factors are imposed simultaneously. Quantitative understanding of crop production under deficit irrigation with saline water is generally based on three assumptions. First, an increase in salinity, above the crop tolerance level, will decrease yield. Second, biomass production is linearly related to transpiration and third, the effects of salt and water stress on yields are additive. The validity of the first two assumptions is well established. The validity of the third assumption is less certain (Shani and Dudley 2001).

Numerous field experimental activities focused upon finding the best irrigation management strategy in order to manage soil and water salinity problems within the interaction between deficit irrigation and leaching. The majority of these investigations focused either on determining the effects of water and salt stress for various crops on yield, e.g. (Shani and Dudley 2001) or on investigating the best field management practices on salt leaching and conservation of water (Ahmed et al. 2010). A third area of research interest aimed at the best selection and screening of various crop genotypes under different drought and salinity stress (Agric et al. 2014).

Al-Lawati & Al-Waihibi (2010) focused on a one-year field experiment. The target was to evaluate the productivity and water-use efficiency of alfalfa as a consequence of the applied irrigation management consisting of three different irrigation regimes and salinity levels in the irrigation water. The investigation summarized that especially the irrigation management plays a mandatory role on Crop Water Productivity (CWP) and that different irrigation practice led to a big range of CWP's. Amer (2010) studied and evaluated in his field experiment in an arid area of Egypt the effect of salinity and irrigation levels on growth and yield of corn. Three salinity levels and five irrigation treatments were arranged in a randomized split-plot design with salinity treatments as main plots and irrigation rates within salinity treatments. Unfortunately, he only reported water application data by disregarding all the relevant information on the field environmental properties. Thus, the findings from such field experiments are severely restricted not only with regard to the applied irrigation management practices but especially depend to a similar extent upon the soil hydraulic properties and other soil specifics. Obviously, there exists still a significant dependence on environmental and climatic characteristics. Thus, applying these experimental findings to other locations and conditions will definitely lead to significant misinterpretation and wrong conclusions.

2.3 Developments in simulation and optimization of irrigation control and scheduling, for full and deficit irrigation practices

Many investigations have been conducted to gain experience in the irrigation of crops to maximize performance, efficiency and profitability. However, investigations as regards water saving irrigation practices are also of primary importance. The saving in irrigation water that can be achieved is crop-dependent and generally governed by the amount of water extracted by plant roots (Shankar, Prasad, and Govindaraju 2013).

There are two basic methods of irrigation scheduling: sensor-based scheduling and simulation-based scheduling. Sensor-based scheduling relies on measurements taken from one or several of the indicators which monitor soil moisture and thus the irrigation requirements at certain locations (Schmitz, Schütze, and Wöhling 2007). Aguilar et al. (2015) in their study investigate the soil moisture sensors and evapotranspiration (ET) based irrigation scheduling. They illustrated the different aspects for such system installation for optimum performance. Ojha et al. (2015) also highlighted the prospects and problems as well as the specific requirements for such sensors and their associated communication technologies in agricultural applications. The major drawback of this method is that the decision to irrigate is made after the plant has suffered some amount of moisture stress, which may adversely affect the crop yield. Moreover, this process is labor-intensive, time consuming, and thus may not be very economical. Although this method is a real-time procedure as far as irrigation control is concerned it generally cannot provide reliable information as far as the need for future water applications is concerned. This is where simulation-based scheduling can help as it enables a sufficiently accurate prediction of future irrigation requirements (Schmitz et al. 2007).

Along these lines, several empirical and simplified analytical models have been developed to mimic irrigation phenomena. Shabani et al. (2014) list examples of such models such as CropSyst (Cropping Systems simulation), CRPSM (Crop Soil Moisture), CERES Project, CSM-CROPGRO (Cropping System Model – Crop Growth) and AquaCrop. Some of these models are complex, difficult to understand and a more widespread application suffers from the lack of required input data. Some less complicated models are empirical models that predict the yield by using regression techniques as reported for cowpeas (Sepaskhah, Rezaee-pour, and Kamgar-Haghighi 2006), rice (Yu et al. 2002); (Pirmoradian and Sepaskhah 2006), and maize (Lizaso, Batchelor, and Westgate 2003). However, these models do not incorporate a sound description of the relevant flow processes and thus, they are not really adequate for optimizing irrigation control and scheduling with respect to a wider practical application ((Ghahraman and Sepaskhah 1997); (Singh et al. 2006); (Moncef et al. 2002); (Elmaloglou and Diamantopoulos 2009); (Cook et al. 2003)).

Physically based comprehensive simulation models are more reliable and efficient for investigating optimal irrigation requirements to support upgraded irrigation management practices. They also offer the possibility to evaluate the impact of water stress on yield as well as to search for optimized water saving and environmentally oriented practices for irrigation water management (Popova & Kercheva 2004; Schmitz et al. 2007; Vrugt & Robinson 2007). Such process models are - due to the complexity of the underlying process descriptions - necessarily numerical models.

A great number of studies use these types of simulation models together with optimization algorithms for obtaining optimal irrigation control and scheduling strategies. Simulation-based optimization is a combination of a simulation model - to simulate water transport and crop growth - and an optimization algorithm - for finding optimal values for the investigated problem. In this context, Fang et al. (2010) propose amongst many others (Shang & Mao 2006; Ghahraman & Sepaskhah 2004; Brown 2007; Linker et al. 2016) a simulation based optimization approach for identifying best irrigation management practices.

Unfortunately, most of the proposed approaches mainly focus on the modeling and optimization aspect. In this context, the realization usually employs physically based models in order to obtain a certain justification for applying the developed methodology also to other regions. Nonetheless, the reliability of such a procedure obviously depends upon the relevance of the field data used for calibration and validation. However, many researchers seriously underestimate the role of rigorous measurements and transient records of physical field properties (Brown 2007; Ghahraman and Sepaskhah 2004; Shang and Mao 2006) which only allow a sufficiently reliable characterization of field relevant parameters.

2.4 Developments in simulation and optimization of irrigation control and scheduling including the leaching problem

The present guidelines for leaching requirements overestimate the leaching requirement and the negative consequences of irrigating with saline water (e.g. FAO, steady-state approach). Transient-state models have been developed which have the potential to more correctly predict the dynamics of the chemical–physical–biological interactions in an agricultural system (Letey et al. 2011). Along these lines, many models have been designed to predict the effects of irrigation with saline water on crop growth. The majority of these models - available for taking into account water and solute transport in the soil (e.g. SWAP, DrainMod-S, UnSatChem, and Hydrus) - are based on the Richard's differential equation for the movement of water in unsaturated soil in combination with Fick's law - a differential convection-diffusion equation for the advection and dispersion of salts.

Noory et al., (2011) focused in their study on investigating the dynamics of the water and salt balances for the Voshmgir Irrigation and Drainage Network (VIDN) study area in Iran. They demonstrated the feasibility of using optimization techniques - by using a physical based agro-hydrological SWAP (Soil–Water–Atmosphere–Plant) model - for optimal water management and crop planning. Silva et al., (2013) also stated that the SALTMED model proved to be an efficient tool for the simulation of crop growth using different irrigation strategies for chickpea in mediterranean conditions in dry and wet years.

These models are either complex or need highly demanding input data, which are not readily available as e.g. the soil hydraulic characteristics, as well as dispersivity and diffusivity data. These highly nonlinear relationships vary largely from place to place and from time to time[11] and cannot be measured straightforwardly. Furthermore, such models are difficult to calibrate under general field conditions because the soil salinity is spatially highly variable. Moreover, those models usually employ short time steps and need at least a daily, if not an hourly database for reliably portraying the hydrodynamic phenomena. This altogether requires for such model applications - especially as regards larger projects - a team of specialists with ample facilities.

Therefore, many efforts have been made to develop a simple model for crop production and yield under different water and salinity levels. Prathapar & Qureshi, (1999) did a study that includes two different cases; theoretical and farmer irrigation practices to analyze their effect on crop transpiration as an indicator for crop yield together with considering root zone salinity and groundwater behavior. Leite et al., (2015) used MOPECO[12] model simulations in order to calculate the optimized regulated deficit irrigation (ORDI) strategy for achieving the maximum yield for a certain water deficit target. The daily soil water balance as calculated by the model is based on the FAO-56 methodology, which determines the actual crop evapotranspiration by considering the soil water and soluble salt content together with the atmospheric saturation deficit. A model to predict the dry matter and yield of rapeseed under salinity and deficit irrigation was investigated by Shabani et al. (2014) using soil water and salt budget and simple plant physiological relationships.

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[11] The relationships between soil moisture content and water tension (water retention curve) and unsaturated hydraulic conductivity i.e., the soil hydraulic characteristics, are at a certain location considered as invariant soil properties.

[12] MOPECO is an economic optimization model for irrigation water management. It comprises three computing models: (1) estimation of net water requirements; (2) derivation of the relationship between gross margin and irrigation depth; and (3) identification of the crop planning and the water volumes to be applied (Ortega Álvarez et al. 2004).

These investigations mostly employ data easily available for model calibration as e.g. irrigation water use, irrigation management, crop growth and yield. Unfortunately, these data do not fully portray the local field and environmental conditions (Battam, Sutton, and Boughton 2003) because they lack a sufficiently reliable characterization of field relevant parameters which, however, control to a significant extent the plant growth dynamics. Thus, the obtained schedules may not lead to the desired optimum crop yield and especially may jeopardize the success of any applications to other regions (Lafolie et al. 1997).

2.5 Combined experimental, modeling and optimization studies for optimizing irrigation efficiency and leaching.

2.5.1 Combining experiments and simulation optimization approaches for full and deficit irrigation

Optimal deficit irrigation strategy has been widely investigated as a valuable and sustainable production approach in semi-arid and arid regions, mainly with drip irrigation technology ((FAO, 2002); (ICARDA 2012)). However, this practice generally needs to optimize the operational parameters that are required in advance by the irrigators, such as the frequency of water application, the corresponding rate and the duration of irrigation process. As well, deficit irrigation requires sufficient knowledge of crop response to drought stress because drought tolerance varies considerably by genotype and phenological stage (Geerts and Raes 2009).

In developing and optimizing deficit irrigation strategies, field research should therefore be combined with crop water productivity modeling (Geerts and Raes 2009) by using physically based process models together with reliable plant growth modeling on the basis of sound physical field data and monitoring records. Along these lines, combined investigations have been conducted - such as Khaledian et al. (2009), who used data from experiments and the simulation model PILOTE to manage water application for corn and durum wheat yield in a mediterranean climate. Moore et al. (2011) applied the model APSIM to evaluate the productivity of wheat fields and different proportions of Lucerne pastures in Australia.

Subsequently, SVAT-models were coupled with optimization methods for finding optimal irrigation schedules and control. Correspondingly, (Seidel 2012) investigated the productivity of wheat, corn and barley as well its nitrogen requirements under special climate effects to obtain optimal irrigation schedules using the DAISY model and a genetic algorithm. Kloss et al. (2014) applied the same model DAISY, together with the task-specific optimization algorithm GET-OPTIS to determine optimal parameters for irrigation schedules and sensor-based full and deficit irrigation control. His investigation was for a maize crop, grown in containers in a greenhouse located at an experimental station in Germany.

However, uncertainties introduced by climate variability and soil heterogeneity restrict the applicability of model results from those studies especially as regards substantially different environmental conditions.

2.5.2 Combining field experiments, simulation models and simulation based optimization approaches for irrigation strategy and leaching

During the next 10 years, simulation model development and application should focus on agricultural water savings, an increase of crop water productivity and the bringing of groundwater-overexploitation to a halt whilst controlling the buildup of soil salinity (Bastiaanssen et al. 2007). To achieve such goals and to build up the necessary target-oriented optimization strategies with reliability under practical field conditions, field research should be combined with crop water productivity modeling (Geerts and Raes 2009).

Since the 1970s, many numerical solutions have been developed to describe water and solute transport. Most of these models are based on numerical solutions of the Richards equation for water flow and the convection-dispersion equation (CDE) for solute transport (Li et al. 2015). Bastiaanssen et al. (2007) give examples of the Richards equation model category: SWATRE, DRAINMOD, UNSAT2, WORM, LEACHM, DRAINMOD-S, ISAREG, OPUS, DRAINET, HYSWASOR, WAVE, MOZART, SWAP, HYDRUS, DSSAT, CROPGRO, CROPSYST, SWMS_3D, SWAT, and SIMODIS.

Models can provide quantitative estimates of grain yield under different environmental conditions, as well as simulation of water and nutrients balance. They may also be used to test the crop response to environmental stresses, e.g. water and salinity stress (Adam et al. 2011). The SALTMED model is one of the few available physically based generic models that have been used to simulate crop growth with an integrated approach that accounts for water, crop, soil, and field management, using an adequate description of water and solute transport, evapotranspiration, and water uptake (Silva et al. 2013). A number of field experiments were conducted to evaluate such models for specific crop response under saline conditions in an arid region (Aly, Al-Omran, and Khasha 2015; Kaya, Yazar, and Sezen 2015; Ranjbar et al. 2015). In this context, Ranjbar et al. (2015) conducted a two year field experiment during 2012-13 to calibrate and validate the SALTMED model for sorghum under saline conditions. Silva et al. (2013) also performed a calibration and validation of the SALTMED model under dry and wet year conditions using chickpea field data from Southern Portugal. Validation of the model showed there was a good fit between observed and simulated values. However, accurate predictions of these models - specifically with respect to a wider range of application - rely on the precise evaluation of soil hydraulic characteristics as well as on site monitoring of transient soil moisture.

Abou Lila et al. (2013) investigated the effect of irrigation water amount, frequency, and emitter depth on the wetted soil volume, soil salinity levels, and deep percolation under subsurface drip irrigation (SDI) for growing tomato. They used brackish irrigation water in three different soil types and employed the numerical model HYDRUS-2D/3D. They confirmed the evidence that with the same amount of irrigation water, the volume of leached soil was larger at lower irrigation frequency. Astonishingly enough, this study claims that the salinity of irrigation water under subsurface drip irrigation with shallow emitter depth did not show any significant effect on increasing soil salinity above tomato crop salt tolerance. During simulation, molecular diffusion and adsorption isotherm coefficients were neglected and it was also assumed that the solutes were non-reactive, and there was neither net solubilization nor dissolution. This negligence of detailed physical field data for calibration might explain the presented strange results. Therefore, this conclusion has to be treated with caution. It contradicts common knowledge and the use of rules derived from this statement might be disadvantageous to the cultivated crop.

In their review paper " Twenty-five years modeling irrigated and drained soils: State of the art" Bastiaanssen et al. (2007) demonstrated a strengths–weaknesses–opportunities–threats (SWOT) analysis of soil water flow models and their applications dealing with irrigation and drainage systems. It clearly stated that the complex interactions between root zone, soil moisture flow, salinity build up and dry-matter production, can no longer be appraised by simple (steady state) concepts and FAO-type of analytical solutions, that was simply modeled by a crop yield response factor. Additionally, the lack of reliable data and sound field measurements is the constraining factor for general applications of most SVAT models.

The complexity of developing an optimized irrigation schedule with regard to crop yield and soil salinity mainly originates from a multitude of possibly relevant combinations[13] to be investigated. Field-testing of all these combinations is difficult, expensive and time-consuming. In this situation, dynamic simulation models that can simulate crop growth and root zone salinity as a function of profile water availability may prove useful when evaluating the feasibility of deficit irrigation with regard to crop yields and soil salinization (Prathapar and Qureshi 1999). Using deficit irrigation together with saline water needs a sound knowledge about the effects of drought stress on crop growth and a good leaching strategy (Letey et al.

[13] Of all the different input parameters together with the corresponding output parameters, that cover the whole range of all realistically feasible combinations for any given set of soil, crop, and climatic conditions. Such combinations also include input/output relationships between soil hydraulic characteristics, initial conditions, emitter discharge rate, application frequency, root characteristics, evaporation, and transpiration, plant uptake, and the frequency of water application ((Schmitz et al. 2007), (Subbaiah 2013)).

2011). This applies even more for the related optimization, i.e. when water application and scheduling parameters have to be evaluated in an attempt to achieve optimal field irrigation efficiency yet still maintaining the sustainability of the system (Schmitz et al. 2007).

2.6 Discussion of current research efforts

A consideration of all the aforementioned research efforts unveils a significant lack of investigations that combine rigorous field experiments, process models and optimization algorithms for obtaining the best leaching practices (see Fig. 2) together with a desired optimal irrigation result (e.g. yield, crop water production). In spite of some limited combination efforts (Fig. 2) with successful applications in certain cases, the negligence of accounting for climate variability and/or a physically based portrayal of soil hydraulic properties in both the experimental and the modeling approaches seriously restrict the general validity and thus the applicability of the findings from these studies, especially with respect to even moderately different environmental conditions.

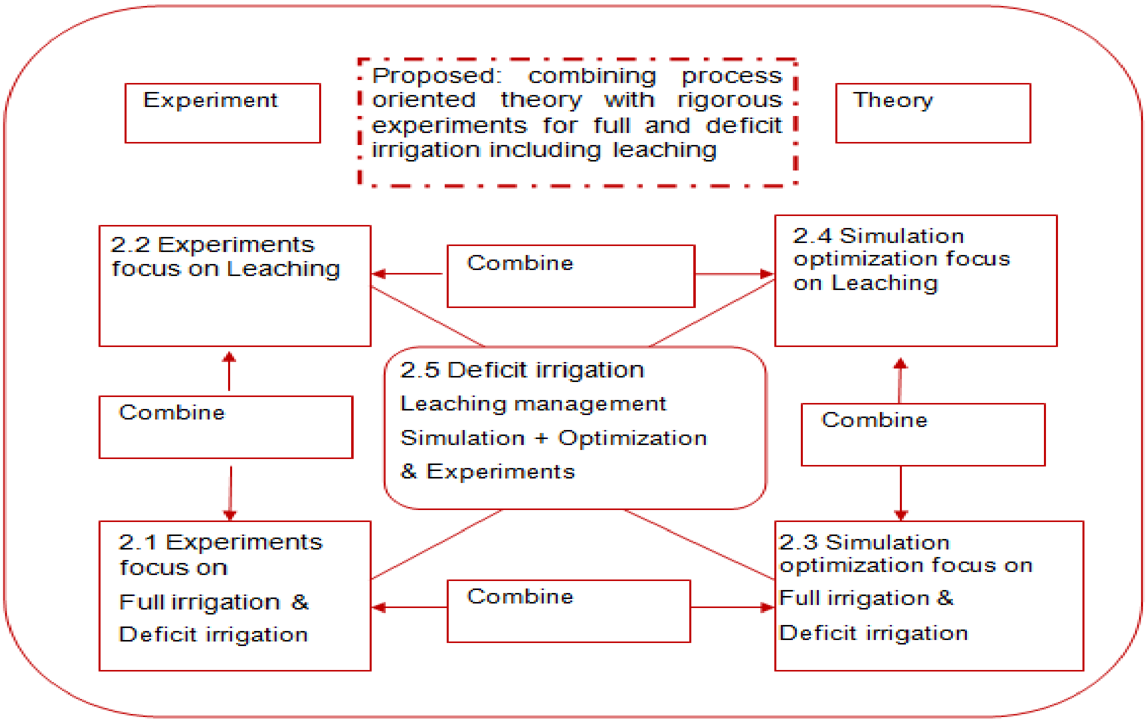

Fig. 2 Interactions between experiments, simulation and optimization approaches

Schütze & Schmitz (2010) developed the framework Optimal Climate Change Adaption Strategies for Irrigation (OCCASION). Besides generating site-specific stochastic crop-water production functions (SCWPF)[14] by regarding variations in underlying climate scenarios they used sound process modeling together with a problem oriented optimization approach for

[14] Stochastic crop-water production functions (SCWPF) for different crops is used as a basic tool for assessing the impact of climate variability on the risk for the potential yield or, for generating maps of uncertainty of yield for specific crops and specific agricultural areas.

evaluating optimal irrigation schedules with respect to maximum crop yield for a given water volume. Using the one-dimensional Soil-Vegetation-Atmosphere Transfer SVAT model DAISY together with historical data, they applied their new technique to maize grown and irrigated at the experimental field site Lavallette of the CEMAGREF institute near Montpellier in France (Seidel et al. 2015). However, notwithstanding the convincing internal modeling concept, the use of only historical data together with the additionally chosen crop growth model DAISY - which is a site-specific model and uses lumped parameters (Li et al. 2007) - still restricts the outcome of this application especially in the view of using the findings also for other regions, i.e. due to missing physical field parameters any sound application to other areas would require new field experiments.

Along these lines, the apparent lack of an approach consisting of a kind of synthesis between rigorously monitored field experiments substantiated by process relevant physical data and a model system of the relevant processes interacting with a problem-oriented method of optimization provided the motivation for this thesis (Fig. 2).

The present study - that has been conducted in Sultanate of Oman - therefore proposes a novel strategy to improve crop water productivity on a larger scale by coordinating both

- a series of planned field experiments with respect to experimental layout, field data acquisition together with monitoring meaningful processes as e.g. soil moisture transfer throughout the course of the experiment
- and a system of interacting physically/physiologically based process models interconnected with a task oriented simulation based optimization technique able to tackle the complex multidimensional and nonlinear optimization problem

More precisely, the aim of this study is to set up and perform rigorously monitored, comprehensive field experiments at the Agricultural Research center Rumais, Sultanate of Oman by always pursuing a full compatibility with the physically based mechanistic (DAISY and APSIM) model[15] and the simulation based optimization within the new evolutionary algorithm for optimal irrigation scheduling of deficit irrigation systems GET-OPTIS[16] (Schütze, Kloss, Lennartz, et al. 2011). The compatibility which especially refers to the overall data and monitoring requirements of the simulation and optimization tools thus allows to evaluate the practical benefit of the simulation and optimization methodology for irrigation scheduling in arid climate under multiple water resources constraints (quantity and quality).

[15] Daisy and Apsim are totally comparable except that APSIM includes salinity transport as a special feature. This was the reason why we started with DAISY and moved later to APSIM.
[16] GET-OPTIS is an acronym that stands for The Global Evolutionary Technique for OPTimal Irrigation Scheduling.

The detailed objectives were

- to develop an adequate experimental design and layout together with a data measurement campaign.
- to perform a series of experiments accompanied by an adequate monitoring of soil moisture transfer.
- calibrate and validate the APSIM model based on TDR readings and the outcome of the irrigation experiments.
- to investigate a highly relevant irrigation phenomenon – namely, the salt accumulation in different soil depths to consider sustainability.
- to directly validate NEMO (Nested Experimental, Modeling, and Optimization Strategy) using a comparison with common irrigation practice (FAO, Class A-Pan) for full irrigation as well as for applications with water limitations in quantity and quality under the specific conditions of the study location in Sultanate of Oman.

3 MATERIAL AND METHODS

The subsequent chapter firstly discusses the basic requirements and necessary preconditions to set up rigorous irrigation field experiments with meaningful results and findings. These experiments then form the basis for incorporating the most up to date problem oriented software tools. Along these lines, the Agricultural Production Systems Simulator (APSIM), the Global Evolutionary Technique for OPTimal Irrigation Scheduling (GET-OPTIS) and the task adapted OCCASION framework - which altogether represent the tools and methods to finally build up the comprehensive strategy for optimizing irrigation scheduling as proposed in chapter 4 - are introduced and their scientific background highlighted.

3.1 Experimental environment

3.1.1 The experimental site

The experiment was conducted in the Directorate General of Agricultural and Livestock Research in Rumais, Al-Batinah region, Sultanate of Oman (latitude 23.6° N, longitude 58.0° E at 24 m above MSL). Al Batinah is the major agriculture region in Oman, located along the coast beginning north of the capital Muscat as shown in Fig. 3. Over half of the agricultural area - which represents about 3 % of the area of the country - is located in the Batinah Plain.

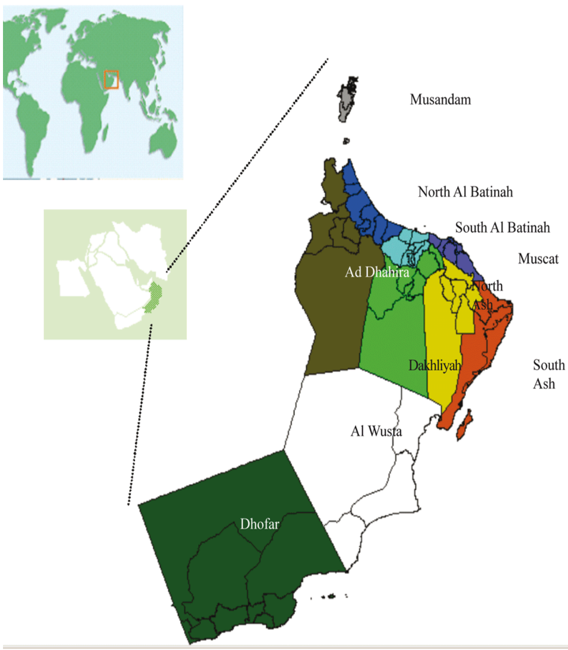

Fig. 3 Oman is situated in the South East of the Arabian Peninsula along the East coast of the Arabian Gulf.(https://f1000research.com/articles/4-891/v1)

Agricultural production in Oman particularly depends on water resources since most crops grown are irrigated and consume more than 94% of the total water use (Omezzine and Zaibet 1998). Therefore, the amount of extracted water needs to be considered carefully.
In Oman, agricultural production grew steadily from 1970 until 1990 and accelerated in the period to 1997. Subsequent years saw a general decrease in agricultural productivity, mainly due to the intrusion of marine saltwater originating from excessive groundwater withdrawal from the coastal aquifer which was caused by over irrigation and unsuitable irrigation practice. Al-Batinah Governorates accounted for 80 percent of this reduction in output (Ministry Of Agriculture And Fisheries (MAF) and International Center For Biosaline Agriculture (ICBA) Dubai 2012).

3.1.2 The soil

In Oman the majority of soils are of Aridisols and Entisols orders, which is a characteristic of desert soils (AL-Ismaily and AL-Maktoumi 2011). Soil pH for the most dominate soils was around 8.0 with the exception of Typic Salorthids loam which had a relatively lower pH = 7.6. This alkaline range in soil pH is normal for soils of dry regions where there is not enough rain to leach the basic cations. Soil forming on the floodplains were salt effected and had the highest salinity levels and especially that of Salorthids. In the coastal plains of the Batinah area, the textural classification ranged from sand and loamy sand to fine-textured silt loams. For the Al-Batinah region, the soil is characteristically sandy loam soil with 50, 36 and 14 % sand, silt and clay, respectively (Abdurrahman, 1993)[17]. The soils are generally calcareous with about 40% calcium carbonate ($CaCO_3$), but low in gypsum calcium sulfate ($CaSO_4$) content. The $EC_{1:5}$ values disclosed the extent of salinization with increasing values of up to 16 dS/m towards the coastal areas of the fine-textured soils. This is coupled with high sodium (Na) adsorption ratios of up to 30 indicating saline-sodic conditions (AL-Ismaily and AL-Maktoumi 2011).

3.1.3 Site climate and weather

The climate in the study area is mostly a subtropical desert climate. It is hot and humid during summer and characterized by moderate temperatures around 23 ^{O}C in the winter. As a consequence, the normal climatic features are clear, bright skies, light winds, pleasantly warm dry winters and oppressively hot dry summers (Stanger 1985). The highest temperatures range between 35 to 50 ^{O}C. and the lowest vary from 7 to 31 ^{O}C. Daily

[17] Abdelrahman, H.A., Lepiece,A., Macalinga,V., 1993: Communications in Soil Science and Plant Analysis, 24(17-18): 2293 - 2305.

sunshine hours typically average about 10 hours. Average annual rainfall ranges between 100 mm to 300 mm and occurs scarcely and randomly.

3.1.4 Background of the experimental design

One of the main aims of the experimental design is to reduce the effect of known or expected sources of variability on the answers to questions of interest. Hence, especially in the case of comparing the yield of a specific crop under different irrigation treatments, it is mandatory to consider the fact those factors such as soil fertility, moisture, and damage by insects, diseases, and birds will definitely affect the yield. Thus, it is essential that all these factors - except those considered as treatments - have to be maintained uniformly for all experimental units. The difference among experimental plots - that are treated in the same way - is then considered as the experimental error. This error is the primary basis for deciding whether an observed difference can be taken as significant or just as a negligible random deviation. In this context, every experiment must be designed in such a way that a relevant experimental error can be identified in order to evaluate the reliability of experimental results. In this regard, statistical procedures - particularly those dedicated to experimental design - are of important assistance. Statistical experimental procedures include a number of features that permit to measure and control the experimental error. These features mainly include replication, randomization, and blocking (Albers and Kratochwill 2010; Kirk 2013).

Consequently, a reference treatment is required in order to evaluate the actual effect between the different treatments. Furthermore, the use of randomization in experiments is common practice to allow for a more representative database. Using randomization is the most reliable method of creating homogeneous treatment groups, without involving any potential biases or judgements. There are several types of randomized experimental designs, the two most common types are completely randomized design and randomized block design. In a completely randomized design, treatments are assigned to groups that can be considered as being completely at random. A randomized block design is preferred when the experimenter is aware of specific differences among a number of treatments within an experimental group. In a block design, treatments are divided first into homogeneous blocks before they are randomly assigned to a treatment group. In addition, in a block design both treatments and randomization are considered (Kwanchai & Arturo 1984).

To improve the significance of an experimental result, replication, i.e., a parallel treatment with identical design, is required. Each treatment should be repeated on a large enough number of units to allow systematic effects to be seen. If a treatment is truly effective, the long-term averaging effect of replication will reflect its experimental worth. Replication reduces variability in experimental results, increasing their significance and the confidence level with which a researcher can draw conclusions (R. Pannerselvam, 2012).

However, in order to obtain a conclusion from a statistical field approach analysis, a precaution needs to be taken as regards the sample submitted for analysis. The sample should be representative with respect to the conditions of use and an acceptable number of samples need to be utilized (Ayers and Westcot 1976).

Due to the generally only marginal knowledge of the local parameter distribution - e.g. soil characteristics - a sound experimental layout often requires a second repetition of the experiment (Jones 2007) i.e. a kind of trial and error approach.

3.1.5 The management practices applied to field experiments

3.1.5.1 Seeding, fertilizing and maintenance:

The crop selected for this study was Maize (Zea Mays, maize sow cultivar = pioneer_3527), due to its importance as a fodder crop. It was sown with a row spacing of 0.5 m and the seeds were planted 25 cm apart. The planting density was 9.7 plants m^{-2}. The soil surface was leveled and chemical fertilizer was applied before sowing with 100 kg ha^{-1} P_2O_5 (200 kg ha^{-1} triple super phosphate) and 50 kg ha^{-1} K_2O (100 kg ha^{-1} potassium sulphate) for grain. The plants were fertilized by 150 kg ha^{-1} nitrogen (326 kg ha^{-1} Urea) in three split doses as follows: ¼ before sowing, ½ one month after germination and ¼ at flag leaf stage. The fertilizers were applied manually at 8-10 cm distance from the plants. Necessary preventive measures were taken to protect plants from pests, diseases, and birds during the growth period. To avoid the field from being attacked by birds, the plants were kept under an agril cover for the first two weeks and it was covered with a net from the flowering stage to the day of harvest Fig. 4.

Fig. 4 A net cover from the flowering stage to the day of harvest.

3.1.5.2 Irrigation treatments and the use of the pre-calculated irrigation schedule

The irrigation treatments used in this study can be divided to two main approaches: the treatments irrigated using the FAO - Class-A Pan Evaporation method and pre-calculated treatments as an output of the simulation based optimization. The surface drip irrigation system (DI) with an emitter spacing of 50 cm was installed with two drip tubes for one plant row resulting in emitter spacing of 0.25 m. The emitter flow rate was 4.2 L h^{-1} at a pressure of 1 bar with dripper uniformity of 92%. The required levels of EC of water were synthesized through the mixing of fresh water and the saline water in appropriate ratios. The crop coefficient of Maize (Kc)[18] was provided by FAO standard values to be:

- 0.5 during the initial stage (25 days)
- 0.85 during the development stage (40 days)
- 1.2 during the mid stage (45 days)
- 0.9 during the late stage (30 days)

The Class-A Pan evaporation treatments were irrigated every two days. A measured amount of irrigation water was applied using water meters. Meter readings were taken before and after irrigation. Valves were shut off when the water meter readings reached the calculated quantities of water.

3.1.5.3 The collected data

3.1.5.3.1 Soil data

Soil data were intensively taken throughout the experimental works. At the beginning, soil samples from 27 plots at the experiment site (5–10, 20–30, 50–60 cm depth) were collected. The soil samples were all subsequently air-dried at 30°C, passed through a 2 mm sieve and stored at room temperature in sealed polyethylene bags. Several physico-chemical properties of the soils were determined. Soil pH was measured by 1:5 extract method. Sand, silt and clay contents were determined by hydrometer method. The table in the appendix A.1 shows the analysis results.

The soil samples were collected before planting and at the harvesting day for each of the experimental series. The soil samples were analyzed for 1:5 ECe. In addition to this, checkup soil samples were taken for soil moisture and salinity.

3.1.5.3.2 Meteorological data

Meteorological data were obtained from a meteorological station on the site - the Directorate General of Agricultural and Livestock Research in Rumais, Sultanate of Oman (latitude 23.6°

[18] Further information could be find in http://www.fao.org/nr/water/cropinfo_maize.html.

N, longitude 58.0^o E at 24 m above MSL). Hourly data were obtained for maximum and minimum temperature, radiation, wind speed, and relative humidity. Additionally, the evaporation rate from class A pan (E_p) was collected, to calculate the evapotranspiration (ETo). The ET_o which was calculated based on evaporation from class A pan (E_p) was compared to the calculated ETo by the CROPWAT model using the site meteorological data.

3.1.5.3.3 Monitoring the soil moisture transfer in the root zone

Time Domain Reflectometry (TDR) probe - was used to measure transient soil water content (Campbell Scientific, USA) and soil water potentials measured by a pF-Meter with a range of about pF 0 to 7. Both of these measurements were taken every 15 minutes. TDR probes and pF-Meters - next to each other as one sensor pair as shown in Fig. 5 - were installed at four different soil depths (10, 20, 50 and 100 cm) at the second replication, as shown in the demonstrated Fig. 6.

Fig. 5 TDR probe and a pF-Meter next to each other as one sensor pair.

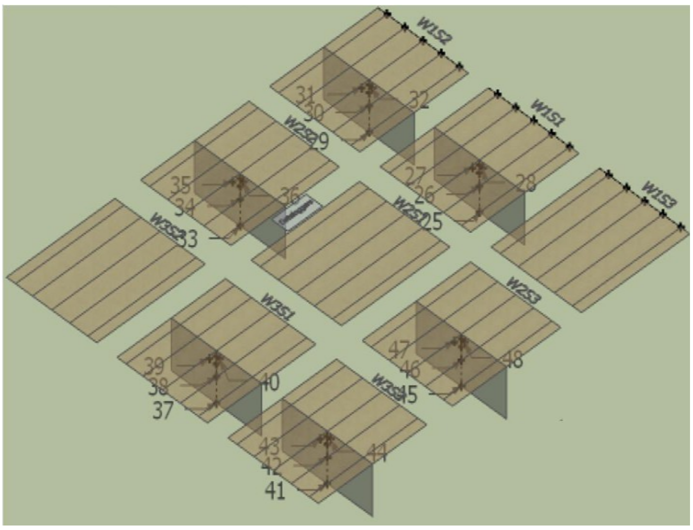

Fig. 6 TDR probes and pF-Meters each installed at four different soil depths (10, 20, 50 and 100 cm) within 6 plots in the experimental site.

3.1.5.3.4 Irrigation data

The Class-A Pan evaporation readings were recorded at intervals of every two days. The amount of the applied irrigation water for each treatment and its quality were also recorded. Any further applied water added to the experimental field – as for leaching, raining, etc – was registered. The table in the appendix A.9 shows the recorded irrigation water quantities during the second experimental series (IrrEx2).

3.1.5.3.5 Plant data

For all the experimental trials, at each development stage three plants at each plot were randomly selected and recorded for plant height, number of leaves, leaf length and leaf width. In addition, LAI data was collected at different stages of plant development.
During the actual harvesting day, the green forage yield and plant parameters were recorded for each plot separately. In addition, four plants were randomly selected at each plot and recorded for plant height, number of leaves, leaf length and leaf width. Furthermore, wet and dry matter weight for leaves, stem, cob and seeds were recorded for each selected plant in each plot; as such shown in appendix A.12. In addition, the root depth was taken from two different plots at the end of IrrEx2; details are shown in appendix A.11.

3.2 The Standard FAO method

3.2.1 Evaluating the crop water requirement

Estimated daily reference crop evapotranspiration (ETo) is normally used to determine the water requirement of crops using the crop factor method. A very common approach to estimate the crop water requirement is provided by the FAO guidelines (FAO 1998). It is often estimated in a two-step process. The first step involves the estimation of the evaporative demand of the environment based on weather conditions. It is often considered as the evapotranspiration from a theoretical, reference grass crop (ETo) with the crop defined as an actively growing, uniform surface of grass, completely shading the ground, and not short of water.
The FAO-modified Penman-Monteith equation for the calculation of the ETo - as recommended by the FAO - represents the sole standard method (FAO 1998):

$$\mathrm{ET_0} = \frac{0.408\Delta(\mathrm{R}_n - \mathrm{G}) + \left(\gamma \frac{900}{\mathrm{T}+273}\right) \mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\mathrm{u_2})}$$

Where:

ETo reference evapotranspiration [mm day^{-1}],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],

T air temperature at 2 m height [°C],

u_2 wind speed at 2 m height [m s^{-1}],

e_s saturation vapor pressure [kPa],

e_a actual vapor pressure [kPa],

$e_s - e_a$ saturation vapor pressure deficit [kPa],

Δ slope vapor pressure curve [kPa °C^{-1}],

γ psychrometric constant [kPa °C^{-1}].

However, this is a complex method requiring several weather parameters, including air temperature, humidity, solar radiation, and wind speed, to be measured following strict rules for the surrounding landscape characteristics together with precise instrumental equipment and rigorous maintenance conditions. Often, limitations (including financial and the lack of skilled personnel) make the required weather data for the FAO-56 method often unavailable (Fisher and Pringle III 2013). Moreover, the parameters in the equation involve some significant uncertainties especially as regards the stomata behavior and turbulent transport. Last but not least, the effort required for finding the values of the parameters in the equation might not always be justified for common irrigation applications (McAneney and Itier 1996).

However, ETo can also be estimated using the evaporation loss from a water surface. In this context, the evaporation rate from pans filled with water can easily be measured in the absence of rain: The amount of water evaporated during a period (mm/day) corresponds to the decrease in water depth throughout that period. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface. For the Pan Evaporation Method, different types of evaporation pans can be used, but the circular Class A evaporation pan is the best known. The pan has to be installed on a surface above a weighing device or with a depth measuring device inside and filled with a known amount of water. In recurrent time intervals, the amount of water left in the pan is measured and the difference between the last measurement and the one before is calculated. The difference is the evaporation rate. The ETo value can be calculated by employing an empirically derived pan coefficient:

$$\mathrm{ETo} = \mathrm{Kp} \times \mathrm{Ep}$$

Where ETo reference evapotranspiration [mm/day],

Kp pan coefficient [-],

Ep pan evaporation [mm/day].

Although the pan responds in a similar fashion to the same climatic factors which affect crop transpiration, there remain significant differences in loss of water from a water surface compared to a cropped surface. Reflection of solar radiation from water in the shallow pan might be different from the assumed 23% for the grass reference surface. Storage of heat within the pan may cause significant evaporation during the night while most crops transpire only during the daytime. There are also differences in turbulence, temperature, and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance (FAO 1998).

The ETo value of the particular crop of interest (ETc) is then calculated using a crop-specific coefficient (Kc) (Fisher and Pringle III 2013). If the ETo is determined using common formulas, the actual crop evapotranspiration (ETc) can be calculated by multiplying with the crop factor (Kc):

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc}$$

The Kc curve is constructed to be a visual and simple tool that displays the impacts of trends and controls by a specific crop to modify the ET estimated by the reference crop. The many examples of its application prove that when appropriate crop and weather data are used, the Kc curve is accurate not only for practical but also for research purposes (Pereira et al. 2014).

3.2.2 The FAO method for leaching requirement calculation

Salinization is the most widespread problem in irrigated areas throughout the world with arid and/or semi-arid climate. Salinization generally occurs when salts accumulate in the soil profile. Irrigation even with slightly saline water requires application of extra water for the leaching of salts from the root zone to prevent excessive accumulation of salts which seriously limits the potential crop yield (Letey et al. 2011).

The ratio of additional irrigation water for leaching, with respect to evaporation and transpiration, is usually expressed as a leaching fraction (*LF*) or a leaching requirement (*LR*), which are identical mathematical expressions. The *LF* is simply the ratio of the total amount of water passing through the soil profile to the total amount of applied irrigation water whereas the *LR* is defined as the fraction of infiltrated water that must pass through the root zone to keep soil salinity from exceeding a critical level which significantly reduces crop yield. This remains valid even under steady-state conditions of the water flow with associated good management and uniformity of leaching (U.S. Salinity Laboratory Staff 1954).

Ayers & Westcot, (1976) calculate the leaching fractions using the formula below:

$$LF = \frac{\text{Drainage Water Amount}}{\text{Irrigation Water Amount}} * 100$$

For calculating the leaching requirement (LR), however, there are several methods for a specific crop and a given water supply. The traditional method used to determine LR was developed from the original steady-state LR model of the U.S. Salinity Laboratory Staff (1954) (U.S. Salinity Laboratory Staff 1954) .

$$LR = EC_w / (5EC_e - EC_w)$$

Where LR = Leaching requirement "the minimum leaching requirement needed to control salts with ordinary surface irrigation methods".

EC_w = Salinity of applied water

EC_e = Soil salinity tolerated by the crop

This traditional method used to determine LR is based on the concept for steady-state[19] conditions with no precipitation or dissolution and good drainage. Unfortunately, steady-state conditions do not really exist under most field situations. A steady-state analysis dictates that water is applied uniformly across the field at a constant rate and salinity. Moreover, the traditional method also ignores the chemical processes of precipitation that can, in some cases, significantly increase the level of soil salinity within the root zone and, thus, lead to higher leaching requirement. Furthermore, in general, leaching is usually not required for each irrigation event and, similarly, this feature isnot accommodated by steady-state analysis (Letey et al. 2011).

3.3 The simulation and optimization tools

3.3.1 The SVAT model DAISY

DAISY (Hansen 2002) is a well-tested physically based 1D and 2D Soil-Vegetation-Atmosphere Transfer (SVAT) model for simulating water balance, heat balance, solute balance, organic matter turnover, and crop development. The mechanistic model consists of the three main components bioclimatic, vegetation and soil, and demands for site-specific driving variables weather, management data, vegetation, and soil parameters (Fig. 7).

[19] Mathematically a steady-state flow analysis does not include a time variable; whereas, a transient-flow analysis does (Letey et al. 2011).

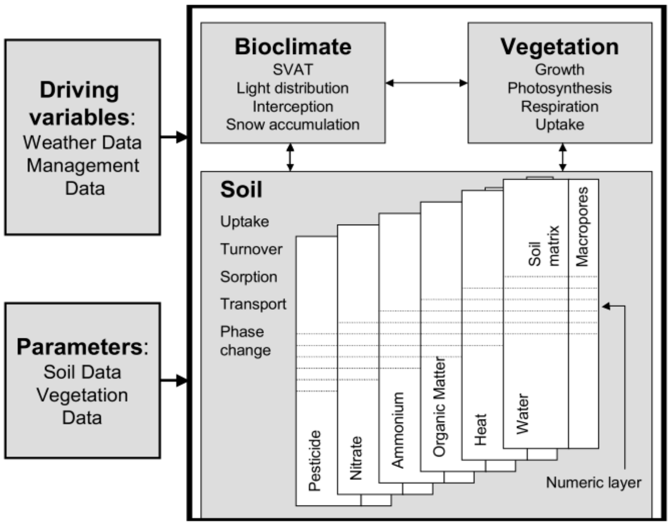

Fig. 7 Schematic representation of the agro-ecosystem model DAISY. (Hansen 2002)

For the preliminary investigation, DAISY was selected for this study due to these reasons:

- DAISY was tested for moderate and no water stress scenarios and performed satisfactorily (Kloss and Pushpalatha 2012).
- The crop data used with the model DAISY was derived from the experimental site Lavallette in Montpellier, France, where maize (variety Pioneer PR36K67) had been cultivated in 2007, and the model was verified by an experimental run in 2009. The detailed plant parameters used for the DAISY setup file can be found in (Mailhol et al. 2011; Seidel 2012).

Details of the data sources for the first DAISY model parameterization (crop, soil and weather data) and more for setting up the model DAISY can be found in chapter 5.

3.3.2 The Agricultural Production Systems Simulator (APSIM)

APSIM is a 1-dimensional modular modeling framework that has been developed by the Agricultural Production Systems Research Unit in Australia (Keating et al. 2003). It was developed to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk, with a specific focus on simulating irrigation management strategies in an arid environment.

The simulator is based on four elements: biophysical modules, management modules, modules for the facilitation of data in-and-out and a simulation engine. These elements of the APSIM framework have been illustrated by the ‘spider diagram’ (Fig. 8) (Keating et al. 2003).

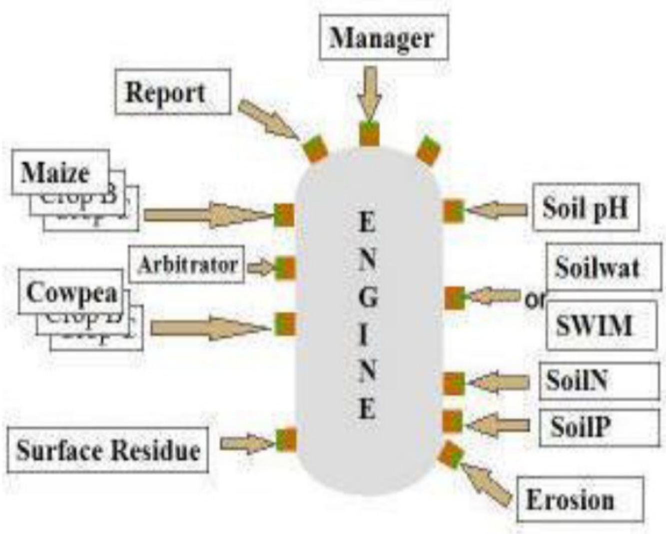

Fig. 8 Diagrammatic representation of the APSIM simulation framework with individual crop and soil modules, module interfaces and the simulation engine (Keating et al. 2003).

These modules (Fig. 8) include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, salinity, erosion and a full range of management controls (such as fertilizing, irrigation, tillage etc).

For further model description refer to "An overview of APSIM, a model designed for farming systems simulation" by Keating et al. (2003).

3.3.2.1 Soil moisture transfer module

Using APSIM, soil water movement can be simulated in two ways: The first one is the simple bucket approach with cascading layers, the second one uses the Richards' equation (Keating et al., 2003). The simple bucket approach is simulated in APSIM-SoilWat and is automatically part of every APSIM simulation that involves soils. The second subsurface flow module in APSIM is called SWIM. It employs the Richards equation and thus can deal with transient soil moisture profiles.

Furthermore, the simulation of the soil water content responds to a change in the status of surface residues and crop cover (via tillage, decomposition, and crop growth). Various water losses such as canopy interception or losses from irrigation infrastructure are calculated in other modules within APSIM. Potential crop water use is calculated by each crop model using methods appropriate to the crop being simulated as specified by each crop model developer.

However, regarding water flow, Soil Water Infiltration and Movements (SWIM) includes a number of simplifications and approximations (Verburg 1996):

- Only one-dimensional flow is considered, therefore lateral equilibrium is assumed i.e., net lateral surface runoff is treated as a sink term at the surface.

- Macropores and bypass flow are only taken into account by empirical coefficients.
- The soil matrix is assumed rigid, so that SWIM is not strictly applicable to swelling soils.
- Soil airflow is ignored.
- Vapour flow within the soil can be included as part of the conductivity term, but only in response to matric potential gradients.
- Temperature effects on water movement are ignored.
- Osmotic effects are ignored, except in water uptake and soil evaporation
- Wetting front instability or fingering is not taken into account.

3.3.2.2 Plant growth module

APSIM, is a modelling environment for crop systems that simulates the dynamics of soil-plant-management interactions within a single crop or a crop system. The existence of a number of different crop modules in APSIM is a result of adaptation of previously developed crop models. These crop models were mostly crop species oriented, i.e. relationships derived and implemented in the models were species-specific. Such a process-oriented model consists of several process subroutines/functions describing the essential physiological processes across crops. Although different modelling approaches have emerged for a given physiological process, especially for different crops, most of the simulated processes share common principles/properties across crop species.

The maize module with a focus on semi-arid and tropical climates - as an example - was developed from a combination of the approaches used in the CM-KEN and CM-SAT models of maize, both derivatives of CERES-Maize (Schütze, Kloss, and Schmitz 2011).

The plant modules simulate key underpinning physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics, and crop management actions (Wang et al. 2002).

3.3.2.3 Salinity module

APSIM does not directly calculate leaching requirements (LR). Instead, a series of seasonal water applications is simulated, from which the lowest application is selected that maintains maximum crop yield, so that actual plant evapotranspiration (ET) is potential plant evapotranspiration (PET)[20].

[20] Potential ET (PET) is defined as the maximum daily or seasonal total plant ET, implying zero crop stress as caused by either reduced irrigation water application or by soil salinity.

Modules e.g. SOILWAT and SWIMv2 are used in APSIM. Both are one-dimensional modules and do not consider lateral flow or horizontal heterogeneity. Some soil water issues can be represented better by the more mechanistic approach in APSWIM involving the simultaneous solution of the flux equations describing the sources and sinks and the redistribution of water in the whole profile.

APSWIM is based on a numerical solution of the Richards' equation combined with the convection-dispersion equation to model solute transport. The implementation in the APSIM model is based on the 'stand alone' SWIMv2.1 (Keating et al. 2003).

3.3.2.4 Data base for running APSIM

The input data needed for APSIM-SWIM are (e.g. Jozefini 2012):

- rainfall, evaporation, solar radiation, humidity;
- Soil: type, depth, bulk density, initial soil water content, hydraulic conductivity, matric potential in the soil;
- Irrigation: applications, infrastructure;
- Salinity: nutrient/ solute concentration.

3.3.2.5 Simulation setup files

With the SVAT 1D mechanistic crop growth model APSIM, it is possible to use either a graphical user interface or a command line approach. In this study the command line approach was used, which required writing three separate text-files (Jozefini 2012; Pistorius 2012): Control File * .com , Parameter file * .par and Meteorology-File * .met.

In the con-file, the paths to the APSIM files needed for the simulations were given. Table 1 listed all the modules that are included in the control file. By linking the control file with ApsimRun.exe, it is also possible to start the simulation.

Table 1 Modules that are included in control file.

Module Name	Purpose
Clock	Processing times
Report	Generates the model output
Input (met)	Entering the meteorological parameters
Manager	Control logical and temporal orders
SWIM2	Water and solute transport model
Solutes	Observation of mass transfer
Irrigation	Irrigation plans and regulations
SoilN	Nitrogen transformation in soil

Fertiliser	Fertilizer applications
Maize	Simulation of the development of corn

In the parameter file "par-file" all settings and information for each used module are made. It is divided into several sections, where all soil and water parameters as well as the irrigation and fertilizer application and the output parameters are specified. In the appendix A.5, an exemplary scenario is presented to show the parameter file with comments for further illustration.

In APSIM there are modules for the two major modelling approaches that are commonly used for the soil water balance, namely cascading layer (SOILWAT) and the Richard's equation methods (SWIM; Soil Water infiltration and Movement) (Keating et al. 2003). In this study, SWIM was used instead of SOILWAT because it is much more capable of giving detailed descriptions of soil water content and solute movement. However, parameterization of the soil water properties for APSWIM requires specification of the soil hydraulic parameters in each soil layer.

In the Meteorology file "met-file" the weather data are specified. However, It could be created first using Excel and then saved as an extension * .met file. For each day of the simulation period, minimum and maximum air temperature (°C), radiation (MJ/m^2), and the rainfall (mm) have to be included. In the case of our study, the minimum and maximum temperature for each day was determined from quarter-hourly temperature measurements. The rainfall is derived from the sum of the daily rainfall reading. The global radiation is converted from the sum of quarter-hourly daily measurements. In addition, the average annual temperature (tav) and the annual amplitude of average monthly temperature (amp) are also indicated in the meteorology file. These two values can be calculated by the TAV_AMP tool which can be obtained free of charge on the APSIM site.

3.3.2.6 Select the tool

APSIM is a highly advanced and internationally recognized irrigation software. There are a number of reasons why we selected APSIM for this study:

- It had already been utilized and tested by two master thesis using the same experimental data as in this thesis:
  - Jozefini, J. (2012). *Evaluation of stochastic irrigation scheduling strategies in an arid region*. Master Thesis, Technischen Universität Dresden, Germany.

    - Pistorius, M. (2012). Modellierung und Optimierung von Leachingstrategien für die Bewässerungslandwirtschaft im Oman. Master Thesis, Technischen Universität Dresden, Germany.
- It combines number of features: 1) high sensitivity of crop modules, 2) ability to simulate a wide range of configurations of crops, sequences, mixtures and management practices and effects on trends in soil productivity, and 3) the software is designed and tested.
- It is based upon the mass balance equation.
- No limit to the number of modules the engine can accommodate. However, there is a growing cost in run speed as the number increases.
- Structure of the program, various high order processes, e.g. production of a crop, soil water balance etc. are represented as modules which relate to each other only through a central control unit, the 'Engine'. Plant growth modules are interchangeable, and more than one growth module can be connected simultaneously. The plug in-pull out capability enables the achievement of flexible simulation of crop systems (sequences and mixtures) while using the crop models most capable of accurate yield prediction. (McCown et al. 1996).
- Highly structured and highly logical in terms of function content (McCown et al. 1996).

However, since APSIM is a 1-dimensional modular model, its application in trickle irrigation management is limited. Multi-dimensional soil moisture redistribution difficulties and surface evaporation make the problem of infiltration from trickle irrigation difficult to solve within acceptable limits of accuracy and computational effort with analytical methods and preferred numerical methods (Subbaiah 2013). Further improvements on this topic require more targeted fieldwork to complement progress with the modelling and scenario analyses. Additionally, the fieldwork should aim to provide improved measurements of soil hydraulic properties and improved measurements of the transient soil–water content.

3.3.3 GET-OPTIS: a task specific genetic optimization algorithm

Recently, the global optimization technique GET-OPTIS (Global Evolutionary Technique for OPTimal Irrigation Scheduling) for optimal irrigation scheduling with limited water supply was developed by Schütze & Schmitz, (2010). The optimal irrigation scheduling used in this investigation was the result of a problem-adapted combination of APSIM and the GET-OPTIS optimization algorithm. This optimization procedure – designed mainly for arid regions – has been proven to be more reliable compared to heuristic and general evolutionary algorithms (Schütze, Kloss, Lennartz et al. 2011). Schütze & Schmitz (2010) stated that the big advantage of this optimization algorithm is that the selection of individuals is restricted which, in consequence, limits the number of individuals to be evaluated and therefore reduces the computational effort. Furthermore, as clearly stated by (Schütze, Kloss, Lennartz et al. 2011), there are number of reasons to select the GET-OPTIS algorithm for this study:

- The introduced tailor-made scheduling optimization algorithm GET-OPTIS is designed for allowing the generation of optimal irrigation schedules for given amounts of water.
- The overall time necessary for one optimization run can be reduced through extensive parallel processing of evaluation of the objective function for all individuals of one generation at once.
- The GET-OPTIS algorithm is able to maximize expected yield and to reduce the variability of potential yield if considerably less water is available than the plant would normally fully require.

The GET-OPTIS provides consistent SCWPF[21] using any reliable irrigation model suitable for the task on hand.

The tailor-made algorithm starts with a set of solutions, called population, which is, in our case, a random set of schedules. Every member of the set has a fitness value assigned which is directly related to the objective function - its crop yield. The fitness, i.e. the grain yield, is calculated by running APSIM with the specified irrigation schedule of the member. In sequential steps, the population of schedules is modified by applying four steps, aiming to imitate biological evolution: selection, crossover, mutation, and reconstruction. The procedure is then repeated until a convergence criterion is reached, or the maximum value of steps is exceeded. The details of the algorithm are presented in (Schütze & Schmitz, 2010 and Schütze, Kloss, Lennartz, Al Bakri, & Schmitz 2011).

In conjunction with a crop model, GET-OPTIS provides an optimal irrigation including application rates for each irrigation schedule to obtain maximum yield per growing season for any given - but limited - amount of total irrigation water.

Fig. 9 shows the framework to generate optimal irrigation schedule using GET-OPTIS.

[21] Stochastic crop-water production functions (SCWPF) for different crops is used as a basic tool for assessing the impact of climate variability on the risk for the potential yield or, for generating maps of uncertainty of yield for specific crops and specific agricultural areas.

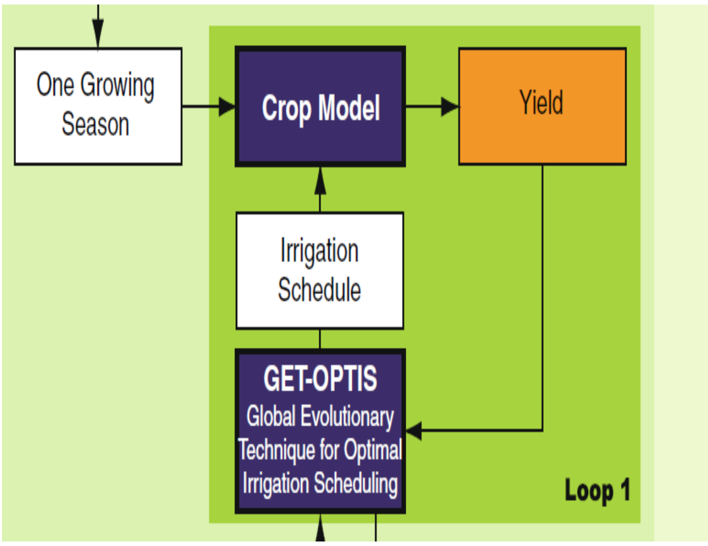

Fig. 9 Framework for generating optimal irrigation schedule (Schütze and Schmitz 2010)

3.3.4 Adapting the OCCASION framework in order to optimize irrigation schedules for full and deficit irrigation of Maize at the experimental plots

In our study, the Agricultural Production Systems Simulator (APSIM), the Global Evolutionary Technique for OPTimal Irrigation Scheduling (GET-OPTIS), and the task adapted OCCASION framework[22] - represent the tools and methods to build up the comprehensive strategy for optimizing irrigation scheduling. The Optimal Climate Change Adaptation Strategies in Irrigation (OCCASION) was developed by Schütze & Schmitz (2010) in order to generate site-specific stochastic crop-water production functions (SCWPF) by regarding variations in underlying climate scenarios. They also used sound process modeling together with a problem oriented optimization approach for evaluating optimal irrigation schedules with respect to maximum crop yield for a given water volume as shown in Fig. 10.

[22] Occasion was also adapted with respect to the setup of the irrigation scheduling; for the experiments the climate variability was accounted and thus, one general schedule for all available climate scenarios was optimized, see Fig. 26.

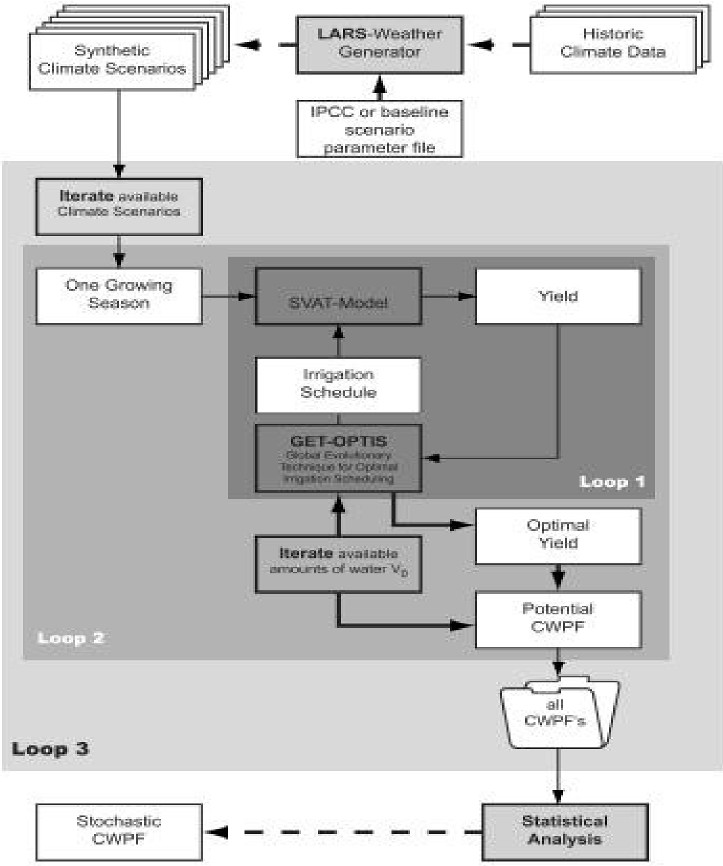

Fig. 10 OCCASION framework for generation of stochastic crop-water production functions (SCWPF) (Schütze and Schmitz 2010).

4 A NOVEL STRATEGY FOR OPTIMAL IRRIGATION SCHEDULES ACCOUNTING FOR BOTH WATER QUANTITY AND WATER QUALITY CONSTRAINTS

Optimal irrigation scheduling essentially relies upon two pillars: (1) a comprehensive process based model to reliably mimic plant behavior under various conditions together with a task oriented optimization procedure, (2) a sound and detailed database that fully allows characterizing the local environmental conditions (climate and soil) including the stochastic nature of the regional weather pattern. The overall target is to provide a sustainable and reliable irrigation management strategy that provides high water productivity (WP) together with a corresponding maximum yield. Along these lines, the proposed strategy NEMO (Nested Experimental, Modeling, and Optimization Strategy) relies, on the one hand, upon a process relevant and sound characterization of the considered cultivated area by physical parameters and a comprehensively monitored field experiment. On the other hand, it is based upon a physically based, process descriptive modeling technique, designed to allow for generalizing the results of a series of rigorous irrigation field experiments with respect to other similar regions. This opens new horizons for a more economic and more straightforward evaluation of optimal irrigation schedules as a basis for a more water efficient irrigated agriculture.

4.1 Overall goals and restrictions for the envisaged optimal irrigation strategy:

For substantially improving the efficiency of irrigated agriculture, the farmer in arid and semi-arid regions urgently needs a reliable strategy for an irrigation scheduling decision with respect to when to irrigate and how much irrigation water to apply. More precisely, this includes:

- Options to target high yields with full irrigation (aiming at highest yield with a most economic water application).
- Deficit irrigation trying to obtain the highest possible yield using only a limited amount of irrigation water.
- A sustainable decision aid which considers different management scenarios with application of irrigation water of different qualities (fresh or saline water).

The proposed methodology for establishing such an efficient irrigation management strategy mainly relies on two factors: on the thorough and comprehensive physical analysis of the considered cultivated area for characterizing its relevant environmental properties and, on the other hand, on the modeling approach which needs to contain submodules which adequately mimic the relevant physical and physiological processes such as e.g. soil moisture transport, evaporation and plant growth phenomena.

Since in general the data quantity and quality for the application, calibration (e.g. soil and plants parameter data) and validation of a relevant process model is normally inadequate, a preliminary experimental setup and subsequent modeling together with a rough optimization can be very helpful.

4.2 The interacting experimental, modeling, and optimization approach: An overview

This study relies upon two pillars:

- On the one hand it employs rigorous physical investigations as e.g. the evaluation of physical environmental field parameters, the characterization of the local weather pattern and - last but not least - a series of comprehensively monitored irrigation field experiments performed over a couple of growing seasons.
- On the other hand, it combines highly reliable up-to-date SVAT-modeling/simulation tools (DAISY and APSIM) together with a problem oriented and highly efficient optimization algorithm (GET-OPTIS).

Fig. 11 shows the scheme of the main interacting components that together synthesize the experiment with the modeling and optimization tools.

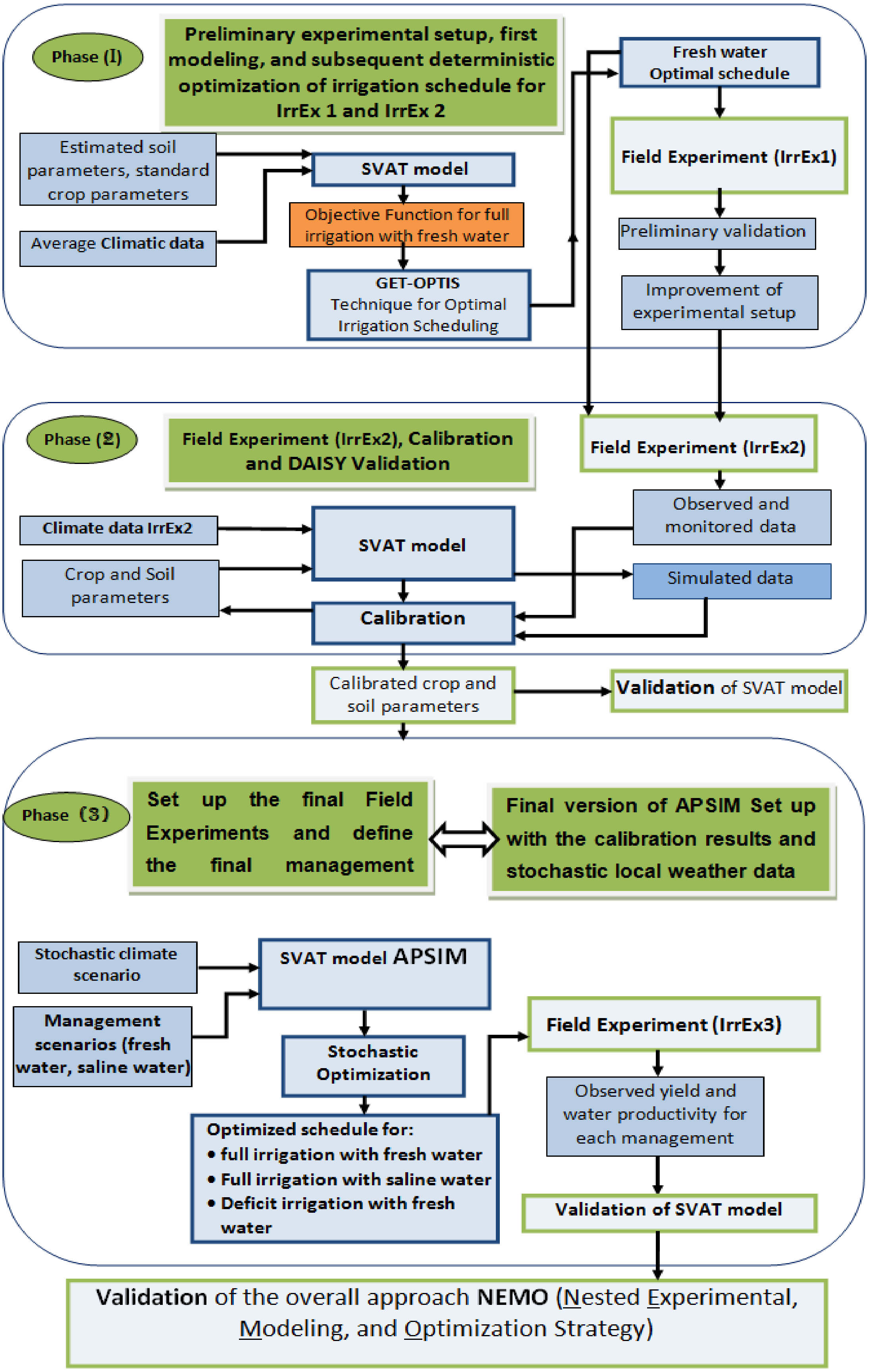

Fig. 11 General workflow scheme for interconnected experiment, modeling and optimization.

The field experiments were generally characterized by limited water and salinity. Three series of rigorously monitored, comprehensive open field experiments with maize were performed under a drip irrigation system during the growing seasons March to June 2011 (94 days), December 2011 to March 2012 (117 days) and December 2012 to March 2013 (117 days). The rather expensive and elaborate field experiments included - amongst other measurements - not only a rigorous monitoring of the subsurface flow system but also the consideration of soil, and management variability. A process relevant and reliable characterization of the considered cultivated area by physical parameters - as well as the initial condition when starting the experiment - opens the possibility for running in a subsequent step a physically and physiologically based irrigation model (SVAT-model) together with a task oriented optimization algorithm for determining optimal irrigation schedules.

Accordingly, the set up of the detailed experimental investigations takes into account the envisaged model application of the new approach. Correspondingly, SVAT models (DAISY and APSIM) were employed for portraying the relevant subsurface soil moisture transfer together with the plant growth processes. Last but not least, the evaluation of optimal irrigation scheduling is based upon a simulation-based optimization, which uses the new evolutionary algorithm GET-OPTIS with a specific focus on deficit irrigation systems.

As the most common and widespread irrigation practice, the standard FAO irrigation schedules using the evaporation pan to calculate Etc was also included in this study to serve as a basis of comparison versus the proposed novel approach NEMO (Nested Experimental, Modeling, and Optimization Strategy).

After preparatory steps had been taken, the working scheme was built up in three phases. The first phase served not only to evaluate the adequacy of the experimental layout but served also as a preliminary basis for comparison between the common irrigation practice and an objectively optimized irrigation schedule. Furthermore, it provided a basis for monitoring the impact of the applied irrigation treatments on plants and soil water availability, as well obtaining the data from a meteorological station on the site.

The main objective of the second phase was to evaluate the soil hydraulic parameters together with site relevant crop parameters. In this context, the records of measured soil moisture provided the basis to evaluate the soil hydraulic characteristics while the outcome of the field experiment (IrrEx2) and the weather data served to determine the plant parameters for the selected crop (Zea mays L., variety Pioneer 3527).

Subsequently, the optimization technique GET-OPTIS was applied to the accordingly parameterized APSIM-SWIM model, to determine the optimal irrigation scheduling. The tailor-made scheduling optimization algorithm GET-OPTIS possesses some unique features, which, in a reliable and computationally efficient manner, allow the generation of optimal schedules for given irrigation amounts of water. In this context, Schütze et al. (2011) could convincingly demonstrate that GET-OPTIS provides consistent crop-water production functions CWPFs using any reliable irrigation model suitable for the task on hand. Further, Schütze et al. (2012) showed clearly that the tailor-made Evolutionary Algorithm in GET-OPTIS is proven to be highly reliable compared to the Nelder-Mead simplex algorithm, simulated annealing and most recent general evolutionary optimization approaches.

The third phase focused on investigating water productivity especially of deficit irrigation using optimal irrigation schedules obtained from the proposed novel technique, i.e. the synthesis of sound experimental data with a task specific, calibrated simulation based stochastic optimization approach.

The optimization results were used to calculate the potential yield and water productivity. Later, the evaluation as regards the reliability of the overall approach NEMO (Nested Experimental, Modeling, and Optimization Strategy) was based on comparing experimental data versus the simulated data with respect to yield and water productivity.

The climate uncertainty as well as measurable physical soil properties and management options had been included for further promoting the possibility to generalize the results as well as to achieve close to optimal water productivities (WP).

5 APPLICATION OF THE NEW APPROACH TO A REAL FIELD SITE IN OMAN

5.1 Phase 1: Preliminary experimental and modeling setup

5.1.1 Phase 1 objectives and framework components

The main objectives of this phase were to utilize the available reference data to estimate an optimal irrigation schedule and to assess the experimental setup. Correspondingly, this part of the study has been conducted to meet the following objectives:

- Building a first location related database including a process relevant and reliable characterization of the considered cultivated area by physical parameters. Along these lines, the course of the field experiments provided, besides the recorded meteorological data from a meteorological station on the site, information about the impact of the applied irrigation treatments on plants and on soil moisture development - altogether an important part of the relevant data.
- Use reference data to build up the basic model files for a first estimate of an optimal irrigation schedule using DAISY.
- Employ the reference data to study the influence of the boundary conditions and assess the sensitivity of the estimated parameters.
- Find out the most suitable experimental layout for phase 2 and 3 based on assessing the preliminary experimental results.

Fig. 12 shows the main interacting components of the phase (1) workflow scheme.

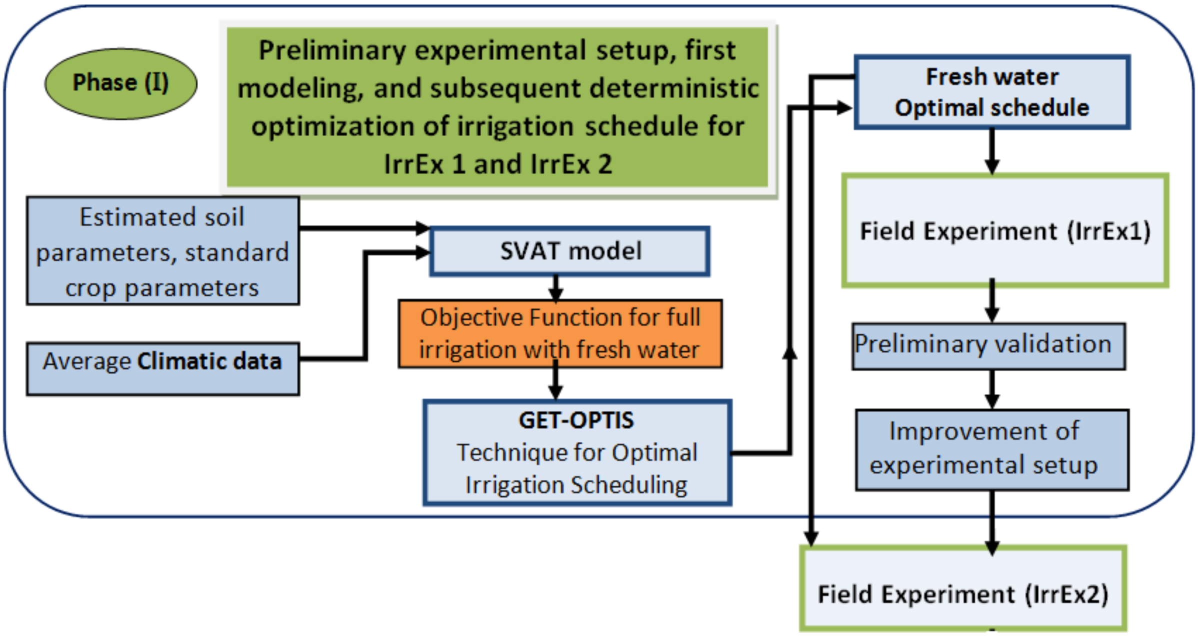

Fig. 12 The main interacting components of the phase (1) workflow scheme.

5.1.2 The first preparatory field experiment (IrrEx1) as a basis for a most adequate layout of the experimental series 2 (IrrEx2) and 3 (IrrEx3)

The experiment focused on two main investigation factors: three irrigation water qualities (Electrical conductivity of 1, 3 & 6 dS m^{-1}) and three irrigation water quantities (100% [W2], 125% [W3] of ETc - using the FAO method - and a Full irrigation schedule (FIS) [W1] for using NEMO. The latter (FIS) [W1] was based on reference local soil and weather conditions and a simulation based optimization employing the DAISY model within the new evolutionary algorithm for optimal irrigation scheduling (GET-OPTIS). The two factors were replicated three times in a split block design as shown in Fig. 13.

Total numbers of plots were 27 (3 x 3 x 3 = 27). Area of each plot area was 6 m^2 (2 X 3 m). The plots were 1 meter apart from each other and a distance of 2 m was kept between the replicate as shown in Fig. 14.

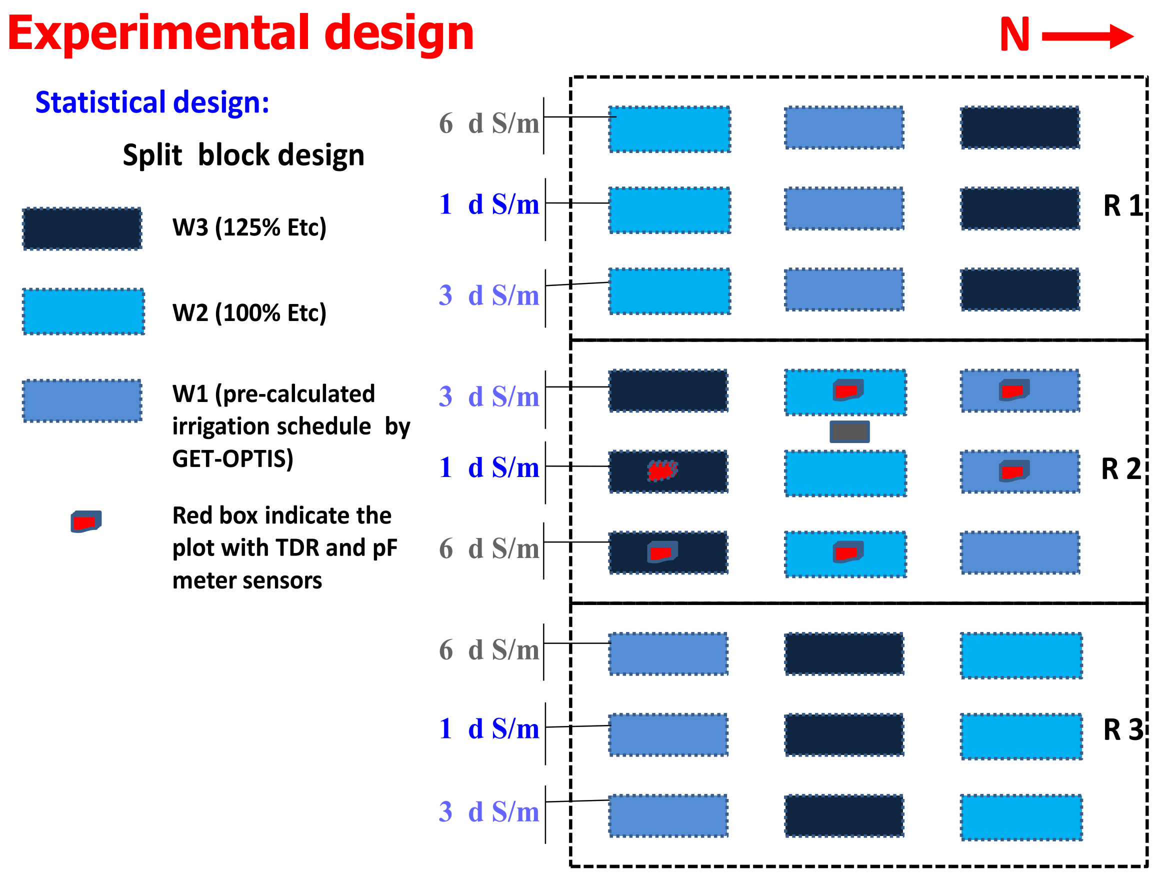

Fig. 13 IrrEx1 experimental design.

Fig. 14 The site for the preparatory experiment (IrrEx1).

5.1.3 The data sources for the first model parameterization (crop, soil and weather data)

Crop data:

For the preliminary investigation, the crop data used with the model DAISY was derived from the experimental site Lavallette in Montpellier, France, where maize (variety Pioneer PR36K67) had been cultivated in 2007, and the model was verified by an experimental run in 2009. The detailed plant parameters used for the DAISY setup file can be found in (Seidel 2012). According to that study the crop parameters were found to be reliable with measured vs. simulated yields of 16 tha^{-1} to 17.5 tha^{-1} for full irrigation (478 mm of total applied water) and 11.8 tha^{-1} to 12.1 tha^{-1} for a deficit irrigation treatment (339 mm of total applied water). Within their study to evaluate crop models for simulating and optimizing deficit irrigation systems in arid and semi-arid countries under climate variability, Kloss & Pushpalatha (2012) utilized the crop parameter findings of (Seidel 2012) in their DAISY model evaluation. They concluded that these crop parameters are robust and - to a limited extent - transferable.

Soil data:

The first model parameterization requires soil hydraulic input data as the parameters of the soil water retention and the hydraulic conductivity curves are generally not available for the considered site. Therefore, the hydraulic characteristics have firstly been estimated according to the corresponding textural class via pedotransfer functions. The pedotransfer functions used data such as particle size distribution and bulk density. In this respect, the results from the lab analysis for the collected soil samples (from 27 plots at the experiment site 5–10, 20–30, 50–60 cm depth) have been used. Appendix A.1 shows the analysis results for sand, silt and clay contents of each sample.

Weather data:

Historical daily weather data for 18 years (1991-2006) available from the nearby weather station Seeb (International airport, Muscat) - were used to generate average daily weather data. This deterministic weather data (appendix A.2) then was selected for simulation/optimization runs of the DAISY crop model.

5.1.4 Setting up the SVAT model DAISY

The SVAT model DAISY was set up for Pioneer - maize that was sown at a crop density of 10 plants per meter, which is typical for (Al- Batinah) region. The management (plowing, seeding date, fertilization, irrigation events, harvesting) was selected according to common practices in the region. Within the soil module of model DAISY, three soil layers were defined (0-30, 30-60, 60-200 cm soil depth). An exemplary setup file can be found in appendix A.3.

5.1.5 Deterministic optimization for full irrigation – objective function, and decision variable

For simulating and optimizing the irrigation scheduling with regard to the objective to achieve maximum crop yield (*Y)* with a given, but generous water volume (V_0) the SVAT model DAISY was coupled with (GET-OPTIS). The optimized irrigation quantities were distributed over the growing period, while minimizing the number of decision variables, i.e. number of irrigation events.

The corresponding optimization problem was then formulated as follows:

$Y^* = \max Y(\mathbf{S}) : \mathbf{S} = \{\mathbf{s}_i\}_{i=1\ldots n} = \{ (d_1, v_1), \ldots (d_n, v_n) \}$ n, $d_i \in$ N, $v_i \in$ R

with the optimal solution for maximizing the yield *Y*:

$\mathbf{S}^* = \arg\max Y(\mathbf{S}) = \arg\max Y(\{(d_i, v_i)\})$, i =1…n

Where **S** is the schedule for the whole growing season, consisting of i =1…n irrigation events $\mathbf{s}_i$ each defined by the date d_i and the irrigation volume v_i. The number n of irrigation events $\mathbf{s}_i$ is not fixed a priori and is a decision variable itself. The arg-operator is the selection of the decision variables of a specific irrigation scenario and the max-operator selects the best scenario with maximum yield. For further details in respect to the optimization formula refer to Schütze et al. (2011).

The GET-OPTIS algorithm was also set for a given yield of 11 tha^{-1} [23] with a reliability of 90%, refer to appendix A.4. For considering that reliability, the given deterministic weather scenarios (average daily weather data for 18 years, 1991-2006) were used.

5.1.6 An evaluation of the results of the first preparatory field experiment (IrrEx1)

The main findings for the subsequent experiments were:

- Within the same plots, there were very high variations in the plant growth. The supposed reason was the wind impact and the variation in the dripper discharge, where - in that time - a manual fix dripper was used.
- Contradicting TDR and pF meters reading.
- Frequent gaps within the measured data due to a technical problem in the electrical power supply.

Thus, further actions had to be taken for the second experimental trial (IrrEx2) in order to:

- Reduce wind impact by increasing plot size with less distance between the plots.

[23] Fig. 26 (shows the empirical distribution yield vs the probability of non-exceedance using local weather data) at point 5.3.3, illustrate the reason for the setted yield of 11 t ha^{-1}.

- Thoroughly and strictly maintain the setting for TDR and pF meters.
- Change the drippers to a GR[24] type in order to have a compensating water discharge.
- Keep checking the power supply.

5.1.7 The experimental series 2 (IrrEx2)

The experimental design and the treatments in the experiment series 2 (IrrEX2) were principally kept the same as it was in the experiment series 1 (IrrEx1). However, the experimental series (IrrEx2) were performed with a substantial change in plot size and space between the plots. In this context, all the lessons learned from the first experiment have been taken into account, such as:

- The plot size has been changed from 6 m^2 (2 X 3 m) to 14 m^2 (3.5 X 4 m) as shown in Fig. 15.
- In order to decrease the wind effect, the space between the plots was reduced, the plots became 0.5 meter apart from each other instead of formerly 1 meter, and a distance of 1 meter was kept between the replicate instead of 2 meters, as shown in Fig. 16.
- TDR and pF meter were thoroughly checked regularly and maintained.
- The seeds were planted 25 cm apart along eight rows whereas before it was 30 cm apart along 5 rows - in each plot.
- The dripper was changed from manual fix type to GR dripper, in order to have more uniformity in dripper discharge and have less fixing problems.
- Two drip tubes - each with an emitter spacing of 50 cm - for one plant row were installed, resulting in emitter spacing of 0.25 m. The emitter flow rate was 4.2 L h^{-1} at a pressure of 1 bar with dripper uniformity of 92%.
- From the flowering stage to the day of harvest the entire field was covered with a net in order to avoid the field from being attacked by birds eating the crop.

[24] The Built-in Dripper (GR), discharge, 4 l h^{-1} design emitter spacing of 30 cm at 1 bar nominal operating pressure in order to find a way to resolve the problem of lack of pressure at the end of lateral lines in the traditional drip irrigation system (Mansour et al. 2010).

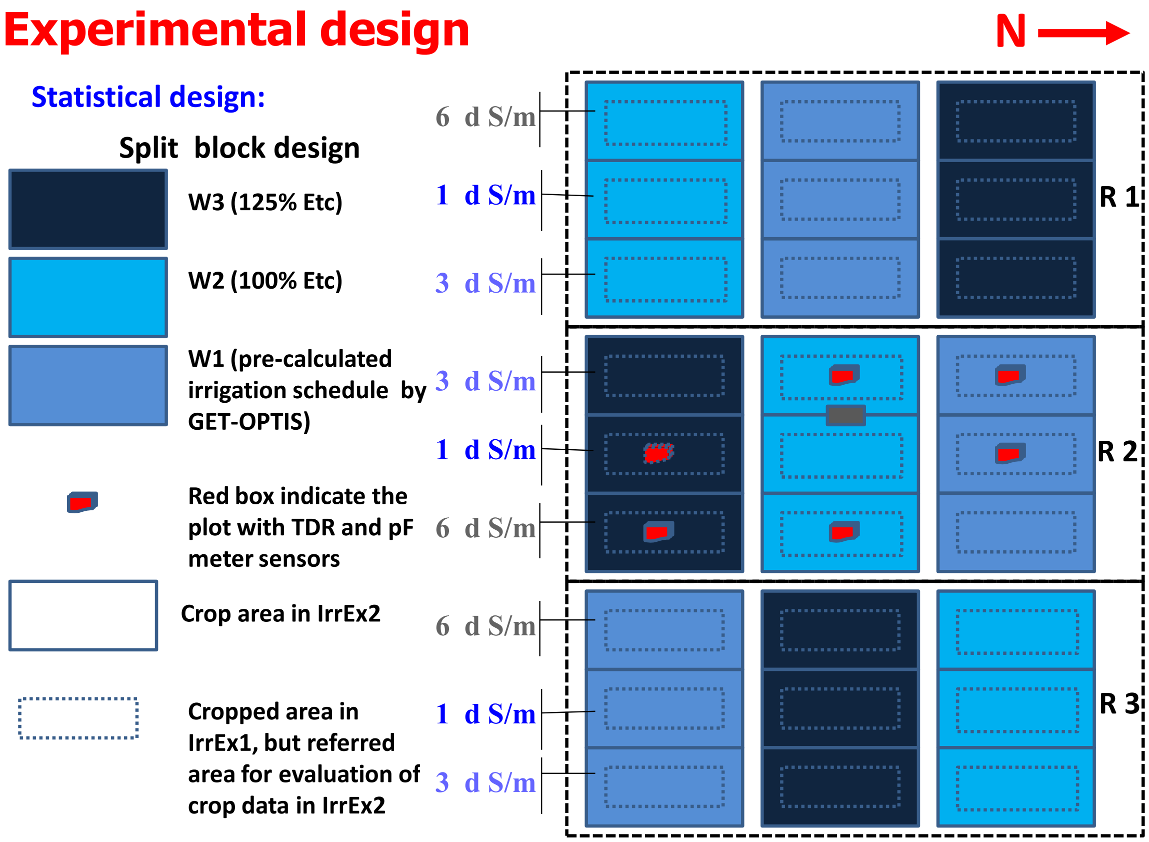

Fig. 15 IrrEx2 experimental design.

Fig. 16 The site for the second experiment (IrrEx2)

5.1.8 The results of the FAO method and of the DAISY model based optimization with GET-OPTIS during the first preparatory series of field experiments

Notwithstanding the fact that the preparatory series of field experiments suffered from a number of significant shortcomings (see 5.1.6), it seems essential to take into account the findings from this experiment. Along these lines, the second field experiment IrrEx2 within this series builds upon these findings. The subsequent paragraphs highlight the most interesting results.

5.1.8.1 Number of irrigations and total applied irrigation water

During the experimental growing period, the number of irrigations for the FAO-ETo approach W2(FAO, 100% ETC) and W3(FAO, 125% ETC) was double as compared to the simulation-based optimization approach W1(NEMO, FIS). For W1 and W3 the total applied irrigation depth was 360 mm and 457 mm corresponding to 98% and 124% of W2 (368 mm), respectively (see Table 2).

Table 2 Number of irrigations and irrigation water volumes for the second field experiment IrrEx2.

Irrigation rates	(CFIS) [W1]			100% [W2] of ETc			125% [W3] of ETc		
Irrigation water quality	1 dSm^{-1} (W1S1)	3 dSm^{-1} (W1S3)	6 dSm^{-1} (W1S6)	1 dSm^{-1} (W2S1)	3 dSm^{-1} (W2S3)	6 dSm^{-1} (W2S6)	1 dSm^{-1} (W3S1)	3 dSm^{-1} (W3S3)	6 dSm^{-1} (W3S6)
Total applied water (mm depth)	359	362	359	367	371	364	456	459	455
Average (mm)	360			368			457		
% of W2 water amount	98			100			124		
No. of irrigations	28	28	28	55	55	55	55	55	55

5.1.8.2 Harvest data

The experimental results from IrrEx2 showed that there is a significant increase in the harvest by increasing the applied irrigation water from W2 (FAO, 100% ETC) to W3 (FAO, 125% ETC). Although the GET-OPTIS irrigation scheduling W1(NEMO, FIS) was applying less total amount of irrigation water[25] with less irrigation frequency, it generally gave better results in comparison to 100 Etc [W2] especially while using good quality water (1 dS m^{-1}) in Fig. 17.

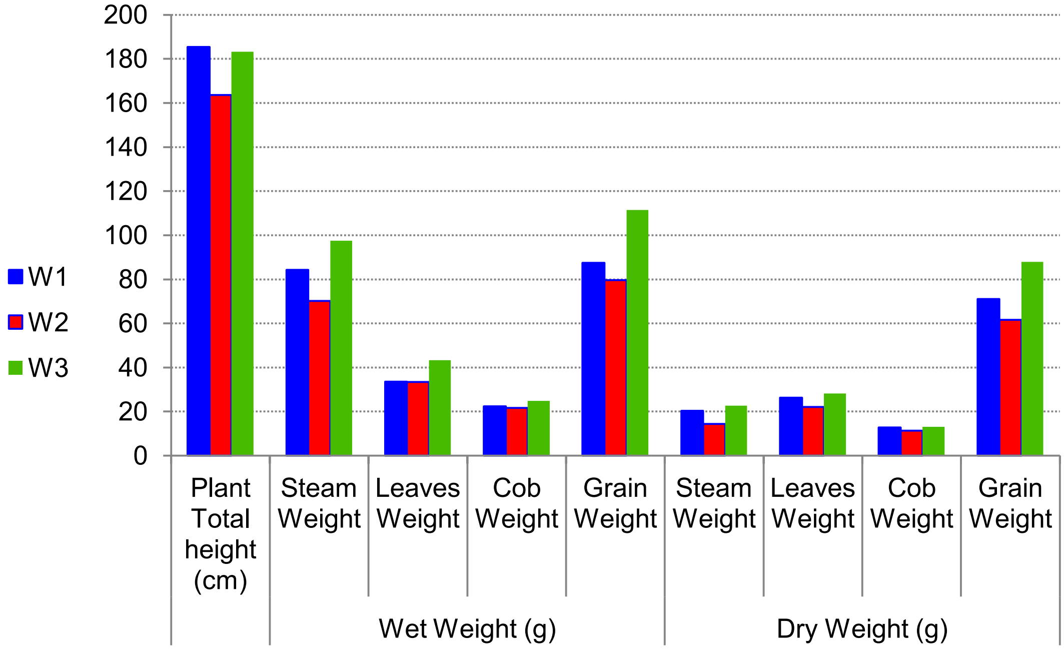

Fig. 17 The average of plant total height (cm), fresh weight biomass (g) and dry weight biomass (g) from five plants randomly selected at each plot out of three replications for W1(NEMO), W2(FAO, 100% ETC) and W3(FAO, 125% ETC) treatments with (1 dS m^{-1}) irrigation water salinity within IrrEx2 experiment.

5.1.8.3 Yield and water productivity

The results of the experiment showed that increasing the amounts of irrigation water from 100% [W2] to 125% Etc [W3] had increased dry grain yield by 33% (from 6.2 to 8.3 ton ha^{-1}) as shown in Fig. 18. However, the water productivity (WP) originating from the GET-OPTIS irrigation scheduling [W1] proved superior (with a of 1.85 kg m^{-3}) as compared to 1.70 and 1.82 kg m^{-3} for 100% [W2] and 125% Etc [W3] respectively as shown in Fig. 19.

[25] It had a higher application depth for the single event.

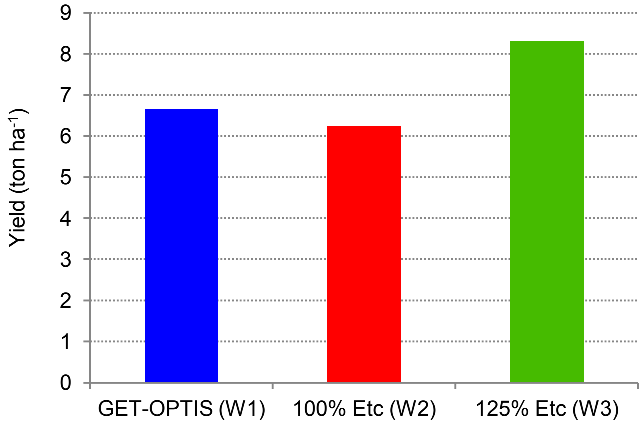

Fig. 18 IrrEx2, the Net average dry grain weight (ton ha^{-1})[26]

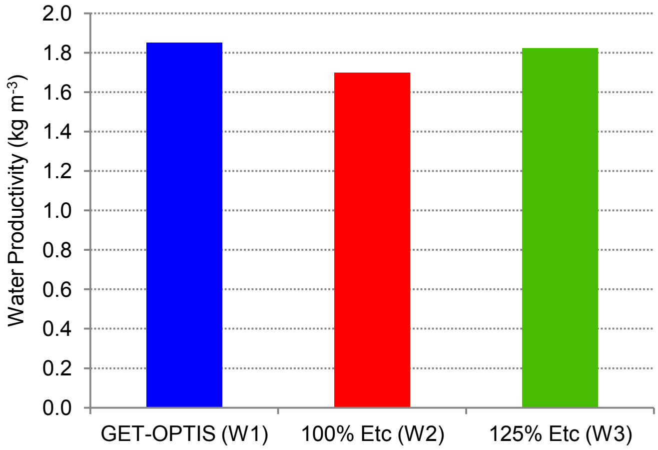

Fig. 19 IrrEx2, the water productivity (kg m^{-3}) out from the dry grain weight and the total applied irrigation water.

5.2 Phase 2: APSIM parameterization and validation of DAISY

5.2.1 Phase 2 objectives and framework components

The main objective of this phase was to establish a reliable and representative database for the soil properties at the considered location. The corresponding calibration was based upon external TDR measurements together with APSIM-SWIM. Contrary to the calibration of the

[26] The net average from the entire experiment that include the different water qualities 1, 3 and 6 dS m^{-1}.

soil model, the parameters of the crop model were evaluated using the outcome of the field experiment, i.e., the harvest data. Accordingly, this part of the study aimed at meeting the following objectives:

- Set up the APSIM model as a sound basis to consider sustainability – namely, the salt accumulation in different soil depths[27]. Consequently, all the collected data related to management practices, irrigation schedule, weather data …etc from experiment 2, served to build the APSIM model set up.
- Calibrate the soil hydraulic properties using the TDR records.
- Obtain (local) region-specific crop parameters using the outcome of IrrEx2.
- Evaluation of the DAISY model using reference data.

The corresponding workflow scheme of the phase (2) is shown in Fig. 20 below.

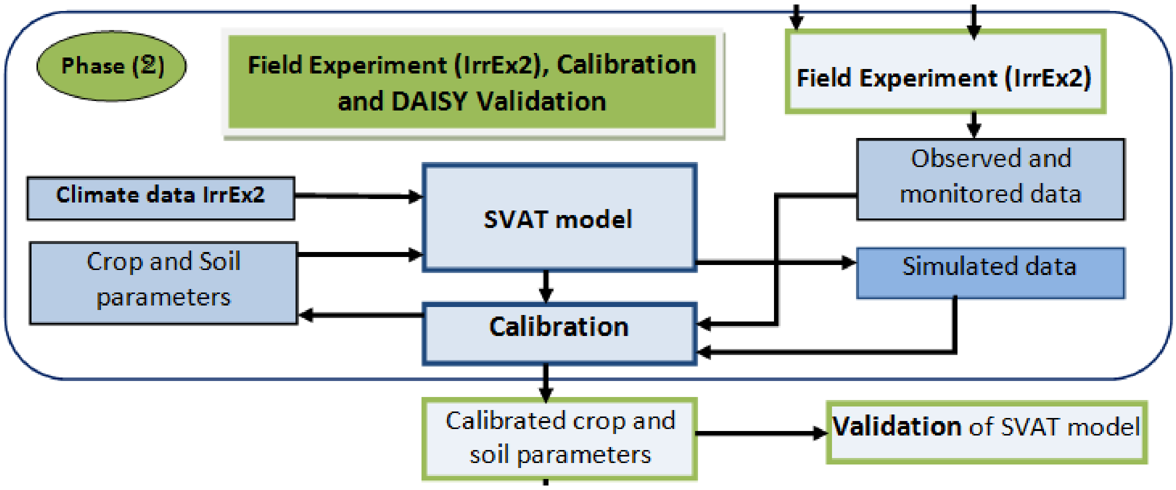

Fig. 20 Phase(2)the main interacting components.

5.2.2 Setting up the SVAT model APSIM

The APSIM model was set up for maize (maize sow cultivar = pioneer_3527) which was sown at a crop density of 9.7 plants m^{-2} and row spacing of 0.5 meter. Simulation was set to start 7 days prior to crop sowing in order to allow the model to properly simulate a bare soil water balance.

One Day was selected as time unit in the Time Information Window. A file for sowing, fertilizer application, irrigation events, and harvesting was created by specifying the date on which the corresponding operation has to be carried out. An APSIM compatible met file was

[27] This is the most important reason for using APSIM.

then created using the weather data on rainfall, maximum temperature, minimum temperature, and solar radiation observed during experiment IrrEX2.

The considered depth of the soil-profile was set to 200 cm and subdivided into 44 layers: 2 cm layer thickness for the first 10 cm and then 5 cm layer thickness until 200 cm.

For the soil water balance, APSIM-SWIM was set to run within APSIM and calculate all flows of water and nutrients through the soil for a given simulation. An Exemplary APSIM setup file can be found in appendix A.5.

5.2.3 Evaluation of soil hydraulic parameters using TDR records and APSIM

To allow for a realistic representation of the soil hydraulic properties in the SVAT models several experiments and measurements were conducted. The results of the dry sieve analysis served for the estimation of pedotransfer functions that were used for the parameterization of the DAISY model as described in appendix A.3. The simulations with this model delivered the first initial irrigation schedules for the field experiments (Phase 1 experiment one (IrrEx1) and two (IrrEx2)).

For the more detailed and refined representation of the natural system by APSIM, the Mualem-van Genuchten (MvG) soil model was used. The data from a pressure plate experiment as well as a multistep outflow experiment served for the calibration of the MvG model (Werisch, Grundmann, Al-Dhuhli, Algharibi, & Lennartz 2014). The main results are included in the appendix A.6.1. However, the soil hydraulic properties still exhibited a considerable degree of variability - which reflects the effects of natural heterogeneity of the layered alluvial soil under study. For obtaining a more accurate description of the soil hydraulic characteristics, the records of onsite transient soil moisture data - measured in the course of the field experiments - were used as more relevant field-scale observation data for evaluating the soil hydraulic parameters. Consequently, the in situ soil moisture measurements from the second field experiment (IrrEx2) were used within the frame of a master thesis (Pistorius 2012).

Within these investigations the observed and calculated model values of transient soil water content were plotted against time[28]. The investigated scenarios from two different locations were W_1S_1 (location 1) and $W_1S_{2.}$ (location 2), where W1 = optimized full irrigation, S_1 = irrigation water quality of 1 dS m^{-1}, and S_2 = irrigation water quality of 3 dS m^{-1}. Four soil layers with the TDR reading at soil depths of 10, 20, 50 and 100 cm were considered in each location. The agreement between model results and observations was visually evaluated.

[28] Days after sowing was used

In this context, the differences between measured and simulated values were minimized by a manual inverse modelling within a guided trial and error approach. The process was repeated for several times until reaching the highest agreement of model output to measured data. The difference between measured and simulated values was evaluated based on root mean square error (RMSE). Within that process the Mualem/van Genuchten parameters (θr, θs, a, n and Ks) were calibrated. The two investigated locations W1S1 and W1S2 revealed that the two locations had two different retention curves (R1 and R2) (appendix A.6.2); the curve R2 was for the top 15 cm soil of location W1S1, and for the remaining soil depth the curve R1 has been used, but in contrast for location W1S2, curve R1 has been used to a depth of 75 cm and curve R2 for the remaining, as shown in Table 3. Therefore, the simulations with combinations of the two retention curves parameters (R1 and R2) were chosen to provide the soil specific parameters for the field experiment 3 (IrrEx3).

Table 3 The manually calibrated retention curves parameters (Pistorius 2012).

Parameter	Retention Curve	
	R1	R2
W1S1 location (1)	< 15 cm ≤ 75 cm	0 ≤ 15 cm
W1S2 location (2)	0 ≤ 15 cm	< 15 cm ≤ 75 cm
θs	0.32	0.32
θr	0.01	0.01
α [cm-1]	0.1	0.1
n	1.3	1.2
Ks (cm h−1)	0.09	0.09
l	0.5	0.5

θs and θr [cm^3 cm^{-3}] are saturated and residual water content, α [cm^{-1}] and n are empirical parameters determining the shape of the retention curve, Ks [cm h^{-1}] is saturated conductivity, and l is a pore connection parameter.

5.2.4 Calibration of the plant growth parameters

Contrary to the calibration of the soil parameters, the outcome of the IrrEx2 experiment together with environmental data (soil hydraulic characteristics and weather data) served to calibrate the plant growth parameters. For the calibration purposes, the field relevant plant data with the scenario W_1S_1[29] - no water stress and non-saline conditions were used.

The calibration employed an inverse modeling with APSIM for minimizing the differences between the measured and simulated plant growth data - including the yield - for different crop parameters. The process was repeated for several times until reaching the best

[29] W1: the optimized fully irrigation, S_1: the irrigation water quality of less than 1 dS m^{-1}.

agreement between model results and measured data. In this context, appendix A.8 shows part of the iteration, where APSIM (Apsim75-r3008\Model\ Maize.xml) was used as the original maize file[30].

5.2.5 IrrEx2: relevant environmental and meteorological data

The weather data during the IrrEx2 experimental periods show that monthly average temperatures from seeding to harvest were 21.6 ^{0}C with a highest temperature of 37.7 ^{0}C. The lowest temperature recorded in this period was 11.3 ^{0}C (Fig. 21). As regards evapotranspiration, daily reference crop evapotranspiration values (ETo) were calculated by the ETo Calculator software[31] using the climatic data collected from WatchDog weather station[32] at the site as shown in Fig. 22. Monthly average values of ETo from seeding to harvest were 3.5 mm day^{-1} with highest of 6.3 mm day^{-1} and the lowest as 1.5 mm day^{-1}.

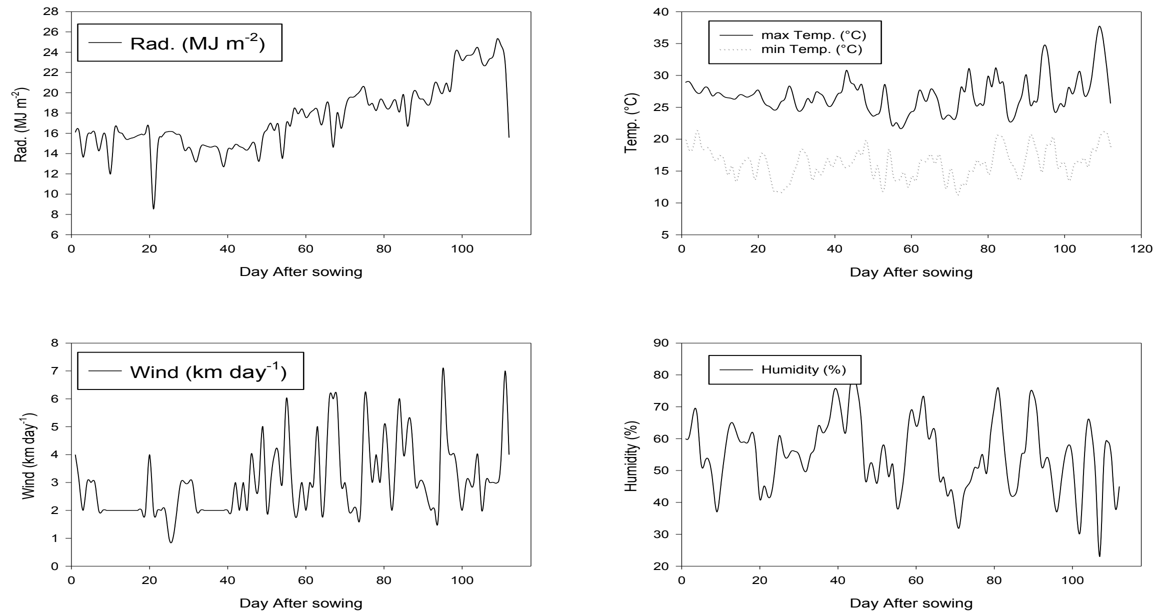

Fig. 21 Radiation, air temperature, relative humidity, and wind for the experimental site from 29 Nov. 2011 to 28 March 2012 from at the site WatchDog weather station.

[30] (Apsim75-r3008\Model\ Maize.xml) is the APSIM-Maize documentation on the APSIM web site.
[31] ETo calculator is a software developed by the Land and Water Division of FAO. Its main function is to calculate Reference evapotranspiration (ETo) according to FAO standards.
[32] https://www.specmeters.com/weather-monitoring/weather-stations/2000-full-stations/

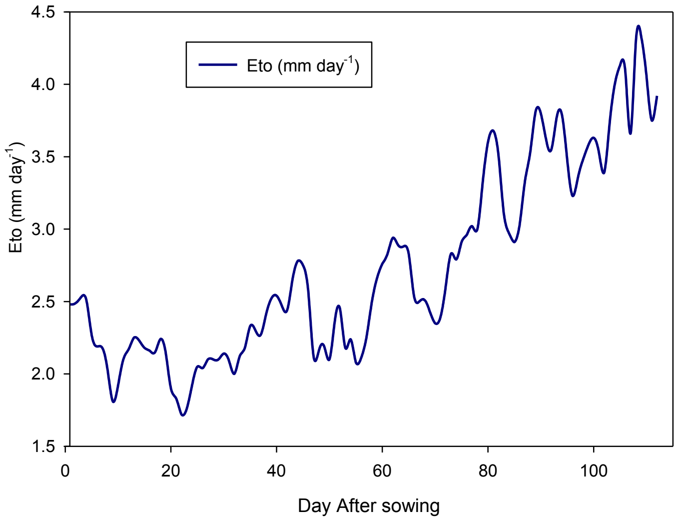

Fig. 22 ETo (calculated by CropWat, using IrrEx2 field meaured climatic data).

5.2.6 Validation of the SVAT model (DAISY)

The model DAISY - that was parameterized with reference data - provided the first initial irrigation schedules for the field experiments (Phase 1 experiment 1 and 2). Thus, the soil water content records and the measured plant growth data obtained during the IrrEx2 experiment represented a consequence of the irrigation schedules originating from GET-OPTIS optimization based upon DAISY applications. In this context, the comparison of these measured soil water and plant growth data with the results of APSIM simulations i.e. the simulated soil moisture transfer values, together with yield and biomass showed a good agreement and thus confirms the reliability of SVAT model DAISY.

5.2.6.1 Comparison of observed and simulated soil water contents

For the model validation by soil water contents, the observed and calculated model values of soil water content were plotted against time[33]. That was done separately for four soil layers and compared with the TDR reading at 10, 20, 50 and 100 cm of soil depths within each treatment. The difference between measured and simulated values was then evaluated by root mean square error (RMSE) as shown in Table 4 .

Table 4 RMSE difference between measured and simulated values for IrrEx2 experiment.

	10/-10 cm	**25/20 cm**	**50/0 cm**	**100/0 cm**
W1S1 RMSE	0.0516	0.0534	0.0390	0.0426
W2S3 RMSE	0.0312	0.0248	0.0302	0.0990

[33] Days after sowing was used

The results show mostly a fit agreement between the recorded and the simulated soil water contents for the majority of all the treatments within the four depths. Exemplarily, the corresponding data of W1S1 (the treatment provided by GET-OPTIS optimization runs for a full irrigation strategy with fresh water) is shown for the different depths in Fig. 23.

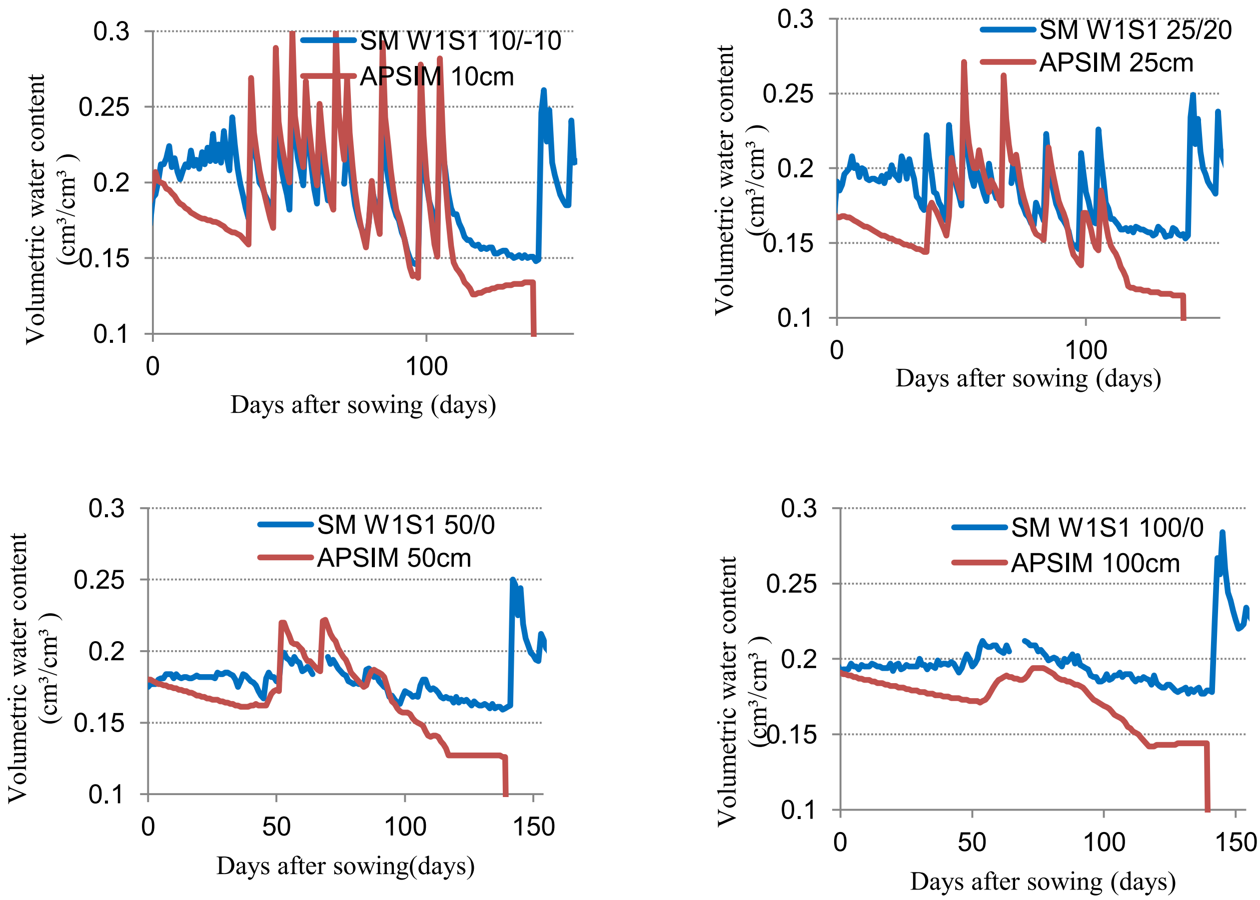

Fig. 23 simulated soil water contents (red line) vs. the observed for W1S1 (blue line) at different soil depths.

5.2.6.2 Model validation by the plant data

In order to validate the SVAT model DAISY on the basis of plant data, the measured values of plant height, Biomass (total above ground biomass), yield (grain yield, dry weight), LAI and root depth from all the different treatments (further from the one used for calibration) within IrrEx2 compared favorably with the output from the model simulation.

The recorded various experimental crop data served as a basis for evaluating the reliability of DAISY. Table 5 shows a good fit with the corresponding data of W1S1 (the treatment provided by GET-OPTIS optimization runs for a full irrigation strategy with fresh water).

Table 5 The different kinds of plant data of the IrrEx2 experiment and simulation, Ob. = measured from the treatment W1S1 which is a DAISY and optimization output , Calc. = calculated using APSIM model.

	Yield (grain yield dry weight) (kg ha^{-1})	Biomass (total above-ground biomass) (kg ha^{-1})	Height (mm)	LAI (m^2 m^{-2})	Root Depth (mm)
Observation	11476	17630	2000	2.17	1000
Simulation	11820	17859	2057	2.82	845

5.3 Phase 3: the final experimental series and the stochastic optimization for evaluating optimal irrigation schedule

5.3.1 Phase 3 objectives and framework components

The main objective of this phase was to evaluate the practical benefit of the new strategy NEMO which uses on the one hand comprehensive irrigation experiments with rigorously measured soil moisture and plant growth development and on the other hand physically based process modeling together with a new problem oriented simulation based optimization. For irrigation scheduling under full and deficit irrigation as well as for analyzing soil salinity accumulation, the approved process model APSIM was also used during phase 3. Correspondingly, this part of the study was conducted to meet the following objectives:

- Set up a final rigorous irrigation experiment
- Define water quantity and water quality application.
- Utilize the outputs from the previous phases to build up a final parameterization of APSIM together with a case related simulation based optimization approach for providing realistic optimal irrigation schedules.
- Take into account the stochastic nature of weather phenomena for enabling continuous future applications of the optimal schedules.
- Define adequate objective functions for the simulation-based stochastic optimization to obtain optimal irrigation schedules not only for the traditional full irrigation but also for the most important deficit irrigation as well as for a saline irrigation water conditions.
- Validation of the SVAT model APSIM based on these experiments.
- Evaluation of the practical benefit of the obtained optimal irrigation schedules in comparison to common irrigation practice i.e., performs a validation of the overall

approach NEMO (Nested Experimental, Modeling, and Optimization Strategy) with respect to the FAO irrigation method.

Fig. 24 shows the main interacting components of the phase (3) workflow scheme.

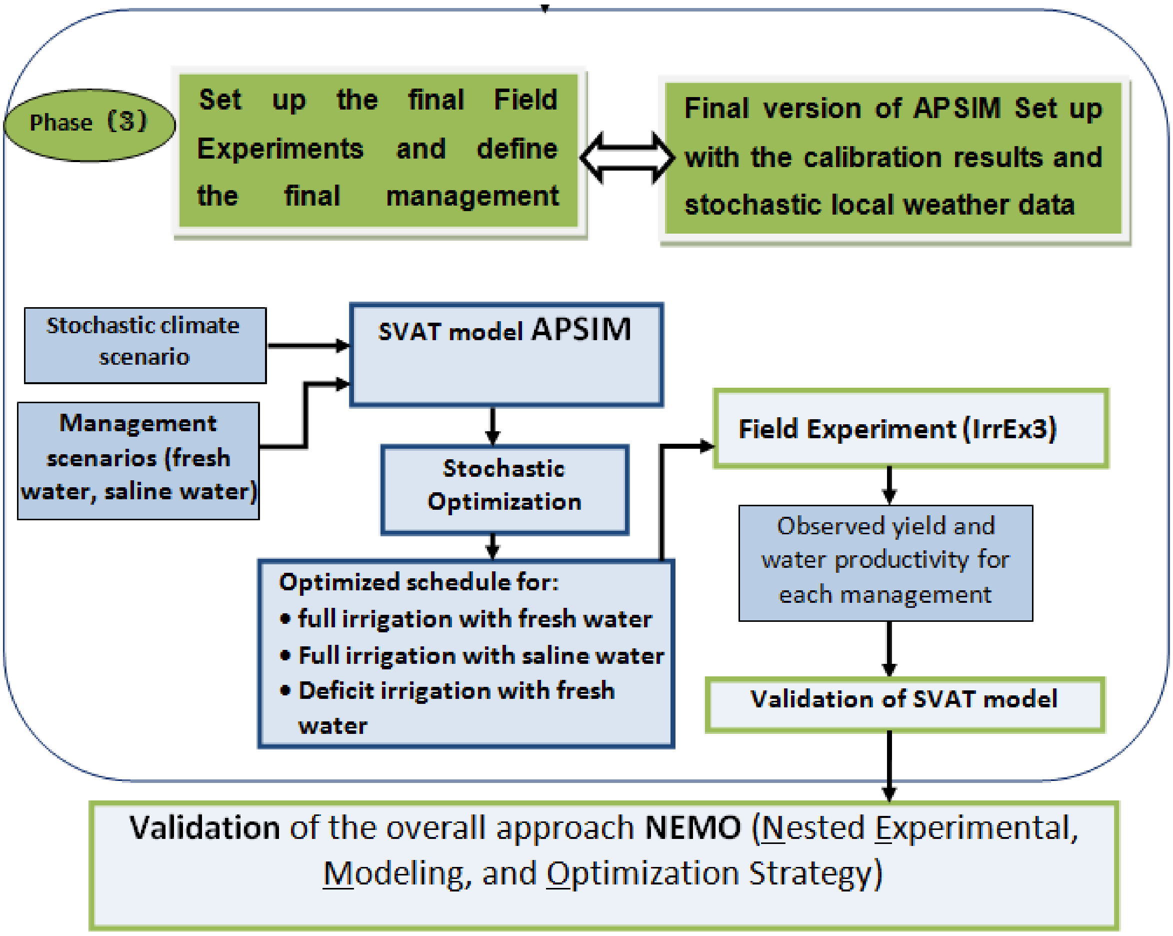

Fig. 24 Phase (3) main interacting components

5.3.2 A series of rigorous irrigation experiments for full and deficit irrigation including saline conditions (IrrEx3)

The experimental series (IrrEx3) were performed with a substantial change from the previous experimental series (IrrEx1 & IrrEx2). It takes into account the results from the TDR based calibration of the soil model and using the plant related output of the second experiments. These series of experiments (IrrEx3) cover not only full irrigation but also different irrigation water qualities (fresh or saline water) and deficit irrigation. The type of seeds, management practices, experimental design, plots size and the space between the lines were principally kept the same as it was in the experiment series 2 (IrrEx2). However, several adjustments were made as shown as following (Fig. 25, Table 6):

IrrEx3 dealing with saline irrigation water:

- The experiment consisted of two different water qualities namely ECw 1 dS m^{-1} and 6 dS m^{-1}.
- In the corresponding third experimental series (IrrEx3), the water quality of 3 dS m^{-1} has been excluded due to low priority.
- The GET-OPTIS optimization runs provided an optimal schedule for full irrigation using an irrigation water salinity of 6 dS m^{-1} (T1).
- Additionally, the traditional FAO approach was applied using an irrigation water salinity of 6 dS m^{-1}. The corresponding water quantities were 100% (T2) of potential crop evapotranspiration (ETc, FAO) and 125% (T3) of potential crop evapotranspiration (ETc, FAO).

IrrEx3 dealing with different irrigation water quantities with mainly focus on deficit irrigation strategies:

- The GET-OPTIS optimization runs provided two optimal schedules using an irrigation water salinity of 1 dS m^{-1}. The two optimal irrigation schedule were (T6) for full irrigation and (T7) for a deficit irrigation.
- Additionally, the traditional FAO approach was applied using an irrigation water salinity of 1 dS m^{-1}. The corresponding water quantities were 95% (T5) and 100% (T4) of potential crop evapotranspiration (ETc, FAO).

IrrEx3 treatments featured a slight change as compared to IrrEx 1 and 2 (Table 6). Additionally the following activities had been included:

- TDR and pF meters sensors were overhauled.
- Three other plots had a new type of sensors (Hydra Probe). The new sensors were placed at 30 cm depth.
- A sensor-based system has been tested in two plots (T8), (T9) had technical problem, and thus no further details are included.
- An automatic Irrigation System (with Netafam Irrigation Controller and smart water meters) was implemented.
- A net windbreak was used to reduce the wind effect.

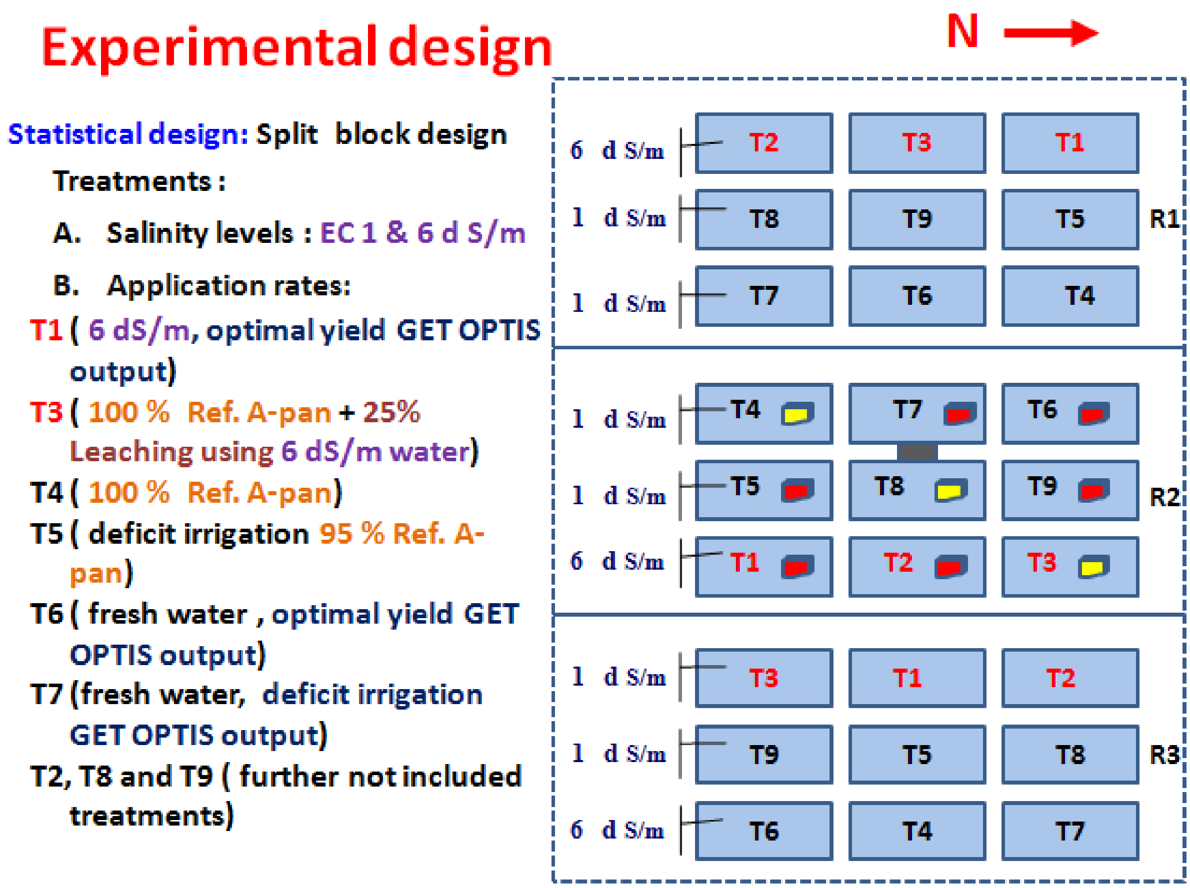

Fig. 25 IrrEx3 experimental design.

Table 6 Comparison of treatments between (IrrEx 1 and 2) vs. (IrrEx 3)

IrrEx 1 and IrrEx 2		IrrEx 3	Where:
W	S [dS/m]	T (W & S)	W : Water application
1	1	T6	S : Irrigation water salinity
1	3	-	W1 : the pre-calculated irrigation schedule
1	6	T1	by GET-OPTIS
2	1	T4	W2 : 100% ETc
2	3	-	W3 : 125% ETc
2	6	T2 *	T5 **: new treatment with 95% ETc.
3	1	-	T7 **: new treatment with GET-OPTIS
3	3	-	output for deficit irrigation.
3	6	T3	T2 *: Unconsidered treatment due to a
	1	T5 **	problem of mixed water qualities.
	1	T7 **	T8 * & T9 *: Unconsidered treatments due
	1	T8 *	to technical problems.
	1	T9 *	

5.3.3 Simulation based stochastic optimization for full (fresh and saline) and deficit irrigation

This part of the study was based on previous efforts to utilize a stochastic optimization framework for irrigation schedules based on scenarios generated by weather generators. Schütze & Paly (2012) investigated the efficiency of a stack-ordering technique[34] for generating high productive irrigation schedules for an agricultural area in the Al-Batinah region of Sultanate of Oman. They used observed daily weather data for 18 years (1991-2006) from Seeb weather station (International airport, Muscat) and selected high emission global climate change scenarios IPCC-B1 and IPCC-A2 for2080.

Two results from Schütze & Paly (2012) originated from the same area as this study. Therefore, these outputs were utilized within this study. First, the generated stochastic weather data has been employed as the weather file within the APSIM model. Second, the probabilities of exceedance of 90% of a yield, corresponding to 0.1 of the probabilities of non-exceedance, as shown in Fig. 26 - were used as reference limits to set up the objective functions for the study scenarios as following:

- 8.5 t ha^{-1} with full irrigation and a irrigation water salinity of (1 dSm^{-1})
- 7 t ha^{-1} with full irrigation and a irrigation water salinity of (6 dSm^{-1})
- 6 t ha^{-1} with deficit irrigation and a irrigation water salinity of (1 dSm^{-1})

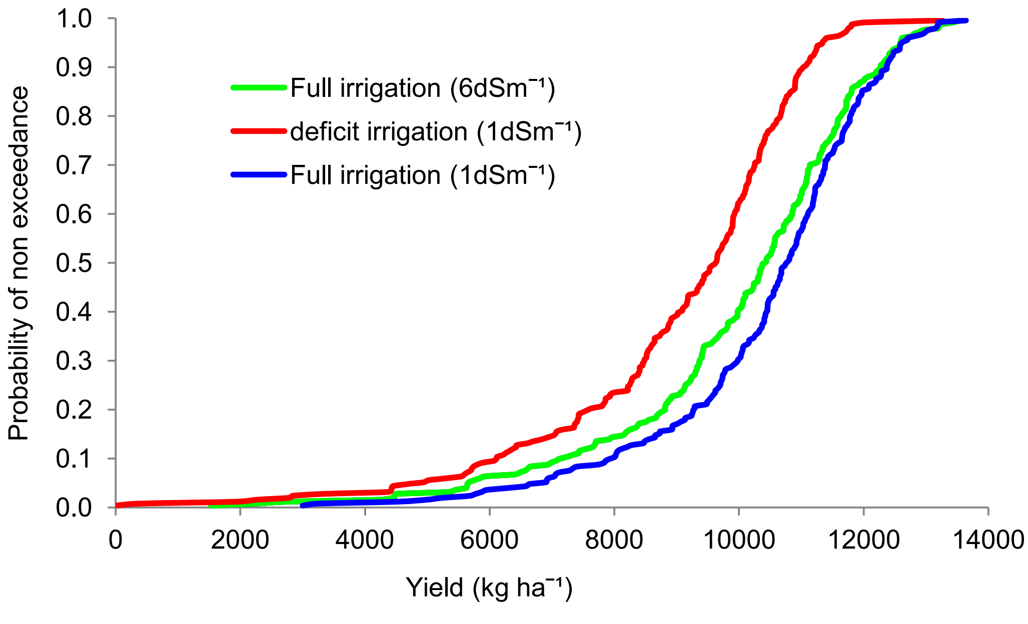

Fig. 26 distribution of yield vs. the probability of non-exceedance using local weather data

[34] The stack-ordering procedure selects the most critical weather scenarios with respect to constraint violations, i.e. scenarios which achieve less than the given yield with the provided schedule from the optimizer (Schütze and Paly 2012).

5.3.3.1 Stochastic optimization for full irrigation - objective function, and decision variable - with various degrees of irrigation water salinity

For this optimization problem, crop yield (Y max) with full irrigation was provided of 8.5 t/ha for an irrigation water salinity of (1 dSm^{-1}) and of 7.0 t/ha for an irrigation water salinity of (6 dSm^{-1}), refer to appendix A.7. The optimization will then run for the optimal irrigation schedule with the objective function to achieve minimum total applied water (min $Q^{0.9}$) with exceedance in 90 of 100 years; the 90% percentile (reliability) while minimizing the number of decision variables, i.e., number of irrigation events, the amount of individual irrigation events and as well as dates when to irrigate.

The corresponding optimization problem was then formulated as follows:

Objective Function: min ($Q^{0.9}$) "minimize water consumption with 90% reliability"

$Q = \Sigma q_i$, q_i = irrigation amount for each day *i*.

Decision variables: Irrigation Calendar; Schedule $\{q_i\}$

$\mathbf{S} = \{\mathbf{s}_i\}_{i=1\ldots n} = \{ (d_1 , v_1), \ldots (d_n,v_n) \}$ n, $d_i \in$ N, $v_i \in$ R

Where **S** is the schedule for the whole growing season, consisting of $i = 1\ldots n$ irrigation events $\mathbf{s}_i$ each defined by the date d_i and the irrigation volume v_i. The number n of irrigation events $\mathbf{s}_i$ is not fixed a priori and is a decision variable itself. For further details in respect to the optimization formula refer to (Schütze, Kloss, Lennartz, et al. 2011).

Condition: the provided yield (Y) with exceedance in 90 of 100 years; 90% reliability.

5.3.3.2 The objective function for maximum yield under deficit irrigation with a irrigation water salinity of 1 dSm^{-1}

In the previous optimization problem with full irrigation, Y max has been provided and the optimization run for the optimal irrigation schedule with the minimum total applied water, While in this optimization problem with deficit irrigation, Q "total applied water" is provided and the optimization will run for the optimal irrigation schedule to give the Y max. Appendix A.7.3 shows the script of the corresponding objective function with regard to achieve the deficit irrigation scheduling. The related optimization problem was formulated as follows:

Objective Function: (Y max) maximum yield with 90% reliability

Decision variables: Irrigation Calendar; Schedule $\{q_i\}$

(Irrigation q_i for each day $_{i)}$ $\{q_i\} = q_{r1}\ q_{r2}\ q_{r3}\ q_{r4}\ q_{r5} \ldots\ldots q_{rn}$

Condition: Given Q "water consumption", $Q = \Sigma q_i$

Where Q with deficit irrigation strategy was (330 mm) < Q was (382 mm) for full irrigation with an irrigation water salinity of (1 dSm^{-1}) and (468 mm) for full irrigation with an irrigation water salinity of (6 dSm^{-1}).

5.3.4 IrrEx3: relevant environmental and meteorological data

Throughout the growing period, the weather station located near the experimental site worked perfectly. The recorded weather data (Fig. 27) shows an overview of field weather data with average temperatures from seeding to harvest of 22.6 ^{0}C and a highest temperature of 36.7 ^{0}C. The lowest temperature during this period was 10.8 ^{0}C.

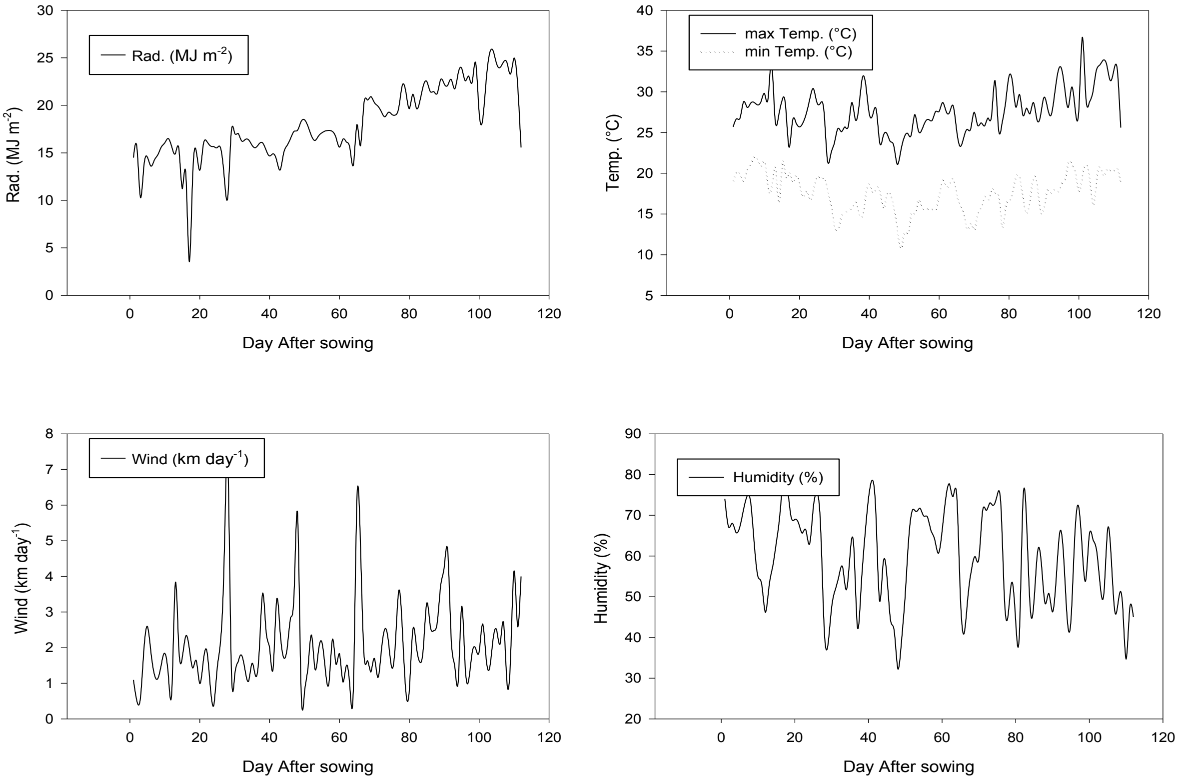

Fig. 27 Radiation, air temperature, relative humidity, and wind for the experimental site from 29 Nov. 2012 to 28 March 2013 from at the site WatchDog weather station.

For creating similar growing conditions throughout the different experimental plots, a windbreak was installed. The dimensioning of the windbreak (Fig. 29) stability was based on maximum wind speed and average wind speed of (km h^{-1}) and on wind direction (Degree) during the crop development stage (Fig. 28).

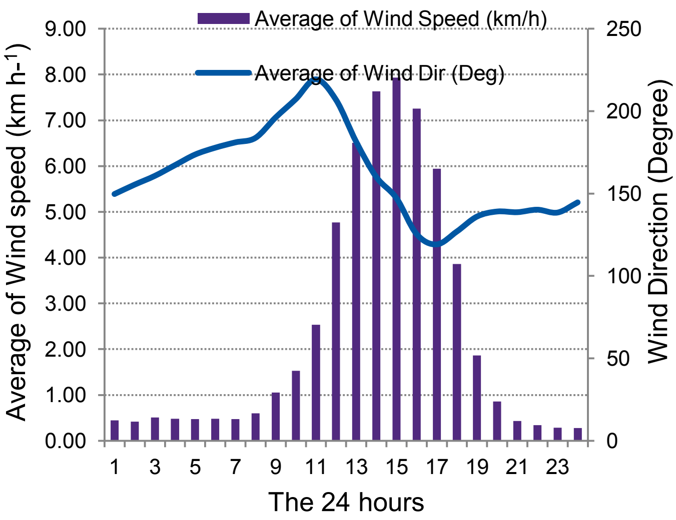

Fig. 28 Average of wind speed (km h^{-1}) and wind direction (Degree) within the 24 hours throughout the experimental (IrrEx3) period.

Fig. 29 IrrEx3 windbreak.

For the comparative FAO experiments, the Class A pan was placed close to the plots. Fig. 30 shows the daily evapotranspiration (ETo) calculated based on evaporation from class A pan (E_p). Average daily calculated ETo based on evaporation from class A pan from seeding to harvest were 3.4 mm day^{-1} with highest of 5.6 mm day^{-1} and the lowest as 1.5 mm day^{-1}.

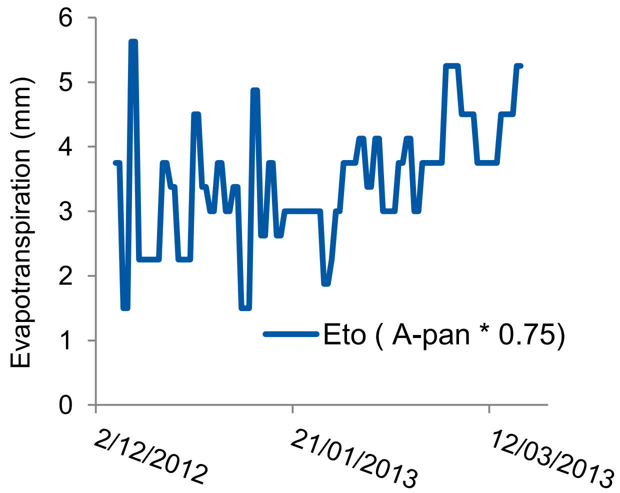

Fig. 30 IrrEx3 daily evapotranspiration (ETo) calculated based on evaporation from class A pan (E_p).

5.4 Results

5.4.1 IrrEx3 number of irrigations and total applied irrigation water

During the IrrEx3 experimental growing period, the number of irrigations for the FAO- ETo approach T4 (FAO, 100% ETc), T5 (FAO, 95% ETc) and T3 (FAO, 125% ETc, + leaching) was one and half times more than the simulation-based optimization approach T1 (NEMO, FIS, 6 dSm^{-1}), T6 (NEMO, FIS, 1 dSm^{-1}) and T7 (NEMO, DIS, 1 dSm^{-1}). However, for T4, T5, T6, and T7 the total applied irrigation water (mm depth) was 377, 358, 396, and 358 mm as equal to 100%, 95%, 105%, and 95% respectively (Table 7).

Table 7 Number of irrigations and irrigation water volumes for the field experiment IrrEx3.

	No. of irrigations	Total applied irrigation water (mm)	% of T4 water quantity (FAO, 100% ETc)
T1 (NEMO,FIS,6 dSm^{-1})	33	472	125
T3 (125%,FAO,6 dSm^{-1})	54	599	159
T4 (100%,FAO,1 dSm^{-1})	54	377	100
T5 (95%,FAO,1 dSm^{-1})	54	358	95
T6 (NEMO,FIS,1 dSm^{-1})	32	396	105
T7 (NEMO,DIS,1 dSm^{-1})	32	358	95

5.4.2 Harvest data

In the day of harvest, four plants randomly selected at each plot were utilized for evaluation of the harvest. The investigated data were plant total height (cm), plant height until flag leave (cm), leaf length (cm), leaf width (cm) as well as wet (total biomass above ground) and dry weight(g) of stem, leaves, cob, and grain. Table 8 shows the recorded plant data under the different irrigation strategies within IrrEx3. Further plant data records can be found in appendix A.11.

Table 8 Average of plant height until flag leave (cm), leaf length (cm), and leaf width (cm) under the different irrigation strategies within IrrEx3.

	Plant height until flag leave (cm)	Leaf Length (cm)	Leaf Width (cm)
T1 (NEMO,FIS,6 dSm^{-1})	183	91	8
T3 (125%,FAO,6 dSm^{-1})	172	91	9
T4 (100%,FAO,1 dSm^{-1})	189	91	8
T5 (95%,FAO,1 dSm^{-1})	177	92	9
T6 (NEMO,FIS,1 dSm^{-1})	181	97	9
T7 (NEMO,DIS,1 dSm^{-1})	188	97	9

5.4.3 The overall yield of IrrEx3 as considered in the light of IrrEx2 results

The NEMO optimal irrigation schedule in IrrEx2 was based on deterministic weather data, while in IrrEx3 the NEMO optimal irrigation schedules used stochastic weather data. There was also a difference in weather data records between IrrEx2 and IrrEx3 with a relevant impact on the FAO class A-pan measurements. Altogether, there was an overall significant increase in the yield production in IrrEx3 versus IrrEx2 (Table 9).

Table 9 The yield production in IrrEx3 versus IrrEx2

R2 Treatment	2012 Dry Grain (ton ha^{-1})	2013 Dry Grain (ton ha^{-1})	% from T4 2013	% from 2012
T1 (NEMO,FIS,6 dSm^{-1})	10.1	13.5	102	133
T3 (125%,FAO,6 dSm^{-1})	4.9	14.0	106	287
T4 (100%,FAO,1 dSm^{-1})	7.0	13.2	100	188
T5 (95%,FAO,1 dSm^{-1})	7.0	9.3	71	133
T6 (NEMO,FIS,1 dSm^{-1})	6.8	14.6	111	214
T7 (NEMO,DIS,1 dSm^{-1})	5.9	13.9	105	235

5.4.4 Validation of the SVAT model (APSIM)

The validation of the SVAT model APSIM represents a mandatory step for securing the consistency of the overall NEMO approach and to prove the reliability of the model. A comparison between observed and simulated soil water contents and between measured and calculated plant data - at selected times during the growing season as well as at harvest - had been used for the model validation.

5.4.4.1 Comparison of observed and simulated soil water contents

For the model validation, the recorded TDR readings and calculated model values of soil water content were plotted against time[35]. That was done separately with the TDR reading at 10, 20, 50 and 100 cm of soil depths within each treatment. The difference between measured and simulated values was then evaluated by root the mean square error (RMSE) as shown in Table 10.

Table 10 RMSE difference between measured and simulated values for IrrEx3 experiment.

	10/-10 cm	**25/20 cm**	**50/0 cm**	**100/0 cm**
T1 (NEMO,FIS,6 dSm^{-1})	0.0256	0.0258	0.0211	0.0328
T2 (100%,FAO,6 dSm^{-1})	0.0137	0.0327	0.0177	0.0322
T5 (95%,FAO,1 dSm^{-1})	0.0180	0.0170	0.0092	0.0357
T6 (NEMO,FIS,1 dSm^{-1})	0.0244	0.0187	0.0269	0.0254
T7 (NEMO,DIS,1 dSm^{-1})	0.0233	0.0177	0.0134	0.0099
T9 (A sensor-based,1 dSm^{-1})	0.0339	0.0168	0.0129	0.0092

The results show mostly a fit agreement between the recorded and the simulated soil water contents for mostly all the treatments within the four depths. Exemplarily, the corresponding data of T7 (the treatment provided by GET-OPTIS optimization runs for a deficit irrigation strategy with fresh water) is shown for the different depths in Fig. 31.

[35] Days after sowing was used

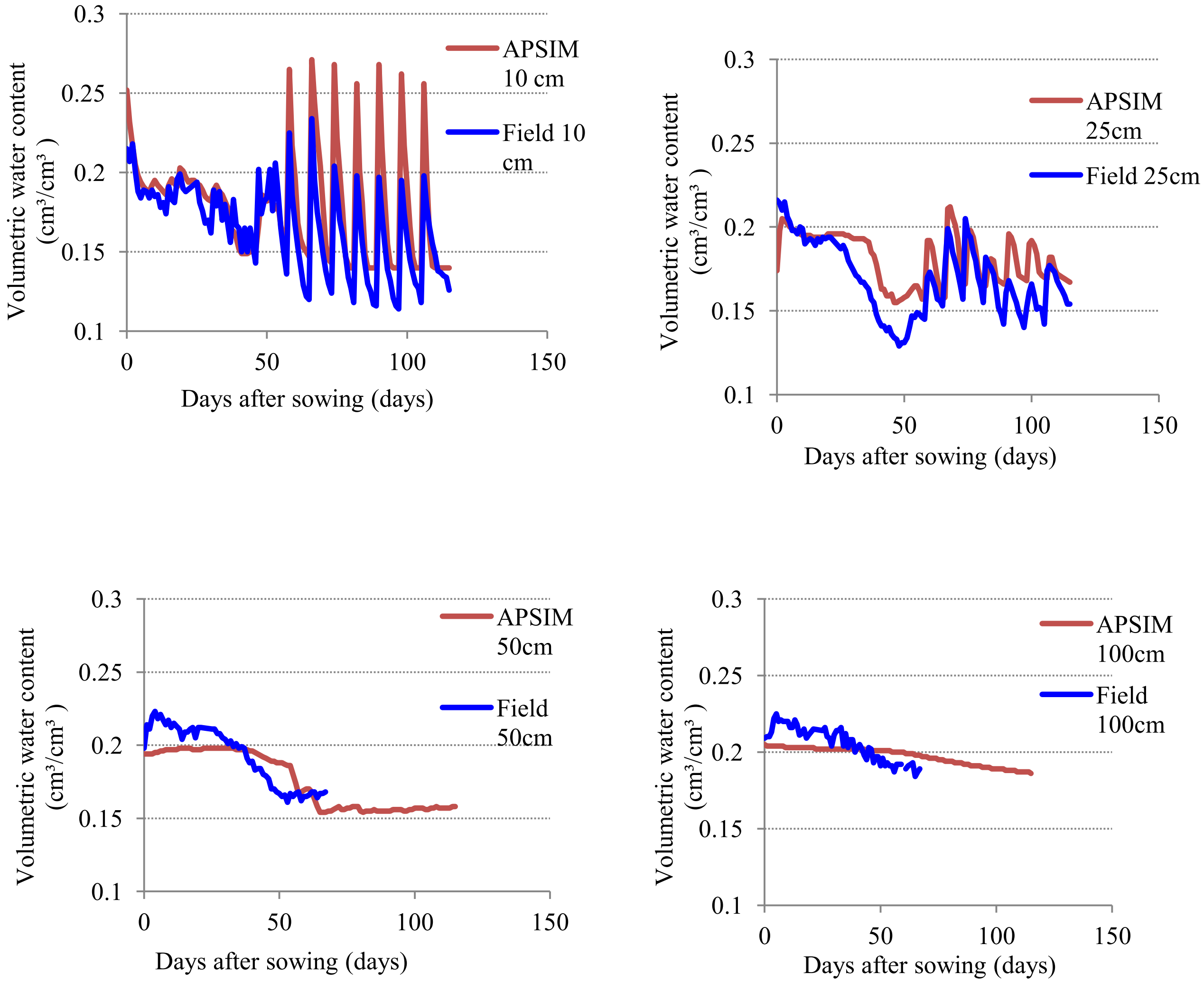

Fig. 31 simulated soil water contents vs. the observed for T7 at different soil depths.

5.4.4.2 Model validation by the plant data

The recorded various experimental crop data served as a basis for evaluating the reliability of APSIM. Table 11 shows a good fit between the calculated plant data as compared to the different plant characteristic measurements.

Table 11 The different kinds of plant data of the IrrEx3 experiment and simulation, Ob. = observed, Calc. = calculated.

	T1 (NEMO,FIS,6 dSm^{-1})		T6 (NEMO,FIS,1 dSm^{-1})		T7 (NEMO,DIS,1 dSm^{-1})	
	Ob.	Calc.	Ob.	Calc.	Ob.	Calc.
Yield (grain yield dry weight)(ton ha^{-1})	13.48	15.05	14.6	12.57	13.9	12.05

Biomass (total above-ground biomass)(ton ha^{-1})	28.13	22.94	31.65	19.86	31.27	19.14
Height (m)	2.36	2.39	2.33	2.38	2.33	2.27

5.5 Validation of NEMO: comparative analysis of the traditional FAO approach and the new strategy

For a first NEMO validation, a comparison between the new methodology versus the standard FAO approach was performed with respect to yield and water productivity.

5.5.1 Yield and water productivity of IrrEx3: results of classical FAO approach versus NEMO

The first analysis considered the treatment applying the FAO recommended water quantity of 100% ETc (T4) which corresponds to full irrigation with good water quality of 1 dSm^{-1}. For the NEMO approach, the corresponding condition was full irrigation with the same quality without fixing the water quantity (T6).

The results showed that NEMO succeeded in achieving a substantial increase in biomass (both for wet and dry) and thus – although it used 5% more water – even a superior water productivity.

Considering the more and more important deficit irrigation strategies, the subsequent comparative investigation focused on the FAO scenario (T5) with a water quantity of 95% ETc and 1 dSm^{-1}. The corresponding NEMO application T7 was restricted to the same amount of irrigation water and salinity. For this application, NEMO came up with a lower number of water applications (32) while the FAO method required significantly more irrigation events (54). As regards the resulting yield (dry grain), the FAO approach obtained with 9.34 t ha^{-1} an astonishingly inferior result as the corresponding NEMO methodology which achieved 13.9 t ha^{-1} which is equal to an increase in yield of 34.6%. Accordingly, the water productivity (T7) rose up an increase of 36.5% of the analogue FAO (T5) result.

Finally, an increased irrigation water salinity of (6 dSm^{-1}) served as a basis for evaluating the efficiency and robustness of both approaches. The subsequent comparative investigation focused on the FAO scenario (T3) with a water quantity of 125% ETc and a water salinity of 6 dSm^{-1} together with a FAO required additional leaching quantity. The corresponding NEMO application T1 used the same water salinity, however, it did not employ a restriction on water quantity. The leaching necessity is automatically included in the new approach. Although, the optimal irrigation schedules provided by the NEMO methodology achieved a minor smaller yield (dry grain) of 4.2% as the traditional irrigation management according to FAO, however, NEMO ended up in using 34% less irrigation water than the FAO method. Thus, the proposed methodology obtained an increase in water productivity of 14.5% of the analogue FAO (T3) result.

Altogether, the NEMO deficit irrigation application T7 resulting with the highest water productivity of 3.9 kg m^{-3} comparing to 3.7, 3.5 and 2.6 kg m^{-3} for T6, T4 and T5 respectively. Thus, the results showed that NEMO succeeded in achieving a superior water productivity although it used deficit irrigation scenario (T7) versus the fully irrigation (T6). However, the subsequent comparative investigation focused on the FAO deficit irrigation scenario (T5) showed the lowest results comparing to the fully irrigation (T4). Also in this context, Fig. 32 and Fig. 33 comprehensibly show the IrrEx3 experimental results for the yield (ton ha^{-1}) and the water productivity (kg m^{-3}) respectively for both approaches.

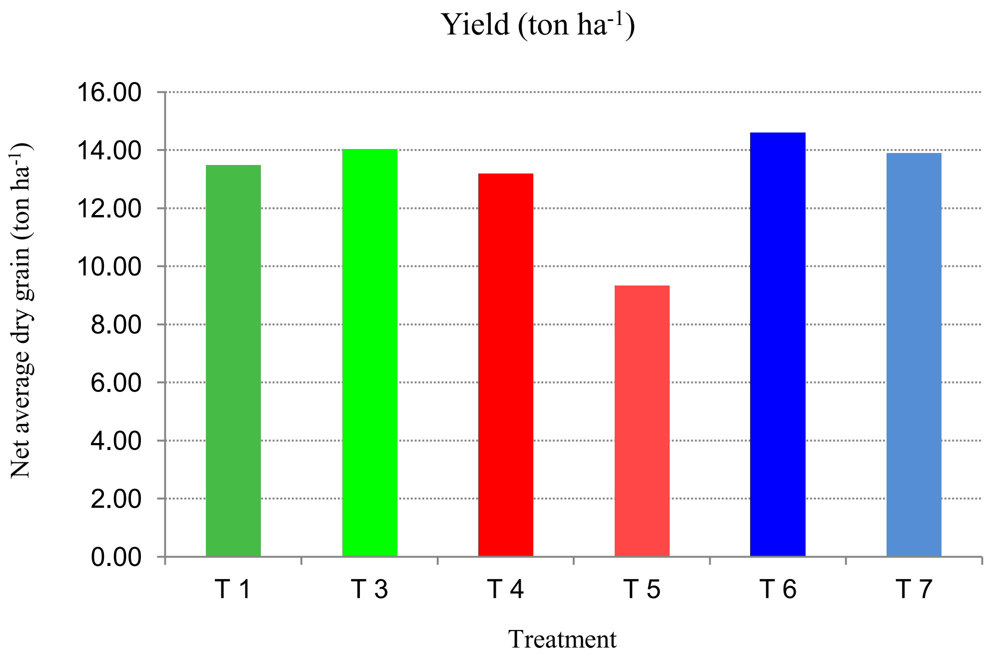

Fig. 32 The Net average dry grain weight (ton ha^{-1}) for the different FAO and NEMO treatments.

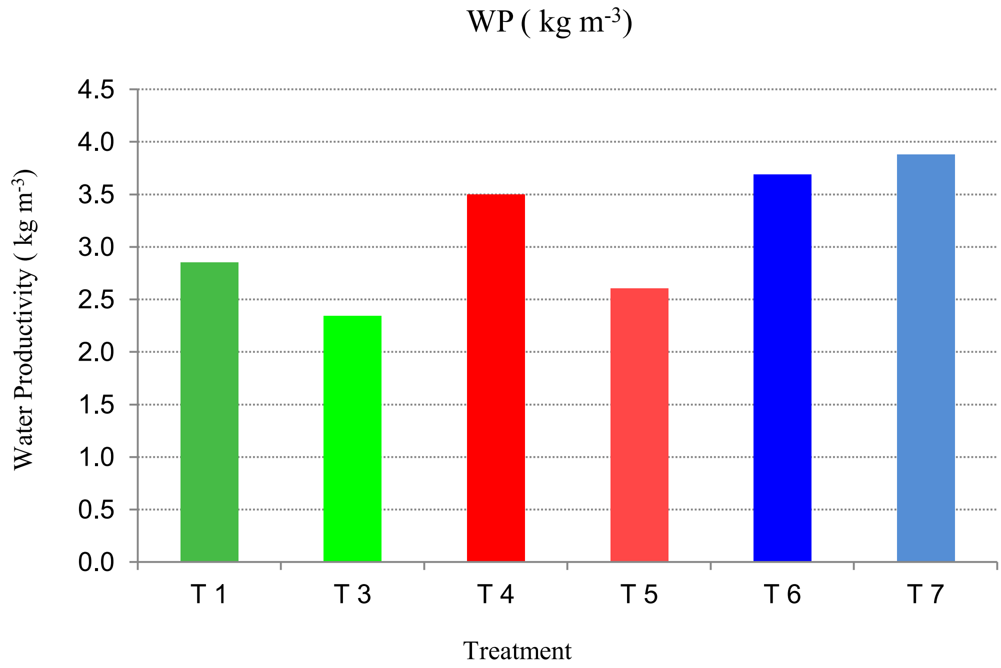

Fig. 33 The water productivity (kg m^{-3}) of the different FAO and NEMO treatments based on dry grain weight and the total water used.

5.5.2 Consequences of NEMO and FAO optimal irrigation schedules as regards accumulation of salinity in the different soil layers.

For the entire treatments, mean soil water ECe was generally recorded to be higher in the upper soil layer (5-10 cm) as compared to the soil layers in 20-30, 40-60 and 80-100 cm depths. Therefore, we used the accumulation of salts in the upper soil layer as a basis for comparing always two different treatments within the FAO and NEMO approaches, respectively. Subsequently, a corresponding comparative analysis was performed for FAO versus NEMO applications.

The first analysis focused on the treatment with the FAO recommended water quantity of 100% ETc (T4) which corresponds to full irrigation and on the FAO scenario (T5) with a water quantity of 95% ETc both with good water quality of 1 dSm^{-1}. The results of soil ECe in 5-10 cm depth indicated that the decreased amounts of irrigation water from T4 (100% ETc, FAO, 1 dSm^{-1}) to T5 (95% ETc, FAO, 1 dSm^{-1}) increased soil water salinity by around 30% (from 698 to 912 ppm). As regards the NEMO approach, the result was different. The corresponding comparison was the T6 treatment (full irrigation, NEMO, FIS, 1 dSm^{-1}) versus the application of T7 (NEMO, DIS, 1 dSm^{-1}) with 10% less irrigation water. Astonishingly enough, there was a decrease in the soil water salinity by 15%, as shown in Fig. 34. The overall reduction of soil water salinity with T7 was for the reason that it had higher application depths for the single irrigation events (appendix A.10).

In the next step a comparison between the FAO scenario T3 (125% ETc, FAO, 6 dSm^{-1}) versus the corresponding NEMO application T1 (NEMO, FIS, 6 dSm^{-1}) was preformed. The soil salinity 1 month after the start of the experiments was still different: NEMO started up with 22% more soil water salinity than the FAO method. However, the optimal irrigation schedules provided by the NEMO methodology achieved at the end of the experiment a little smaller soil water salinity by around 2% (1325 to 1341 ppm) as the traditional irrigation management according to FAO. Thus, it led to an overall reduction of soil water salinity by 3% during the growing period while the overall soil water salinity increased in the same period by 20% for the FAO (T3), in spite that it was applying 34% more water Fig. 34.

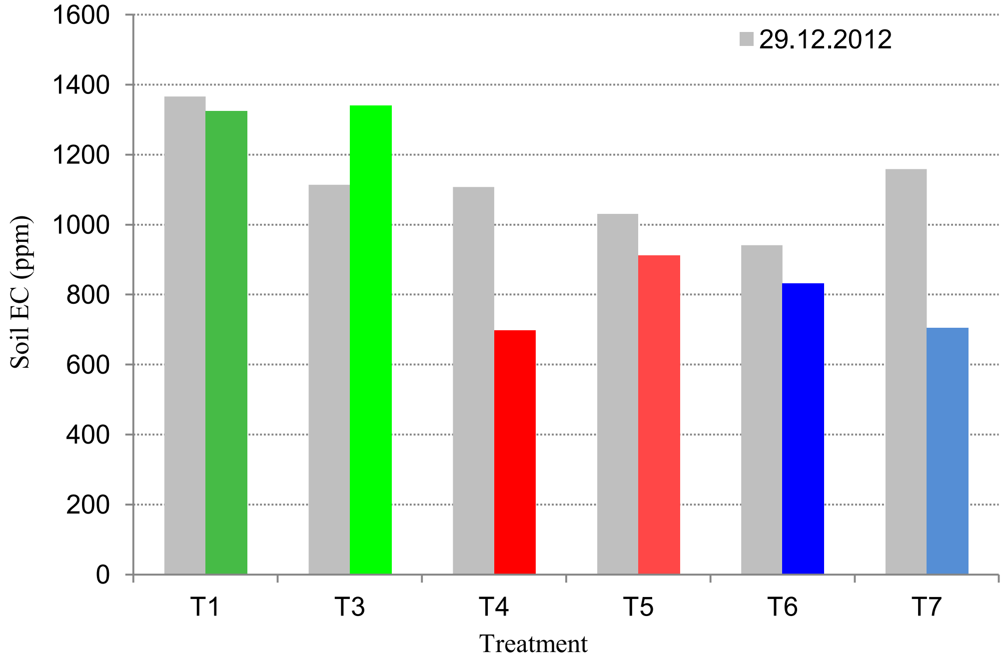

Fig. 34 IrrEx3 pre and post harvest EC (soil samples analysis) at 5-10 cm depth.

6 DISCUSSION

This thesis proposes a novel approach for a more reliable and efficient optimal irrigation scheduling and control. In this context, the following discussion aims at analyzing the new approach NEMO. Subsequently, the corresponding evaluation of NEMO includes a comparison with the common irrigation management methodology according to the FAO Class A-Pan method.

Like other approaches in this field, the proposed methodology may also have some shortcomings and - in this context - a preferred field of applications. Along these lines, the highly elaborate and expensive field experiments already seem to represent a serious problem for a common and widespread use of this technology because:

- There are many cumbersome and critical steps in the course of the experimental set up. This already starts with the detailed experimental design, the most adequate sensor locations, and their reading schedules. More detailed, the following necessary measures may create problems:
    - A high level of technical knowledge is required for successfully dealing with the different measurement devices, especially with the highly sensitive sensors like TDR and pF meter devices. The respective sensor calibrations, their rather sophisticated installment as well as the settings and the sound connection with the data loggers need quite a lot of experience in working with complex instruments.
    - Very elaborate and comprehensive rigorous field working programs need quite well educated staff for dealing with all the organizational aspects and execution of the work and the instructive details like e.g. scheduling fertilizer application and managing irrigation scenarios, as well as all the data collections which need to be done with precise timing and with high accuracy; for example as regards the harvest data.

  In addition, performing the modeling and optimization task also includes considerable challenges:
    - The required comprehensive and systematical local data for weather, soil hydraulic parameters, and plant properties are not easily available.
    - Setting up the simulation model together with the optimization algorithm requires high professional skills. Altogether, running such programs is generally complex.
    - Large amounts of data need to be thoroughly treated and analyzed.

However, these disadvantages have to be seen in the light of the potential advantages and considerable benefits of the NEMO strategy, which also need to be analyzed. This concerns mainly the highly reliable NEMO irrigation schedules, which demonstrate not only excellent results as regards yield, but also a substantial increase of water productivity. Thus, a reduction of the water use is assured which, – in view of growing water shortage – is of great importance. This comes even together with a more sustainable irrigation management in case of the frequently occurring water quality problems. More detailed:

- NEMO applications provide not only excellent yield but also a highly efficient irrigation schedule when using water with different quality, especially as regards the accumulation of salt in the soil as negative consequences of irrigating with saline waters.
- The optimal irrigation schedule is based on long-term stochastic weather data, thus has an extended validity, and thus can offer long planning horizons for decision-making, i.e. it can be transferred in time at the same site.
- The optimal irrigation schedule relies upon physically based process modeling and long-term stochastic weather data. Thus, the once established NEMO software has a high potential transferability to environmentally similar arid regions since plant characteristics normally do not significantly change within these regions and because such a transfer principally requires only physical data as e.g. soil hydraulic properties or field dimensions, i.e. it can be transferred in space.
- The stochastic (process based) simulation optimization can make large numbers of investigations on the efficiency of different treatments more straightforward by only changing the relevant physical parameters and thus can avoid additional experimental expenditures.

The following comparative analysis discusses the aforementioned disadvantages and advantages of NEMO in contrast to the commonly used traditional FAO approach. Starting with a more general view as regards a critical investigation of both the performances of the classical FAO approach and the NEMO approach, the economic efficiency is first considered. Although the FAO method initially appears much better than NEMO because of NEMO’s cumbersome setup and implementation, this demanding task for a considered area has not only to be seen in the light of the initial effort. Its benefit becomes already obvious if considering the validity of the optimal irrigation schedule, which relies on long-term stochastic weather data and therefore - contrary to the FAO approach - offers long application periods with numerous growing seasons and thus long-term planning possibilities. This is especially important as regards e.g. land development projects and may represent a great aid in decision-making. Moreover, other than the FAO method, the once established NEMO software has a high potential of transferability to environmentally similar arid regions. Finally, it has also to be kept in mind that the operation of the A-pan FAO approach requires always-frequent measurements and a continuous follow-up with considerable calculations during the growing season.

These positive aspects of NEMO gain even more importance when considering the results of the series of the comprehensive field experiments IrrEx2 and IrrEx3. The subsequent discussion aims at an overall evaluation as regards the efficiency of NEMO in the light of the common and seemingly easy to use FAO method. Summarizing the most important aspects of the corresponding results (for details see chapter 5) yields:

- Using only 5% more water than FAO, NEMO (full irrigation) came up with an increase of dry grain yield by 11% (Table 9) and almost half of the number of water applications. The latter leads to a saving of operational workload and thus represents an important economic factor.
- As regards deficit irrigation strategies, the corresponding NEMO application brought up a striking gain in yield by 34% as compared to the FAO outcome with a water productivity as high as 36% (refer to Fig. 33) which obviously is of mandatory economic significance.
- As regards saline irrigation water, the NEMO application achieved at the end of the experiment - even with less water - a significant decrease in salt accumulation (20%) than the traditional FAO method, refer to (Fig. 34). This demonstrates the potential of the proposed approach in terms of long-term sustainability.

As exemplarily highlighted, the NEMO applications generally show a substantial higher benefit as regards economic and environmental efficiency than the FAO method. Already the increase in yield and the reduction of workload offers a high potential as regards economic aspects and thus an increase in farming income, which is of great significance for preventing a rural exodus. Along these lines, the much more sustainable use of irrigation water as regards quantity and quality also highlights the promising possibilities of NEMO applications with respect to long-term irrigation management. However, it has to be kept in mind that the relative expensive and demanding implementation of NEMO requires to exploit both its potential regarding the long-term validity of optimal irrigation schedules as well as its transferability to environmentally similar regions.

7 OUTLOOK

The proposed methodology NEMO (Nested Experimental, Modeling, and Optimization Strategy) employs physically based process modeling on the basis of long-term stochastic weather data for executing field experiments in the Al-Batinah region, Sultanate of Oman. After some experimental and modeling effort, the proposed strategy could contribute to a significant overall improvement of irrigated agriculture thus opening wide possibilities for a cost effective application also to other arid or semi-arid areas. Since plant characteristics normally do not change within these regions, the transfer of the simulation based optimal irrigation approach would only require physical (measurable) data as e.g. soil hydraulic prosperities or field dimensions. Along these lines, mainly the subsequent steps could significantly contribute to overcome the last hurdles towards a widespread application in irrigation management practice:

1. The long-term validity of the optimal irrigation schedules could be confirmed by repeating the same field experiment (IrrEx3) for more growing seasons by using the same irrigation schedule. Besides a substantial gain in economic efficiency and simpler application, this would open even longer planning horizons for land development.
2. To give this study a wider applicability, further studies should be made to provide onsite schedules for a wider variety of typical crops. In this context, it could be investigated if the corresponding experimental effort could be avoided by using available standard crop parameters.
3. Further investigations as regards the transferability of NEMO applications to other regions with similar weather characteristic should be performed by executing the same experiments to environmentally similar arid regions by only changing the relevant physical parameters.
4. On-site applications have to be simple and robust. Implementing the optimal schedules and their application details in a microcontroller could further contribute to benefit from an optimal irrigation control without the need for expert knowledge. With modern communication media on the rise, shifting to a mobile app would be feasible as well.

8 SUMMARY AND CONCLUSIONS

This thesis aimed at providing sustainable and reliable irrigation management strategies that provide high water productivity (WP) together with a corresponding maximum yield. The proposed methodology NEMO (Nested Experimental, Modeling, and Optimization Strategy) relies upon two pillars,

- on the one hand it employs rigorous physical investigations as e.g. the evaluation of physical environmental field parameters, the stochastic characterization of the local weather pattern and last but not least a series of comprehensively monitored irrigation field experiments performed over a couple of growing seasons.
- On the other hand, most reliable up-to-date SVAT-modeling/simulation tools (DAISY and APSIM) together with a problem oriented and highly efficient optimization algorithm (GET-OPTIS) are jointly used within a stochastic optimization procedure.

After the successful setup, NEMO provided - in contrast to common management tools - optimal irrigation schedules for the whole growing season. Thus, its application in the course of rigorous field experiments turned up to be rather simple and straightforward. As regards the overall performance of NEMO, a comprehensive comparative analysis versus the common irrigation management methodology according to the FAO Class A-Pan method was subsequently performed. The comparison was based upon the outcome of the field experiments which were executed synchronously using schedules according to NEMO and the FAO method. Three scenarios were investigated: (1) options to target high yields with full irrigation (aiming at highest yield with a most economic water application), (2) deficit irrigation trying to obtain the highest possible yield using only a limited amount of irrigation water, and (3) various management scenarios with saline irrigation water of different qualities.

Based on the outcome of the field experiments, throughout all scenarios, NEMO applications demonstrated a striking superiority compared to the FAO method as regards economic efficiency and sustainable use of irrigation water. This concerns yield as well as water productivity and saline irrigation management. Taking still into account the validity of the optimal irrigation schedule - which relies on long-term stochastic weather data - together with its high potential of transferability to other similar regions, NEMO can contribute to a substantial improvement of irrigated agriculture in arid regions.

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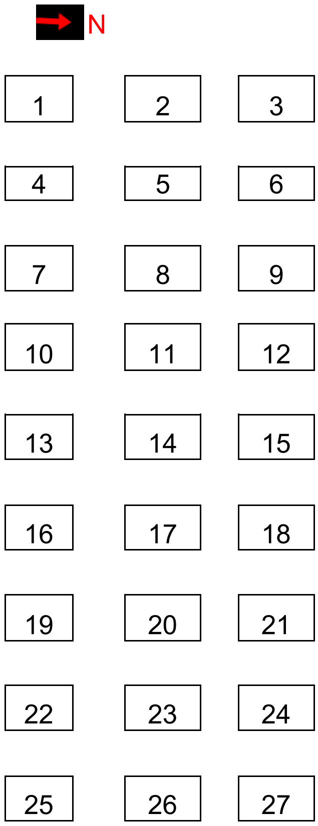
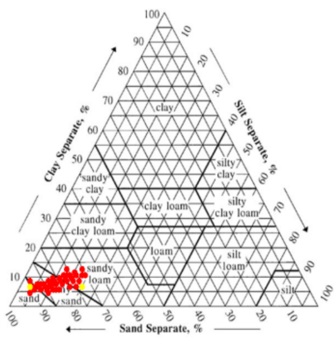
A. APPENDIX

A.1. Research soil lab analysis

Table 12 Soil texture analysis

	Depth (cm)	Clay %	Silt %	Sand %	Soil Texture	Gravel %
1	0 - 10	7	7	86	Loamy Sand	7.1
	20 - 30	9	17	74	Sandy Loam	4.4
	40 - 60	11	13	76	Sandy Loam	3.3
2	0 - 10	7	3	90	Sand	15.4
	20 - 30	11	17	72	Sandy Loam	4.1
	40 - 60	11	11	78	Sandy Loam	7.7
3	0 - 10	7	3	90	Sand	9.5
	20 - 30	5	3	92	Sand	7.0
	40 - 60	11	12	77	Sandy Loam	5.4
4	0 - 10	9	2	90	Sand	7.9
	20 - 30	7	5	88	Loamy Sand	29.1
	40 - 60	11	15	74	Sandy Loam	9.6
5	0 - 10	7	1	91	Sand	8.2
	20 - 30	5	3	92	Sand	15.0
	40 - 60	10	8	82	Loamy Sand	6.1
6	0 - 10	6	4	90	Sand	16.7
	20 - 30	8	5	87	Loamy Sand	14.6
	40 - 60	13	16	71	Sandy Loam	9.9
7	0 - 10	7	8	85	Loamy Sand	12.6
	20 - 30	7	7	86	Loamy Sand	12.4
	40 - 60	10	12	78	Sandy Loam	11.1
8	0 - 10	7	9	84	Loamy Sand	13.7
	20 - 30	5	9	86	Loamy Sand	7.6
	40 - 60	10	12	78	Sandy Loam	10.1
9	0 - 10	8	9	83	Loamy Sand	16.1
	20 - 30	7	5	88	Loamy Sand	7.8
	40 - 60	12	14	74	Sandy Loam	12.3
10	0 - 10	8	9	83	Loamy Sand	14.5
	20 - 30	10	14	76	Sandy Loam	8.5
	40 - 60	11	18	71	Sandy Loam	9.4
11	0 - 10	8	12	80	Loamy Sand	16.1
	20 - 30	8	9	83	Loamy Sand	11.1
	40 - 60	11	12	77	Sandy Loam	11.4
12	0 - 10	9	7	84	Loamy Sand	14.4





	20 - 30	8	10	82	Loamy Sand	10.4
	40 - 60	10	12	78	Sandy Loam	12.5
13	**0 - 10**	6	6	88	Loamy Sand	14.0
	20 - 30	4	0	96	Sand	12.4
	40 - 60	11	13	76	Sandy Loam	9.6
14	**0 - 10**	7	1	91	Sand	14.1
	20 - 30	6	1	94	Sand	36.5
	40 - 60	9	11	80	Loamy Sand	16.1
15	**0 - 10**	7	5	88	Loamy Sand	14.2
	20 - 30	7	19	74	Sandy Loam	6.0
	40 - 60	9	15	76	Sandy Loam	11.1
16	**0 - 10**	7	7	86	Loamy Sand	18.1
	20 - 30	7	17	76	Sandy Loam	10.8
	40 - 60	9	11	80	Loamy Sand	10.7
17	**0 - 10**	7	7	86	Loamy Sand	16.1
	20 - 30	7	5	88	Loamy Sand	11.8
	40 - 60	11	13	76	Sandy Loam	11.5
18	**0 - 10**	7	5	88	Loamy Sand	15.8
	20 - 30	5	3	92	Sand	6.4
	40 - 60	9	13	78	Sandy Loam	12.8
19	**0 - 10**	7	17	76	Sandy Loam	17.1
	20 - 30	7	15	78	Loamy Sand	9.7
	40 - 60	9	13	78	Sandy Loam	10.2
20	**0 - 10**	7	7	86	Loamy Sand	13.5
	20 - 30	9	15	76	Sandy Loam	9.9
	40 - 60	11	13	76	Sandy Loam	11.2
21	**0 - 10**	7	7	86	Loamy Sand	16.8
	20 - 30	9	9	82	Loamy Sand	14.7
	40 - 60	13	12	76	Sandy Loam	12.1
22	**0 - 10**	8	10	82	Loamy Sand	14.2
	20 - 30	8	12	80	Loamy Sand	8.5
	40 - 60	10	14	76	Sandy Loam	12.8
23	**0 - 10**	8	10	82	Loamy Sand	12.6
	20 - 30	8	4	88	Loamy Sand	12.0
	40 - 60	8	8	84	Loamy Sand	14.1
24	**0 - 10**	6	8	86	Loamy Sand	13.5
	20 - 30	6	10	83	Loamy Sand	12.8
	40 - 60	10	10	80	Sandy Loam	10.0
25	**0 - 10**	8	6	86	Loamy Sand	11.3
	20 - 30	8	8	83	Loamy Sand	8.0
	40 - 60	10	10	80	Sandy Loam	11.0
26	**0 - 10**	6	10	84	Loamy Sand	12.4

	20 - 30	8	6	86	Loamy Sand	23.8
	40 - 60	8	10	82	Loamy Sand	11.6
27	**0 - 10**	6	12	82	Loamy Sand	13.1
	20 - 30	8	4	88	Loamy Sand	9.5
	40 - 60	8	10	82	Loamy Sand	10.3

A.2. 1-year Daily Average data for 18 years (1991–2006) from Seeb weather station (International airport, Muscat)

Station: Oman
Elevation: 220 m
Longitude: 57.8 dgEast
Latitude: 23.7 dgNorth
TimeZone: 15 dgEast

Year	Month	Day	T_min	T_max	GlobRad	RefEvap	Precip
year	month	mday	dgC	dgC	W/m^2	mm/d	mm/d
(1991–2006)	1	2	16.4	26	188.655	4	0.00000
(1991–2006)	1	3	16.9	27	118.054	2.5	0.00000
(1991–2006)	1	4	15.5	26.1	133.1	2.8	0.00000
(1991–2006)	1	5	16.2	25.5	151.619	3.2	0.00000
(1991–2006)	1	6	15.9	24.7	167.822	3.5	0.00000
(1991–2006)	1	7	18.1	27.2	168.98	3.7	0.00000
(1991–2006)	1	8	19.2	26.1	175.924	3.8	0.00000
(1991–2006)	1	9	17.7	24.2	164.35	3.5	0.00000
(1991–2006)	1	10	18	25	160.878	3.4	0.00000
(1991–2006)	1	11	14.5	22.9	193.285	3.9	0.00000
(1991–2006)	1	12	17.3	25.5	193.285	4.1	0.00000
(1991–2006)	1	13	15.8	24.7	194.442	4.1	0.00000
(1991–2006)	1	14	16.5	25	195.6	4.1	0.00000
(1991–2006)	1	15	14.2	23.6	195.6	4	0.00000
(1991–2006)	1	16	12.4	23.2	192.128	3.8	0.00000
(1991–2006)	1	17	12.7	19.4	162.035	3.1	1.30000
(1991–2006)	1	18	14.3	24.3	197.915	4.1	0.00000
(1991–2006)	1	19	14.1	22.3	199.072	4	0.00000
(1991–2006)	1	20	13.6	21.7	200.229	4	0.00000
(1991–2006)	1	21	15	22.3	201.387	4.1	0.00000
(1991–2006)	1	22	14.2	19.5	202.544	4	0.00000
(1991–2006)	1	23	14	23.1	202.544	4.1	0.00000
(1991–2006)	1	24	13.2	24.2	180.554	3.7	0.00000
(1991–2006)	1	25	13.2	25.3	157.406	3.2	0.00000
(1991–2006)	1	26	14.6	25.7	197.915	4.1	0.00000
(1991–2006)	1	27	15.8	26.6	207.174	4.4	0.00000
(1991–2006)	1	28	14.1	25.9	196.757	4.1	0.00000

(1991–2006)	1	29	14.6	22.5	160.878	3.3	0.00000
(1991–2006)	1	30	14.6	23.6	173.609	3.6	0.00000
(1991–2006)	1	31	14.2	25.1	171.295	3.5	0.00000
(1991–2006)	2	1	15.2	24.7	192.128	4	0.00000
(1991–2006)	2	2	16.3	25	171.295	3.6	0.00000
(1991–2006)	2	3	19.2	25.2	199.072	4.3	0.00000
(1991–2006)	2	4	15.9	23.1	216.433	4.5	0.00000
(1991–2006)	2	5	18.6	24.9	204.859	4.4	0.00000
(1991–2006)	2	6	17.2	23.6	209.489	4.4	0.00000
(1991–2006)	2	7	14.4	22.4	208.331	4.2	0.00000
(1991–2006)	2	8	14.9	24.1	219.905	4.6	0.00000
(1991–2006)	2	9	18.4	29.2	172.452	3.8	0.00000
(1991–2006)	2	10	18.9	27.3	212.961	4.7	0.00000
(1991–2006)	2	11	16.1	23.5	225.692	4.7	0.00000
(1991–2006)	2	12	18.4	26.6	226.849	4.9	0.00000
(1991–2006)	2	13	14.6	22.1	228.007	4.6	0.00000
(1991–2006)	2	14	16	25.1	229.164	4.8	0.00000
(1991–2006)	2	15	17.3	26.8	231.479	5	0.00000
(1991–2006)	2	16	19.7	25.6	232.636	5.1	0.00000
(1991–2006)	2	17	20.8	28.4	233.794	5.2	0.00000
(1991–2006)	2	18	20.5	28.8	234.951	5.3	0.00000
(1991–2006)	2	19	17.6	24.9	237.266	5	0.00000
(1991–2006)	2	20	18.2	23.6	238.423	5	0.00000
(1991–2006)	2	21	19.6	25.7	201.387	4.4	0.00000
(1991–2006)	2	22	18.3	27.5	199.072	4.3	0.00000
(1991–2006)	2	23	16.8	26.8	203.702	4.4	0.00000
(1991–2006)	2	24	18	26.8	224.535	4.9	0.00000
(1991–2006)	2	25	17.6	25.6	203.702	4.4	0.00000
(1991–2006)	2	26	14.8	23.7	246.525	5.1	0.00000
(1991–2006)	2	27	16.9	25.4	248.84	5.3	0.00000
(1991–2006)	2	28	16.9	24.9	249.997	5.3	0.00000
(1991–2006)	3	1	18	24.2	211.803	4.5	0.00000
(1991–2006)	3	2	21.6	26.4	163.193	3.6	0.00000
(1991–2006)	3	3	22.3	28.5	201.387	4.5	0.00000
(1991–2006)	3	4	24.3	31.7	239.581	5.6	0.00000
(1991–2006)	3	5	21.5	29.1	256.942	5.8	0.00000
(1991–2006)	3	6	20	27.5	259.257	5.7	0.00000
(1991–2006)	3	7	18.2	27.5	260.414	5.7	0.00000
(1991–2006)	3	8	17.1	26.9	261.571	5.7	0.00000
(1991–2006)	3	9	20.8	31.2	262.729	6	0.00000
(1991–2006)	3	10	19.8	29.2	265.044	5.9	0.00000
(1991–2006)	3	11	20.4	28.3	261.571	5.8	0.00000
(1991–2006)	3	12	21.7	29.9	254.627	5.8	0.00000
(1991–2006)	3	13	19.9	30.5	245.368	5.5	0.00000
(1991–2006)	3	14	19.7	31.5	224.535	5.1	0.00000
(1991–2006)	3	15	18.7	33.8	271.988	6.2	0.00000
(1991–2006)	3	16	18.3	31	243.053	5.5	0.00000

(1991–2006)	3	17	19.1	29.2	274.303	6.1	0.00000
(1991–2006)	3	18	17.6	27.5	268.516	5.9	0.00000
(1991–2006)	3	19	17.4	25.6	277.775	6	0.00000
(1991–2006)	3	20	18.7	26.5	278.932	6.1	0.00000
(1991–2006)	3	21	20.7	27.5	280.09	6.3	0.00000
(1991–2006)	3	22	20.1	29.9	281.247	6.4	0.00000
(1991–2006)	3	23	18.7	29	282.404	6.3	0.00000
(1991–2006)	3	24	16.7	24.7	284.719	6	0.00000
(1991–2006)	3	25	19.4	28.1	285.877	6.3	0.00000
(1991–2006)	3	26	22.6	31.2	259.257	6	0.00000
(1991–2006)	3	27	22	29.5	202.544	4.6	0.00000
(1991–2006)	3	28	22.9	30.5	178.239	4.1	0.00000
(1991–2006)	3	29	22.3	29.3	214.118	4.9	0.00000
(1991–2006)	3	30	19.2	27.6	260.414	5.7	0.00000
(1991–2006)	3	31	19.8	28.9	288.191	6.5	0.00000
(1991–2006)	4	1	21	31.8	293.978	6.8	0.00000
(1991–2006)	4	2	19.1	30.2	275.46	6.2	0.00000
(1991–2006)	4	3	20.8	32.1	296.293	6.8	0.00000
(1991–2006)	4	4	21.4	32.9	278.932	6.5	0.00000
(1991–2006)	4	5	24.5	32.6	298.608	7.1	0.00000
(1991–2006)	4	6	24.4	30.9	295.136	6.9	0.00000
(1991–2006)	4	7	21.3	29	300.923	6.8	0.00000
(1991–2006)	4	8	21.8	27.9	233.794	5.3	0.00000
(1991–2006)	4	9	22.7	31.8	304.395	7.1	0.00000
(1991–2006)	4	10	21.1	30.6	304.395	7	0.00000
(1991–2006)	4	11	22.5	33.3	283.562	6.6	0.00000
(1991–2006)	4	12	21.9	29.1	306.71	7	0.00000
(1991–2006)	4	13	23.3	31.7	307.867	7.2	0.00000
(1991–2006)	4	14	24.7	33	309.025	7.3	0.00000
(1991–2006)	4	15	25.5	34.6	310.182	7.5	0.00000
(1991–2006)	4	16	24.8	35.9	311.339	7.5	0.00000
(1991–2006)	4	17	23.9	31.2	312.497	7.3	0.00000
(1991–2006)	4	18	26.8	35.9	312.497	7.6	0.00000
(1991–2006)	4	19	25.2	32.9	313.654	7.5	0.00000
(1991–2006)	4	20	25.4	36.3	314.812	7.6	0.00000
(1991–2006)	4	21	23.5	37	315.969	7.6	0.00000
(1991–2006)	4	22	22	33.9	315.969	7.4	0.00000
(1991–2006)	4	23	24.8	36.8	317.126	7.7	0.00000
(1991–2006)	4	24	24	36.1	318.284	7.7	0.00000
(1991–2006)	4	25	23.8	36.3	319.441	7.7	0.00000
(1991–2006)	4	26	25.8	39.3	204.859	5	0.00000
(1991–2006)	4	27	26.2	43.7	194.442	4.9	0.00000
(1991–2006)	4	28	24.7	40.3	239.581	5.9	0.00000
(1991–2006)	4	29	22.8	37	236.109	5.6	0.00000
(1991–2006)	4	30	25.7	39.4	246.525	6.1	0.00000
(1991–2006)	5	1	26.1	39.9	270.831	6.7	0.00000
(1991–2006)	5	2	25	40.2	212.961	5.2	0.00000

(1991–2006)	5	3	22.9	32.9	266.201	6.2	0.00000
(1991–2006)	5	4	24.7	32.9	270.831	6.4	0.00000
(1991–2006)	5	5	28.1	39.2	318.284	7.9	0.00000
(1991–2006)	5	6	30.5	41.8	298.608	7.6	0.00000
(1991–2006)	5	7	28	41.2	256.942	6.4	0.00000
(1991–2006)	5	8	25.5	38.8	302.08	7.4	0.00000
(1991–2006)	5	9	25.7	39.5	274.303	6.8	0.00000
(1991–2006)	5	10	28.2	39.5	143.517	3.5	0.00000
(1991–2006)	5	11	28.5	38.4	158.563	3.9	0.00000
(1991–2006)	5	12	30.3	36.6	157.406	3.8	0.00000
(1991–2006)	5	13	29.5	38.1	209.489	5.2	0.00000
(1991–2006)	5	14	29.7	39.8	261.571	6.6	0.00000
(1991–2006)	5	15	31.5	37.8	253.47	6.3	0.00000
(1991–2006)	5	16	28.6	39.5	238.423	5.9	0.00000
(1991–2006)	5	17	26.1	36.6	276.617	6.7	0.00000
(1991–2006)	5	18	30.2	38.8	287.034	7.2	0.00000
(1991–2006)	5	19	29.5	42.1	324.071	8.2	0.00000
(1991–2006)	5	20	32.3	42.6	298.608	7.7	0.00000
(1991–2006)	5	21	30.2	40.2	269.673	6.8	0.00000
(1991–2006)	5	22	27.2	41	260.414	6.5	0.00000
(1991–2006)	5	23	27.6	38.6	231.479	5.7	0.00000
(1991–2006)	5	24	28.1	36.5	232.636	5.7	0.00000
(1991–2006)	5	25	30.9	43.4	241.896	6.2	0.00000
(1991–2006)	5	26	31.4	45.2	295.136	7.6	0.00000
(1991–2006)	5	27	33.2	42	288.191	7.4	0.00000
(1991–2006)	5	28	28.2	37.7	274.303	6.8	0.00000
(1991–2006)	5	29	28.8	36.8	256.942	6.3	0.00000
(1991–2006)	5	30	27.1	35.8	248.84	6	0.00000
(1991–2006)	5	31	26.2	39.3	247.683	6.1	0.00000
(1991–2006)	6	1	28.9	41.2	263.886	6.6	0.00000
(1991–2006)	6	2	32	44.6	280.09	7.2	0.00000
(1991–2006)	6	3	30.8	41.2	251.155	6.4	0.00000
(1991–2006)	6	4	30.3	40	273.145	6.9	0.00000
(1991–2006)	6	5	31.2	39.9	288.191	7.3	0.00000
(1991–2006)	6	6	27	34.8	329.858	8	0.00000
(1991–2006)	6	7	27.4	36.6	208.331	5.1	0.00000
(1991–2006)	6	8	27.8	37.9	241.896	6	0.00000
(1991–2006)	6	9	27.8	36	268.516	6.5	0.00000
(1991–2006)	6	10	27.2	35.5	255.784	6.2	0.00000
(1991–2006)	6	11	30.8	42.4	228.007	5.8	0.00000
(1991–2006)	6	12	30.6	39.2	223.377	5.6	0.00000
(1991–2006)	6	13	28.3	37	268.516	6.6	0.00000
(1991–2006)	6	14	32.3	35.8	302.08	7.5	0.00000
(1991–2006)	6	15	29.3	36.5	296.293	7.3	0.00000
(1991–2006)	6	16	28.3	37.9	280.09	6.9	0.00000
(1991–2006)	6	17	30	44.3	251.155	6.4	0.00000
(1991–2006)	6	18	31	47.9	237.266	6.2	0.00000

(1991–2006)	6	19	29.6	42.2	295.136	7.5	0.00000
(1991–2006)	6	20	29	42.3	275.46	7	0.00000
(1991–2006)	6	21	30.9	45.9	327.543	8.5	0.00000
(1991–2006)	6	22	31.3	44.7	339.117	8.8	0.00000
(1991–2006)	6	23	31.7	45.9	337.959	8.8	0.00000
(1991–2006)	6	24	33.5	45.3	317.126	8.3	0.00000
(1991–2006)	6	25	34.2	46.4	299.765	7.9	0.00000
(1991–2006)	6	26	32.8	44.1	283.562	7.3	0.00000
(1991–2006)	6	27	30.4	37.8	304.395	7.6	0.00000
(1991–2006)	6	28	27.4	32.8	315.969	7.6	0.00000
(1991–2006)	6	29	28.4	33.9	328.7	8	0.00000
(1991–2006)	6	30	29.5	38.2	287.034	7.2	0.00000
(1991–2006)	7	1	28.1	34.5	282.404	6.9	0.00000
(1991–2006)	7	2	29.5	39.2	331.015	8.3	0.00000
(1991–2006)	7	3	30.3	36.8	336.802	8.4	0.00000
(1991–2006)	7	4	31.8	42	339.117	8.7	0.00000
(1991–2006)	7	5	30.5	36.9	322.913	8.1	0.00000
(1991–2006)	7	6	29.7	34.7	310.182	7.6	0.00000
(1991–2006)	7	7	28.4	34.3	326.385	8	0.00000
(1991–2006)	7	8	30	37.8	295.136	7.3	0.00000
(1991–2006)	7	9	29.3	36.8	299.765	7.4	0.00000
(1991–2006)	7	10	28.3	39.6	276.617	6.9	0.00000
(1991–2006)	7	11	26.1	33.8	273.145	6.6	0.00000
(1991–2006)	7	12	26.6	33.1	314.812	7.6	0.00000
(1991–2006)	7	13	26.9	32.2	253.47	6	0.00000
(1991–2006)	7	14	28.6	29.9	166.665	3.9	0.00000
(1991–2006)	7	15	30.9	32.2	226.849	5.5	0.00000
(1991–2006)	7	16	31.4	35.1	211.803	5.2	0.00000
(1991–2006)	7	17	28.9	35.5	214.118	5.2	0.00000
(1991–2006)	7	18	26.7	38.9	254.627	6.3	0.00000
(1991–2006)	7	19	28.1	38.1	241.896	6	0.00000
(1991–2006)	7	20	29.3	38.9	288.191	7.2	0.00000
(1991–2006)	7	21	27	37	267.358	6.5	0.00000
(1991–2006)	7	22	26.1	30.7	249.997	5.9	0.00000
(1991–2006)	7	23	26.6	32.2	283.562	6.8	0.00000
(1991–2006)	7	24	28.1	36.6	214.118	5.2	0.00000
(1991–2006)	7	25	27.7	34	182.868	4.4	0.00000
(1991–2006)	7	26	29	39.3	172.452	4.3	0.00000
(1991–2006)	7	27	27.3	34.8	206.016	5	0.00000
(1991–2006)	7	28	30.6	38.1	215.276	5.3	0.00000
(1991–2006)	7	29	31.7	42.3	259.257	6.6	0.00000
(1991–2006)	7	30	31.6	41.5	239.581	6.1	0.00000
(1991–2006)	7	31	31.6	45.2	210.646	5.4	0.00000
(1991–2006)	8	1	32.6	46.7	216.433	5.6	0.00000
(1991–2006)	8	2	29.1	39.1	251.155	6.3	0.00000
(1991–2006)	8	3	29.3	38.6	284.719	7.1	0.00000
(1991–2006)	8	4	30.2	37	243.053	6	0.00000

(1991–2006)	8	5	28.8	35.8	246.525	6	0.00000
(1991–2006)	8	6	26.6	36.1	233.794	5.7	0.00000
(1991–2006)	8	7	27.8	39.4	229.164	5.7	0.00000
(1991–2006)	8	8	27.9	39.8	273.145	6.8	0.00000
(1991–2006)	8	9	28.1	37.7	256.942	6.3	0.00000
(1991–2006)	8	10	28.3	42	259.257	6.5	0.00000
(1991–2006)	8	11	28.1	37.1	256.942	6.3	0.00000
(1991–2006)	8	12	27.5	34.2	237.266	5.7	0.00000
(1991–2006)	8	13	28.6	34.8	247.683	6	0.00000
(1991–2006)	8	14	25.6	31.7	276.617	6.5	0.00000
(1991–2006)	8	15	25	31.1	320.599	7.5	0.00000
(1991–2006)	8	16	25.2	31.2	295.136	6.9	0.00000
(1991–2006)	8	17	25.6	30.9	303.238	7.2	0.00000
(1991–2006)	8	18	25.6	30.6	318.284	7.5	0.00000
(1991–2006)	8	19	25.9	33.1	284.719	6.8	0.00000
(1991–2006)	8	20	27.1	33.2	233.794	5.6	0.00000
(1991–2006)	8	21	29.5	37.7	214.118	5.3	0.00000
(1991–2006)	8	22	27.3	31.1	295.136	7	0.00000
(1991–2006)	8	23	28.1	35.7	281.247	6.9	0.00000
(1991–2006)	8	24	26.8	35.3	255.784	6.2	0.00000
(1991–2006)	8	25	27.9	36.9	300.923	7.4	0.00000
(1991–2006)	8	26	27.5	36	217.59	5.3	0.00000
(1991–2006)	8	27	30.6	37.5	306.71	7.7	0.00000
(1991–2006)	8	28	30.5	39.9	292.821	7.4	0.00000
(1991–2006)	8	29	31.1	42.8	273.145	7	0.00000
(1991–2006)	8	30	31.3	41.3	265.044	6.7	0.00000
(1991–2006)	8	31	29.3	40	255.784	6.4	0.00000
(1991–2006)	9	1	29.7	39.3	239.581	6	0.00000
(1991–2006)	9	2	26.8	39.4	189.813	4.6	0.00000
(1991–2006)	9	3	28.1	39.2	173.609	4.3	0.00000
(1991–2006)	9	4	28	37	267.358	6.6	0.00000
(1991–2006)	9	5	29.3	39.6	300.923	7.5	0.00000
(1991–2006)	9	6	27.2	37.9	251.155	6.2	0.00000
(1991–2006)	9	7	26.9	38.5	253.47	6.2	0.00000
(1991–2006)	9	8	27.3	37.4	222.22	5.4	0.00000
(1991–2006)	9	9	28.1	37.1	230.322	5.7	0.00000
(1991–2006)	9	10	25.9	36.2	200.229	4.8	0.00000
(1991–2006)	9	11	26.4	37.5	225.692	5.5	0.00000
(1991–2006)	9	12	27.8	36.7	187.498	4.6	0.00000
(1991–2006)	9	13	11.2	14.7	290.506	5.3	0.40000
(1991–2006)	9	14	10.7	14.2	270.831	4.9	0.700000
(1991–2006)	9	15	27.8	40.5	288.191	7.2	0.00000
(1991–2006)	9	16	26.4	37.3	287.034	7	0.00000
(1991–2006)	9	17	27.6	35.4	285.877	7	0.00000
(1991–2006)	9	18	26.9	35.5	284.719	6.9	0.00000
(1991–2006)	9	19	26.6	35.6	282.404	6.9	0.00000
(1991–2006)	9	20	26	33.7	281.247	6.7	0.00000

(1991–2006)	9	21	26.9	33.4	280.09	6.7	0.00000
(1991–2006)	9	22	26.1	36.1	268.516	6.5	0.00000
(1991–2006)	9	23	26.1	38.8	277.775	6.8	0.00000
(1991–2006)	9	24	25.9	36.8	267.358	6.5	0.00000
(1991–2006)	9	25	26.4	36.6	273.145	6.7	0.00000
(1991–2006)	9	26	27.1	36.9	243.053	5.9	0.00000
(1991–2006)	9	27	26.2	37.5	271.988	6.6	0.00000
(1991–2006)	9	28	24.6	35.3	270.831	6.5	0.00000
(1991–2006)	9	29	25.8	36.7	247.683	6	0.00000
(1991–2006)	9	30	25.5	37	261.571	6.4	0.00000
(1991–2006)	10	1	25.9	34.6	266.201	6.4	0.00000
(1991–2006)	10	2	24.3	34.5	265.044	6.3	0.00000
(1991–2006)	10	3	23.1	35.9	259.257	6.2	0.00000
(1991–2006)	10	4	24.2	38.2	221.063	5.3	0.00000
(1991–2006)	10	5	22.5	33.6	260.414	6.1	0.00000
(1991–2006)	10	6	23.6	33.8	233.794	5.5	0.00000
(1991–2006)	10	7	24.4	36.1	209.489	5	0.00000
(1991–2006)	10	8	24.1	36.8	232.636	5.6	0.00000
(1991–2006)	10	9	24.8	36.3	233.794	5.6	0.00000
(1991–2006)	10	10	25.3	34.8	229.164	5.5	0.00000
(1991–2006)	10	11	23.4	34.5	244.21	5.8	0.00000
(1991–2006)	10	12	23.3	35.7	249.997	6	0.00000
(1991–2006)	10	13	25.5	37.7	217.59	5.3	0.00000
(1991–2006)	10	14	26.6	38	231.479	5.7	0.00000
(1991–2006)	10	15	27.9	38.5	209.489	5.2	0.00000
(1991–2006)	10	16	27.5	39.3	234.951	5.8	0.00000
(1991–2006)	10	17	24.7	34.5	212.961	5.1	0.00000
(1991–2006)	10	18	24.4	34.9	206.016	4.9	0.00000
(1991–2006)	10	19	22.4	34.5	239.581	5.6	0.00000
(1991–2006)	10	20	23.2	34.2	219.905	5.2	0.00000
(1991–2006)	10	21	23.3	34.6	237.266	5.6	0.00000
(1991–2006)	10	22	22.9	33.3	209.489	4.9	0.00000
(1991–2006)	10	23	22.5	34.6	187.498	4.4	0.00000
(1991–2006)	10	24	24.5	35.3	193.285	4.6	0.00000
(1991–2006)	10	25	23.9	35.9	200.229	4.8	0.00000
(1991–2006)	10	26	25.5	36.3	229.164	5.5	0.00000
(1991–2006)	10	27	23.9	33.7	228.007	5.4	0.00000
(1991–2006)	10	28	24.3	36.1	226.849	5.4	0.00000
(1991–2006)	10	29	22.1	34	225.692	5.3	0.00000
(1991–2006)	10	30	22.7	33.6	224.535	5.2	0.00000
(1991–2006)	10	31	24	35.2	223.377	5.3	0.00000
(1991–2006)	11	1	25	37	200.229	4.8	0.00000
(1991–2006)	11	2	24.9	34.1	211.803	5	0.00000
(1991–2006)	11	3	25.1	34	209.489	5	0.00000
(1991–2006)	11	4	23.7	32.8	217.59	5.1	0.00000
(1991–2006)	11	5	23.7	33	216.433	5.1	0.00000
(1991–2006)	11	6	23.4	29.6	212.961	4.9	0.00000

(1991–2006)	11	7	23.7	29.1	214.118	4.9	0.00000
(1991–2006)	11	8	22.5	28.8	212.961	4.8	0.00000
(1991–2006)	11	9	22.9	30.1	201.387	4.6	0.00000
(1991–2006)	11	10	19.6	28.8	210.646	4.7	0.00000
(1991–2006)	11	11	21.6	30.2	209.489	4.8	0.00000
(1991–2006)	11	12	18.7	28.8	208.331	4.6	0.00000
(1991–2006)	11	13	21.2	31.5	207.174	4.7	0.00000
(1991–2006)	11	14	21	32	206.016	4.7	0.00000
(1991–2006)	11	15	17.9	31.3	204.859	4.6	0.00000
(1991–2006)	11	16	16.4	28.9	194.442	4.2	0.00000
(1991–2006)	11	17	17.3	30.3	202.544	4.5	0.00000
(1991–2006)	11	18	19.9	32	202.544	4.6	0.00000
(1991–2006)	11	19	18.9	30	201.387	4.5	0.00000
(1991–2006)	11	20	17.6	28.8	200.229	4.4	0.00000
(1991–2006)	11	21	21.4	34.1	199.072	4.6	0.00000
(1991–2006)	11	22	21.7	32.7	197.915	4.6	0.00000
(1991–2006)	11	23	20.6	32.1	163.193	3.7	0.00000
(1991–2006)	11	24	19.2	31.1	185.183	4.1	0.00000
(1991–2006)	11	25	18.9	29.8	178.239	3.9	0.00000
(1991–2006)	11	26	18.7	30.5	179.396	4	0.00000
(1991–2006)	11	27	20.9	31.4	129.628	2.9	0.00000
(1991–2006)	11	28	20.6	30.5	85.6473	1.9	0.00000
(1991–2006)	11	29	20.1	29.7	124.999	2.8	0.00000
(1991–2006)	11	30	18.1	28.1	135.415	2.9	0.00000
(1991–2006)	12	1	18.5	26.1	124.999	2.7	0.00000
(1991–2006)	12	2	18	27.3	165.508	3.6	0.00000
(1991–2006)	12	3	25.4	32	172.452	4	1.10000
(1991–2006)	12	4	20	28.8	189.813	4.2	0.00000
(1991–2006)	12	5	19.9	28.9	187.498	4.2	0.00000
(1991–2006)	12	6	18.8	29.1	185.183	4.1	0.00000
(1991–2006)	12	7	20.7	29	188.655	4.2	0.00000
(1991–2006)	12	8	23	27.4	188.655	4.2	0.00000
(1991–2006)	12	9	21.3	27.2	187.498	4.2	0.00000
(1991–2006)	12	10	23.5	30.5	163.193	3.7	0.200000
(1991–2006)	12	11	24.2	33.2	166.665	3.9	12.9000
(1991–2006)	12	12	23.9	33.1	144.674	3.3	1.50000
(1991–2006)	12	13	24.2	33.8	150.461	3.5	0.600000
(1991–2006)	12	14	21.8	28.8	178.239	4	0.00000
(1991–2006)	12	15	21.3	26.7	72.9159	1.5	0.100000
(1991–2006)	12	16	15.8	25	27.7775	0.5	0.00000
(1991–2006)	12	17	17.9	24.3	152.776	3.2	61.9000
(1991–2006)	12	18	19.7	25.5	186.341	4	0.00000
(1991–2006)	12	19	20.5	28	185.183	4.1	0.00000
(1991–2006)	12	20	19.2	25.3	185.183	4	0.00000
(1991–2006)	12	21	17.9	25	138.887	2.9	0.00000
(1991–2006)	12	22	14.9	23	163.193	3.3	0.00000
(1991–2006)	12	23	14.4	22.1	101.851	2	0.00000

(1991–2006)	12	24	16.9	24.3	116.897	2.4	0.00000
(1991–2006)	12	25	16.6	26.5	141.202	3	0.00000
(1991–2006)	12	26	17.1	28.6	143.517	3.1	0.00000
(1991–2006)	12	27	16.9	29.1	177.081	3.8	0.00000
(1991–2006)	12	28	16.3	29.2	184.026	4	0.00000
(1991–2006)	12	29	15.9	26.7	186.341	4	0.00000
(1991–2006)	12	30	17.9	26.4	187.498	4	0.00000
(1991–2006)	12	31	15.4	22.5	79.8603	1.6	34.0000

A.3. DAISY input file for the phase 1 optimization

```
;;  Arbeitsverzchnis
(directory ".")
;;  Verzechnis der Programmbibliotheken
;; => ggfs. anpassen <=
(path "." "C:/Programme/Daisy 4.57/lib")

;; Implementierung externer Programmbibliotheken
(input file "tillage.dai")
(input file "crop.dai")
(input file "../maizelavalette2.dai")
(input file "log.dai")
(input file "fertilizer.dai")
```

Crop, calibrated for Montpellier, France

```
;; maizelavalette: Lavalette Kalibrierungen für Pioneer Mais, von Fahle,
Def  in maislavalette.dai
(defcrop "Pioneer Freising"
"Pioneer Maize Lavalette 2007 ohne Sprinkler, y_half vaiabel"
(enable_N_stress false))
```

Weather data, 1-year

```
;; Wetterdaten
(weather default "../weather/weather140.dwf")

;;  Projektbezeichnung
(description "Test_Oman Batinah")
```

Soil, Pedotransfer function

```
;; Van Genuchten/Mualem Parameter
(defhorizon A FAO3
  "Schicht 0 - 0.30m"
  (clay 0.08 []) ;; Angaben nur für Gesamtboden vorhanden, nicht für
einzelne Schichten
  (silt 0.10 [])
  (sand 0.82 [])
  (humus 0.01 []) ;; Humusgehalt größer Null gewählt, da Programm sonst
nicht lauffähig war
```

Percentage of soil type

```
  (hydraulic M_vG
      (K_sat 5.4 [cm/h])
      (Theta_res 0.01 [])
      (Theta_sat 0.32 [])
      (alpha 0.04 [cm^-1])
      (n 1.6)))
```

Hydraulic soil parameters

```
(defhorizon B FAO3
  "Schicht 0.30 - 0.60m"
  (clay 0.09 [])
```

```
  (silt 0.15 [])
  (sand 0.75 [])
  (humus 0.01 [])

  (hydraulic M_vG
        (K_sat 5.4 [cm/h])
        (Theta_res 0.01 [])
        (Theta_sat 0.32 [])
        (alpha 0.04 [cm^-1])
        (n 1.6)))

(defhorizon C FAO3
  "Schicht 0.60 - 2.00m"
  (clay 0.08 [])
  (silt 0.06 [])
  (sand 0.85 [])
  (humus 0.01 [])

  (hydraulic M_vG
        (K_sat 5.4 [cm/h])
        (Theta_res 0.01 [])
        (Theta_sat 0.32 [])
        (alpha 0.04 [cm^-1])
        (n 1.6)))


;;  Parametrisierung der Bodensäule

(defcolumn "Batinah" default
      (Bioclimate default (pet weather))
        ;;zeigt an, dass Referenzevaporation in der Wetterdatei angegeben
ist

      (SoilWater (initial_Theta  (-10 [cm] 0.2 [])
                                        (-180 [cm] 0.2 [])))
       ;;Bodenwassergehalte am Tag der Aussaat

                 )
       ;;Erhöhung der maximalen zeitlichen Auflösung

        (Movement vertical (Geometry(zplus -0.5 -1 -1.5 -2 -2.5 -3 -4 -6 -8 -10  -15 -20 -25 -30 -35 -40 -
45 -50 -55 -60 -70 -80 -90 -95 -96 -98 -100 -110 -120 -130 -140 -150  -160  [cm]))
                                (matrix_water (richards
                                (max_time_step_reductions 16)
                                (time_step_reduction 6)
                                (max_iterations 25)
                                (max_absolute_difference 0.04 [cm])
                                (max_relative_difference 0.002)
                                )
                                lr)
                )

      (Soil (horizons (  -30 [cm] "A")
                      (  -60 [cm] "B")
                      ( -200 [cm] "C"))

        ;;    (zplus -1 -2.5 -4 -5.5 -7.5 -9 -11 -13 -16 -20 -25 -30 -35
-40 -45 -50 -55 -60
       ;;            -70 -80 -90 -95 -96 -98 -100 -110 -120 -130 -140 -150
-160 -170 -180 -190 -200 [cm])
```

Initial soil moisture

Numerical parameters

Soil Layers

```
;; Vorgabe einer räumlichen Diskretisierung

(MaxRootingDepth 200 [cm])) ;;obligatorische Angabe, keine
Einschr„nkung hinsichtlich Durchwurzelung

(Groundwater deep))

;; Auswahl der Bodensäule
(column "Batinah")
;; Simulation start and stop dates.
(time 2011 11 01 10)  ;;wird mit Freising Wetterfile nicht reif
(stop 2012 04 30 10)

(manager activity
  (wait (at 2011 11 29 12))
    (sow "Pioneer Freising")

     (wait_mm_dd 12 1) ;; Monat und Tag der Bewsserung
     (irrigate_surface 12[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 2) ;; Monat und Tag der Bewsserung
     (irrigate_surface 7[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 3) ;; Monat und Tag der Bewsserung
     (irrigate_surface 3[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 4) ;; Monat und Tag der Bewsserung
     (irrigate_surface 3[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 5) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 7) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 9) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 11) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 13) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 15) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 17) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 19) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 21) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 23) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 25) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 12 28) ;; Monat und Tag der Bewsserung
     (irrigate_surface 4[mm/h] (hours 1)) ;;
    (wait_mm_dd 1 4) ;; Monat und Tag der Bewsserung
     (irrigate_surface 25[mm/h] (hours 1)) ;;
    (wait_mm_dd 1 13) ;; Monat und Tag der Bewsserung
     (irrigate_surface 30[mm/h] (hours 1)) ;;
    (wait_mm_dd 1 19) ;; Monat und Tag der Bewsserung
     (irrigate_surface 20[mm/h] (hours 2)) ;;
    (wait_mm_dd 1 24) ;; Monat und Tag der Bewsseru
     (irrigate_surface 15[mm/h] (hours 1)) ;;
    (wait_mm_dd 1 29) ;; Monat und Tag der Bewsserung
     (irrigate_surface 15[mm/h] (hours 1)) ;;
```

Simulation period

Application of irrigation water

Additional parameters

```
         (wait_mm_dd 2 4) ;; Monat und Tag der Bewsserung
          (irrigate_surface 20[mm/h] (hours 2)) ;;
         (wait_mm_dd 2 7) ;; Monat und Tag der Bewsserung
          (irrigate_surface 20[mm/h] (hours 1)) ;;

;; => Bewässerungs- und Düngungsplan einfügen <=
   (wait_mm_dd 2 16) ;; Monat und Tag der Bewässerung
    (irrigate_surface 8.45[mm/h] (hours 1)) ;;

;; => Ende Bewässerungs- und Düngungsplan <=

   (wait (or (crop_ds_after "Pioneer Freising" 2.0)
        (at 2012 04 20 1)))
   ;; Ernte nach Reife, spätestens am 30.3.
   (harvest "Pioneer Freising")
   (stop)

   )

(deflog "Ernte" crop
   (where "${colfid}crop_prod.dlf")
   (when (hour 12))                    ;When the stress is highest.
   (entries ;; Year Month MDay

           (number (path column "${column}" Vegetation crops crops
"${crop}"
                        Prod WSOrg)
                  (dimension "Mg DM/ha")
                  (factor 0.01))

           ))

 (output harvest

        ;;("Field nitrogen" (when monthly))
        ;;("Soil nitrogen" (when daily) (from 0 [m]) (to -1 [m]))
        ;;("Field water" (when monthly))
        ;;("Soil water" (when daily) (from 0 [m]) (to -1 [m]))
        ("Ernte"
              (print_initial false)
  (print_header false)
  (print_dimension false)
  (print_tags false)
  (time_columns false)
              (when (crop_ds_after "Pioneer Freising" 2.0))

         (crop "Pioneer Freising")  (where "ernte0.txt")
         )

)
```

A.4. DAISY harvest file for the phase 1 optimization

dlf-0.0 -- harvest

VERSION: 4.57
LOGFILE:
harvest.dlf
RUN: Mon Feb 13 06:01:08 2012

SIMFILE: bewaesserung_lavalette_mit_stickstoff.tmp
SIM: Test_Oman Batinah

----

year	month	day	column	crop	stem_DM	dead_DM	leaf_DM
					t/ha	t/ha	t/ha
2000	3	24	Batinah	Pioneer Freising	4.72392	2.38075	0.689254

sorg_DM	stem_N	dead_N	leaf_N	sorg_N	WStress	NStress	WP_ET
t/ha	kg/ha	kg/ha	kg/ha	kg/ha	d	d	kg/m^3
10.9657	6.27052	9.12262	0.914913	50.9452	0.873905	73.7272	2.33746

A.5. Exemplary APSIM setup file.

```xml
<?xml version="1.0"?>
<simulation executable="%apsim%/Model/ProtocolManager.dll" version="7.3">
  <title>W2S3</title>
  <component name="clock" executable = "%apsim%/Model/clock.dll">
    <initdata>
      <include>%apsim%/Model/clock.xml</include>
      <start_date>01/10/2012</start_date>
      <end_date>27/04/2013</end_date>
    </initdata>
  </component>
  <component name="report" executable = "%apsim%/Model/report.dll">
    <initdata>
      <outputfile>W2S3_output.out</outputfile>
      <variable>clock.day</variable>
      <variable>clock.year</variable>
      <variable>maize.stage</variable>
      <variable>maize.yield</variable>
      <variable>maize.biomass</variable>
      <variable>irrigation.irrigation</variable>
      <variable>maize.transpiration</variable>
      <variable>maize.cep</variable>
      <variable>SWIM2.eo</variable>
      <variable>SWIM2.es</variable>
      <variable>SWIM2.drain</variable>
      <variable>maize.nfact_grain</variable>
      <variable>maize.nfact_photo</variable>
      <variable>maize.nfact_expan</variable>
      <variable>maize.swdef_pheno</variable>
      <variable>maize.swdef_photo</variable>
      <variable>maize.swdef_expan</variable>
      <variable>solute.cl_ppm</variable>
      <variable>SWIM2.sw</variable>
      <variable>SWIM2.psi</variable>
    </initdata>
  </component>
  <component name="met" executable = "%apsim%/Model/input.dll">
    <initdata>
      <filename>E:\Oman\OmanStack\Apsim\weather_apsim\climate_250.met</filename>
    </initdata>
  </component>
  <component name="fertiliser" executable = "%apsim%/Model/fertiliser.dll">
    <initdata>
      <include>%apsim%/Model/fertiliser.xml</include>
    </initdata>
  </component>
  <component name="irrigation" executable = "%apsim%/Model/irrigation.dll">
    <initdata>
      <include>%apsim%/Model/irrigation.xml</include>
      <manual_irrigation>on</manual_irrigation>
      <irrigation_efficiency>1</irrigation_efficiency>
      <default_cl_conc>0 (ppm)</default_cl_conc>
    </initdata>
  </component>
  <component name="manager" executable = "%apsim%/Model/manager.dll">
    <initdata>
      <script name="sample.end_of_day">
        <text><![CDATA[
        report do_output
```

Simulation Period (start_date, end_date)

Weather data (climate_250.met)

Salinity of the irrigation (default_cl_conc)

```
        ]]>
        </text>
        <event>end_of_day</event>
      </script>
      <script name="sample.start_of_day">
        <text><![CDATA[
        if day = 333 and year = 2012 then
          maize sow cultivar = pioneer_3527, plants = 10, sowing_depth = 10 (mm), sowing_density =
9.7 (plants/m2), row_spacing = 0.5 (m)
        endif
```

Sowing

```
        if day = 85 and year = 2013 then
          maize harvest
          maize kill_crop
          maize end_crop
        endif
```

Harvest

```
        ! ------------------- initial layer information -----------------------------------------------------------
        ]]>
        </text>
        <event>start_of_day</event>
      </script>
    </initdata>
  </component>
    <component   name="Irrigate   on   fixed   date1"   executable="C:\Programme   (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('20-Nov')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '50' (mm)
          endif </rule>
      </initdata>
    </component>
```

To simulate initial conditions (does not count as an irrigation event)

```
    <component   name="Irrigate   on   fixed   date1"   executable="C:\Programme   (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('29-Nov')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '5.6' (mm)
          endif </rule>
      </initdata>
    </component>
```

Irrigation

```
  <component   name="Irrigate   on   fixed   date2"   executable="C:\Programme   (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('04-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '3' (mm)
          endif </rule>
      </initdata>
    </component>
  <component   name="Irrigate   on   fixed   date3"   executable="C:\Programme   (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
```

```
          if (today = date('05-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '3.4' (mm)
          endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date4" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('7-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '7.6' (mm)
          endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date5" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('9-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '4.7' (mm)
          endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date6" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('11-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '4.2' (mm)
          endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date7" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('13-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '8.2' (mm)
          endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date8" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
          if (today = date('15-Dec')) then
            'Irrigation' set irrigation_efficiency = 1
           'Irrigation' apply amount = '3.8' (mm)
          endif </rule>
      </initdata>
```

```
   </component>
  <component name="Irrigate on fixed date9" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
         if (today = date('17-Dec')) then
           'Irrigation' set irrigation_efficiency = 1
          'Irrigation' apply amount = '5.5' (mm)
         endif </rule>
     </initdata>
   </component>
  <component name="Irrigate on fixed date10" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
         if (today = date('19-Dec')) then
           'Irrigation' set irrigation_efficiency = 1
          'Irrigation' apply amount = '3.8' (mm)
         endif </rule>
     </initdata>
   </component>
  <component name="Irrigate on fixed date11" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
         if (today = date('21-Dec')) then
           'Irrigation' set irrigation_efficiency = 1
          'Irrigation' apply amount = '6.4' (mm)
         endif </rule>
     </initdata>
   </component>
  <component name="Irrigate on fixed date12" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
         if (today = date('23-Dec')) then
           'Irrigation' set irrigation_efficiency = 1
          'Irrigation' apply amount = '5.7' (mm)
         endif </rule>
     </initdata>
   </component>
  <component name="Irrigate on fixed date13" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
         if (today = date('25-Dec')) then
           'Irrigation' set irrigation_efficiency = 1
          'Irrigation' apply amount = '3.8' (mm)
         endif </rule>
     </initdata>
   </component>
  <component name="Irrigate on fixed date14" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
```

```
      <rule name="start_of_day - start_of_day" condition="start_of_day">
        if (today = date('27-Dec')) then
          'Irrigation' set irrigation_efficiency = 1
         'Irrigation' apply amount = '3.8' (mm)
        endif </rule>
     </initdata>
    </component>
  <component name="Irrigate on fixed date15" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
        if (today = date('29-Dec')) then
          'Irrigation' set irrigation_efficiency = 1
         'Irrigation' apply amount = '7.6' (mm)
        endif </rule>
     </initdata>
    </component>
  <component name="Irrigate on fixed date16" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
        if (today = date('31-Dec')) then
          'Irrigation' set irrigation_efficiency = 1
         'Irrigation' apply amount = '5.7' (mm)
        endif </rule>
     </initdata>
    </component>
  <component name="Irrigate on fixed date18" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
        if (today = date('01-Jan')) then
          'Irrigation' set irrigation_efficiency = 1
         'Irrigation' apply amount = '7.5' (mm)
        endif </rule>
     </initdata>
    </component>
  <component name="Irrigate on fixed date19" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
        if (today = date('09-Jan')) then
          'Irrigation' set irrigation_efficiency = 1
         'Irrigation' apply amount = '15' (mm)
        endif </rule>
     </initdata>
    </component>
  <component name="Irrigate on fixed date20" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
     <initdata>
      <rule name="start_of_day - start_of_day" condition="start_of_day">
        if (today = date('17-Jan')) then
          'Irrigation' set irrigation_efficiency = 1
         'Irrigation' apply amount = '15' (mm)
        endif </rule>
```

```
      </initdata>
    </component>
  <component name="Irrigate on fixed date21" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
           if (today = date('25-Jan')) then
              'Irrigation' set irrigation_efficiency = 1
             'Irrigation' apply amount = '26.25' (mm)
           endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date22" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
           if (today = date('02-Feb')) then
              'Irrigation' set irrigation_efficiency = 1
             'Irrigation' apply amount = '26.25' (mm)
           endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date23" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
           if (today = date('10-Feb')) then
              'Irrigation' set irrigation_efficiency = 1
             'Irrigation' apply amount = '26.25' (mm)
           endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date24" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
           if (today = date('18-Feb')) then
              'Irrigation' set irrigation_efficiency = 1
             'Irrigation' apply amount = '26.25' (mm)
           endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date25" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
      <initdata>
        <rule name="start_of_day - start_of_day" condition="start_of_day">
           if (today = date('26-Feb')) then
              'Irrigation' set irrigation_efficiency = 1
             'Irrigation' apply amount = '26.25' (mm)
           endif </rule>
      </initdata>
    </component>
  <component name="Irrigate on fixed date26" executable="C:\Programme (x86)/Apsim74-
r2286/Model/Manager.dll">
  <executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
```

```
<initdata>
  <rule name="start_of_day - start_of_day" condition="start_of_day">
    if (today = date('06-Mar')) then
      'Irrigation' set irrigation_efficiency = 1
     'Irrigation' apply amount = '26.25' (mm)
    endif </rule>
</initdata>
</component>
<component name="Irrigate on fixed date27" executable="C:\Programme (x86)/Apsim74-r2286/Model/Manager.dll">
<executable>C:\Programme (x86)\Apsim74-r2286/Model/Manager.dll</executable>
<initdata>
  <rule name="start_of_day - start_of_day" condition="start_of_day">
    if (today = date('14-Mar')) then
      'Irrigation' set irrigation_efficiency = 1
     'Irrigation' apply amount = '18.75' (mm)
    endif </rule>
</initdata>
</component>
<component name="SWIM2" executable = "%apsim%/Model/SWIM2.dll">
 <initdata>
  <include>%apsim%/Model/SWIM2.xml</include>
  <init>
   <x>0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 225 250 275 300 325 350 375 400 425 450 475 500 525 550 575 600 625 650 675 700 725 750 775 800 825 850 875 900 925 950 975 1000 1025 1050 1075 1100 1125 1150 1175 1200 1225 1250 1275 1300 1325 1350 1375 1400 1425 1450 1475 1500 (mm)</x>
   <soil_type>soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil1 soil2 soil2 soil2 soil2 soil2 soil2 soil2 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil3 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4 soil4</soil_type>
   <psi>-3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -3191 -2539 -2539 -2539 -2539 -2539 -2539 -2539 -2539 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -2922 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 -1771 (cm)</psi>
   <slmin>-1.0</slmin>
   <slmax>10.0</slmax>
   <bypass_flow>off</bypass_flow>
   <runoff>1</runoff>
   <top_boundary_condition>0</top_boundary_condition>
   <bottom_boundary_condition>0</bottom_boundary_condition>
   <vapour_conductivity>off</vapour_conductivity>
   <subsurface_drain>off</subsurface_drain>
   <run_solutes>cl no3 nh4</run_solutes>
  </init>
  <soil1>
   <sl>-1.000 -0.800 -0.600 -0.400 -0.200 0.000 0.200 0.400 0.600 0.800 1.000 1.200 1.400 1.600 1.800 2.000 2.200 2.400 2.600 2.800 3.000 3.200 3.400 3.600 3.800 4.000 4.200 4.400 4.600 4.800 5.000 5.200 5.400 5.600 5.800 6.000 6.200 6.400 6.600 6.800 7.000</sl>
   <wc>0.320 0.320 0.320 0.320 0.320 0.319 0.319 0.317 0.316 0.312 0.307 0.300 0.289 0.275 0.259 0.241 0.224 0.207 0.192 0.178 0.165 0.153 0.143 0.134 0.125 0.118 0.112 0.106 0.101 0.096 0.092 0.088 0.085 0.082 0.079 0.077 0.075 0.073 0.071 0.070 0.069</wc>
   <wcd>-0.000 -0.000 -0.000 -0.001 -0.001 -0.002 -0.004 -0.007 -0.012 -0.020 -0.031 -0.046 -0.062 -0.076 -0.085 -0.088 -0.086 -0.081 -0.074 -0.067 -0.061 -0.054 -
```


Soil data

Soil assignment

Initial tension

Deep groundwater

Data for retention function and conductivity

0.049 -0.043 -0.039 -0.035 -0.031 -0.027 -0.025 -0.022 -0.019 -0.017 -0.015 -0.014 -0.012 -0.011 -0.010 -0.009 -0.008 -0.007 -0.006</wcd>
<hkl>0.659 0.624 0.583 0.534 0.477 0.408 0.324 0.221 0.093 -0.068 -0.269 -0.520 -0.828 -1.192 -1.606 -2.060 -2.541 -3.040 -3.550 -4.066 -4.587 -5.109 -5.632 -6.156 -6.681 -7.206 -7.730 -8.255 -8.780 -9.305 -9.830 -10.355 -10.880 -11.405 -11.930 -12.455 -12.980 -13.505 -14.030 -14.555 -15.080</hkl>
<hkld>-0.162 -0.189 -0.222 -0.263 -0.315 -0.380 -0.463 -0.572 -0.714 -0.897 -1.125 -1.394 -1.682 -1.954 -2.180 -2.346 -2.457 -2.527 -2.568 -2.593 -2.607 -2.615 -2.619 -2.622 -2.623 -2.624 -2.624 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625</hkld>
<bulk_density>1.4</bulk_density>
<solute_name>no3 nh4 cl</solute_name>
<exco>0 0.1 0</exco>
<fip>1 1 1</fip>
<dis>2 2 1</dis>
</soil1>
<soil2>
<sl>-1.000 -0.800 -0.600 -0.400 -0.200 0.000 0.200 0.400 0.600 0.800 1.000 1.200 1.400 1.600 1.800 2.000 2.200 2.400 2.600 2.800 3.000 3.200 3.400 3.600 3.800 4.000 4.200 4.400 4.600 4.800 5.000 5.200 5.400 5.600 5.800 6.000 6.200 6.400 6.600 6.800 7.000</sl>
<wc>0.320 0.320 0.320 0.320 0.320 0.319 0.319 0.318 0.316 0.313 0.309 0.303 0.294 0.282 0.269 0.254 0.239 0.225 0.211 0.198 0.186 0.175 0.164 0.155 0.146 0.139 0.132 0.125 0.119 0.114 0.109 0.104 0.100 0.097 0.093 0.090 0.087 0.085 0.082 0.080 0.078</wc>
<wcd>-0.000 -0.000 -0.000 -0.001 -0.001 -0.002 -0.004 -0.006 -0.011 -0.017 -0.026 -0.038 -0.051 -0.063 -0.071 -0.074 -0.074 -0.072 -0.068 -0.063 -0.058 -0.053 -0.049 -0.045 -0.041 -0.037 -0.034 -0.031 -0.028 -0.026 -0.023 -0.021 -0.020 -0.018 -0.016 -0.015 -0.013 -0.012 -0.011 -0.010 -0.009</wcd>
<hkl>0.392 0.350 0.303 0.248 0.183 0.107 0.016 -0.094 -0.228 -0.393 -0.596 -0.845 -1.145 -1.495 -1.891 -2.322 -2.778 -3.252 -3.737 -4.227 -4.722 -5.219 -5.717 -6.216 -6.715 -7.215 -7.715 -8.215 -8.715 -9.215 -9.715 -10.215 -10.715 -11.215 -11.715 -12.215 -12.715 -13.215 -13.715 -14.215 -14.715</hkl>
<hkld>-0.192 -0.221 -0.255 -0.297 -0.350 -0.415 -0.498 -0.605 -0.741 -0.914 -1.125 -1.370 -1.628 -1.871 -2.075 -2.228 -2.332 -2.399 -2.441 -2.465 -2.480 -2.488 -2.493 -2.496 -2.498 -2.499 -2.499 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500</hkld>
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<solute_name>no3 nh4 cl</solute_name>
<exco>0 0.1 0</exco>
<fip>1 1 1</fip>
<dis>2 2 1</dis>
</soil2>
<soil3>
<sl>-1.000 -0.800 -0.600 -0.400 -0.200 0.000 0.200 0.400 0.600 0.800 1.000 1.200 1.400 1.600 1.800 2.000 2.200 2.400 2.600 2.800 3.000 3.200 3.400 3.600 3.800 4.000 4.200 4.400 4.600 4.800 5.000 5.200 5.400 5.600 5.800 6.000 6.200 6.400 6.600 6.800 7.000</sl>
<wc>0.320 0.320 0.320 0.320 0.320 0.319 0.319 0.317 0.316 0.312 0.307 0.300 0.289 0.275 0.259 0.241 0.224 0.207 0.192 0.178 0.165 0.153 0.143 0.134 0.125 0.118 0.112 0.106 0.101 0.096 0.092 0.088 0.085 0.082 0.079 0.077 0.075 0.073 0.071 0.070 0.069</wc>
<wcd>-0.000 -0.000 -0.000 -0.001 -0.001 -0.002 -0.004 -0.007 -0.012 -0.020 -0.031 -0.046 -0.062 -0.076 -0.085 -0.088 -0.086 -0.081 -0.074 -0.067 -0.061 -0.054 -0.049 -0.043 -0.039 -0.035 -0.031 -0.027 -0.025 -0.022 -0.019 -0.017 -0.015 -0.014 -0.012 -0.011 -0.010 -0.009 -0.008 -0.007 -0.006</wcd>
<hkl>0.659 0.624 0.583 0.534 0.477 0.408 0.324 0.221 0.093 -0.068 -0.269 -0.520 -0.828 -1.192 -1.606 -2.060 -2.541 -3.040 -3.550 -4.066 -4.587 -5.109 -5.632 -6.156 -6.681 -7.206 -7.730 -8.255 -8.780 -9.305 -9.830 -10.355 -10.880 -11.405 -11.930 -12.455 -12.980 -13.505 -14.030 -14.555 -15.080</hkl>

<hkld>-0.162 -0.189 -0.222 -0.263 -0.315 -0.380 -0.463 -0.572 -0.714 -0.897 -
1.125 -1.394 -1.682 -1.954 -2.180 -2.346 -2.457 -2.527 -2.568 -2.593 -2.607 -2.615 -
2.619 -2.622 -2.623 -2.624 -2.624 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -
2.625 -2.625 -2.625 -2.625 -2.625 -2.625 -2.625</hkld>
<bulk_density>1.4</bulk_density>
<solute_name>no3 nh4 cl</solute_name>
<exco>0 0.1 0</exco>
<fip>1 1 1</fip>
<dis>2 2 1</dis>
</soil3>
<soil4>
<sl>-1.000 -0.800 -0.600 -0.400 -0.200 0.000 0.200 0.400 0.600 0.800 1.000
1.200 1.400 1.600 1.800 2.000 2.200 2.400 2.600 2.800 3.000 3.200 3.400
3.600 3.800 4.000 4.200 4.400 4.600 4.800 5.000 5.200 5.400 5.600 5.800
6.000 6.200 6.400 6.600 6.800 7.000</sl>
<wc>0.320 0.320 0.320 0.320 0.320 0.319 0.319 0.318 0.316 0.313 0.309
0.303 0.294 0.282 0.269 0.254 0.239 0.225 0.211 0.198 0.186 0.175 0.164
0.155 0.146 0.139 0.132 0.125 0.119 0.114 0.109 0.104 0.100 0.097 0.093
0.090 0.087 0.085 0.082 0.080 0.078</wc>
<wcd>-0.000 -0.000 -0.000 -0.001 -0.001 -0.002 -0.004 -0.006 -0.011 -0.017 -
0.026 -0.038 -0.051 -0.063 -0.071 -0.074 -0.074 -0.072 -0.068 -0.063 -0.058 -0.053 -
0.049 -0.045 -0.041 -0.037 -0.034 -0.031 -0.028 -0.026 -0.023 -0.021 -0.020 -0.018 -
0.016 -0.015 -0.013 -0.012 -0.011 -0.010 -0.009</wcd>
<hkl>0.392 0.350 0.303 0.248 0.183 0.107 0.016 -0.094 -0.228 -0.393 -0.596
-0.845 -1.145 -1.495 -1.891 -2.322 -2.778 -3.252 -3.737 -4.227 -4.722 -5.219 -5.717 -
6.216 -6.715 -7.215 -7.715 -8.215 -8.715 -9.215 -9.715 -10.215 -10.715 -11.215 -11.715 -
12.215 -12.715 -13.215 -13.715 -14.215 -14.715</hkl>
<hkld>-0.192 -0.221 -0.255 -0.297 -0.350 -0.415 -0.498 -0.605 -0.741 -0.914 -
1.125 -1.370 -1.628 -1.871 -2.075 -2.228 -2.332 -2.399 -2.441 -2.465 -2.480 -2.488 -
2.493 -2.496 -2.498 -2.499 -2.499 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -
2.500 -2.500 -2.500 -2.500 -2.500 -2.500 -2.500</hkld>
<bulk_density>1.4</bulk_density>
<solute_name>no3 nh4 cl</solute_name>
<exco>0 0.1 0</exco>
<fip>1 1 1</fip>
<dis>2 2 1</dis>
</soil4>
<solute>
<solute_name>no3 nh4 cl</solute_name>
<slupf>1 0 0</slupf>
<slos>0 0 0.85</slos>
<d0>0 0 0</d0>
<a>0 0 0
<dthc>0 0 0</dthc>
<dthp>1 1 1</dthp>
<disp>1 1 1</disp>
<ground_water_conc>0 0 0</ground_water_conc>
</solute>
<calc>
<dtmin>0.0</dtmin>
<dtmax>60.</dtmax>

Time step 1 h

<ersoil>0.000001</ersoil>
<ernode>0.000001</ernode>
<errex>0.01</errex>
<dppl>2</dppl>
<dpnl>1</dpnl>
<max_water_increment>1.</max_water_increment>
<swt>0.0</swt>
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<slswt>0.0</slswt>

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      <rainfall_source>rain</rainfall_source>
      <evap_source>calc</evap_source>
      <salb>0.23</salb>
    </climate>
    <bottom_boundary>
      <constant_gradient>1</constant_gradient>
    </bottom_boundary>
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      <min_xylem_potential>-15000   (cm)</min_xylem_potential>
      <root_radius>1      (mm)</root_radius>
      <root_conductance>1.4d-7</root_conductance>
    </crop>
  </initdata>
</component>
<component name="soiln" executable = "%apsim%/Model/soiln.dll">
  <initdata>
    <include>%apsim%/Model/soil.xml(soiln)</include>
    <amp>13.39</amp>
    <tav>28.42</tav>
    <root_cn>40</root_cn>
    <root_wt>1000</root_wt>
    <soil_cn>12</soil_cn>
    <oc>1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00</oc>
    <ph>8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50
8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50
8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50
8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50
8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50   8.50</ph>
    <fbiom>0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040
0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040
0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040
0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040  0.040
0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040   0.040
0.040</fbiom>
    <finert>0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400
0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400
0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400
0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400  0.400
0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400   0.400
0.400</finert>
    <no3ppm>1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000
1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000
1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000
1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000
1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000    1000
1000    1000    1000    1000    1000    1000    1000    1000    1000    1000</no3ppm>
    <nh4ppm>1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1    1    1    1    1    1</nh4ppm>
    <enr_a_coeff>7.4</enr_a_coeff>
    <enr_b_coeff>0.2</enr_b_coeff>
    <profile_reduction>off</profile_reduction>
```

```
    </initdata>
  </component>
  <component name="solute" executable = "%apsim%/Model/solute.dll">
    <initdata>
      <include>%apsim%/Model/solute.xml</include>
      <solute_names>cl</solute_names>
      <cl_ppm>432   432   432   432   432   432   432   432   432   432   432   432   432   432
432   432   432   432   432   432   432   432   432   432   432   432   432   432   432   432
432   432   432   432   432   432   432   432   432   432   432   432   432   432   432   432
432   432   432   432   432   432   432   432   432   432   432   432   432   432   432   432
432   432   432   432   432   432   432   432   432   432   432 (ppm)</cl_ppm>
    </initdata>
  </component>
  <component name="maize" executable = "%apsim%/Model/maize.dll">
    <initdata>
      <include>%apsim%/Model/maize.xml</include>
      <uptake_source>apsim</uptake_source>
      <ll>0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112
0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.132  0.132  0.132  0.132  0.132  0.132  0.132
0.132  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112  0.112
0.112  0.112  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132
0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132  0.132
0.132</ll>
      <kl>0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060
0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060
0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060
0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060
0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060  0.060
0.060</kl>
      <xf>0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560
0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560
0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560
0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560
0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560  0.560
0.560</xf>
    </initdata>
  </component>
</simulation>
```


Salinity initial concentration

A.6. Soil calibration reference files

A.6.1. Werisch, S., Grundmann, J., Al-dhuhli, H., Algharibi, E., & Lennartz, F. (2014). A Multiobjective Framework for Robust Parameter Estimation of Soil Hydraulic Properties and its Application for a Field Site in Oman. *Journal of Environmental Earth Sciences*. http://doi.org/10.1007/s12665-014-3537-6

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Table 5 The estimated soil hydraulic parameters of the MvG model, namely the residual water content θ_r, the saturated water content θ_s, the shape parameters α and n, the saturated hydraulic conductivity K_s and the shape parameter τ, are given for the individual core samples and both optimisation problems P_1 and P_2

		θ_r		θ_s	α		n		K_s		τ	
		$\left[\frac{cm^3}{cm^3}\right]$		$\left[\frac{cm^3}{cm^3}\right]$	$[cm^{-1}]$		$[-]$		$\left[\frac{cm}{min}\right]$		$[-]$	
		P_1	P_2		P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
C3	$\check{\Phi}_1$	0.14	0.14	0.35	0.018	0.016	3.45	3.89	7.9E-04	2.6E-03	0.5	1.62
	$\bar{\Phi}_m$	0.11	0.13		0.019	0.022	2.09	2.08	3.9E-03	5.2E-04		−2.87
	$\bar{\Phi}_e$	0.12	0.13		0.018	0.022	2.18	2.08	3.8E-03	5.2E-04		−2.87
	$\check{\Phi}_2$	0.09	0.09		0.023	0.023	1.73	1.74	1.2E-02	8.0E-04		−3.54
	B_{min}	0.09	0.09		0.019	0.022	1.74	1.74	3.6E-03	5.6E-04		−3.80
	$\tilde{B}$	0.10	0.11		0.021	0.023	1.88	1.83	6.0E-03	7.4E-04		−3.57
	B_{max}	0.12	0.12		0.023	0.024	2.09	1.92	1.3E-02	1.2E-03		−3.26
	$\sigma(B)$	6.22E-03	7.73E-03		1.07E-03	2.09E-04	1.01E-01	5.21E-02	2.25E-03	1.10E-04		9.51E-02
C4	$\check{\Phi}_1$	0.06	0.01	0.33	0.028	0.037	1.78	1.50	3.3E-02	9.3E-03	0.5	−3.31
	$\bar{\Phi}_m$	0.01	0.02		0.046	0.060	1.54	1.48	3.1E-02	2.3E-03		−5.37
	$\bar{\Phi}_e$	0.01	0.01		0.047	0.059	1.54	1.48	3.1E-02	2.8E-03		−5.10
	$\check{\Phi}_2$	0.04	0.04		0.068	0.068	1.57	1.57	1.4E-01	1.5E-03		−4.64
	B_{min}	0.03	0.03		0.056	0.063	1.56	1.51	4.6E-02	8.3E-04		−5.90
	$\tilde{B}$	0.04	0.04		0.060	0.065	1.58	1.54	6.8E-02	1.4E-03		−5.40
	B_{max}	0.04	0.04		0.068	0.068	1.59	1.57	1.5E-01	2.1E-03		−4.88
	$\sigma(B)$	3.63E-03	5.22E-03		3.19E-03	1.59E-03	6.21E-03	1.78E-02	2.35E-02	3.09E-04		2.80E-01
C6	$\check{\Phi}_1$	0.00	0.00	0.34	0.122	0.150	1.14	1.14	2.8E-01	2.7E-01	0.5	−1.18
	$\bar{\Phi}_m$	0.00	0.02		0.104	0.104	1.14	1.15	2.9E-01	1.8E-01		−0.60
	$\bar{\Phi}_e$	0.01	0.02		0.104	0.104	1.14	1.15	2.8E-01	1.8E-01		−0.61
	$\check{\Phi}_2$	0.01	0.01		0.124	0.124	1.13	1.13	5.3E-01	2.4E-01		−3.34
	B_{min}	0.00	0.00		0.101	0.102	1.13	1.13	2.2E-01	1.2E-01		−3.68
	$\tilde{B}$	0.00	0.00		0.113	0.117	1.14	1.14	3.7E-01	2.2E-01		−0.89
	B_{max}	0.02	0.05		0.124	0.150	1.15	1.16	8.3E-01	2.9E-01		−0.05
	$\sigma(B)$	5.27E-03	1.50E-02		6.18E-03	1.13E-02	2.96E-03	7.64E-03	1.60E-01	3.95E-02		1.10E+00
C7	$\check{\Phi}_1$	0.11	0.12	0.29	0.015	0.016	2.54	2.63	3.3E-02	6.6E-03	0.5	−1.12
	$\bar{\Phi}_m$	0.09	0.09		0.016	0.016	2.14	2.19	2.8E-02	3.0E-02		0.65
	$\bar{\Phi}_e$	0.09	0.09		0.016	0.016	2.14	2.22	2.8E-02	2.2E-02		0.24
	$\check{\Phi}_2$	0.08	0.08		0.019	0.019	2.00	2.01	1.3E-02	2.4E-03		−1.25
	B_{min}	0.08	0.08		0.016	0.016	2.00	1.95	1.2E-02	1.4E-03		−2.09
	$\tilde{B}$	0.08	0.09		0.017	0.016	2.06	2.09	2.4E-02	2.1E-02		0.06
	B_{max}	0.09	0.10		0.019	0.020	2.26	2.25	3.1E-02	4.1E-02		0.91
	$\sigma(B)$	3.78E-03	4.10E-03		8.72E-04	1.30E-03	6.82E-02	9.09E-02	5.02E-03	1.20E-02		1.01E+00
C9	$\check{\Phi}_1$	0.00	0.00	0.34	0.027	0.031	1.38	1.36	6.6E-02	2.0E-02	0.5	−2.94
	$\bar{\Phi}_m$	0.03	0.02		0.034	0.039	1.41	1.37	4.1E-02	9.8E-03		−4.36
	$\bar{\Phi}_e$	0.03	0.02		0.033	0.037	1.40	1.37	6.3E-02	1.1E-02		−4.08
	$\check{\Phi}_2$	0.03	0.03		0.043	0.043	1.36	1.36	4.5E-01	9.6E-03		−5.12
	B_{min}	0.01	0.00		0.030	0.033	1.36	1.35	2.9E-02	8.0E-03		−5.56
	$\tilde{B}$	0.03	0.02		0.034	0.036	1.40	1.37	6.6E-02	1.2E-02		−4.19
	B_{max}	0.03	0.03		0.043	0.043	1.43	1.38	4.5E-01	1.8E-02		−3.27
	$\sigma(B)$	4.57E-03	7.65E-03		3.17E-03	2.69E-03	1.03E-02	5.08E-03	3.97E-02	2.64E-03		4.96E-01

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Table 5 continued

		θ_r		θ_s	α		n		K_s		τ	
		$\left[\frac{cm^3}{cm^3}\right]$		$\left[\frac{cm^3}{cm^3}\right]$	$[cm^{-1}]$		$[-]$		$\left[\frac{cm}{min}\right]$		$[-]$	
		P_1	P_2		P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
C10	$\check{\Phi}_1$	0.13	0.11	0.33	0.018	0.026	2.66	2.06	2.0E-02	6.5E-04	0.5	−3.56
	$\tilde{\Phi}_m$	0.07	0.06		0.026	0.037	1.97	1.64	1.9E-03	4.9E-04		−5.12
	$\tilde{\Phi}_e$	0.10	0.06		0.023	0.037	2.49	1.65	1.0E-03	4.9E-04		−5.08
	$\check{\Phi}_2$	0.06	0.06		0.028	0.027	1.86	1.86	2.7E-03	1.8E-03		0.09
	B_{min}	0.06	0.05		0.025	0.027	1.86	1.61	1.4E-03	4.7E-04		−5.14
	$\bar{B}$	0.08	0.06		0.025	0.034	2.06	1.66	1.7E-03	7.3E-04		−4.19
	B_{max}	0.08	0.07		0.028	0.038	2.15	1.89	2.9E-03	2.8E-03		0.19
	$\sigma(B)$	5.90E-03	3.19E-03		7.56E-04	2.45E-03	8.41E-02	6.70E-02	3.69E-04	6.24E-04		1.52E+00

The parameters of the Pareto extreme solution $\check{\Phi}_1$ (best fit to the MSO results), $\check{\Phi}_2$ (best fit to the retention curves) are given along with the compromise solutions estimated from the Manhattan distance $\tilde{\Phi}_m$ and the Euclidean distance $\tilde{\Phi}_e$. In addition, the main statistical parameters of the behavioral subsets (B) are given : B_{min} the minimum, B_{max} the maximum, $\sigma(B)$ the standard deviation and the median $\bar{B}$

A.6.2. Pistorius, M. (2012). Modellierung und Optimierung von Leachingstrategien für die Bewässerungslandwirtschaft im Oman. Master Thesis, Technischen Universität Dresden, Germany.

Multistep-Outflow und Equi-pF Messungen getätigt, sowie eine Überdruckmethode mittels des Drucktropfverfahrens angewandt. Die Bestimmung der Parameter für den Ansatz nach van Genuchten-Mualem erfolgte anschließend über eine inverse Modellierung unter HYDRUS 1D. Für einen detaillierten Einblick in den Versuchsaufbau und die Durchführung, kann (Helmrich, 2011) herangezogen werden. Abbildung 4-3 gibt den Verlauf der Retentionskurve wieder und in Tabelle 4-5 können die Parameter der Funktion eingesehen werden.

Tabelle 4-5: Parametrisierung der gegebenen Retentionskurve

Parameter	*Wert*
θ_S	0,32
θ_R	0,01
α	0,04 cm^{-1}
n	1,6
K_s	0,09 cm/min
l	0,5

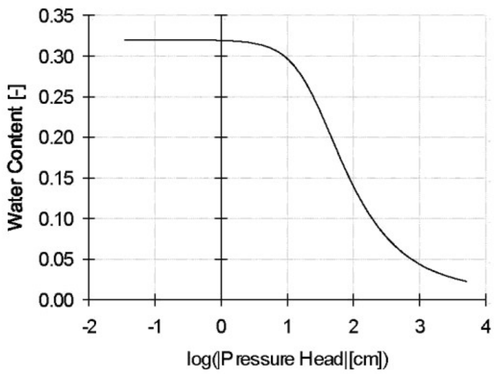


Abbildung 4-3: Graphische Darstellung der gegeben Retentionskurve

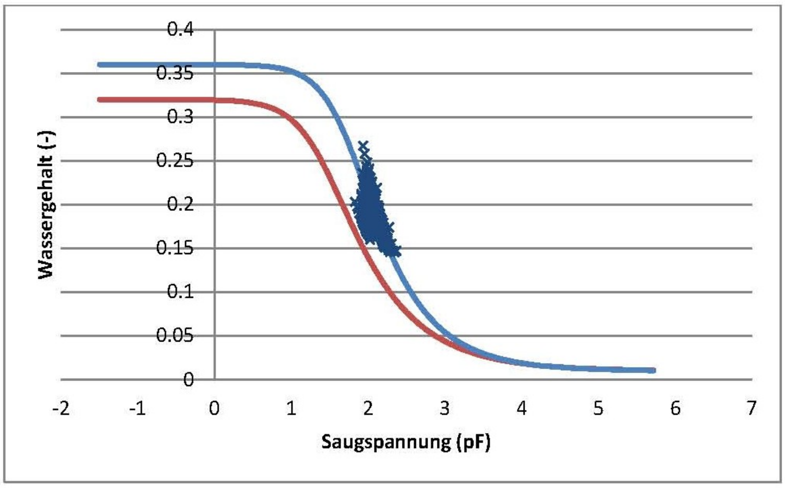


Abbildung 4-7: Durch RETC optimierte Retentionskurve (blaue Linie) nach van Genuchten-Mualem samt verwendeter Messpunkte (dunkel blaue Kreuze) und Ausgansretentionskurve (rote Linie) nach Tabelle 4-5

Tabelle 4-8: Parameter der von RETC optimierten Retentionskurve nach van Genuchten-Mualem

Parameter	*Wert*
θ_S	0,36
θ_R	0,01
α	0,01859 cm^{-1}
n	1,70505
K_s	0,09 cm/min
l	0,5

Tabelle 4-9: Finale Retentionskurven für die anschließende Hauptsimulation

Parameter	*Retentionskurve*	
	R1	*R2*
θ_S	0,32	0,32
θ_R	0,01	0,01
α $[cm^{-1}]$	0,1	0,1
n	1,3	1,2
K_s $[cm/min]$	0,09	0,09
l	0,5	0,5

A.7. The objective function files for phase 3 optimization

A.7.1. The objective function, under fully irrigation with 1 dSm^{-1}

```
function [fitness isconstrained water yield]=wbirrreducemodel(x,realization)

isconstrained=false;

yield=calc_apsim(x,realization)/1000;%nun in t/ha

water=sum(x);

id_irr=find(not(x==0));
max_gap=0;
for ii=1:(length(id_irr)-1)
   (id_irr(ii+1)-id_irr(ii));
   if ((id_irr(ii+1)-id_irr(ii))>max_gap)
      max_gap=id_irr(ii+1)-id_irr(ii);
   end
end
message=['Ertrag ist ' num2str(yield) ' t/ha -- ' 'größter Zwischenraum ist: ' num2str(max_gap)];
disp(message);
%% Pennalty für long irrigation intervalls
% yield=yield-(max_gap)^2;
% disp(['Zielfunktionswert ist: ' num2str(yield)]);



if(yield<8.5)
   isconstrained=true;
   fitness=(8.5-yield).^2*100+1000;  %hefty penalty if we fail, the parameters for the penalty
function may have to be tuned to make everything more efficient and stable currently we risk to
get stuck in cases where the population is converged and suddenly a constraining scenario pops
up
else
   fitness=water+(max_gap)^2;
end
disp(['wasserproduktivity=' num2str(yield/water*10) ' kg/m³'])
disp(['größter Zwischenraum=' num2str(max_gap)])
disp(['wasserverbrauch=' num2str(water*10)])
disp(['ernte=' num2str(yield)])
disp(['fitness=' num2str(fitness)])
disp(['Scenario=' num2str(realization)])
disp(['---------------------------------------------------']);
end
```

A.7.2. The objective function, under fully irrigation with 6 dSm^{-1}

```
function [fitness isconstrained water yield]=wbirrreducemodel(x,realization)

isconstrained=false;

yield=calc_apsim(x,realization)/1000;%nun in t/ha

water=sum(x);

id_irr=find(not(x==0));
max_gap=0;
for ii=1:(length(id_irr)-1)
   (id_irr(ii+1)-id_irr(ii));
   if ((id_irr(ii+1)-id_irr(ii))>max_gap)
      max_gap=id_irr(ii+1)-id_irr(ii);
   end
end
message=['Ertrag ist ' num2str(yield) ' t/ha -- ' 'größter Zwischenraum ist: ' num2str(max_gap)];
disp(message);
%% Pennalty für long irrigation intervalls
% yield=yield-(max_gap)^2;
% disp(['Zielfunktionswert ist: ' num2str(yield)]);



if(yield<7.0)
   isconstrained=true;
   fitness=(7.0-yield).^2*100+1000;  %hefty penalty if we fail, the parameters for the penalty
function may have to be tuned to make everything more efficient and stable currently we risk to
get stuck in cases where the population is converged and suddenly a constraining scenario pops
up
else
   fitness=water+(max_gap)^2;
end
disp(['wasserproduktivity=' num2str(yield/water*10) ' kg/m³'])
disp(['größter Zwischenraum=' num2str(max_gap)])
disp(['wasserverbrauch=' num2str(water*10)])
disp(['ernte=' num2str(yield)])
disp(['fitness=' num2str(fitness)])
disp(['Scenario=' num2str(realization)])
disp(['-----------------------------------------------------']);
end
```

A.7.3. The objective function, under deficit irrigation with 1 dSm^{-1}

```
function [fitness isconstrained water yield]=wbirrreducemodel(x,realization)

isconstrained=false;

yield=calc_apsim(x,realization)/1000;%nun in t/ha

water=sum(x);

id_irr=find(not(x==0));
max_gap=0;
for ii=1:(length(id_irr)-1)
   (id_irr(ii+1)-id_irr(ii));
   if ((id_irr(ii+1)-id_irr(ii))>max_gap)
      max_gap=id_irr(ii+1)-id_irr(ii);
   end
end
message=['Ertrag ist ' num2str(yield) ' t/ha -- ' 'größter Zwischenraum ist: ' num2str(max_gap)];
disp(message);
%% Pennalty für long irrigation intervalls
% yield=yield-(max_gap)^2;
% disp(['Zielfunktionswert ist: ' num2str(yield)]);



if(yield<6.0)
   isconstrained=true;
   fitness=(6.0-yield).^2*100+1000;  %hefty penalty if we fail, the parameters for the penalty
function may have to be tuned to make everything more efficient and stable currently we risk to
get stuck in cases where the population is converged and suddenly a constraining scenario pops
up
else
   fitness=water+(max_gap)^1.5;
end
disp(['wasserproduktivity=' num2str(yield/water*10) ' kg/m³'])
disp(['größter Zwischenraum=' num2str(max_gap)])
disp(['wasserverbrauch=' num2str(water*10)])
disp(['ernte=' num2str(yield)])
disp(['fitness=' num2str(fitness)])
disp(['Scenario=' num2str(realization)])
disp(['----------------------------------------------------']);
end
```

A.8. Part of the iteration for calibrating the plant growth parameters

parameter	Initial (Apsim75-r3008\Model\ Maize.xml) was used as the original maize file[36]	Calibrated
rue (radiation-use efficiency)	<rue>00 1.68 1.68 1.68 1.68 1.68 1.47 1.365 1.365 0 0</rue>	<rue>0 0 2 2 2 2 2 1.75 1.625 1.625 0</rue>
Pioneer_3527 cultivar		
head_grain_no_max	750	770
grain_gth_rate units="mg/grain/day"	8.0	10
tt_emerg_to_endjuv units="oC"	240	200
t_flower_to_maturity	980	900
x_stem_wt units="g/stem" description="look up table for canopy height"	80	60
y_height units="mm" description="plant canopy height"	2000	2510

[36] (Apsim75-r3008\Model\ Maize.xml) is the APSIM-Maize documentation on the APSIM web site.

A.9. The irrigation rates during the second experiment (IrrEx2) in mm depth

irrigation rates	(CFIS) [W1]			100% [W2] of ETc			125% [W3] of ETc		
irrigation water quality	1 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	1 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	1 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}
29/11/2011	11.7	12.9	12.0	10.7	13.7	8.6	11.7	14.7	11.6
1/12/2011	3.3	3.7	1.9	3.2	3.7	1.9	3.5	3.6	2.0
2/12/2011	4.2	4.7	4.6	4.1	4.6	4.8	4.4	4.4	4.8
3/12/2011	2.2	2.2	2.2	2.6	2.6	2.6	3.3	3.3	3.3
4/12/2011	3.0	3.0	3.0	1.5	1.5	1.5	1.9	1.9	1.9
5/12/2011	4.0	4.0	4.0	1.5	1.5	1.5	1.9	1.9	1.9
7/12/2011	4.0	4.0	4.0	3.7	3.7	3.7	4.7	4.7	4.7
9/12/2011	4.0	4.0	4.0	4.9	4.9	4.9	6.1	6.1	6.1
11/12/2011	4.0	4.0	4.0	5.1	5.1	5.1	6.4	6.4	6.4
13/12/2011	4.0	4.0	4.0	5.1	5.1	5.1	6.4	6.4	6.4
15/12/2011	4.0	4.0	4.0	3.8	3.8	3.8	4.8	4.8	4.8
17/12/2011	4.0	4.0	4.0	4.5	4.5	4.5	5.6	5.6	5.6
19/12/2011	4.0	4.0	4.0	5.7	5.7	5.7	7.2	7.2	7.2
21/12/2011	4.0	4.0	4.0	5.7	5.7	5.7	7.2	7.2	7.2
23/12/2011	4.0	4.0	4.0	5.7	5.7	5.7	7.2	7.2	7.2
25/12/2011	4.0	4.0	4.0	5.7	5.7	5.7	7.2	7.2	7.2
27/12/2011				5.7	5.7	5.7	7.2	7.2	7.2
28/12/2011	4.0	4.0	4.0						
29/12/2011				4.5	4.5	4.5	5.6	5.6	5.6
31/12/2011				5.1	5.1	5.1	6.4	6.4	6.4
2/1/2012				6.4	6.4	6.4	8.0	8.0	8.0
4/1/2012	25.0	25.0	25.0	5.1	5.1	5.1	6.4	6.4	6.4
6/1/2012				5.1	5.1	5.1	6.4	6.4	6.4
8/1/2012				2.5	2.5	2.5	3.2	3.2	3.2
11/1/2012				8.9	8.9	8.9	11.2	11.2	11.2
13/1/2012	30.0	30.0	30.0	6.3	6.3	6.3	7.9	7.9	7.9
15/1/2012				6.3	6.3	6.3	7.9	7.9	7.9
18/1/2012				7.2	7.2	7.2	9.0	9.0	9.0
19/1/2012	40.0	40.0	40.0	8.1	8.1	8.1	10.1	10.1	10.1

22/1/2012				9.0	9.0	9.0	11.3	11.3	11.3
24/1/2012	15.0	15.0	15.0	10.8	10.8	10.8	13.5	13.5	13.5
27/1/2012				9.9	9.9	9.9	12.4	12.4	12.4
29/1/2012	15.0	15.0	15.0	7.2	7.2	7.2	9.0	9.0	9.0
31/1/2012				7.2	7.2	7.2	9.0	9.0	9.0
4/2/2012	40.0	40.0	40.0	11.5	11.5	11.5	14.3	14.3	14.3
6/2/2012				5.4	5.4	5.4	6.8	6.8	6.8
8/2/2012	15.0	15.0	15.0	6.8	6.8	6.8	8.4	8.4	8.4
11/2/2012				10.8	10.8	10.8	13.5	13.5	13.5
14/2/2012				8.8	8.8	8.8	11.0	11.0	11.0
16/2/2012	15.0	15.0	15.0	8.8	8.8	8.8	11.0	11.0	11.0
19/2/2012				7.4	7.4	7.4	9.3	9.3	9.3
21/2/2012	32.0	32.0	32.0	5.4	5.4	5.4	6.8	6.7	6.7
23/2/2012				7.4	7.4	7.4	9.3	9.3	9.3
25/2/2012				7.4	7.4	7.4	9.3	9.3	9.3
27/2/2012				5.4	5.4	5.4	6.7	6.7	6.7
29/2/2012				9.4	9.4	9.4	11.8	11.8	11.8
3/3/2012				8.8	8.8	8.8	11.0	11.0	11.0
5/3/2012				11.5	11.5	11.5	14.3	14.3	14.3
6/3/2012	30.0	30.0	30.0						
7/3/2012				7.4	7.4	7.4	9.3	9.3	9.3
9/3/2012				8.8	8.8	8.8	11.0	11.0	11.0
11/3/2012				5.4	5.4	5.4	6.7	6.7	6.7
13/3/2012	30.0	30.0	30.0	8.8	8.8	8.8	11.0	11.0	11.0
15/3/2012				10.1	10.1	10.1	12.7	12.7	12.7
17/3/2012				8.1	8.1	8.1	10.1	10.1	10.1
19/3/2012				8.8	8.8	8.8	11.0	11.0	11.0
21/3/2012				6.1	6.1	6.1	7.6	7.6	7.6
Total applied water (mm depth)	359.4	361.5	358.6	367.3	371.3	364.5	456.2	459.2	454.9
average		359.8			367.7			456.8	
%		97.9			100			124.2	
No. of irrigations	28	28	28	55	55	55	55	55	55

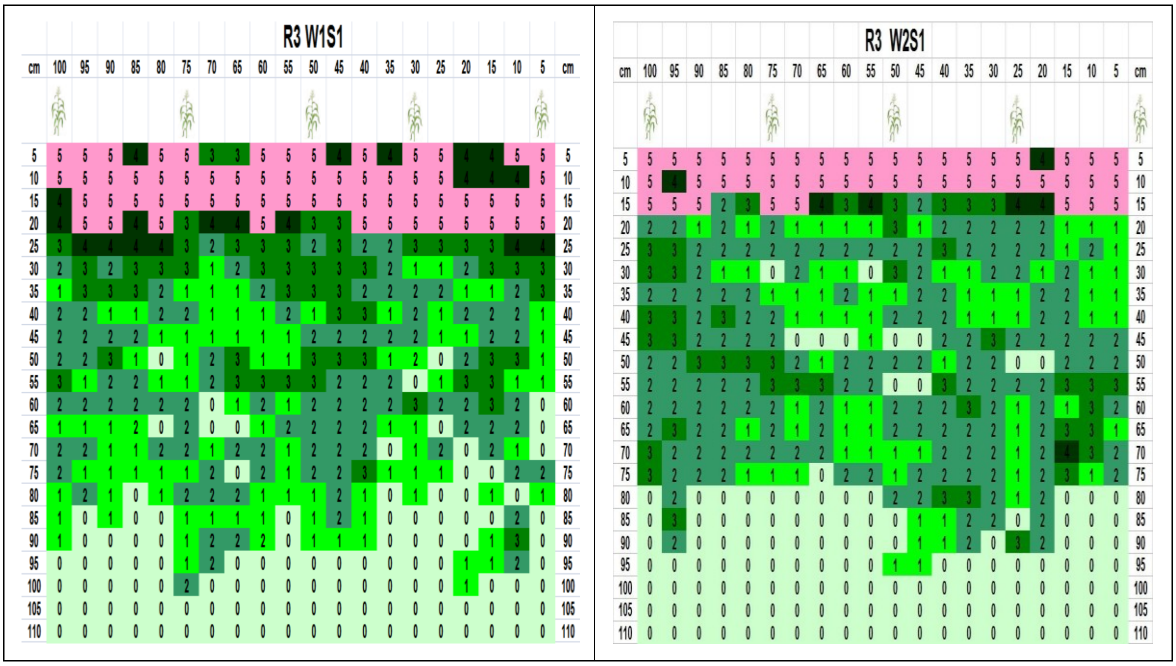
A.10. The irrigation rates for the simulation-based optimal schedules during the third experiment (IrrEx3) in mm depth.

T6 (NEMO,FIS,1 dSm^{-1})	
Date	mm
29/11/2012	3.2667
4/12/2012	3.0000
12/5/2012	3.4119
12/7/2012	7.6310
12/9/2012	4.6875
12/11/2012	4.2375
12/13/2012	8.2875
12/15/2012	3.8250
12/17/2012	5.4792
12/19/2012	3.8250
12/21/2012	6.3750
12/23/2012	5.7375
12/25/2012	3.8250
12/27/2012	3.8250
12/29/2012	7.6500
12/31/2012	5.7375
1/2/2013	5.1000
1/5/2013	6.3750
1/7/2013	5.1000
1/9/2013	5.7375
1/16/2013	19.0000
1/22/2013	27.5000
1/28/2013	23.7500
2/4/2013	24.7000
2/9/2013	12.5000
2/15/2013	20.0000
2/21/2013	20.0000
2/26/2013	20.0000
3/3/2013	20.0000
3/8/2013	30.0000
3/14/2013	40.0000

T1 (NEMO,FIS,6 dSm^{-1})	
Date	mm
29/11/2012	3.4810
4/12/2012	3.0000
12/5/2012	3.6310
12/7/2012	7.6310
12/9/2012	4.6875
12/11/2012	4.2375
12/13/2012	8.2875
12/15/2012	3.8250
12/17/2012	5.4863
12/19/2012	3.8250
12/21/2012	6.3750
12/23/2012	5.7375
12/25/2012	3.8250
12/27/2012	3.8250
12/29/2012	7.6500
12/31/2012	5.7375
1/2/2013	5.1000
1/5/2013	6.3750
1/7/2013	5.1000
1/9/2013	5.7375
1/15/2013	21.5000
1/20/2013	35.0000
1/25/2013	22.0000
1/29/2013	20.0000
2/4/2013	27.5000
2/10/2013	27.5000
2/15/2013	33.0000
2/20/2013	25.0000
2/26/2013	22.0000
3/3/2013	35.0000
3/8/2013	35.0000
3/14/2013	40.0000

T7 (NEMO,DIS,1 dSm^{-1})	
Date	mm
29/11/2012	3.3738
4/12/2012	3.0000
12/5/2012	3.2048
12/7/2012	7.6310
12/9/2012	4.6875
12/11/2012	4.2375
12/13/2012	8.2875
12/15/2012	3.8250
12/17/2012	5.4506
12/19/2012	3.8250
12/21/2012	6.3750
12/23/2012	5.7375
12/25/2012	3.8250
12/27/2012	3.8250
12/29/2012	7.6500
12/31/2012	5.7375
1/2/2013	6.3750
1/5/2013	9.2438
1/7/2013	6.3750
1/9/2013	7.1719
1/17/2013	15.0000
1/25/2013	26.0000
2/2/2013	27.5000
2/10/2013	27.5000
2/18/2013	27.5000
2/26/2013	27.5000
3/10/2013	27.5000
3/6/2013	20.0000
3/14/2013	16.0000

A.11. The root depth profiles from two different plots (W1S1 and W2S1) at the end of IrrEx2, classified by a qualitative information from 0 (no roots) to 5 (many roots)



0	1	2	3	4	5
No roots	Low roots	Little roots	Medium roots	High roots	Many roots

A.12. Harvest wet and dry matter weight for leaves, stem, cob and seeds for four selected plant in each plot within the experimental series 3 (IrrEx3).

Rep	Water Quantity Treatment	Water Quality Treatment (dS m^{-1})	Wet Weight				Dry Weight			
			Stem Weight (g)	Leaves Weight (g)	Cob Weight (g)	Grain Weight (g)	Stem Weight (g)	Leaves Weight (g)	Cob Weight (g)	Grain Weight (g)
R1	**T2**	**6**	145.15	53.42	31.71	193.73	33.22	41.75	19.5	149
			148.76	62.04	28.01	176.93	33.7	47.14	18.4	136.01
			116.87	56.9	41.74	214.66	31.56	41.08	25.5	168.8
			92.33	44.62	42.32	215.25	24.99	35.86	25.19	166.4
R1	**T3**	**6**	167.98	65.89	32.21	230.62	57.83	48.12	24.7	187.6
			145.37	69.56	23.94	200.58	36.4	49.83	19.4	162.9
			148.1	63.77	36.95	212.47	31.86	38.16	22.5	164.3
			134.22	58.62	36.18	209.93	31.91	42.24	20.4	163.2
R1	**T1**	**6**	87.98	39.88	26.2	177.32	22.54	34.05	15.6	135.3
			71.53	43.83	30.21	173.27	22.66	32.96	16	129.5
			106.73	55.53	33.31	192.5	27.62	39.56	21.49	147.52
			139.92	60.15	40.86	225.67	30.25	50.99	28.83	177.1
R1	**T8**	**1**	82.19	46.77	22.13	120.71	30.46	32.72	13.83	90.9
			94.02	65.6	20.36	90.3	30.29	44.3	11.09	60.39
			61.67	28.57	23.51	174.15	14.03	19.84	17.24	137.4
			75.01	42.16	19.31	106.74	20.24	32.43	11.16	76.97
R1	**T9**	**1**	135.11	59.26	23.66	140.92	39.76	45.68	14.6	107.1
			152.43	50.84	33.27	202.8	36.47	35.7	20.66	150.26
			165.52	62.6	36	226.09	39.08	43.9	21.7	178.5
			115.75	62.03	34.17	177.59	27.43	43.42	23.43	138.55
R1	**T5**	**1**	163.33	64.29	33.56	228.2	45.11	50.97	21.78	175.8
			89.83	43.5	26.71	165	25.68	33.33	13	119.64
			134.67	44.03	28.94	161.67	31.48	33.64	16.18	123.3
			150.29	55.34	40.14	225.58	36.16	42.62	21.63	174.24
R1	**T7**	**1**	121.75	50.39	27.37	196.64	29.28	37.4	19.6	163.8
			81.13	53.24	24.72	186.62	27.04	41.22	16.3	145.1
			106.76	45.09	25.53	187.03	26.54	35.43	17.63	148.81
			109.16	53.65	32.34	189.78	31.94	38.32	18.7	147
R1	**T6**	**1**	150.66	59.46	35.78	212	40.66	50.87	22.8	162
			98.23	55.12	27.59	150.71	25.18	45.64	16.1	114
			143.05	52.27	26.11	168.58	29.44	40.59	16.9	131.7
			149.26	51.33	29.92	187.7	38.98	43.03	18.12	148.13

R1	T4	1	139.09	62.03	38.19	223.54	31.96	49.87	24.5	182.7
			141.39	48.54	32.27	200.29	37.28	39.37	18.2	155.8
			115.89	49.19	30.99	194.27	32.19	41.49	17.6	147.8
			111.03	49.92	34.66	206.44	34.81	39.82	19.1	162.4
R2	T4	1	121.23	52.23	22.69	151.91	28.71	32.98	13.69	115.92
			124.13	49.23	25.26	161.32	32.19	40.31	15.89	124.86
			136.13	54.43	26.48	171.57	31.83	37.65	14.47	133.06
			188.33	70.43	34.37	214.1	42.51	54.73	21.5	170.3
R2	T7	1	169.13	55.03	36.4	172.7	39.41	41.98	18.1	125.6
			188.53	66.13	39.37	191.58	38.33	45.72	20.7	141.4
			190.43	81.43	44.47	231.36	40.96	52.25	21.35	168.48
			188.53	57.23	38.2	194	41.29	43.51	19.03	137.62
R2	T6	1	204.23	101.23	41.18	221.96	41.44	51.42	25.02	144.43
			184.63	61.53	34.17	192.82	34.79	43.16	16.9	143.8
			209.03	71.73	41.8	220.68	40.76	48.38	23.04	175.56
			202.33	68.63	36.48	187.02	44.83	45.36	17.9	138.1
R2	T5	1	93.13	49.93	22.24	135.04	19.76	30.81	12.53	91.48
			105.93	46.13	18.73	109.5	21.22	30.03	10.89	78.98
			216.73	94.63	31.12	159.28	57.84	49.56	21.65	123.84
			160.23	68.23	20.36	125.11	31.02	41.41	12.8	90.8
R2	T8	1	100.23	50.43	25.17	144.62	19.93	34.19	13.35	106.12
			157.73	70.83	34.11	166.09	37.4	39.2	16.4	112.3
			168.73	68.63	37.72	194.58	38.36	47.42	23.3	150.45
			166.83	85.23	38.61	201.56	38.37	45.43	19.3	149.4
R2	T9	1	125.53	48.23	30.15	137.72	23.54	29.71	14.73	95.71
			249.03	75.63	37.65	189.9	25.8	50.44	22.8	131.09
			230.43	70.93	37.36	193.22	47.56	49.81	22.1	148.4
			135.63	47.43	27.45	147.63	28.31	36.09	15.57	110.88
R2	T1	6	167.63	68.23	25.88	180.77	33.57	42.17	16.61	140.35
			175.43	78.23	32.05	208.64	37.34	48.11	20.91	166.01
			163.73	54.83	31.52	155.55	32.22	41.48	17.01	115.4
			209.03	69.63	31.14	175.83	43.96	45.2	17.59	134.11
R2	T2	6	151.23	70.73	30.24	195.28	34.01	47.48	21.12	155.59
			199.33	70.93	31.89	200.02	39.08	51.1	20.11	174.48
			168.93	63.23	36.5	212.31	35.61	32.52	18.4	155.6
			159.43	59.33	34.29	203.8	37.2	47.69	21.44	158.12
R2	T3	6	149.23	50.83	33.03	197.6	32.52	39.3	19.33	151.41
			162.23	61.43	42.9	228.99	34.02	44.21	20.23	158.43
			160.03	73.93	32.71	194.22	33.19	42.84	18.88	147.78
			137.93	57.63	31	163.28	30.92	38.04	15.65	121.34
R3	T3	6	152.77	91.38	35.7	228.96	34.11	49.08	19.5	173
			168.06	80.32	39.5	224.63	38.7	15.36	22.31	166.79

			141.33	97.28	40.5	233.34	27.55	54.11	21.3	174.6
			189.94	95.43	50.99	252.55	34.87	57.39	26.3	186.3
R3	**T1**	**6**	174.61	59.78	32.6	210.29	41.73	41.14	22.01	164.8
			145.48	64.89	28.75	177.89	23.13	39.03	17.61	139.07
			100.22	58.67	32.5	207.29	27.23	43.96	20.18	164.73
			135.71	57.53	28.65	170.23	29.43	45.63	15.73	130.65
R3	**T2**	**6**	214.71	74.2	42.46	241.55	39.08	56.46	26.1	187
			147.1	68.39	35.61	201.44	34.49	46.11	17.3	152.7
			200.06	100.92	41.77	221.76	43.53	60.78	24.32	173.37
			180.05	69.61	42.89	218.56	40.44	54.67	24.3	166.6
R3	**T9**	**1**	213.44	91.15	44.19	249.91	57.53	56.67	24.6	189.4
			161.77	89.68	40.89	238.73	23.4	51.97	22.6	183.8
			88.85	64.86	29.38	133.08	31.24	40.93	19.26	99.13
			190.11	77.98	49.19	231.68	38.42	53.93	28.66	182.6
R3	**T5**	**1**	105.85	40.45	26.6	154.81	24.48	31.23	14.45	115.16
			118.13	52.06	37.22	202.08	32.66	39.19	19.75	157.3
			140.21	76.34	35.56	213.55	36.99	47.68	23.26	169.44
			112.6	57.62	28.28	183.75	28.43	37.21	16.51	141.78
R3	**T8**	**1**	178.32	69.9	45.26	244.69	39.16	53.76	24.6	183.6
			124.51	74.22	38.51	214.41	31.97	47.44	20.8	172.1
			166.39	82.09	39	210.89	39.22	52.97	23.1	160.9
			169.27	67.86	39.53	208.1	38.4	42.69	22.52	151.61
R3	**T6**	**1**	194.09	108.72	41.92	269.78	37.98	60.02	24.6	202.2
			119.49	78.63	33.6	229.31	28.06	38.13	18.2	176.5
			161.95	91.83	28.5	174.59	37.83	51.89	15.1	131.6
			112.19	53.84	33.5	222.52	25.9	38.14	21.2	164.7
R3	**T4**	**1**	152.63	60.03	35.11	203.12	31.68	42.02	20.4	160
			164.71	91.2	35.08	212.23	34.98	48	19.16	162.71
			99.69	57.98	28.74	184.95	22.73	32.35	16.1	137.8
			165.23	58.31	40.73	210.79	36.73	44.83	24.7	168.4
R3	**T7**	**1**	129.83	68.18	50.03	197.21	26.82	41.17	25.3	143.1
			153.48	113.14	39	228.35	57.25	70.13	22.27	173.43
			278.8	130.08	57.61	290.06	57.25	70.13	34.61	217.61
			208.88	95.49	48.23	261.51	45.33	61.21	26.9	199.03