

Assessing Impacts of Decision-Making Theories on Agrohydrological Networks Using Agent-Based Modelling.

Orduña Alegria Maria Elena¹, Schütze Niels¹, Al Khatiri, Ayisha¹, Oleksandr Mialyk¹, and Grundmann Jens¹

¹Technische Universität Dresden

November 16, 2022

Abstract

Water scarcity, population growth and climate change dilemmas imperatively require adaption strategies for a more efficient and sustainable use of water resources. Agricultural systems are part of a wider network, where all social, economic and, ecologic parameters must be taken into consideration to assess the performance and resilience of said network. The importance of accounting the complexity of human decisions and their impact on the water cycle has been increasingly studied, nevertheless the integration and analysis of different decision making theories into hydrological models still remains a major challenge and uncertainty source. Therefore, the ongoing project is aimed to improve the understanding of social dynamics in agrohydrological networks by assessing different irrigation practices including rainfed agriculture and deficit irrigation within a hydro-economic network. We developed an agent-based model (ABM) of farmer decision making on crop water productivity and groundwater levels using two existing optimization models: (i) the Assessment, Prognosis, Planning and Management Tool (APPM) (Schmitz, et al. 2010) that integrates the complex interactions of the strongly nonlinear meteorological, hydrological and agricultural phenomena, considering the socio-economic aspects and (ii) the Deficit Irrigation Toolbox (DIT) (Schütze and Mialyk 2019) to maximize crop-water productivity by analyzing the crop yield response to climate change, soil variability, water management practices. The developed ABM was assessed with the different theories on human decision-making based on the Modelling Human Behavior (MoHuB) framework (Schlüter, et al. 2017). As a result of this study, a sensitivity analysis of how different behavioral theories affect the dynamics of social-ecological systems which enables the evaluation of the robustness of policy implementation to different assumptions of human behavior where cooperation is a mechanism to improve resilience. This research was funded by the Technische Universität Dresden, by means of the Excellence Initiative by the German Federal and State Governments.

Assessing Impacts of Decision-Making Theories on Agrohydrological Networks Using Agent-Based Modelling.

Assessing Impacts of Decision-Making Theories on Agrohydrological Networks Using Agent-Based Modelling.
 María Elena Orduña Alegría, Ayisha Al Khatri, Oleksandr Mialyk, Jens Grundmann, and Niels Schütze.
 Institute of Hydrology and Meteorology, Technische Universität Dresden

INTRODUCTION
 Problem Statement and Study Objective

Agricultural systems are part of a complex network, where social, economic, and environmental dynamics interact and co-evolve. These relationships need to be taken into consideration to find the required adaptation strategies to the prospective climate change, especially in the coastal agricultural areas due to the sea-level rise.

STUDY AREA
 Al Batinah coastal area in Oman

Al Batinah coastal area is located at the Sea of Oman. It represents about 25% of the area of the country and was formed by rivers descending from the Al Hajar Mountains. Most of the population concentration along the coast and depend on irrigated agricultural production.

METHODOLOGY
 Research Design

The IBM, named **SAR_0 (Sustainable Agrohydrological Innovation in Oman)** of farmer decision making on crop water productivity and groundwater levels was developed using two existing simulation models: the **SoilWat** (Schmitz, 2015) and the management module of the **Agwatershed**, **Agwatershed**, **Planning and Management Tool (APMT)** (Grundmann et al., 2015). The simulations were carried out for 5 different policy scenarios considering 5 different behavior theories from the **Decision-Making Framework (DMF)** (Schmitz et al., 2015).

RESULTS
 ABM of Agrohydrological Innovation and Sensitivity Analysis

The developed IBM, **Sustainable Agrohydrological Innovation in Oman (SAR_0)**, combined on the analysis of innovation implementation of sustainable agrohydrological adaptations. **SAR_0** was modeled using the **UrbSim** software (Döll) a modeling and simulation development environment for building spatially explicit agent-based simulations using a high-level and intuitive

CONCLUSIONS

"Innovation in groundwater utilization will add significant value to the economy and enable agriculture to be sustained in Al Batinah."
 (Oman Ministry of Agriculture and Fisheries, 2012)

There is an increasing recognition of the importance of including a broader understanding of human behavior into the study of social-environmental systems. The proposed framework is a modest step to facilitate this understanding and assessment.

The current study is a novel agrohydrological framework for exploring the effects of social, economic and environmental factors on the decision-making process of the farmers to adapt with crop water and water resources

Project Outline

- Problem Statement**: The water in agrohydrological networks is a complex problem especially in the coastal agricultural areas due to the sea-level rise.
- Study Area**: Al Batinah coastal area is located at the Sea of Oman, where the population mostly depend on irrigated agricultural production.
- Objective**: Assess the co-evolving of social, economic and environmental in sustainable agrohydrological adaptation in Oman.

María Elena Orduña Alegría, Ayisha Al Khatri, Oleksandr Mialyk, Jens Grundmann, and Niels Schütze.

Institute of Hydrology and Meteorology, Technische Universität Dresden



PRESENTED AT:

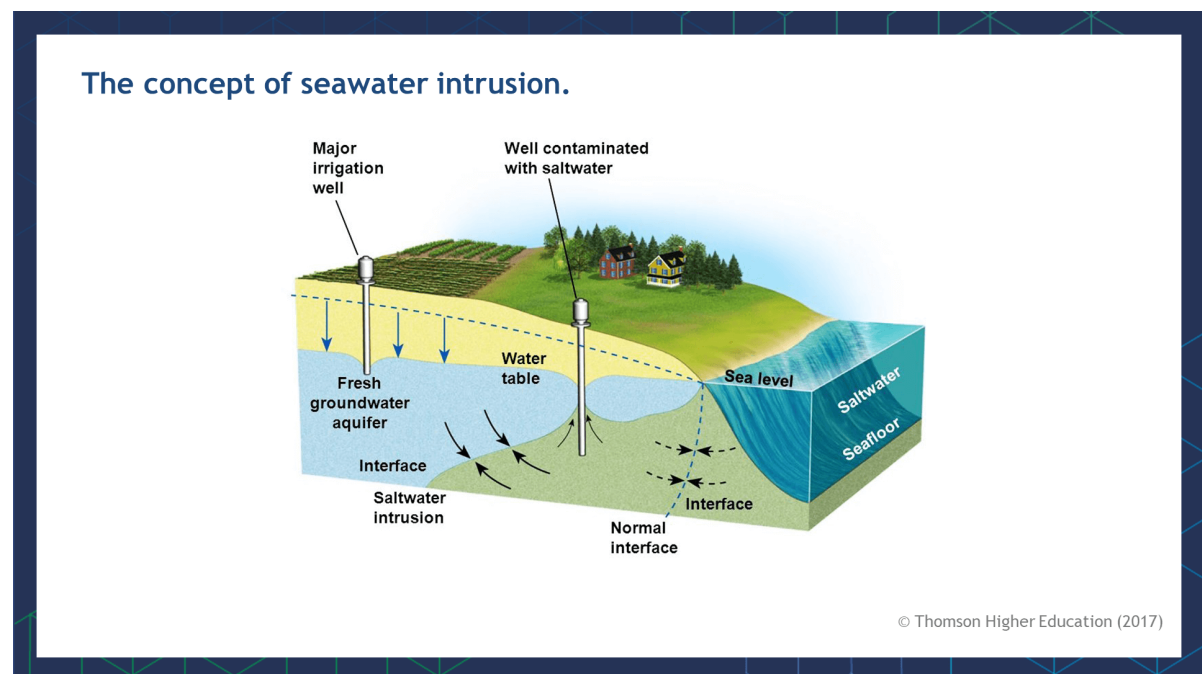
AGU 100
 ADVANCING EARTH AND SPACE SCIENCE

FALL MEETING
 San Francisco, CA | 9–13 December 2019

INTRODUCTION

PROBLEM STATEMENT AND STUDY OBJECTIVE

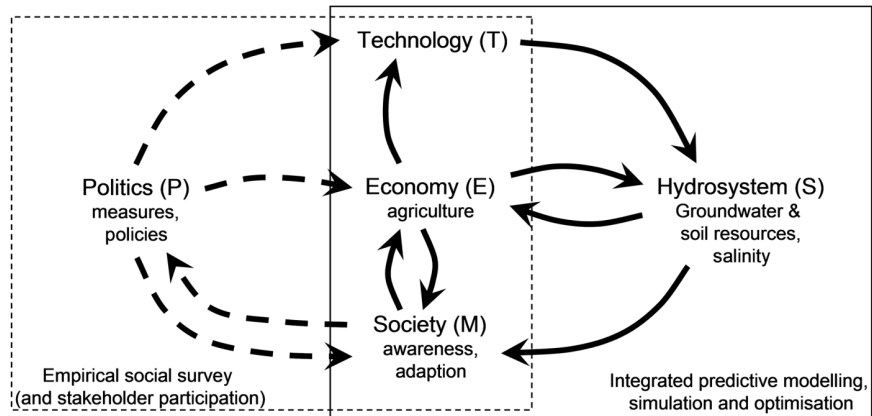
Agricultural systems are part of a complex network, where social, economic and, environmental dynamics interact and co-evolve. These relationships must be taken into consideration to find the required adaptation strategies to the prospective climate change, especially in the coastal agricultural areas due to the seawater intrusion.



In recent years, a variety of interdisciplinary approaches have been developed to unravel the complex interdependent dynamics of the socio-hydrological networks and help building strategies for water resources management.

While the importance of accounting for the complexity of human behavior has been increasingly recognized, its integration into formal models remains a major challenge.

System dynamics for managing saltwater intrusion in agricultural coastal plain.



© Grundmann et al. (2016)

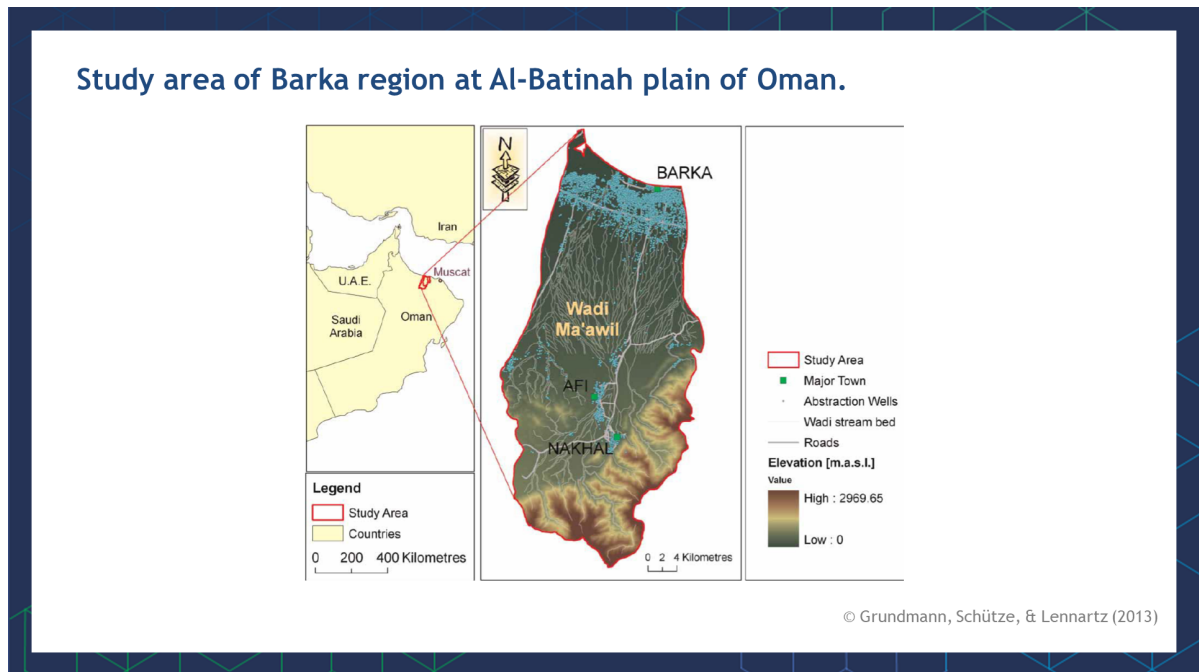
Objective

This ongoing project presents an innovative agrohydrological agent-based model (ABM) with the aim to assess the co-evolving of social, economic and environmental factor in sustainable agricultural adaptation in Oman.

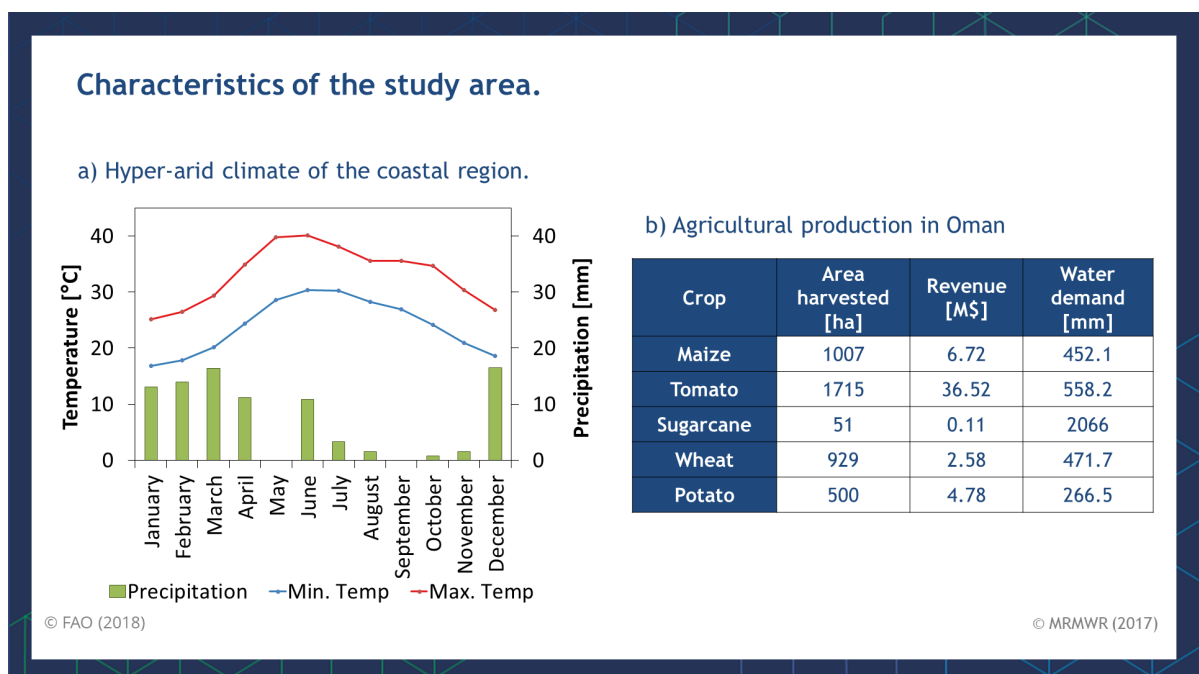
STUDY AREA

AL BATINAH COASTAL AREA IN OMAN

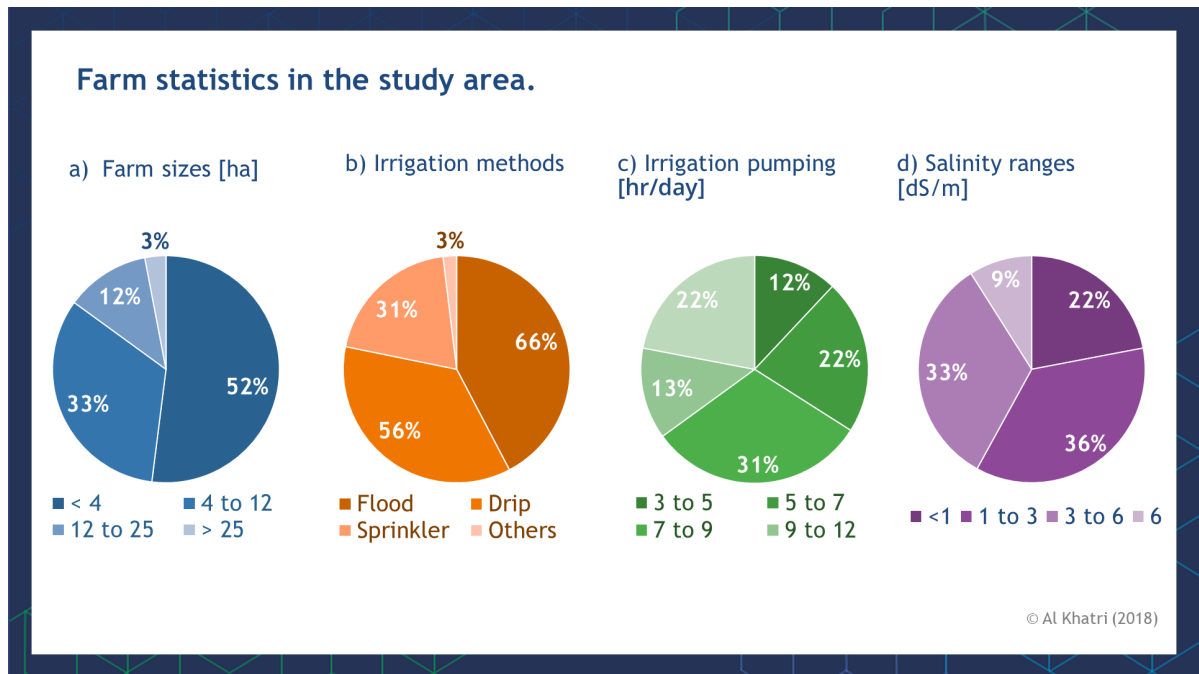
Al Batinah coastal area is located at the Sea of Oman. It represents about 3% of the area of the country and was formed by valleys descending from the Al Hajar Mountains. Most of the population concentrates along the coast and depend on irrigated agricultural production.



Al Batinah region is providing a variety of different crops by small-scaled farms owned by local farmers. 86% of the water use is consumed by agricultural sector.



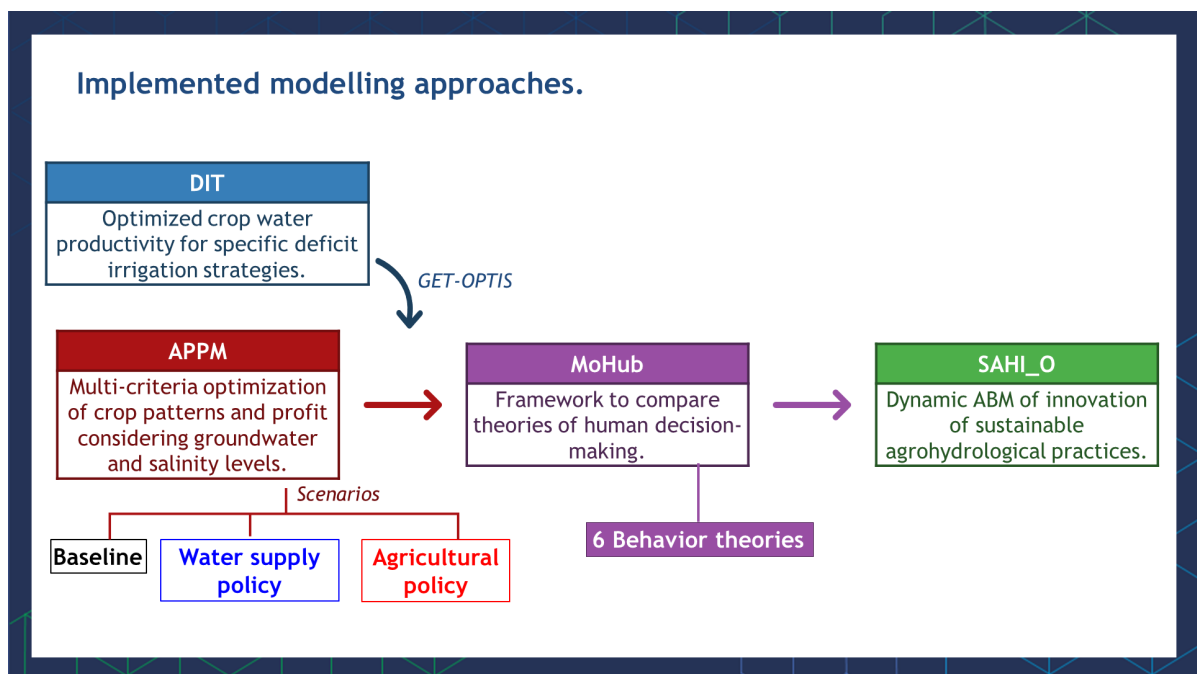
The imbalance between the abstraction rates, and recharge rates led to a dramatic decline in groundwater levels accompanied with saltwater intrusion into the coastal aquifer of the region.



METHODOLOGY

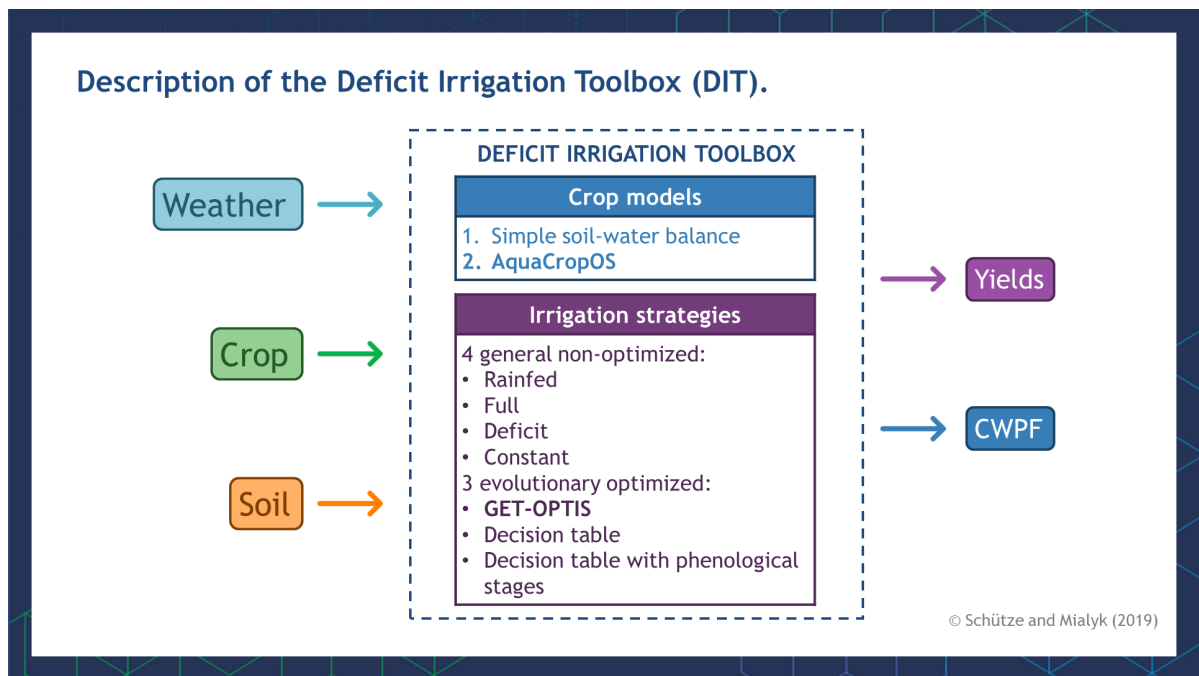
RESEARCH DESIGN

The ABM, named **SAHI_O (Sustainable Agrohydrological Innovation in Oman)** of farmer decision making on crop water productivity and groundwater levels was developed using two existing optimization models: The **Deficit Irrigation Toolbox (DIT)** (N. Schütze and O. Mialyk, 2019) and the management module of the **Assessment, Prognosis, Planning and Management Tool (APPM)** (J. Grundmann et al., 2011). The simulations were carried out for 3 different policy scenarios considering 6 different behavior theories from the **Modelling Human Behavior framework (MoHub)** (M. Schlüter et al., 2017).

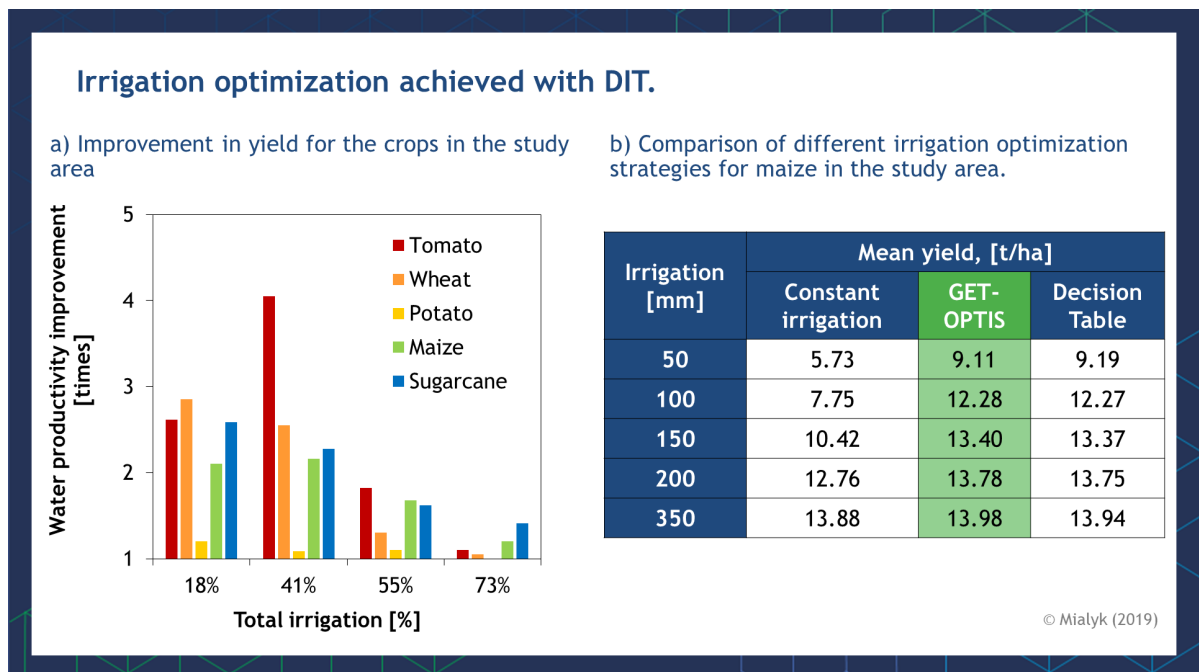


DIT

The **DIT** (link <https://tu-dresden.de/bu/umwelt/hydro/ihm/hydrologie/services/software/DIT>) allows complex analysis of crop yield response to climate change, soil variability, and water management practices. The DIT includes 9 irrigation strategies including rainfed, soil-moisture based, constant, and optimized open-loop and closed-loop irrigation scheduling strategies.

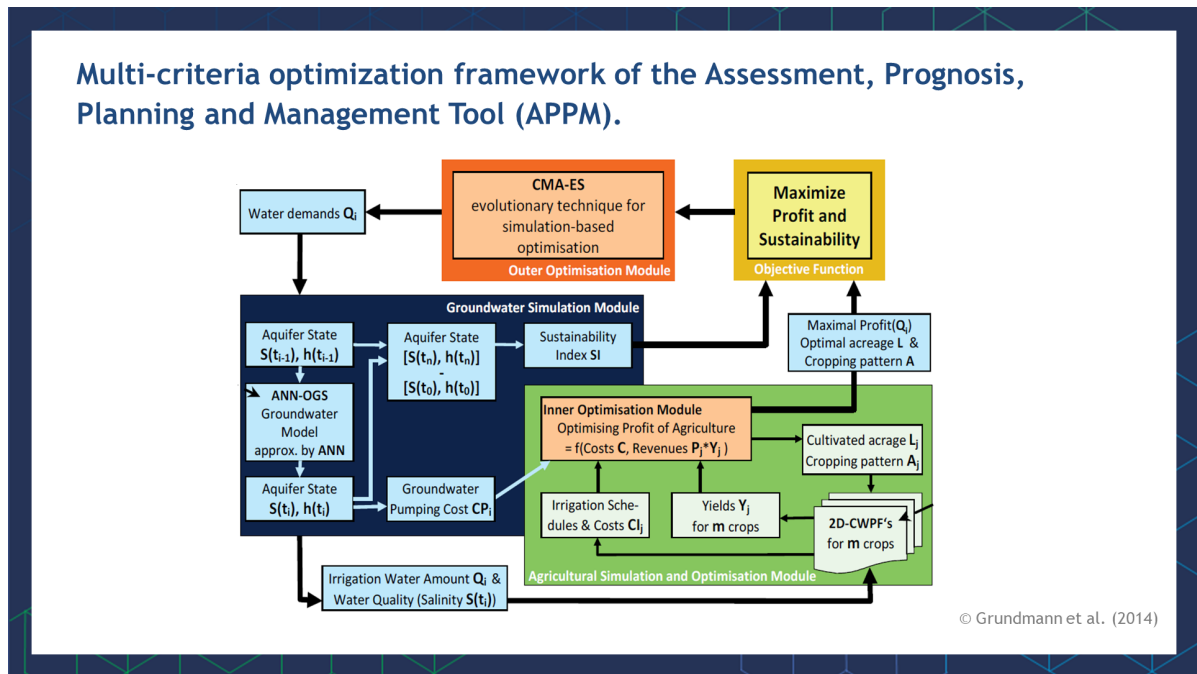


As a result, the DIT generates Crop-Water Production Functions (CWPf) which allows the assessment of water needs for the current production target and, estimates the potential crop production for fixed available water volumes.



The CWPf obtained with GET-OPTIS algorithm were selected for this study due to its lower computational demands and simplicity in real-life implementation.

The APPM integrates the complex interactions of the strongly nonlinear meteorological, hydrological and agricultural phenomena, considering the socio-economic aspects. Implementing the set of predefined crop-water production functions (CWFs) by DIT, the APPM calculates potential crop pattern and profits for specific objective function considering groundwater and salinity dynamics.



Three main agricultural management scenarios were analyzed:

1. **Baseline scenario:** There is a low irrigation efficiency of 60% and farmers' decision making only follows the market prices allowing monoculture production.
2. **Water supply policy scenario:** Investment in artificial recharge practices adds 10 million m^3 to the inflow. The government obliges farmers to decrease the total abstraction by 40 million m^3 . At the same time, new sources of water supply from desalinated and treated wastewater are introduced. Moreover, all irrigation systems are substituted by drip technology to reach 90% efficiency. Crop patterns is not controlled.
3. **Agricultural policy scenario:** The government puts limitations on crop production in order to move from monoculture to polyculture. There is a requirement to have at least 60% of the field area covered by maize, wheat, and sorghum proportionally

Abstraction rate, profit and groundwater productivity for each policy scenario.

Objective function	Scenario	Average groundwater abstraction [Mm ³ /year]	Average profit [M\$/year]	Groundwater Productivity [\$/m ³]
Sustainable (0.51)	Baseline	1.03	4.4	4.33
	Water policy	0.81	6.3	7.76
	Agricultural policy	0.84	3.2	3.82
Profitable (0.54)	Baseline	2.76	8.3	3
	Water policy	2.75	8.6	3.14
	Agricultural policy	2.78	4.4	1.58

© Mialyk (2019)

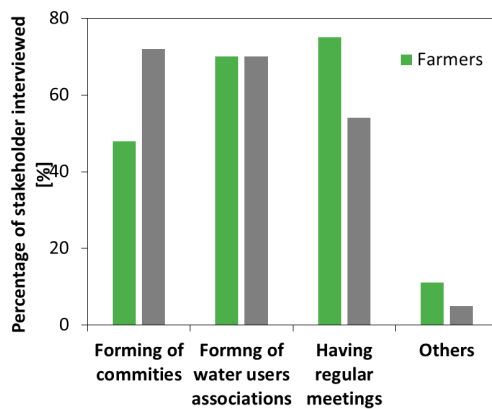
For each agricultural management scenario, two different groundwater management scenarios were selected based on the sustainability indexes (calculated from groundwater and salinity levels), a profitable one of 0.54 and sustainable one of 0.51.

MoHuB

The MoHuB framework facilitates the broader inclusion of knowledge on human decision making into formal models of social-environmental systems by providing and defining a set of concepts commonly found across social sciences.

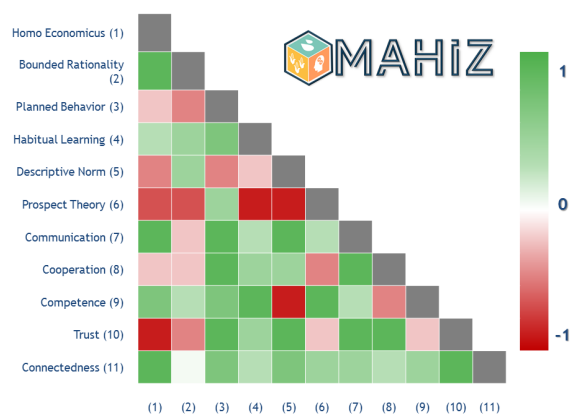
Source of social parameters selected for this study.

a) Cooperation options between farmers and managers in the study area



© Al Khatri (2018)

b) Correlation matrix of social parameters



© Orduña-Alegria (2019)

Based on previous studies and interviews with farmer on the study area and the recent study with the serious board game MAHIZ (link (<https://tu-dresden.de/bu/umwelt/hydro/ihm/hydrologie/services/serious-games/mahiz>)) the most important social parameters of each behavior theory were identified and analyzed.

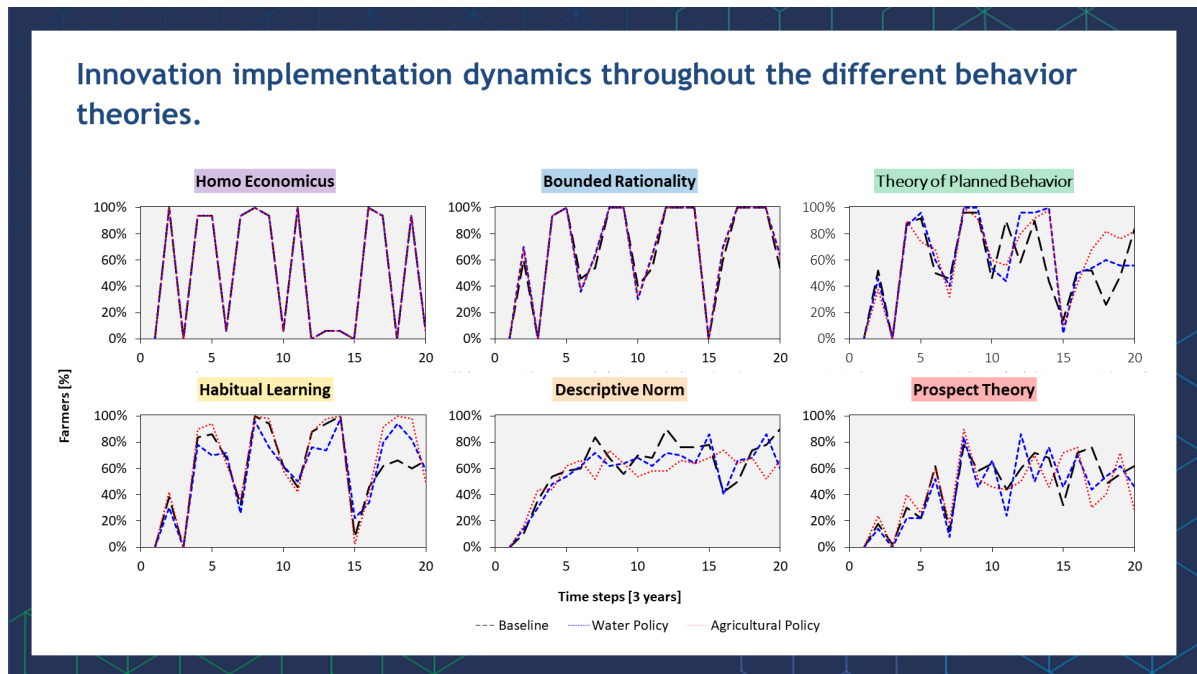
Description of behavior theories and chosen parameters.

Behavior Theory	Description	Parameters		
		Connectedness	Trust	Communication
Homo Economicus	Completely rational.	Perfect (very high)	None	Perfect
Bounded Rationality	Limited by available information and cognitive capacity.	High	Low and equal for all types of connection.	Very efficient
Theory of Planned Behavior	Mediated by intentions and perceived behavioural control.	Medium (realistic)	Variable dynamic values depending on the type of connection: <ul style="list-style-type: none"> • High for collective. • Medium for neighbors and friends. 	Ok
Habitual Learning	Behavioural learning that originates in the classical and operant conditioning theories.	Medium (realistic)	Variable static trust depending on the type of connection: <ul style="list-style-type: none"> • High for collective. • Medium for neighbors and friends. 	Efficient
Descriptive Norm	Influence of perceiving what other people do.	Medium (realistic)	Maximum, static and equal for all types of connection.	Perfect
Prospect Theory	Willingness to seek or avoid risk.	Low	Variable dynamic trust depending on the type of connection: <ul style="list-style-type: none"> • High for collective. • Medium for friends. • Low for neighbors. 	Low

[VIDEO] <https://www.youtube.com/embed/7QD6E5n75e0?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0>

The groundwater productivity generally increased in the water supply policy scenario when compared to the baseline situation. Moreover, the variability of annual profits significantly decreased which could provide more economic stability.

The groundwater productivity generally decreased in the agricultural policy because the monoculture production was not allowed. Consequently, highly priced crop was no longer a dominant crop.



The main effects in groundwater, salinity levels and profit were that once the parameters of each behavior theories are implemented, the levels calculated with traditional homogeneous models are over estimated. Once social parameters are introduced, the decision-making processes co-evolve, and the individuality of each agent is enhanced, leading to different impact of the policies.

[VIDEO] <https://www.youtube.com/embed/WGtZeo18tgE?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0>

CONCLUSIONS

”Reduction in groundwater utilization will add significant value to the economy and enable agriculture to be sustained in Al-Batinah.”

Omani Ministry of Agriculture and Fisheries, 2012

There is an increasing recognition of the importance of including a broader understanding of human behavior into the study of social-environmental systems. Our proposed framework is a modest step to facilitate this understanding and assessment.

The current study is a novel agro-hydrological framework for exploring the effects of social, economic and environmental factors on the decision-making process of the farmers in relation with crop choice and water conservation strategies.

The results of the proposed framework can enlighten important insights for the policymakers about the future sustainable agrohydrological trajectories in Oman. Applying a set of different decision models can help assess the robustness of a policy to behavioral uncertainty or explain a particular policy outcome when actors are not consider rational and selfish but make decisions according to other behavioral theories.

ABSTRACT

Water scarcity, population growth and climate change dilemmas imperatively require adaption strategies for a more efficient and sustainable use of water resources in agriculture. Agricultural systems are part of a wider network, where all social, economic and, ecologic parameters must be taken into consideration to assess the performance and resilience of said network.

The importance of accounting the complexity of human decisions and their impact on the water cycle has been increasingly studied, nevertheless the integration and analysis of different decision making theories into hydrological models still remains a major challenge and uncertainty source. Therefore, the ongoing project is aimed to improve the understanding of social dynamics in agrohydrological networks by assessing different irrigation practices including rainfed agriculture and deficit irrigation within a hydro-economic network.

We developed an agent-based model (ABM) of farmer decision making on crop water productivity and groundwater levels using two existing optimization models: (i) the Assessment, Prognosis, Planning and Management Tool (APPM) (Schmitz, et al. 2010) that integrates the complex interactions of the strongly nonlinear meteorological, hydrological and agricultural phenomena, considering the socio-economic aspects and (ii) the Deficit Irrigation Toolbox (DIT) (Schütze and Mialyk 2019) to maximize crop-water productivity by analyzing the crop yield response to climate change, soil variability, water management practices.

The developed ABM was assessed with the different theories on human decision-making based on the Modelling Human Behavior (MoHuB) framework (Schlüter, et al. 2017). As a result of this study, a sensitivity analysis of how different behavioral theories affect the dynamics of social-ecological systems which enables the evaluation of the robustness of policy implementation to different assumptions of human behavior where cooperation is a mechanism to improve resilience.

REFERENCES

- Grundmann, J., Al-Khatri, A., & Schütze, N. (2016). Managing Saltwater Intrusion in Coastal Arid Regions and its Societal Implications for Agriculture. In Proceedings of the International Association of Hydrological Sciences (Vol. 373, pp. 31-35). <http://doi.org/10.5194/piahs-373-31-2016>
- Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M. A., McAllister, R.R.J., Müller, B., Orach, K., Schwarz, N., Wijermans, N. (2017). A Framework for Mapping and Comparing Behavioral Theories in Models of Social-Ecological Systems. *Ecological Economics* (Volume 131, pp. 21-35). <https://doi.org/10.1016/j.ecolecon.2016.08.008>
- Grundmann, J., Schütze, N., Schmitz, G.-H., & Al-Shaqsi, S. (2011): Towards an Integrated Arid Zone Water Management Using Simulation Based Optimization. *Environ. Earth Sci.*, 65(5): 1381-1394
- Taillandier, P., Gaudou, B., Grignard, A., Huynh, Q.-N., Marilleau, N., P. Caillou, P., Philippon, D., & Drogoul, A. (2019). Building, composing and experimenting complex spatial models with the GAMA platform. *Geoinformatica*, (2019), 23 (2), pp. 299-322, [doi:10.1007/s10707-018-00339-6]
- Grundmann, J.; Schütze, N.; Lennartz, F. (2013): Sustainable management of a coupled groundwater-agriculture hydrosystem using multi-criteria simulation based optimisation. In *Water Science & Technology* 67 (3), p. 689. DOI: 10.2166/wst.2012.602.
- Schütze, Niels; Kloss, Sebastian; Lennartz, Franz; Al Bakri, A.; Schmitz, Gerd H. (2012): Optimal planning and operation of irrigation systems under water resource constraints in Oman considering climatic uncertainty. In *Environ Earth Sci* 65 (5), pp. 1511-1521. DOI: 10.1007/s12665-011-1135-4.
- Mialyk, O. (2018): Integrated scenario analysis for the sustainable management of coastal groundwater-agricultural systems. Master's thesis. TU Dresden.
- Al Khatri, A. (2018): Behavior Analysis and Modeling of Stakeholders in Integrated Water Resource Management with a Focus on Irrigated Agriculture: A Case Study for an Agricultural Coastal Region in Oman. PhD's thesis. TU Dresden.