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Optimization of land and resource use at farm-aggregated level in the Aral Sea Basin of Uzbekistan with the integrated model FLEOM – model description and first application

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List of Acronyms and Abbreviations

BMBF	Bundesministerium für Bildung und Forschung (= German Ministry of Education and Research)
CropSyst	Cropping System Simulation Model
DSS	Decision Support System
FAO	Food and Agricultural Organization of the United Nations
FLEOM	Farm-Level Economic-Ecological Optimization Model
GAMS	General Algebraic Modeling Software
MAWR	Ministry of Agriculture and Water Resources of Uzbekistan
OblStat	Regional Department of Statistics in Khorezm
OblSelVodKhoz	Regional Department of Agriculture and Water Resources in Khorezm
PM-WUA	Pakhlavan-Makhmud Water User Association
SANIIRI	Central Asian Scientific Irrigation Research Institute
UNESCO	United Nations Educational, Scientific and Cultural Organization
USD	United States Dollar
USDA	United States Division of Agriculture
WARMAP	Water Resources Management and Agricultural Production project
WUA	Water Users Association
ZEF	Zentrum für Entwicklungsforschung (Center for Development Research)

Optimization of land and resource use at farm-aggregated level in the Aral Sea Basin of Uzbekistan with the integrated model FLEOM – model description and first application

Abstract

Land use and crop production in the Khorezm region in western Uzbekistan, exemplarily for the irrigated low-lands of Central Asia, is adversely affected by the excessive, non-sustainable use of irrigation water on one hand, repeated droughts on the other hand, and by soil degradation by secondary salinization. One of the research objectives of the German-Uzbek Khorezm project, funded by the German Ministry for Education and Research (BMBF) and led by ZEF, is to better understand options for land use and choice of technology at the farm level in order to evaluate and propose technological alternatives and policy options for sustainable land use in Khorezm. To address the latter, the integrated so-called *Farm-Level Economic-Ecological Optimization Model* (FLEOM) was developed. FLEOM optimizes farm-level land and resource use while at the same time assessing the respective economic and environmental impacts. The model captures the basic features of the regional agriculture and the interrelations of production activities most prevalent to the local farmers. FLEOM builds on an economic farm-household linear-programming (LP) optimization routine and a comprehensive agronomic data base established with the cropping system simulation model, CropSyst. A graphical user-interface programmed in Java provides for easy usability, by which settings and results of FLEOM are visualized in tables and figures or as maps via a GIS-environment. The present discussion paper provides a technical introduction to FLEOM and discusses first application results.

Kurzfassung

Die Landnutzung und landwirtschaftliche Produktion in der Khorezm-Region im Westen von Usbekistan – beispielhaft für das bewässerte Tiefland von Zentralasien – leidet zum einen unter nicht nachhaltigen, übermäßiger Nutzung von Bewässerungswasser, zum anderen aber auch unter Dürreperioden, sowie unter Bodendegradation durch Bodenversalzung. Eines der Ziele des Deutsch-Usbekischen Khorezm Projekts, finanziert mit Mitteln des Bundesministeriums für Bildung und Forschung (BMBF) und unter Leitung des ZEF, ist es die verschiedenen Optionen von Landnutzung und der Wahl von Technologien auf Farmebene besser zu verstehen, um letztlich Vorschläge zu alternativen Technologien und agrarpolitischen Entscheidungsoptionen für nachhaltige Landwirtschaft in Khorezm machen zu können. Dazu wurde das sogenannte integrierte *Farm-Level Economic-Ecological Optimization Model* (FLEOM) entwickelt. FLEOM optimiert auf Farmebene Land- und Ressourcennutzung, wobei gleichzeitig die entsprechenden ökonomischen- und Umwelteinflüsse berücksichtigt werden. Das Modell berücksichtigt die spezifischen Grundzüge der zugrunde liegende regionalen Landwirtschaft sowie die Zusammenhänge der verschiedenen landwirtschaftlichen Produktionsaktivitäten. Dazu nutzt FLEOM eine ökonomische lineare Farmhaushalts-Optimierungsroutine (LP-Modell) und eine umfangreiche agronomische Datenbank. Letztere wurde mit dem Pflanzenwachstumsmodell CropSyst erstellt. Ein graphisches Nutzerinterface, programmiert in Java, erlaubt die einfache Nutzung von FLEOM, wobei Modelleinstellungen und Ergebnisse von FLEOM in Tabellen, Grafiken oder als Karten innerhalb einer eigens dafür programmierten GIS-Umgebung visualisiert werden. Das vorliegende Diskussionspapier gibt eine technische Einführung zu FLEOM und diskutiert Ergebnisse einer ersten Anwendung.

1 Introduction

In the last 50 years, the Aral Sea in Central Asia has shrunken to a quarter of its former size of 66,100 km^2. The once world's fourth largest inland lake with an estimated volume of previously around 1,100 km^3 has lost more than 80% of its former volume. Water salinity increased from 10 to above 70 g per liter. It is estimated that in the coming years the southern part of the Aral Sea will completely disappear, engendering a large-scale ecological catastrophe with severe impacts on human health and livelihood (cf. UNESCO, 2000, Roll et al., 2004 or Micklin, 2007 for details).

Desiccation of the Aral Sea is human-made. Since mid-20th century, large amounts of river water have been withdrawn from the main tributaries of the Aral Sea, the Amu Darya and Syr Darya. Agriculture is the main user of this water, as crop cultivation in this arid region fully relies on irrigation. As it is, the agricultural production is ecologically highly unsustainable. Khorezm, one of the twelve administrative regions of Uzbekistan located in the north-western part of the country, in the Aral Sea delta, with a total water intake of roughly 6-9 km^3 per year (Müller, 2006) is a major consumer of water.

One of the most important crops in Uzbekistan is cotton (*Gossypium hirsutum L.*). Uzbekistan, after the USA and India, is the world's third largest exporter of cotton lint. In the last three years, annually between 0.97 and 1.05 million metric tons of cotton lint, i.e. ~80% of the national total, were exported (USDA, 2008). About 8% of the cotton in Uzbekistan is produced in Khorezm. Countrywide per hectare raw-cotton production in 2005 was estimated to 2.7 Mg (FAOSTAT, 2006). This was a higher productivity than the world average (1.9 Mg ha^{-1}) but less than achieved under similar climatic conditions in Australia (4.2 Mg ha^{-1}).

In view of the moderate yields, irrigation water use is high. Official recommendations by the Central Asian Scientific Irrigation Research Institute (SANIIRI) range between 500-800 mm. However, recent studies showed that more than 1,200 mm, sometimes up to 1,700 mm, of water are applied for cotton production (Conrad, 2006). Additionally, on average 430 mm of water are used for pre-season salt leaching on 85% of the irrigated land in Khorezm (Djanibekov, 2008a). At the same time, seepage loss of water in irrigation channels is notoriously high, as since decades the infrastructure is operated without modernization (Abdullaev, 2003). Hence, FAO (1997) estimated that about 37% of the diverted river water for irrigation was lost before it reached the fields. Not always are large amounts of water available. Khorezm repeatedly experienced shortages of water, the most recent events in response to the droughts in 2000-2001 and 2007-2008. In 2001 water availability was less than 25% of that of normal years (Müller, 2006). In the course of global climate change the frequency of such droughts is estimated to increase.

Furthermore, despite heavy leaching, salinization of soils is a major problem. About 94 % of the irrigated areas in Khorezm are saline (Shirokova, unpublished). Secondary soil salinization by capillary rise of shallow groundwater (and salt) into the rooting zone plays a major role, which nullifies the pre-season salt leaching efforts and, by increasing the demand for leaching water, creates a vicious circle.

In a nutshell, Khorezm – exemplarily for the irrigated low-lands of Central Asia – faces two major problems: (i) the excessive, unsustainable use of irrigation water and at the same time (ii) soil degradation by salinization.

However, it is naïve and unrealistic to call for an end of irrigation agriculture in the Aral Sea basin. In the year 2000, 41.5 million people lived in this region with almost 8 million ha of land under irrigation (Roll et al., 2004). Agriculture is the predominating source of income for the rural population. In 2001, agriculture contributed 31 % to the gross domestic product of Uzbekistan (Müller, 2006).

The only way out of the dilemma lies in an economic-ecological restructuring of land and water use in the region; the ultimate aim of the German-Uzbek Khorezm project initiated in 2001, funded by the German Ministry for Education and Research (BMBF), supported by UNESCO, and led by ZEF (Vlek et al., 2003; ZEF, 2003, Martius et al., 2009). The ZEF-Khorezm project is based on long-term commitment and partnership and comprises a range of activities, engaging economists, social, political and natural scientists. The project is based on an interdisciplinary approach. This endeavor is backed up by computer simulations and optimization studies of economic and ecological processes, such as regional or farm economy and regional hydrology or field-level agronomy/crop growth. One of the research objectives of the ZEF-Khorezm Project is to better understand the options of land use decisions and choice of technology at the farm level in order to evaluate technological alternatives and policy options for sustainable land use in Khorezm.

To address the latter, the so-called integrated Farm-Level Economic-Ecological Optimization Model (FLEOM), a site-specific integrated model was developed. FLEOM optimizes farm-level land and resource use while at the same time assessing the respective economic and environmental impacts. The model captures the basic features of the regional agriculture and the interrelations of production activities most prevalent to the local farmers. It allows for various changes in the fixed production factors and input-output relationships and features regionally specified input-output parameters and restrictions on resource availability in order to capture comparative advantages between cropping activities. FLEOM aggregates and integrates field-level management decisions on the allocation of water, resources and labor under a given set of production constraints and displays the respective ecological and economic consequences in a spatially explicit way. The operationally manageable (computable) size of a target area for FLEOM currently lies in the range of a Water User Association (WUA) of around one thousand hectares.

FLEOM draws on a range of biophysical studies carried out in the ZEF-Khorezm project. These studies contributed to developing a comprehensive system-understanding that underlies FLEOM. Furthermore, FLEOM builds on an economic farm-household linear-programming (LP) optimization routine programmed in the General Algebraic Modeling Software, GAMS v.

21.1. The optimization routine is the basic core of FLEOM. As it is, FLEOM is a static model. However, FLEOM is not a mere script written in GAMS, but a stand-alone software programmed in Java. User-friendliness and easy usability were important aspects when building FLEOM. The optimization component is connected to a comprehensive agronomic data base. The data base was established with the cropping system simulation model, CropSyst (Stockle et al., 2003), using data sets, field experience and knowledge of a range of agronomic and hydrological studies. Settings and results of FLEOM are visualized in tables and figures or via a GIS-environment.

FLEOM does not dynamically address the interactions of a "human-landscape system", as well as the complex nature of autonomous human drivers and the involved sociological feedback mechanisms. In other words, FLEOM does not, or only indirectly, explain why things are like they are, but it is rather a tool for scenario analyses (what-if) and for showing possibilities, potentials and constraints for alternative land-management.

Potential users of FLEOM are medium-level stakeholders such as WUA representatives, and the local water authority. Besides, FLEOM is intended to be a tool for scientists and it may have an important role in University education.

The present discussion paper provides a technical introduction to FLEOM (chapters 2-4) and discusses first application results (chapter 5). Strengths and weaknesses of FLEOM are provided in a comprehensive from in the Appendix.

2 Background and rationale

Many process based models have been developed by natural scientists to model processes such as crop growth under different irrigation and fertilization practices in order to provide biophysical-response data for more comprehensive farm-level models (Ellis et al., 1991). Their outputs were applied in numerous LP models for farm planning to integrate bio-physical and economic circumstances at field and farm levels (e.g. Hochman and Zilberman, 1978; Just and Antle, 1990; Goddard et al., 1996; Fleming and Adams, 1997; Antle et al., 2000; Brown, 2000; Antle and Capalbo, 2001; Antle and Stoorvogel, 2001; Mathur, 2003; Stoorvogel et al., 2004, La Rovere et al., 2005). Such farm models can describe the physical, technical, biological and managerial aspects of cropping systems and compare farm performance and agroecological indicators by means of scenario analysis in order to make proposals on how to promote new technologies and resource management in farming systems. Geo-referenced inputs can be used for GIS visualization to relate cropping pattern of different sizes and area, dynamics of soil fertility and economic indicators.

The main feature of such a modeling approach is that, by imposing assumptions over a mixture of historically observed and synthetic data, it gives representation for a single producer in a multi-output and multi-input framework that is consistent with economic theory (McCarl and Spreen, 1980). For several reasons, this approach is the most appropriate for modeling the agricultural production systems in Khorezm. First, the optimization model incorporates relationships between different production variables and regional cross-effects (Apland et al., 1994). Second, it can be applied as a quantitative tool for assessing the effects of new technology and policy options, especially the potential effects of previously unprecedented ones (Norton and Solis 1983, McCarl and Spreen, 1980, McCarl and Spreen, 1997). For instance, the effect of water pricing can be evaluated exogenously by increasing the variable costs for crop production per unit of irrigation water required in the model. Another example would be the liberalization of cotton and input markets that can be examined by removing the minimum production level constraints for cotton and using new raw-cotton and input prices. A new production technology can be defined as a new input or output level of a production activity such as a new crop variety, changes in crop yields or current production practices (Anderson and Hardaker, 1979). Third, this approach seems most suitable given constraints such as limited data availability and lack of historical observations as well as the poor knowledge about the rules according to which individual producers and consumers behave and interact (that would be required for agent-based models). Forth, providing a framework to systematize and categorize available information, it allows for a detailed description of the dependencies of production variables on exogenous changes in the regional agriculture and more detailed analysis of problems with spatially competing dimensions (Hazell and Norton, 1986). As Valdivia (2002) and Antle et al. (2005) showed, the farm model based on micro-level scale can properly incorporate the complex information on interactions among site-specific biophysical and economic conditions. In addition to determining the optimal levels of farm activities, the farm LP model provides important information such as shadow costs of activities, shadow prices of constraints, and input use levels which can be valuable for researchers and policy makers (Pannell, 1997). Dent et al. (1986) and Pannell (1997) provide extensive discussions on the interpretation and use of this extra information derived through the solution of LP models.

A weakness of a farm LP model is that it does not explicitly capture the interaction between the agents (if these are known, see above), and it does not fully take into account the spatial dimension of agricultural activities. Nevertheless, requiring many simplifying assumptions, optimization models can be used to quickly screen many alternatives. The limitations of the farm LP model include the relative complexity and the amount of the information required for proper representation of biological and economic situation in farm. Other limitations are related to the basic assumptions of LP such as divisibility of inputs and outputs, the relationship between variables, and the additivity of the combined effect of inputs and outputs (Pannell 1997). Most limitations raised by these assumptions can largely be overcome through various modeling techniques (Pannell, 1997).

Box 1: Integrated land and water resources modeling – Definitions and classification

Definitions are tricky in that just the simple act of defining something reduces and limits its essence. (Rizzoli et al., 2007)

It is unclear when the term 'integrated modeling' was first introduced, but it might well be a result of the public and scientific debate starting in the 1980s on the limited contribution of mono-disciplinary approaches to a sustainable management of land and water resources, and the plea for an integrated resource management.

Neelamkavil (1987) defines models as *"a simplified representation of a system (or process or theory) intended to enhance our ability to understand, predict, and possibly control the behavior of the system"*. The term 'integrated' modeling (of e.g. land and water resources) points towards a multi-disciplinary approach, which by the very nature of the issue involves economists and social, political and natural scientists. Not surprisingly, (environmental) decision support systems, (E)DSS, go hand in hand with environmental modeling environments or frameworks, i.e. are realized in such. Clearly, however, this is not a necessary automatism, as a DSS can be anything from hand-drawn maps or informal discussions to full-fledged modeling frameworks as outlined in the following (see Power, 2007, for a history of DSSs).

The terms 'modeling framework' and 'model environment' are often confounded. Argent and Houghton (2001) clarify that a model environment contains *"all the tools and components that support execution of a program or system function"* and that a framework is *"similar to an environment, but with additional features that support functions external to program execution. A framework may contain a number of environments such as a model development environment, a data editing environment and a model selection environment"*. Well-known tools (or systems) like DSSAT (Decision Support System for Agrotechnology Transfer; Jones et al., 2003), APSIM (Agricultural Production Systems Simulator; Keating et al., 2003), CropSyst (Stockle et al., 2003), but also GAMS (http://www.gams.com) and FLEOM are thus in a strict sense frameworks. In this case, the term framework is used as a synonym for a bundled set of ready-available simulation models or algebraic tools (e.g. solver) as well as editing and visualization environments.

Besides, the term 'model framework' (and if appropriate also 'model environment') is used to describe abstract, theoretical building tools, *"which allow for the composition of models across [research] domains and scales"* (Rizzoli et al., 2004). Here, neither models nor scales are fixed. If tailored to tackle environmental problems, these frameworks are abbreviated to EIMF, which stands for Environmental Integrated Modeling Frameworks (see Argent, 2004 and Denzer, 2005 for a theoretical overview). Modeling building frameworks first appeared in the field of management science at the end of 1980s (Dolk and Geoffrion, 1987; Kottemann 1993). Countless model (building) frameworks have been established since then, such as the Modular Modeling System (MMS; Leavesley et al., 1996), the Spatial Modeling Environment (SME; Maxwell, 1999), the Open Modelling Engine (OME; Reed et al., 1999), ModCom (Hillyer et al., 2003), Simile (Muetzelfeldt and Massheder, 2003), JDEVS (Filippi and Bisgambiglia, 2004), SEAMFRAME (Rizzoli et al., 2005), LIS (Kumar et al., 2006), or a framework for water resource allocation and management (Letcher et al., 2007), to mention a few (see http://www.idsia.ch/~andrea/simtools.html for more). Unfortunately, EIMFs have never been categorized or made transparent in a way to overcome the *"veritable zoo of solutions"* (Argent and Houghton, 2001). Thus, *"from the point of view of the engineering-trained modeller, these solutions present a confusing array of alternatives that require considerable exploration and testing before appropriate approaches or combinations of options become apparent"* (Argent and Houghton, 2001). Rizzoli et al., (2007) in this regard state: *"A frequently asked question is: "why do we need yet another modelling framework"? The reasons why … software environments are not up to the task of deploying effective and usable EDSSs are often unclear, and there is always the option of re-using an existing EIMF. Yet, this option is often disregarded, again without clear reasoning behind it."*

Box 2: History, success and failure of integrated modeling

While mono-disciplinary modeling of land and/or water resource use had started already in the 60s of the last century, integrated modeling was undertaken only later, notably in the 1990s.

Van Ittersum et al. (2003) provide a comprehensive overview of model activities in The Netherlands. Starting with the pioneer work on model development of the de-Wit-group – earliest publications can be traced back to 1965 (de Wit, 1965), a number of biophysical simulation tools were developed in the following. See Bouman et al. (1996) for a graphical display of the history of the so called "School of de Wit" models. The most well-known model is probably SUCROS (Van Keulen, et al., 1982; van Laar et al., 1997). Approaches or sourcecode of SUCROS were inherited to almost all major recent crop models such as APSIM (Keating et al., 2003) or DSSAT (Jones et al., 2003). SUCROS is also the basis of the more recent models developed in Wageningen, such as WOFOST (Van Keulen and Wolf, 1986; Boogaard et al., 1998), MACROS (Penning de Vries et al., 1989), and ORYZA (Bouman et al., 2001).

First integrative studies comprised the (loose) coupling of two or more biophysical models (e.g. a crop and a pest model; Rabbinge and Bastiaans, 1989). While these were point-scale approaches, later-on, during the "operationalization" period of models (Bouman et al., 1996), a spatial integration on higher level was pursued. (Point scale) biophysical models were used to describe and quantify a range of land use systems which were then aggregated-to / optimized-for the farm or regional scale, among others using linear programming, cost-benefit and trade-of-analyses. Ten Berge et al. (2000) describe the outcome of such a study, in this case on designing environmentally friendly systems for arable farming in the Netherlands. Analogous earlier studies were carried out by Van de Ven (1996; Dutch dairy farming) and Rossing et al. (1997; Dutch flower bulb production).

Integrated modeling was the backbone of the research program “Sustainable Land Use and Food Security in the Tropics” (abbreviated to DLV in Dutch) established by the Dutch Agricultural Research Department and a number of departments of Wageningen Agricultural University. Van Keulen et al. (1998) explained the theoretical background of DLV’s approach to policy support:

> *“The immediate reason to establish the programme was the need felt for scientific support for rural development programmes in tropical low-income countries to explore options for sustainable land use and to analyse the effects of agronomic technological innovations and policy measures on land use, food security, income, employment and objectives pursued by the different stakeholders in the development process”.*

To enable the integration of agroecological and socio-economic information, four modules were integrated by the DLV scientists (Ruben et al., 1998):

> *“1. Agroecological simulation models for agricultural activities that offer a wide range of technological (input-output) coefficients for current and potential activities…; 2. farm-household modeling that specifies the underlying behavioural relations regarding farm household resource allocations and consumption priorities…; 3. linear programming optimization procedures as a method for the appraisal of farm household response to policy instruments; and 4. aggregation procedures to address the effectiveness of policy instruments for sustainable land use and farmers’ welfare at regional level.”*

The "Quantitative Land Use Analysis in Costa Rica" starting in the late 1980s was part of this portfolio led by Wageningen scientists in collaboration with scientists from Costa Rica. Disciplinary studies were integrated in an attempt to formulate policy and management options for sustainable land use at farm and regional level (see the special issue of the Netherlands Journal of Agriculture Science, vol. 43, 1995, for full details).

Box 2: cont'd

As one result, USTED, consisting of an LP model, a GIS tool and a crop growth modeling routine, was developed for the analysis of different scenarios on the effect of changes in the socio-economic and/or biophysical environment on agricultural land use (Stoorvogel et al., 1995). Chapter 3 will show that this work in some ways inspired the theoretical setup of FLEOM.

Likewise in Wageningen, also research groups in the USA and Australia have an impressive record of land use modeling activities.

DSSAT, the Decision Support System for Agrotechnology Transfer is an integrative simulation framework developed in the USA (Jones et al., 2003). It consists of a range of crop simulation models, such as CERES for wheat, maize, sorghum and rice (Ritchie et al., 1985; Jones and Kiniry, 1986; Alargarswamy et al., 1991, Alociljha and Ritchie, 1991), SOYGRO for soybean (Wilkerson et al., 1983) PNUTGRO for peanut (Boote et al., 1986) and SUBSTOR for Potato (Ritchie et al., 1995), to mention a few. DSSAT has been integrated together with a livestock and household model into IMPACT and applied to smallholder farming systems studies in Africa (Thournton and Herrero, 2001; Galvin, et al., 2006; Herrero et al., 2007). Cabrera et al., 2006, describe the integrated, 'Dynamic North Florida Dairy Farm Model' (DyNoFlo), which also builds on DSSAT for crop simulations.

APSIM, the Agricultural Production Systems Simulator (Keating et al., 2003), might be considered the Australian complement to DSSAT, yet with a shorter history. Its development started in 1991 together with the formation of the Agricultural Production Systems Research Unit (APSRU). As was the case for DSSAT, APSIM developers were engaged in biophysical modeling before that time and tools like AUSIM (McCown and Williams,1989), PERFECT (Littleboy, 1992) or a cotton model (later-on called OZCOT; Hearn, 1994) had been built. APSIM development draws on this and other available knowledge of biophysical modeling, with many bits and pieces borrowed from CERES/DSSAT, EPIC, and CENTURY (Parton et al., 1994). Keating et al. (2003) emphasize that APSIM was developed to address "*important systems' aspects of cropping*". However, reality falls a bit short of expectations, as obviously system's aspects of cropping were considered to comprise only biophysical issues. Comprehensive socio-economic sub-routines (or optimization) are not part of APSIM. This holds also true for DSSAT. Thus, as compared to the Wageningen efforts to integrate also full-fledged socio-economic models into the different land use modeling frameworks, the DSSAT and APSIM framework lack those components; a rather common shortcoming of environmental modeling frameworks developed in the 1990s (Reed et al., 1999). In this regard, it seems to be a widespread work-around to carry out socio-economic analyses without the aid of a computer (program), sort of "on the fly" while using integrated, biophysical models during stakeholder meetings/workshops. APSIM for instance was used for farm decision support in Australia within the so-called FARMSCAPE program (Carberrry et al., 2002) and by APSRU and CIMMYT scientists in the so-called Risk Management Project in Zimbabwe and Malawi (Shamudzarira and Robertson, 2000; Shamudzarira et al., 2000, Robertson et al., 2000). Both studies had been carried out in a strongly participatory manner in close interaction with farmers, and it seems unlikely that (farm-household) socio-economy was not an issue of debate.

There are a number of further examples for integrated modeling for decision support in literature. Oxley et al., (2004) describe the MODULUS project. The project aimed at integrating scientific and local experience, which had been applied in ten mono-disciplinary models, into an interactive decision-support system addressing physical, economic and social aspects of land degradation in the Mediterranean. The commercially available spatial model building environment GEONAMICA (http://www.riks.nl/products/GEONAMICA) was used for this task. In their conceptional setup, MODULUS scientists distinguished between research and policy models, depending on whether they originated in the problem-driven empirical or theoretical domain (-> research model), or in the value-driven perceptual domain (-> policy model). Oxley et al. (2004) argue that "*the starting point for development, whether research or policy, will have a significant bearing on the criteria used to develop, evaluate, use and interpret a model*".

Box 2: cont'd

Their starting point was research, and "*the task for MODULUS was to transform a selection of disparate research models - through integration, adaptation or rebuilding – into an integrated policy model accessible to the policy-making community.*" This is similar to the starting point for FLEOM, i.e. integrating existing knowledge and simulation tools into a user-friendly model, though as compared to MODULUS, FLEOM appears modest. In an upfront way, Oxley et al. (2004) describe a range of (technical) problems encountered during model development, such as the integration of models that run at different time steps, as well as the quite time consuming testing phase. In their chapter 'Policy makers and end-users' an overview of lessons learned is given. The importance of early stakeholder involvement/participation and transparent communication is stressed. Over-simplification of complex problems by scientists, differences in problem-perception and knowledge management/translation, or poor effectiveness of communication between scientists and policy makers were identified as, among others, basic obstacles in tackling the issue. Finally the authors state that they "*were also hampered by the fact that the initiative for the project came from outside the area for which it was destined*" and as such "*could be seen as 'imposed 'or at least 'unsolicited'* " – a fact that 100% applies to constructing FLEOM.

Ascough et al. (2001) describe a decision support tool for sustainable management of farms in the Great Plains of the USA. The so-called GPFARM model was designed to provide crop and livestock management support with emphasis on water, nutrient, and pesticide management. It also provided economic and environmental analyses, site database generation and site-specific management with the overall goal to determine the long-term effects of alternative Great Plains farming practices on environmental and economic sustainability. In 2001 Ascough et al. (2001) stated that "*GPFARM will continue to be developed and tested, and has a strong potential for extension to agricultural management support on a national basis*", which indicates that at this time it had not yet been applied in "real-life". A more recent publication from 2005, i.e. 4 years after the first publication, describes that GPFARM had been "*fallen short of the high expectations*" and "*adoption rate of GPFARM is slow*" (Ascough et al., 2005). The honest, upfront report provides an overview on the details of GPFARM and lessons learnt including a comprehensive description of the reasons for its failure as a DSS of wider application in the region.

Other examples on integrated modeling are that described by Ochola and Kerkides (2004; land quality assessment in Kenya) and Quinn et al. (2004; assessment of hydroclimatic impacts on land and water resources in California). Finally, also the ZEF-Khorezm's sister-project "Glowa-Volta" is following an integrated modeling approach to describe the interactions between the hydrologic cycle, the biosphere and land use (Rogers and Vlek, 2006). No account of integrated modeling that targeted land or water resource use in Central Asia could be found in literature.

In summary numerous success stories of integrated land and water resources modeling can be found in literature, basically all with the same tenor as that of Ascough et al. (2001, see above). However, it has to be said that, despite the number of publications, none of these examples seem to have found its way into wider public discussion, or as de Kok and Wind (2003) have stated it "*practical application of decision-support systems still runs behind the availability of these tools*". Only a limited number of publications explore on the reasons for failure of integrated modeling and DSS. Such negative results are obviously more difficult to "sell" to journal editors than success stories. First of all, it seems that the "*there is no consensus at present on how best to integrate the insights from different disciplines for different purposes or how best to turn these insights into effective policy-support*" (Oxley et al., 2004). As a consequence numerous, in some way competing frameworks are developed, none of which might turn out useful in the very particular case as many of them "*do not provide programming structures such as classes, components, objects, design patterns to be used to create end-user applications*" (Rizzoli, et al., 2005).

Box 2: cont'd

Secondly, when resources are limited or skills and workload of involved tasks underestimated, often integrated models are made by non-programmers rather than professionals (Rizolli et al., 2007), entailing various problems regarding quality and extendibility of the product or in-time delivery. But even if the integrated model or DSS is ready for use, Stephens and Middleton (2002) and Matthews et al. (2007) provide a number of explanations for poor uptake by users. Regarding model construction this is blamed on: (i) an inappropriate focus on scientific issues that are not relevant to day-to-day (farm) decisions (questions phrased incorrectly!), (ii) no clear advantages over present practice, and (iii) failure to define the target users / involve users in development. Regarding the marketing and support of the DSS poor uptake could arise from: (i) poor marketing / dissemination, (ii) a lack of training, (iii) a too-short shelf-life (iv) an institutional resistance ("why change the way of current decision making?"). Especially the latter issue has led to a point where scientists are asked to develop DSS *with* rather than *for* practitioners.

Carberry et al. (2002) summarize the striking criticism of the Ridge and Cox report (first drafted in 1995, later-on published in 2001) regarding the development of APSIM and its pilot on-farm application within the FARMSCAPE program (see above):

> *"Their principal accusation was that we were ignoring the real research needs of farmers by persisting with our research question of whether farmers could value simulation as a tool in helping to manage their farming system."* And further-on*: "Peter Cox exposed us to an emerging world view whereby scientists were under attack for their self-centered research programs and lack of concern for achieving purposeful change".*

Carberry et al. (2002) furthermore highlight the need for a broader view of disciplinary scientists to overcome these obvious shortcomings in the traditional research agenda:

> *"We have become students of the broader systems literature as a means of understanding the philosophical context of our and others' research agendas … and we have applied this learning to real-world problems (Carberry, 2001)".*

In the course of this debate, Matthews et al. (2007) draw the conclusion that probably best reflects current thinking within the scientific community:

> *"To abandon DSS as a techno-centric dead-end would be premature. Agricultural systems remain the principal land using sectors in terms of area for much of the world and the effects of management decisions have profound effects for both rural and urban communities. There remain significant win-win improvements to resource management within farming systems that are possible and for which agricultural DSS are a suitable vehicle to influencing practice."*

Box 3: Economic optimization in farm planning

In technical terms, an integrated economic-ecological optimization modeling relies on the availability of datasets. By the very nature of this endeavor, there are problems of data availability, especially, when working in developing countries or transition economies such as Uzbekistan. Lack of long historical dataset limits the degrees of freedom and makes the parameterization of quantitative input-output interrelations of different production variables infeasible (Hazell and Norton 1986).

Optimization models which provide a tool for planning purposes have been developed already more than 50 years ago and are well documented in literature (Agrawal and Heady, 1972; Hazell and Norton, 1986). So called Linear Programming (LP) models were first developed by economists in the 1930s concerned for the optimal allocation of scarce resources. Dantzig formulated the general LP problem and devised the simplex method of solution in 1947. Development of algorithms in the 1980s for solving huge LP problems beyond the scope of the simplex method gave a new wave for optimization modeling (Karmarkov, 1984; Hillier and Lieberman, 2001). Standard LP algorithms and programs (e.g. GAMS) became available for the solution of problems expressed in the understandable form. Because of ease of implementation and relative flexibility in depicting a large array of economic conditions, farm models based on LP optimization technique were widely adopted (Ellis et al*.*, 1991).

Optimization model solves problems defined in terms of an objective function to be maximized or minimized; a set of possible activities; and a set of constraints of available resources (Dent et al*.*, 1986; Pannell 1997). In other words, a farmer will select the optimal combination of activities that best fulfill his objectives and are feasible in terms of physical, human and capital constraints. A farm LP model can be used for joint examination of farm activities within the range of resource constraints and costs and returns of modifications in production technologies or any other exogenous change. Moreover, by optimizing a specified objective function, the LP model can attempt to replicate and show the trends of how a rationally behaving farmer would adjust his production activities to a technological advancements/innovations or any other notable changes in on-farm and external conditions.

A series of economic factors, i.e. existing policies, and input and output prices, as well as biophysical factors, i.e. environmental conditions, production technologies, land characteristics, of a farming system decide farm management decisions regarding land use. The physical relationships between bio-physical attributes of land and farm management practices codetermine agricultural and environmental outcomes. In this respect, an optimization model allows combination of biophysical and socioeconomic information at different scales for farm-household research in developing country agriculture (Bőrner, 2006).

A proper specification of the modeling framework requires detailed information of realistic technical ratios and biological relationships between inputs and output. Cooperation of agricultural economists and agronomists has led to the development of various models for reflecting the decision environment faced by farmers and the stochastic nature of agricultural production (Ellis et al*.*, 1991). Most of the existing publications about bio-economic models applied for land use management and agroecological systems deal with optimization models. These models were built for analyzing different agroecological systems for the adoption of alternative agricultural practices or to assess the introduction of technological advancements and innovations.

According to Lee (1983), the role of farm-level modeling within a policy formulation is to qualitatively understand the likely responses of producers to various market conditions and policy provisions. Cole and English (1990) provided a list of criteria for evaluating such models. Accordingly, the model should be flexible to incorporate alternative crops using renewed version of crop-growth component over a multi-period horizon with structure and database transferable between modeled objects and to users for analytical purposes. Additionally, being tested for reliability the model must be able to incorporate various governmental policies and to simulate the cash-flow process in farm based on some type of decision making routine and farm-level information.

Box 3: cont'd

Although the environmental and crop process models work at the plot level, the decisions take place at aggregated scales such as a single farm or a group of farms (Kruseman et al., 1996; Kam et al., 2000). Hence, the biophysical economic (or in short bio-economic) models based on components at micro-level scales are further aggregated to regional and national levels depending on the scale of problem (Antle et al., 2000). Results of farm model may vary with respect to the assumed problem target (Setia 1987; Brink and McCarl 1978). With the right modeling framework, the modelers can for instance assess the effects of agricultural policies on soil quality. Constructing such a decision framework is not an easy task, and practical policy analysis, therefore, tends toward the use of a profit maximization framework (Ellis et al., 1991, Rola et al., 1988; Setia and Magleby, 1981; Prato and Shi, 1990).

3 Conceptual framework

The conceptual layout of FLEOM is the result of a long, interactive (learning) process. This involved a series of transdisciplinary workshops and numerous meetings, in which the basic systematic concept of FLEOM was summarized in use-case diagrams and a use-case narrative as well as an activity diagram following the notation of the Unified Modeling language (UML). The final description of FLEOM was documented in a Software Requirement Specification (German: "*Pflichtenheft*"). In conclusion, using UML tools was a worthwhile exercise to streamline and pinpoint the different views and opinions of the project members and agreeing upon a common understanding of the functionalities of FLEOM. However, the established diagrams and narrative were of limited use for the software development process *per s*e. Here, creativity and freedom of choice was in one or the other way hampered by the software tools and modeling frameworks already in use (e.g. GAMS and CropSyst), the in-house software programming expertise, time limitations, as well as anticipated follow-up (software licenses) and maintenance costs ("keep things simple and cheap").

The integration was done using standard tools, namely Java (NetBeans) in combination with the OpenMap GIS API and the Microsoft Access ODBC data source (see chapters 4.4 and 4.5 for details). The advantages of this approach, such as less required software-technical man-power and at the same time a higher public awareness, availability and professional support (if required) of the used tools, outweigh potential disadvantages, such as a missing generic plug-in-pull-out functionality or limitations regarding a potential future web-base implementation of FLEOM.

FLEOM comprises the following sub-models (Figure 1) a graphical user interface (FLEOM-GUI) programmed in Java, a GIS visualization component realized with the Open Systems Mapping Technology (OpenMap, http://openmap.bbn.com/), and an economic-ecological optimization routine written in GAMS. The optimization component is connected to a MS-Access agronomic database. The data base was established with the cropping system simulation model, CropSyst (Stockle et al., 2003), using data sets, field experience and knowledge of a range of agronomic and hydrological studies (see chapter 4.1 for details).

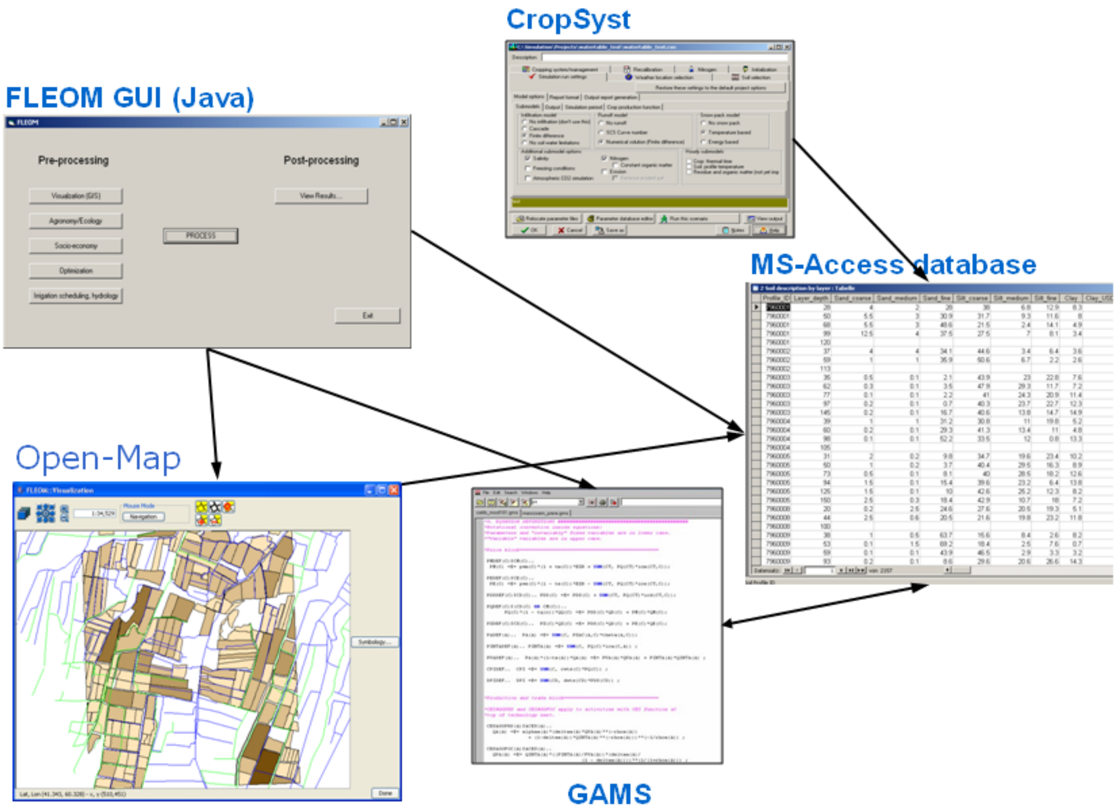


Figure 1: Components of FLEOM and their links

Arrows in Figure 1 detail the flow of data or information. The GUI has access to the database and can read or modify it (e.g. prices for commodities), or add new data (results). The OpenMap GIS interface shows existing farm attributes and provides several options for user-specified visualization or for highlighting/excluding certain fields or attributes. It also can display results of scenario analyses such as tables or figures and store or export them in a summary file (pdf format). Currently, the database also contains results from the spatial Multiple-Criteria Evaluation (MCE) on the suitability of land for non-core farming activities such as the establishment of fish ponds, forest-shelter belts, timber plantation and forest plantation for bio-drainage purposes (Kranz, 2005). The latter would be displayed in the GIS interface. Subsequently, the user can select certain fields and reserve them for these purposes, i.e. exclude them from the following agronomic analysis of FLEOM.

After proper setup and start of the optimization analysis, the GUI launches the optimization routine (LP) in GAMS. This sub-model receives all necessary data from the database. The GAMS routine itself is a slimmed-down version of the Linear Programming (LP) optimization routine developed to describe, simulate and optimize the farm-household economy in Khorezm. Figure 2 illustrates the GAMS-optimization workflow.

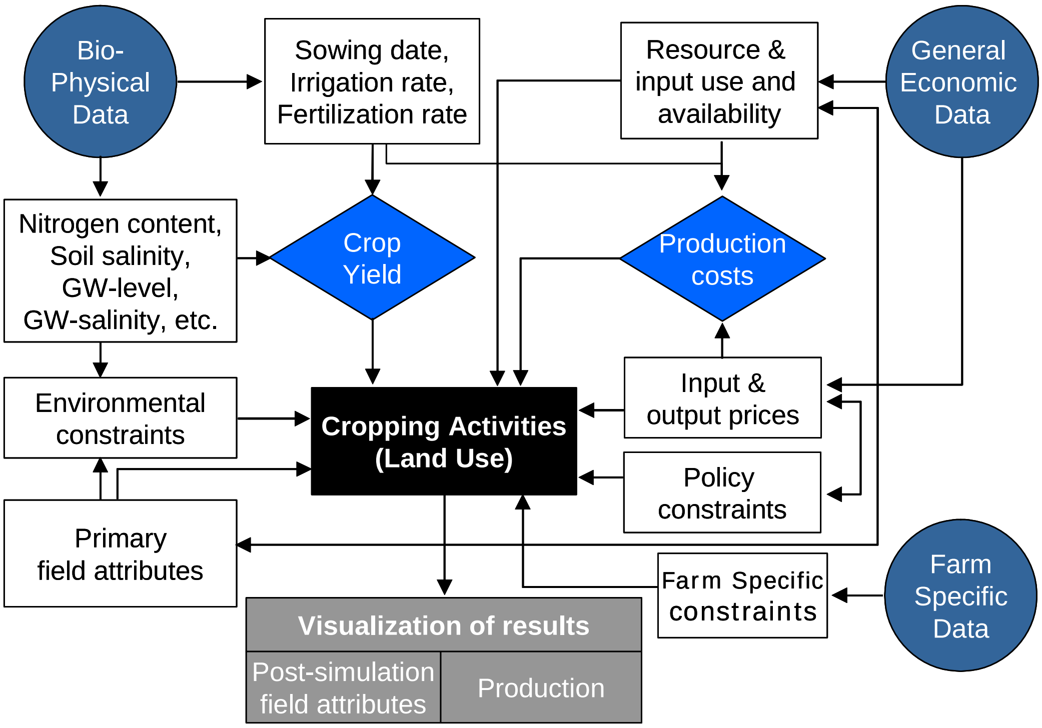


Figure 2: Workflow of the optimization sub-routine of FLEOM

It should be emphasized that, though a complete farmer-association/WUA area is tackled (optimized) at once, still single farm properties and constraints are equally and simultaneously considered. This is of utmost importance to produce scenario-results that reflect actual conditions, in which farm-household do "optimize" their own activities somewhat independent of higher-level WUA goals.

4 Components, tools and data

4.1 CropSyst

CropSyst is a multi-crop, daily time step cropping system simulation model. It belongs to the class of dynamic deterministic, mechanistic, bio-physical models. Its characteristics are described in detail by Stockle et al. (2003). A number of studies with CropSyst have been documented in literature (e.g. Pannkuk et al., 1998; Peralta and Stockle, 2001; Confalonieri and Bechini, 2004; Confalonieri and Bocchi, 2005; Bechini et al., 2006, Sommer et al., 2007). CropSyst is freely available and frequently updated (http://www.bsyse.wsu.edu/cropsyst).

CropSyst had been applied to wheat, maize, barley, rice, sorghum, potato, alfalfa and some other crops, tree crops and grassland. Thus, modeling crop growth is the primary field of application of CropSyst. It is capable of simulating the influence of climate/weather, soil water, groundwater, salt and N-stress on plant growth and yield. One of the big advantages of CropSyst is its generic crop routine to simulate the growth of annual (herbaceous) plants. This routine can be adapted to any new crop meeting the criteria. This is possible as the algorithms for some biological processes are simple in comparison to other crop-soil simulation models. Thus, CropSyst is appreciated for its "small appetite for data" (Confalonieri and Bechini, 2004) with regard to crop parameters.

CropSyst had not been applied to simulate cotton growth. Therefore, simulating cotton using the generic crop routine of CropSyst (Sommer et al., 2008), as done in various studies of the ZEF-Uzbekistan Project, was a novelty. Sommer et al. (2007) were the first who successfully applied CropSyst to conservation agriculture, comprising zero-tillage and surface residue retention; an agronomic practice that is also a key-component in the ZEF-Uzbekistan Project.

No attempts are documented in literature to use CropSyst in an integrated modeling framework as was done in this study within FLEOM.

In the following details are provided how CropSyst was applied to produce the input-output tables of the FLEOM data base. The chapter starts with detailing agronomic management as well as biophysical data and settings on which the simulations were based. Subsequently, the resulting simulation scenarios are listed, and finally the calibration of CropSyst is briefly outlined. Pakhlavan-Makhmud water user association (PM-WUA) was chosen as the benchmark study area. Therefore, in the course of detailing CropSyst, whenever necessary also PM-WUA characteristics are provided.

4.1.1 Agronomic management scenarios

Agronomic management of crops comprises a range of issues. Most important parameters for modeling crop growth with CropSyst, or any other biophysical crop model, are the phenological and eco-physiological characteristics of the chosen crop variety, the time of planting, the timing and amount of fertilization and irrigation and the type of tillage operations that are undertaken (or not – "zero-tillage"). By their very nature, mechanistic models simplify reality to some extent. This means that for example fertilizer management and crop nutrition beyond nitrogen is rarely simulated, and the same is true for the impact of pesticide and herbicide application, respectively crop pests and diseases.

In the course of producing the input-output table for FLEOM with CropSyst, a selection of management practices had to be made allowing on one hand for a sufficient overview of agronomic management in Khorezm. On the other hand, the total number of simulations had to be kept at a manageable size, mostly because of limitation given by computing time as well as handling resulting data sets of several gigabytes.

4.1.1.1 Crops and varieties

FLEOM version 1.0 includes biophysically-based input-output tables for the three crops **cotton** (*Gossypium hirsutum L.*), **maize** (*Zea mais L.*) and **winter-wheat** (*Triticum aestivum L.*), which are three of the four most important crops in Khorezm (the fourth being rice). On the other hand, only for these crops experiments of sufficient detail were carried out within ZEF's Uzbekistan Project until 2007; data of which could serve for model calibration (chapter 4.1.7.). **Rice** (*Oryza sativa L.*), which is the most important cash crop for farmers in Khorezm, is also part of version 1.0. However, details are solely based on the socio-economic evaluation done by Djanibekov (2008b). Results of more comprehensive agronomic field studies on rice will be available earliest in late 2010.

According to the remote-sensing based land use classification of Conrad (2006), in 2004 and 2005 cotton, wheat and rice together occupied 93 % and 89 %, respectively, of the total cropping area of Khorezm (Table 1).

Table 1: Area coverage and percent land use of cotton, winter-wheat and rice in 2004 and 2005; land use classification done with time series of MODIS images (250 m resolution; Conrad, 2006)

Crop	Land use			
	2004		2005	
	(ha)	(%)	(ha)	(%)
Cotton	148,190	54	142,233	46
Winter-wheat	44,531	16	70,880	23
Rice	59,825	22	64,891	21
Rest	19,722	7	33,283	11
Total	272,268		311,287	

For cotton the variety *Khorezm-127* was simulated, as this has been the most commonly used variety in Khorezm in the last years (50-60 % of the cotton growing area in 2005-2007). It was also intensively studied by Kienzler (2010). Thus, CropSyst simulations were based on a comprehensive data set of irrigation and fertilizer response of *Khorezm-127*. The same was true for the winter-wheat variety *Kupava*, which was intensively studied by Djumaniyazova et al. (2010). Maize yield response of the variety *M-215* (from Moldavia) was studied by the project in a crop-rotation fertilizer-response trial carried out in 2005-2006 (Kienzler, unpublished). The data set for modeling however merely comprised biomass, yield and leaf area index data for maize grown under optimal conditions. Field data on water- and fertilizer-response could not be included, as they had not been processed yet. Instead, for maize standard literature information on water- and N-fertilizer response was used.

4.1.1.2 Planting date

In Khorezm optimal timing of planting is important for at least three reasons:

(i) achieving best possible yields by avoiding temperature (early and late season) stress (see for example Ortiz-Monasterio et al., 1994 or Hobbs et al., 1997 for details on wheat in Central Asia) or intermediate secondary re-salinization of topsoils (e.g. for late-planted cotton);

(ii) allowing for harvest in good time and optimal planting time of the subsequent crop (example winter-wheat – rice rotation); and

(iii) making best profits in cotton; cotton picked before a certain deadline obtains premium-prices.

To account for this, CropSyst simulations comprised three different planting dates for cotton, namely early, (15 April), regular (1 May) and late (15 May). The first date corresponds to present recommendations, whereas the second and third correspond to project's encounter of reality. Time did not allow including different planting dates for winter-wheat and maize. This is foreseen for a follow-up version of FLEOM. In the current version winter-wheat was planted 1 October and maize 21 July.

4.1.1.3 Irrigation

Irrigation of annual crops in an arid and salinity-affected region like Khorezm has to consider a range of aspects. These are first of all the actual crop water requirements, which have to be balanced against issues such as soil salinity management and irrigation system specifications. Regarding the latter, the aim is to minimize system losses while at the same time maintaining operability and functionality of the total system. The necessity of pre-season salt-leaching adds to complexity of irrigation management in Khorezm.

In view of this, in simulations with CropSyst, irrigation was probably the factor that had to be simplified to the largest extent. Irrigation amount and timing was merely set to comply with crop water requirements. Therefore, the well-established Uzbek Hydro-Mod(ule) scheme (Soyusnihi, 1992) for irrigation recommendations was used as baseline. In short, the Hydro-Mod scheme gives (furrow) irrigation recommendations according to climate, crop, maximum rooting depth, soil texture, groundwater depth and field efficiency. Soil texture is divided into nine classes, of which in Khorezm only the classes VII, VIII and IX are found. Loamy sand and sandy loams are represented by class VII. Light to moderately loamy soils (=loams according to USDA classification) are part of class VIII. Class IX includes heaver soils; absent at PM-WUA.

On Hydro-Mod VII soils in Khorezm, influenced by shallow groundwater, cotton should receive 640 mm of water applied in six doses of 100 to 110 mm in 15-22 day-intervals. First irrigation is foreseen for end of May. Hydro-Mod VIII soils are supposed to receive one irrigation less, in total 490 mm.

To simplify things, we used Hydro-Mod VII for all soils as a baseline for well-irrigated cotton. Subsequently irrigation amounts were reduced and if necessary timing altered to mimic water shortages in dry years, respectively, to simulate crop response to sub-optimal irrigation (=water stress; Table 2).

Table 2: Date and amount of irrigation and leaching of cotton grown in Khorezm under full (Hydro-Mod VII), medium and low irrigation management as defined for CropSyst simulation scenarios

No.	Type/ Days after sowing	FULL	MEDIUM	LOW	
		Amount (mm)		Days after sowing	Amount (mm)
Pre-season salt leaching					
1	-20	100	100	-20	75
2	-10	100	100	-10	75
Irrigation					
1	51	100	60	60	50
2	69	100	60	90	50
3	83	110	66	120	50
4	97	120	72		
5	113	110	66		
6	132	100	60		
Sum		**840**	**584**		**300**

The medium and low irrigation levels in total corresponded to 60 % and 23 % of the full level. The low level was not chosen arbitrarily but equaled the percentage availability of irrigation water in the exceptionally dry years 2000-2001 (Müller, 2006). Irrigation frequency at low level had to be reduced to avoid too small doses at single events that would be impractical, if not impossible, to distribute homogenously. Amounts for pre-season salt leaching were based on rule-of-thumb irrigation recommendations (Bernhard Tischbein, personal communication). Real amounts of water spent for leaching of cotton-fields in Khorezm might exceed the simulated amounts by a factor of two, as sometimes fields are leached three or even four times (Djanibekov, 2008b). Forkutsa (2006) however could show that exaggerated application of leaching water does not have any additional, beneficial effect on soil salinity, but rather is a waste of water on large scale. She furthermore concluded that it is rather an effective timing of leaching in view of anticipated seeding of cotton that determines leaching efficiency. The aim should be to narrow the gap between second leaching and seeding as much as possible to prevent secondary re-salinization of the topsoil. A ten-day gap, as it was realized in our CropSyst simulations, seems a realistic time, as it allows sufficient drying of topsoil for subsequent tractor field operations.

An analogous procedure was applied for defining irrigation scenarios for winter-wheat (Table 3) and maize (Table 4).

Table 3: Date and amount of irrigation of winter-wheat grown in Khorezm under full (Hydro-Mod VII), medium and low irrigation management as defined for CropSyst simulation scenarios

No.	Date	FULL Amount (mm)	MEDIUM Amount (mm)	LOW Date	LOW Amount (mm)
1*	26/Spt/05	50	30	26/Spt/05	30
2	01/Apr/06	80	50	09/Apr/06	30
3	18/Apr/06	80	50	30/Apr/06	30
4	30/Apr/06	80	50	18/May/06	30
5	12/May/06	80	50		
6	25/May/06	80	50		
Sum		**450**	**280**		**120**

*= Irrigation-leaching

Table 4: Date and amount of irrigation of maize grown in Khorezm under full (Hydro-Mod VII), medium and low irrigation management as defined for CropSyst simulation scenarios

		FULL	MEDIUM	LOW	
No.	**Date**	**Amount (mm)**		**Date**	**Amount (mm)**
1*	15/Jul/06	80	48	15/Jul/06	30
2	27/Aug/06	80	48	30/Aug/06	45
3	02/Sep/06	110	66	18/Sep/06	45
4	08/Sep/06	110	66		
5	29/Sep/06	80	48		
Sum		**460**	**276**		**120**

*= Irrigation-leaching

Single events were in some cases increased to 30 mm, which was assumed to be the lowest amount of water that could be distributed homogenously. As opposed to Table 2, Table 3 and Table 4 contain real dates, because planting dates of winter-wheat and maize scenarios were not (yet) altered, and thus exact instead of relative dates could be given.

It has to be underlined that the given irrigation amounts are actually on-field (net) amounts, whereas the point-scale model CropSyst did not simulate surface runoff or imbalanced (up-furrow – down-furrow) application, i.e. field efficiency of irrigation in CropSyst was always 1. Consequently, irrigation system conveyance losses must be added to these amounts to determine farm-gate or Water-User-Association water requirements (gross amounts; see chapter 4.1.6).

4.1.1.4 Fertilization

For cotton, winter-wheat and maize each time four different fertilization scenarios were simulated, namely standard, medium, low and zero levels of application (Table 5).

Table 5: Date and amount of N-fertilization of cotton, winter-wheat and maize under standard, medium and low fertilization scheme as defined for CropSyst simulation scenarios; zero level of fertilization not listed; DAS = days after sowing; DAF = days after flowering

Date	STANDARD	MEDIUM	LOW
	-------------- (kg N ha^{-1}) ---------------		
Cotton			
1 DAS	100	60	20
60 DAS	50	30	10
1 DAF	50	30	10
Sum	**200**	**120**	**40**
Wheat			
01/10/05	60	38	15
13/03/06	90	56	23
01/05/06	90	56	22
Sum	**240**	**150**	**60**
Maize			
20/07/06	54	32.4	10.8
09/08/06	63	37.8	12.6
27/08/06	63	37.8	12.6
Sum	**180**	**108**	**36**

Standard fertilization amounts and timing followed Uzbek norms for the crops (for details see Kienzler, 2010). Medium and low application corresponded to 60 % and 20 % of the full amounts. Contrary to irrigation, single fertilizer applications were not pooled. In all simulations, N-fertilizer was broadcasted as ammonium-nitrate.

4.1.1.5 Tillage and Residue Management

In CropSyst simulations for FLEOM 1.0 only standard tillage practices were realized. These were, in accordance with common practice, for all crops one pass with a moldboard-plow (NRCS implement no. 150) and a spike-tooth-harrow (NRCS implement no. 70) one week before planting. Therewith 99 % of all surface residues of a previous crop were buried to a maximum depth of 20 cm. In this regard, cotton and winter wheat were assumed to be cropped after cotton, and maize after winter wheat. In Khorezm, farmers remove all cotton residues and wheat straw. The woody stems of cotton are used as fuel and the wheat straw as fodder. Thus, we set up CropSyst simulations to keep only 5 % of the remainders of the last cotton as surface residues, and 10 % of straw of the last wheat crop as standing stubbles. It was assumed that dead roots from previous crops would amount to 2 Mg ha^{-1}, having a vertical mass distribution as simulated with CropSyst (roots at crop maturity). Also for N-concentrations and area-to-biomass ratios of residues as well as decomposition times CropSyst defaults were used.

An updated version of FLEOM should also comprise conservation agriculture practices with zero-tillage and residue retention. Our current (early 2010) knowledge on the impact of these practices did not allow implementing them into CropSyst simulations.

4.1.2 Climate

4.1.2.1 General

Khorezm is located in northwestern Uzbekistan, on the left bank of the Amu Darya River within the transition zone of the Karakum and Kyzylkum deserts. This region is characterized by a semi-desert climate. Potential evapotranspiration exceeds precipitation during most of the year (dotted area inFigure 3). Hot and dry summers alter with cold winters. The region receives some precipitation from October to May (~101 mm per year), but neither summer nor winter precipitation plays a significant role in the water balance of the region. Crop production fully relies on irrigation water that is withdrawn from the Amu Darya.

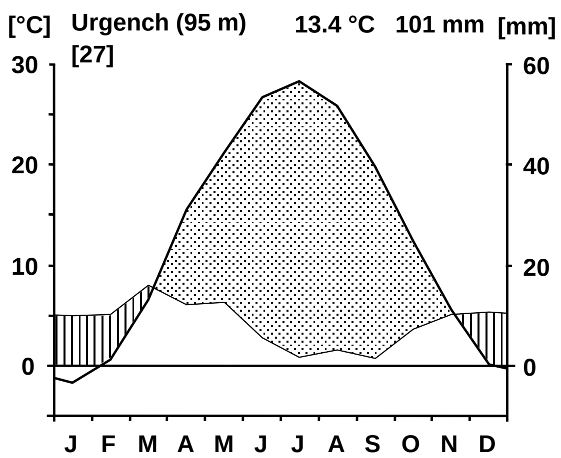


Figure 3: 1980-2006 monthly mean air temperature and monthly precipitation in Khorezm, station "Urgench", 95 m above sea level (diagram according to Walter-Lieth notation)

4.1.2.2 Vapor pressure deficit and evapotranspiration

CropSyst requires a minimum weather data set comprising daily data on precipitation, solar radiation, and minimum and minimum maximum air temperature. With only those, potential evapotranspiration (ET_{pot}) is calculated using the Priestley-Taylor (PT) equation (Priestley and Taylor, 1972). However, McAneney and Itier (1996) clearly demonstrated that in case daytime mean vapor pressure deficit (D) surpasses 10 g m^{-3}, the PT-equation fails to provide any reasonable estimates of ET_{pot}.(Figure 4) shows that this threshold was consistently exceeded from May till October of 2004, 2005 and 2006, and there is no doubt that this would be the case also in other years. Thus, the Priestley-Taylor equation should not be used in Khorezm.

CropSyst uses the FAO-56-Penman-Monteith (PM) equation (Allen et al., 1998) as second option to calculate ET_{pot}. In addition to the above-mentioned data it requires daily minimum and maximum relative humidity and wind speed.

These data were measured starting from May 2004 at "Maxhud garden" located in Yangibazar district of Khorezm (41°36'10.92" N 60°30'50.60" E, 96 m above sea level). In Maxhud garden also the cotton and winter-wheat trials were established that were used for model calibration. Missing data (see gaps in Figure 4) were substituted by data from the closest project weather station (station "Yangibazar"), which was located in the same district 10.4 km northwest of Maxhud garden.

The resulting PM-ET_{pot} is shown in Figure 5 for the years 2004 till 2006. Peak values reached 9 mm day^{-1} in July. Annual ET_{pot} was 1007 mm in 2004, 1093 mm in 2005 and 1112 mm in 2006.

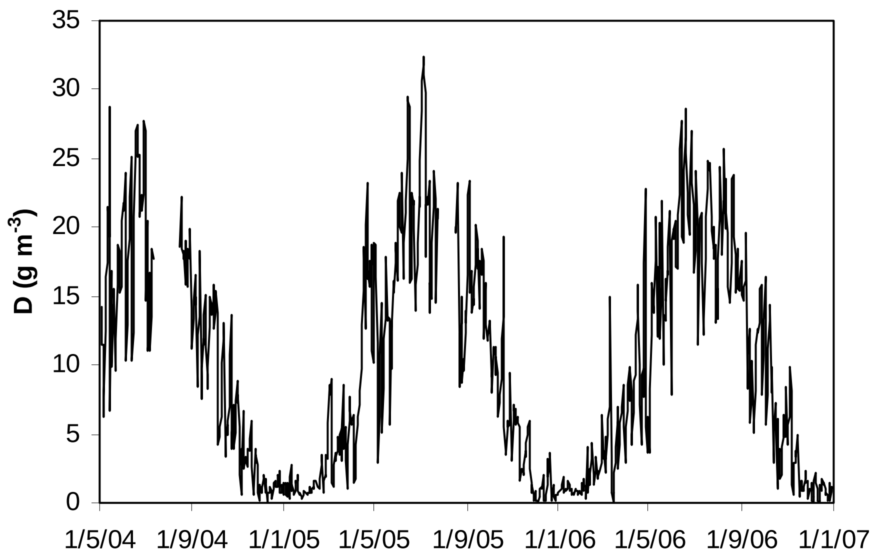


Figure 4: Vapor pressure deficit, D (g m^{-3}), from 1 May 2004 till end of 2006 at station "Maxhud garden" (41°36'10.92'' N 60°30'50.60 E, 96 m above see level)

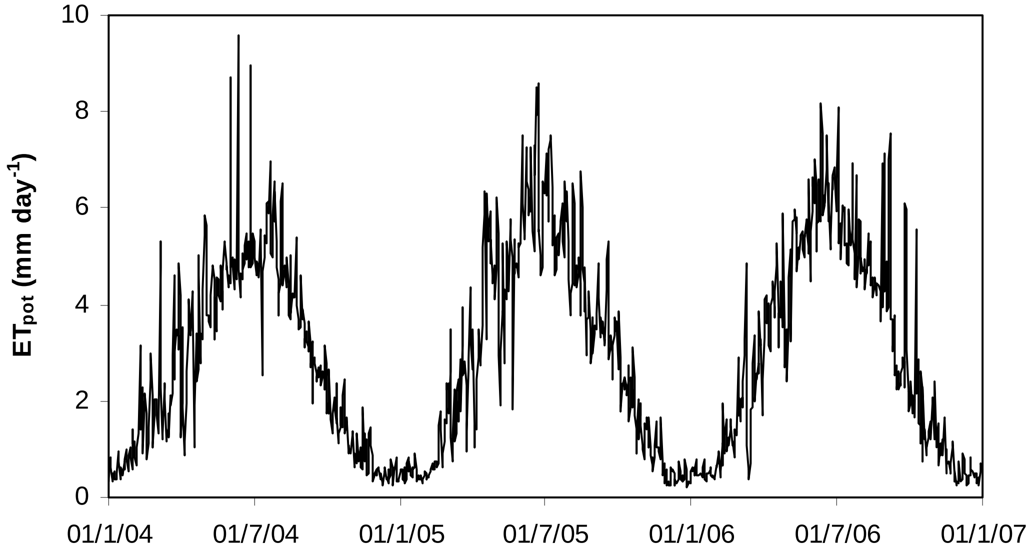


Figure 5: FAO-56-Penman-Monteith potential evapotranspiration at "Maxhud garden" in 2004-2006

At regional, Khorezm-wide level, there is some slight variation in weather conditions. Basically the southwest of Khorezm is slightly warmer and the vegetation period by some days prolonged as compared to the northeast of Khorezm. In some years, thus, cotton can be planted a few days earlier and winter-wheat development and maturity is accelerated. Yet, the number of weather stations (in total three) as well as the covered periods (< 5 years) and accuracy of measurements was not sufficient to cover this issue in a scientifically sound way.

4.1.3 Soils

CropSyst, like any other full-fledged crop model, requires three different types of soil information:

i. physical and hydrological description (texture, bulk density, water retention and hydraulic conductivity);
ii. initialization of state variables (SOM, N_{min}, soil salinity, water content); and
iii. temporal description of the model system's lower boundary, i.e. in case of the influence of a shallow groundwater table the time and depth of groundwater and -salinity.

This chapter explains how these attributes were derived, and, in short, their spatial (and temporal) patterns. It is not meant to be a complete and comprehensive description of soils in Khorezm. This can be found in Akramkhanov (2005), I. Forkutsa (2006), O. Forkutsa (2006) as well as Kienzler (2008) and Scheer (2008). Only crop-model relevant details are portrayed. The description and later classification is largely based on a comprehensive data base of soils in Khorezm (henceforth called: Khorezm soil data base) from the Uzbekistan Soil Science and

Agrochemistry Research Institute (Bairov et al., unpublished) and, in the case of soil organic matter, supported by a comprehensive literature study carried out by Kuziev (2006). Soils of PM-WUA were described in detail by Akramkhanov (2005). Groundwater dynamics and salinity in Khorezm were analyzed by Ibrakhimov (2004).

4.1.3.1 Texture and soil horizons

Khorezm

The Khorezm soil data base describes 511 soil profiles and altogether 2,157 soil layers. Out of these 1,884 soil layers have complete textural (% sand, silt and clay) information. Figure 4 shows the spatial distribution of the soil profiles, indicating a homogenous and thus representative sampling scheme. Soil samples taken in the Shavat and Pitnyak Rayons were not geo-referenced.

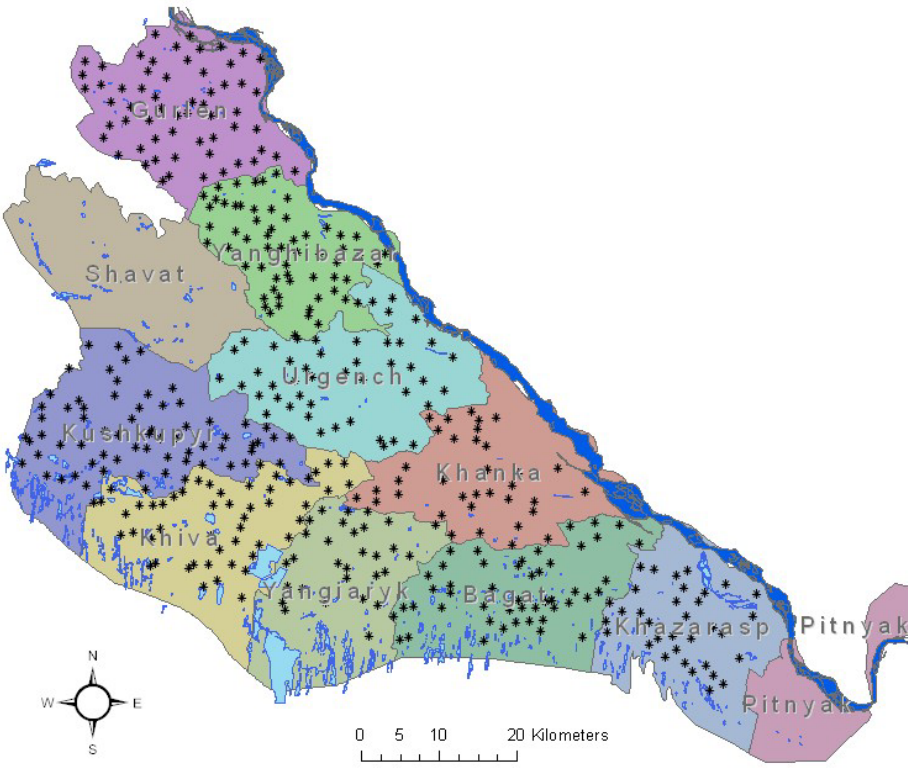


Figure 6: Sampling locations (stars) of profile descriptions carried out in the soil survey by Bairov et al. (unpublished) in Khorezm

Most soils in Khorezm are silt loams (USDA soil texture classification). Silt loam layers together with sandy loams and loams constitute 80 % of all soil layers (Table 6).

Table 6: Frequency of soil texture classes (Khorezm soil data base, Bairov et al., unpublished)

Soil texture	N	%
Sand	59	3.1
Loamy sand	86	4.6
Sandy loam	229	12.2
Clay loam	25	1.3
Loam	241	12.8
Sandy clay loam	8	0.4
Silt loam	1039	55.1
Silt	84	4.5
Silty clay loam	109	5.8
Silty clay	3	0.2
Clay	1	0.1
all	1884	

Heavier, clayey soils are largely absent in Khorezm (Figure7).

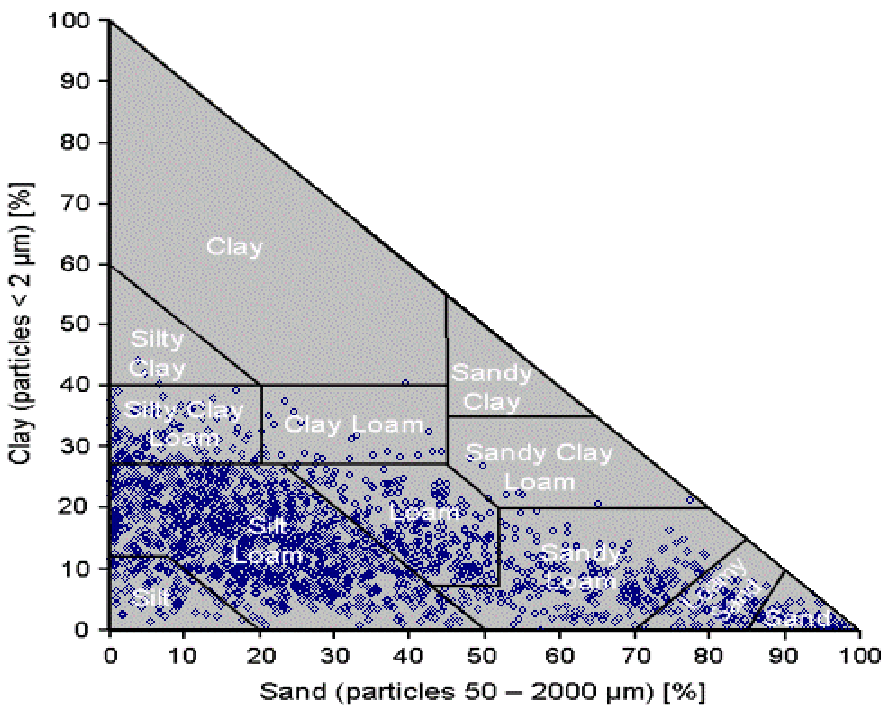


Figure 7: USDA soil texture classification and respective distribution of all soil layers described in the Khorezm soil data base

On average four generic soil horizons per profile are given in the data base. For merely 35 soil profiles (~7 %) more than five, at maximum seven, horizons were identified.
The mean lower boundary of the first five horizons is 32, 60, 95, 129 and 156 cm (Figure 8).

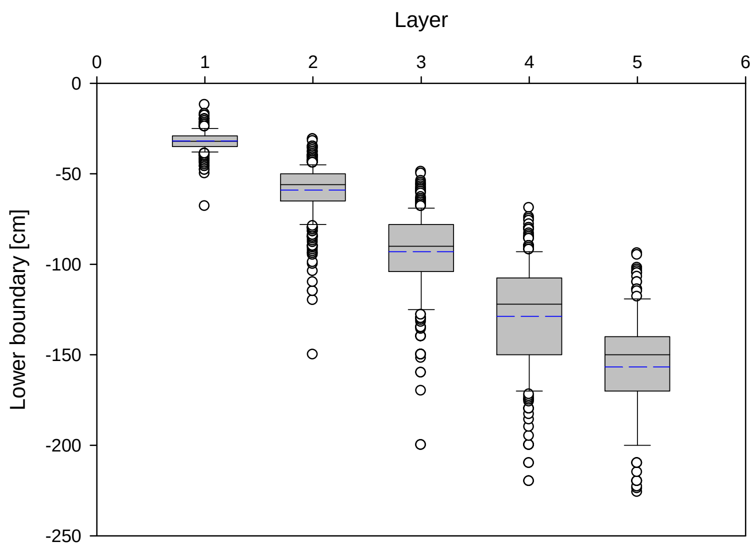


Figure 8: Box-whisker plot of the depth of the lower boundary of the defined soil horizons; blue dotted line = mean

The percentage abundance of soil texture classes does not change notably with depth (Figure 9). Rather the heavy soils became more abundant with depth. This means that the impact of shallow groundwater and groundwater salinity on crop growth and secondary soil salinization, respectively, is generally potentially significant because heavier soils better support capillary rise of groundwater.

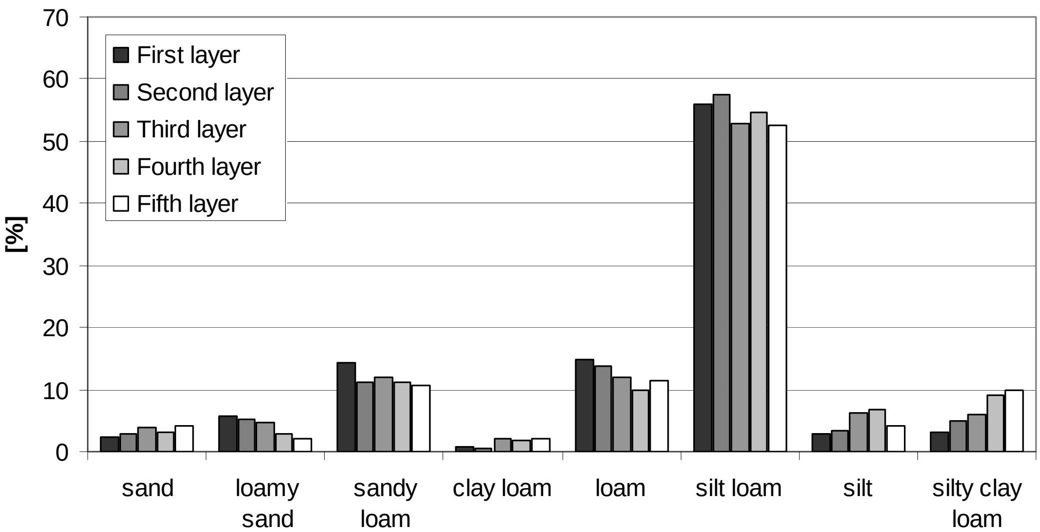


Figure 9: Frequency of soil texture classes of the upper five soil layers

From Figure 9 one should expect that soil profiles are rather homogenous. Indeed, in 207 out of 511 cases (41 %) a silt loam topsoil overlays a subsequent silt loam layer. Analogously, additional 75 soil profiles have identical first and second soil layer textural classes other than silt loam. Hence, altogether 55 % of the soils have a homogenous ~56 cm topsoil. Further 33 % of all soil profiles had close matching first and second soil layers (i.e. neighboring soil textural classes inFigure 7). This means that only about 12 % of all soil profiles would show a rather abrupt texture changes in the top 56 cm soil. Considering the first four soil layers, this percentage increases to 25 %, meaning that still 75 % of the soils in the Khorezm soil data base have a quite homogenous texture in the top ~129 cm. This is an important aspect, as it allows a quite robust estimation of vertical distribution of soil texture based only on topsoil data.

PM-WUA

Topsoil (0-30 cm) texture was determined by Akramkhanov (2005) for the center region of the PM-WUA. Four soil textures prevailed: sand, loamy sand, sandy loam and loam (Table 7).

Table 7: Frequency of soil texture classes at PM-WUA

No.	Soil texture	% of fields
1	Sand	34.4
2	Loamy sand	8.0
3	Sandy loam	23.2
4	Loam	32.6
5	Silt loam	1.8

Lighter soils were generally found in the south and heavier soils in the north of the PM-WUA (Figure 10).

Figure 10: Soil texture distribution at PM-WUA

4.1.3.2 Soil water retention and hydraulic conductivity

A detailed description of soil hydraulic properties was not available for a larger data set; neither for Khorezm as a whole nor for the PM-WUA. In depth studies in this regards in Khorezm were only carried out by the ZEF-Khorezm project for the first time.

Forkutsa (2005) described in detail the soil water retention and hydraulic conductivity of a **sand** and **sandy loam** located south of the PM-WUA in the discernible rectangle enclosed from three sides by the PM-WUA. She applied the Hydrus-1D model (Simunek et al., 2005) based on the Richards equation (Richards, 1931) to simulate water and salt transport in these soils. She described the soil hydraulic properties with the modified Mualem-van-Genuchten (MvG) model (Vogel and Cislerova, 1988).

Instead of the modified MvG model CropSyst uses the simpler Campbell model (Campbell, 1985) if soil water fluxes are simulated with the Richards equation. Thus, some transformation of soil hydraulic parameters is necessary, when moving from MvG to Campbell. The details of this transfer are described by Sommer and Stockle (2010).

In 2005, Kienzler (2010) studied crop growth and fertilizer-response of cotton on a **loam** (gleyic Arenosol) located in the Urgench district of Khorezm (41° 36' 13" N 60° 30' 49" E). Winter-wheat followed in 2006 (Djumaniyazova et al., 2010) on a directly neighbored site (same texture). Water dynamics were studied in both years on these fields by simultaneous automated measurements of soil moisture (FDR; theta probe, Delta-T Devices, UK) and soil pressure head (pF Meter, GeoPrecision, Germany). The water and salt dynamics of cotton in 2005 again was first of all described with the Hydrus-1D model (Forkutsa et al., 2009). It followed a transformation of soil hydraulic parameters from MvG to Campbell as described above, and subsequently a simulation of salt, water and N-dynamics with CropSyst.

On the PM-WUA only four **silty loam** fields were bigger than 0.5 ha, which was considered the smallest size of fields to be included in the FLEOM optimization. Given the low count of silty loam fields, the small covered acreage (sum = 15.5 ha) and the soil physical similarity between silty loam and loam, the silty loam soils were considered as loams.

The soil hydraulic properties of the **loamy sand** were derived from % sand, silt and clay and bulk density data applying the (CropSyst-intrinsic) pedo-transfer function of Saxton et al. (1986). This comparably crude estimation of soil hydraulic properties was necessary as no field studies had so far been done on this type of soil.

Using the above outlined data (inverse estimation of soil hydraulic properties, or pedo-transfer functions), altogether four soils were described and used for simulations in CropSyst (Table 8).

Table 8: Soil texture and water retention characteristics of the four soils predominating at PM-WUA; BD = soil bulk density; texture of loamy sand estimated, BD of loamy sand equal sandy loam

Soil		Sand	Clay	Silt	Water content (cm cm^{-1}) at			BD
		------- % -------			15,000 hPa	330 hPa	Saturation	(g cm^{-3})
Sand								
	0-10 cm	86.4	8.5	5.2	0.002	0.031	0.494	1.34
	10-30 cm	95.4	1.2	3.4	0.017	0.090	0.366	1.68
	30-60 cm	90.9	1.4	7.7	0.008	0.050	0.370	1.67
	60-200 cm	99.3	0.1	0.7	0.006	0.076	0.396	1.60
Loamy sand								
	0-11 cm	82.0	5.0	13.0	0.070	0.167	0.457	1.44
	11-26 cm	82.0	5.0	13.0	0.066	0.158	0.408	1.57
	26-45 cm	82.0	5.0	13.0	0.062	0.148	0.366	1.68
	45-85 cm	82.0	5.0	13.0	0.065	0.155	0.396	1.60
	85-135 cm	82.0	5.0	13.0	0.028	0.099	0.400	1.59
	135-200 cm	82.0	5.0	13.0	0.007	0.047	0.385	1.63
Sandy loam								
	0-11 cm	74.0	12.0	14.0	0.066	0.174	0.457	1.44
	11-26 cm	69.0	9.0	22.0	0.097	0.186	0.408	1.57
	26-45 cm	71.0	6.0	23.0	0.098	0.177	0.366	1.68
	45-85 cm	72.0	5.0	23.0	0.103	0.190	0.396	1.60
	85-135 cm	40.0	16.0	44.0	0.053	0.137	0.400	1.59
	135-200 cm	44.0	9.0	47.0	0.078	0.197	0.385	1.63
Loam								
	0-5 cm	46.8	16.1	37.1	0.108	0.235	0.424	1.53
	5-25 cm	46.8	16.1	37.1	0.112	0.243	0.458	1.43
	25-45 cm	42.9	13.8	43.2	0.095	0.227	0.386	1.63
	45-70 cm	50.0	15.8	34.2	0.107	0.227	0.417	1.54
	70-100 cm	44.2	18.4	37.4	0.110	0.230	0.386	1.63
	100-200 cm	44.2	18.4	37.4	0.109	0.230	0.385	1.63

Besides texture and soil hydraulic properties, the soils differed in the number and thickness of layers. The soil hydraulic conductivity curves of the four soils are given in Figure 11.

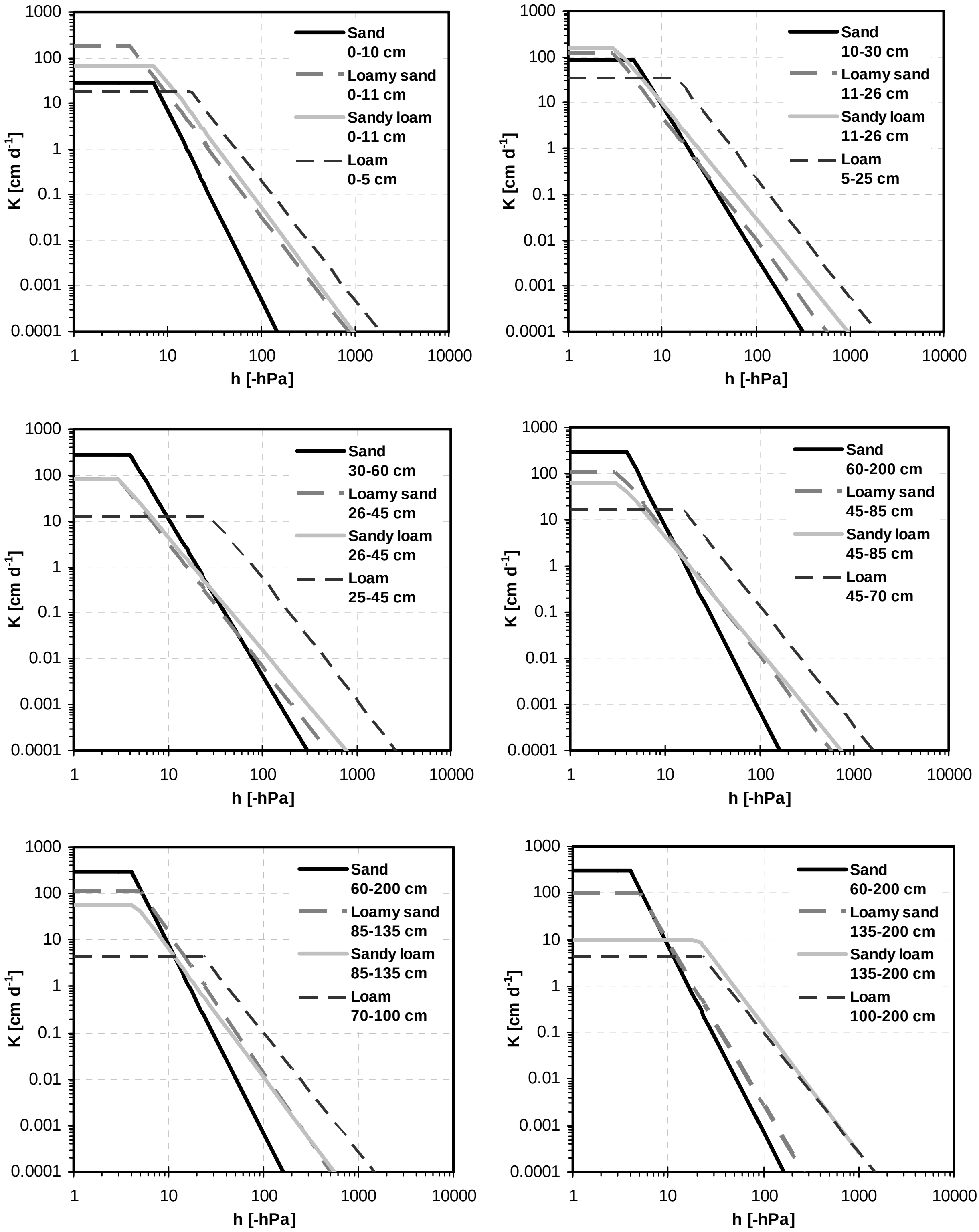


Figure 11: Soil hydraulic conductivity – pressure head, K(h), curve of the different soil layers of the sand, loamy sand, sandy loam and loam; for easy comparison conductivity of sand at 60-200 cm is shown in three graphs

In all soil layers (except topsoil) the sand had the highest K_s and the lowest unsaturated hydraulic conductivity below ~-30 hPa. K_s decreased and unsaturated hydraulic conductivity increased successively with decreasing sand and increasing clay content of the soil layers; a quite likely and expected result of soil hydraulic properties of these soil textures.

4.1.3.3 Soil organic matter

Khorezm

The Khorezm soil data base contains 1806 entries for soil organic matter (SOM). Soil organic carbon (SOC) is conventionally determined chemically using a slightly modified form of the Walkley-Black wet-oxidation (potassium dichromate) method (Nelson and Sommers, 1982). For conversion into SOM, it is assumed that SOM contains 58 % C (Shirokova, personal communication).

Organic matter is low in soils of Khorezm. According to data of the Khorezm soil data base it is on average 7.5 g kg^{-1} in the topsoil layers decreasing to 3.9 g kg^{-1} at 156-210 cm depth, with considerable natural variation. The lower quartile of SOM at 0-32 cm was 5.4 g kg^{-1} and the upper quartile 9.4 g kg^{-1} (Figure 12).

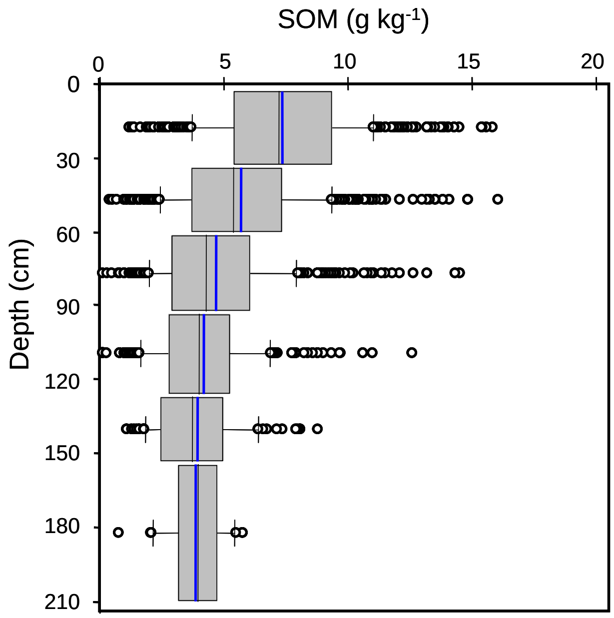


Figure 12: SOM of soils in the Khorezm soil data base; box-whisker plot, blue lines: average values

SOM contents of the data set (n=148) described by Kuziev (2006) generally concur with those of the Khorezm soil data base. Additionally they show that SOM in the top centimeters of soil can in some instances surpass 10 g kg^{-1} and reach at maximum 31 g kg^{-1}).

PM-WUA

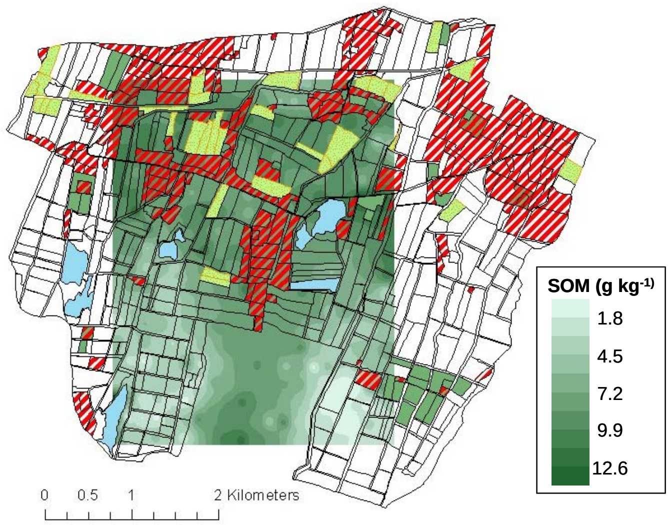
SOM of the top 30 cm of fields at PM-WUA ranged between 1.6 and 11.3 g kg^{-1} (Akramkhanov, unpublished data; Figure 13a). Based on the abundance of SOM in the topsoil as characterized in Figure 7, the topsoil OM of PM-WUA could be distinguished into three classes, whereas the range between the lower and upper quartile was assumed to enclose mean values of SOM in the topsoil (Table 9).

Table 9: Classification of SOM in the topsoil layer (0-30 cm) of fields at PM-WUA

Level	**SOM content [g kg^{-1}]**	**% of fields**
low	< 5.4	36
medium	5.4 to 9.4	51
high	> 9.4	14

Therewith, about half of all fields were classified as soils with medium SOM level; 36 % had a low SOM content and only 14 % ranked as high (Figure 13b).

a)



b)

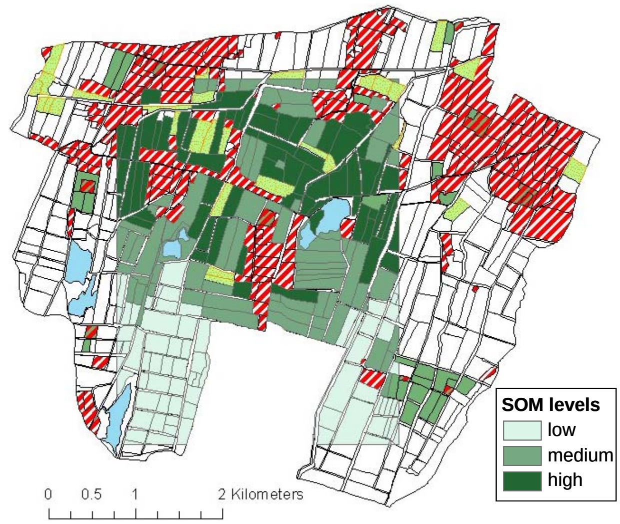


Figure 13: a) SOM distribution at the PM-WUA; b) SOM classified per individual field into low, medium and high levels

At PM-WUA, no information was available for SOM below 30 cm depth. Thus, for the CropSyst simulations it was assumed that (initial) SOM would decrease with depth as characterized in Figure 10, whereas the mean SOM level would follow medium levels, and low and high levels would approximately follow the quartiles (Figure 14).

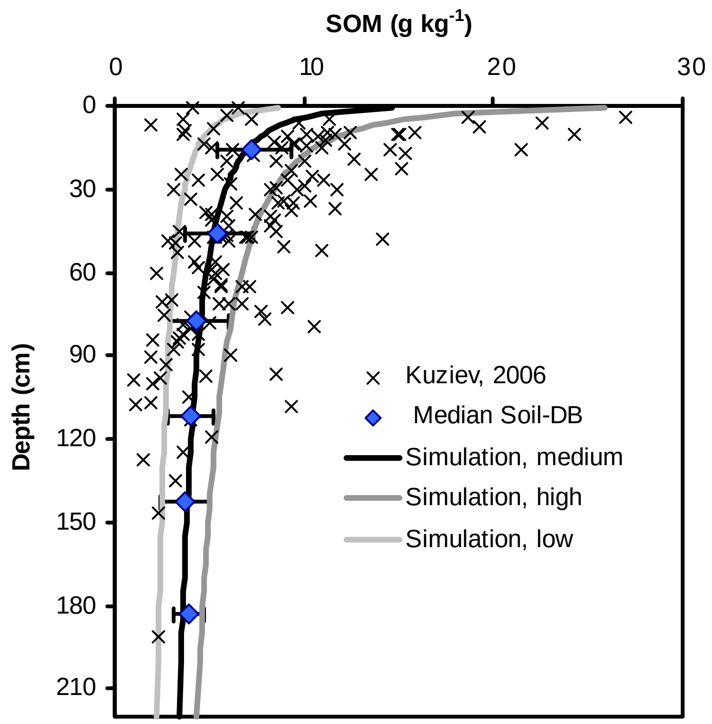


Figure 14: SOM content in soils of Khorezm according to Kuziev (2006), the Khorezm soil data base and as parameterized in FLEOM; bars denote the lower and upper quartile; $SOM_{medium} = 14.68*depth^{-0.27}$; $SOM_{high} = 25.86*depth^{-0.33}$; $SOM_{low} = 8.62*depth^{-0.25}$

With this distribution SOM in 0-1 m depth amounted to 31.2, 50.5 and 73.5 Mg ha^{-1} for low medium and high SOM levels, respectively; overall slightly varying in response to differing soil bulk densities of the four distinguished soil textures.

4.1.3.4 Mineral nitrogen

Khorezm

The Khorezm soil data base contains 1869 entries for soil nitrate. It contains only three entries for ammonium, omitting any reasonable evaluation. The Uzbek method to determine soil mineral N (NO_3 and NH_4), is for various reasons (e.g. air-dry soil samples, different chemical analysis) not 1:1 comparable with standard "western" mineral N determinations. The classification of NO_3 contents with regard to optimal crop growth deviates therefore from western norms (Table 10)

Table 10: Classification of soil mineral N content with regard to optimal plant growth (WARMAP & EC-IFAS, 1998) and its equivalent amount considering exemplarily 0-30 cm soil depth (soil bulk density assumed to equal 1.5 g cm^{-3}).

Mineral N content (mg kg^{-1})	Classification	Mass equivalent [kg N ha^{-1} 30 cm^{-1}]
< 20	very low	< 90
20-30	Low	90-135
30-50	Medium	135-225
50-60	High	225-270
> 60	very high	> 270

It appears that the Uzbek chemical analysis of mineral N produces considerably higher concentrations of NO_3 and NH_4 than standard western analysis, and that the classification was adjusted accordingly. In Khorezm topsoil NO_3 contents alone, with on average 34.5 mg kg^{-1} (median: 19.6), would classify the soil to be medium-rich in mineral N (Figure 15).

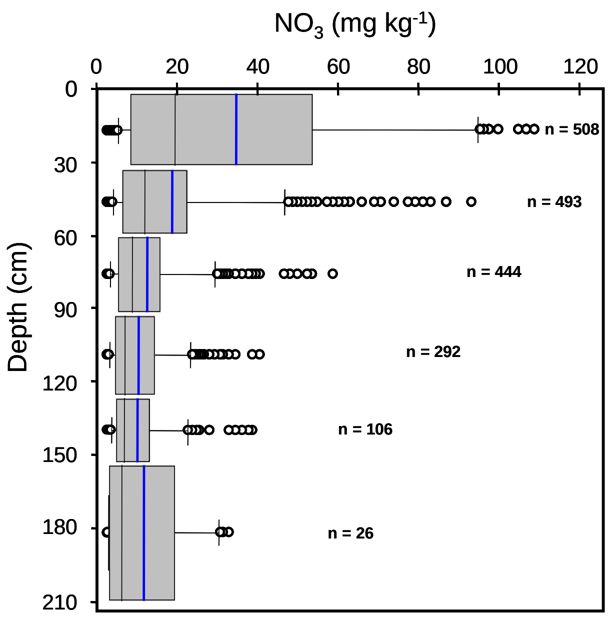


Figure 15: NO_3 content of soils in the Khorezm soil data base; box-whisker plot, blue lines average

Heterogeneity of NO_3 contents in 0-30 cm depth was high ranging from a lower quartile of 8.5 mg kg^{-1} to an upper quartile of 53.7 mg kg^{-1}. Median NO_3 content decreased from 12.0 mg kg^{-1} in 30-56 cm depth to 6.3 mg kg^{-1} below 156 cm. Interestingly, NO_3 contents below 156 cm varied stronger than in the three layers above. This might be related to some topsoil nitrate leaching and accumulation in this sub-layer in some soils.

The trend of decreasing NO_3 content with depth could be described with the power-function $[NO_3] = a \cdot Depth^b$ (depth in cm; R^2 = 0.125** n = 1869).

PM-WUA

Soil mineral N contents (Nmin) were not determined on PM-WUA. To derive Nmin data sets (initial conditions) for simulations in CropSyst the following procedure was applied:

- Initial, field-level Nmin contents were assumed to equal initial SOM contents, i.e. fields with low SOM content would also obtain a low mineral N content.
- initial soil NH4 contents were assumed to equal 6 % of soil NO3 contents (Kienzler, 2010).
- Levels (high, medium and low) of soil NO3 contents and vertical decline were derived from the Khorezm soil data base.

Regarding the latter, it was assumed – analogously to SOM – that NO3 contents would decrease with depth as characterized in Figure 15 using the above power function. In addition, we assumed that a high soil Nitrate level would only equal observed medians, a medium level would equal approximately the lower (25 %) quartile and low levels the lowest observed values in the Khorezm soil data base (Figure 16).

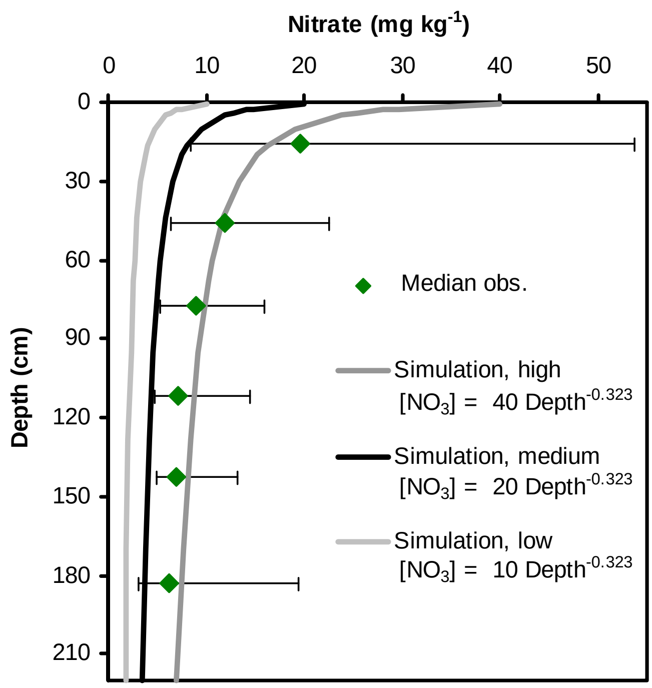


Figure 16: NO_3 in soils of Khorezm (Median obs., Khorezm soil data base) and as parameterized in FLEOM (Simulation, high, medium and low); error bars denote the upper and lower quartile

This "shift" in level-assignation was necessary as preliminary simulations with higher-than-median NO_3 contents resulted in N-saturated crop growth, with no notable impact of N-fertilization; a result that did not coincide with field observations. The shift was furthermore necessary to account for the Uzbek N_{min} analyzes outlined above; as an attempt to bring down N_{min} contents to, in terms of western soil science, acceptable values.

Using the power functions displayed inFigure 16, soils that were classified as high in soil mineral N contained 352 kg N ha^{-1} in the upper 2 m of soil (320 kg N in the form of NO_3 and 32 kg NH_4-N), medium N_{min} soils contained 110 kg N ha^{-1} 2 m^{-1} and low N_{min} soils 55 kg N ha^{-1} 2 m^{-1}. Approximately 63 % of this mineral N was in the upper 1 m of soil, i.e. potentially within direct reach of (mature) crop roots.

4.1.3.5 Soil salinity

Khorezm

The Khorezm soil data base contained during the preparation of this report 2053 entries for soil salinity expressed in total dissolved solids percentages (% TDS). These values were converted into electrical conductivity, EC_e, using the equation of Abrol et al. (1988):

$$EC_e \, (dS \, m^{-1}) = \%TDS / 0.064$$

The median EC_e decreased from 10.1 dS m^{-1} in 0-32 cm to roughly half of this value (4.7 dS m^{-1}) in 32-60 cm depth. Below 60 cm depth the median soil salinity was basically constant at around 3.8 dS m^{-1} (Table 11).

Table 11: Salinity of soils in Khorezm (Khorezm soil data base, Bairov et al., unpublished)

Soil depth	**0-32 cm (dS m^{-1})**	**32-60 cm**	**60-95 cm**	**95-129 cm**	**129-156 cm**	**156-210 cm**
Median	10.1	4.7	3.7	3.8	3.8	3.8
Average	17.6	9.6	7.5	6.2	6.8	5.8

As was the case for NO_3, the heterogeneity of soil salinity was high in the topsoil, where EC_e ranged from a lower quartile of 3.3 dS m^{-1} to an upper quartile of 25.8 dS m^{-1} (Figur 17).

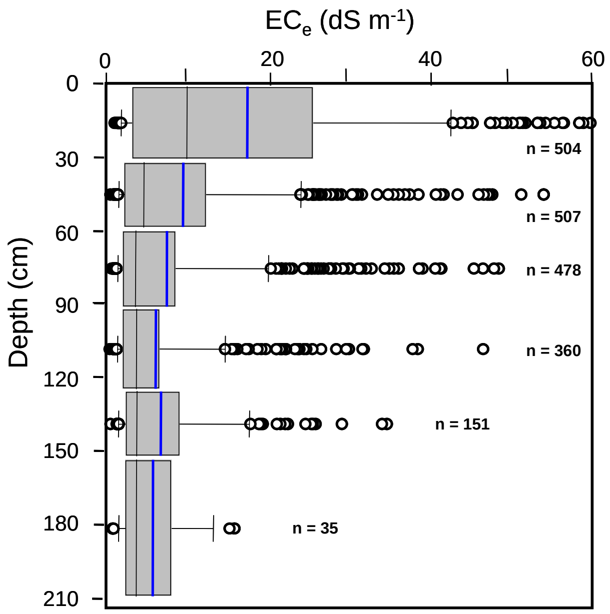


Figure 17: Salinity of soils in the Khorezm soil data base; box-whisker plot, blue lines indicate average values

According to the classification of soil salinity given by Abrol et al. (1988; Table 12) most subsoils in Khorezm are slightly- to medium-saline, whereas the majority of topsoils above 60 cm are strongly saline.

Table 12: Classification of soil salinity (Abrol et al., 1988)

Class	EC_e (dS m^{-1})
Non saline	0-2
Slightly saline	2-4
Medium saline	4-8
Strongly saline	8-16
Very strongly saline	>16

PM-WUA

Soil salinity was intensively studied at PM-WUA by Akramkhanov (2005). Figure 18 shows the spatial distribution of topsoil salinity at PM-WUA.

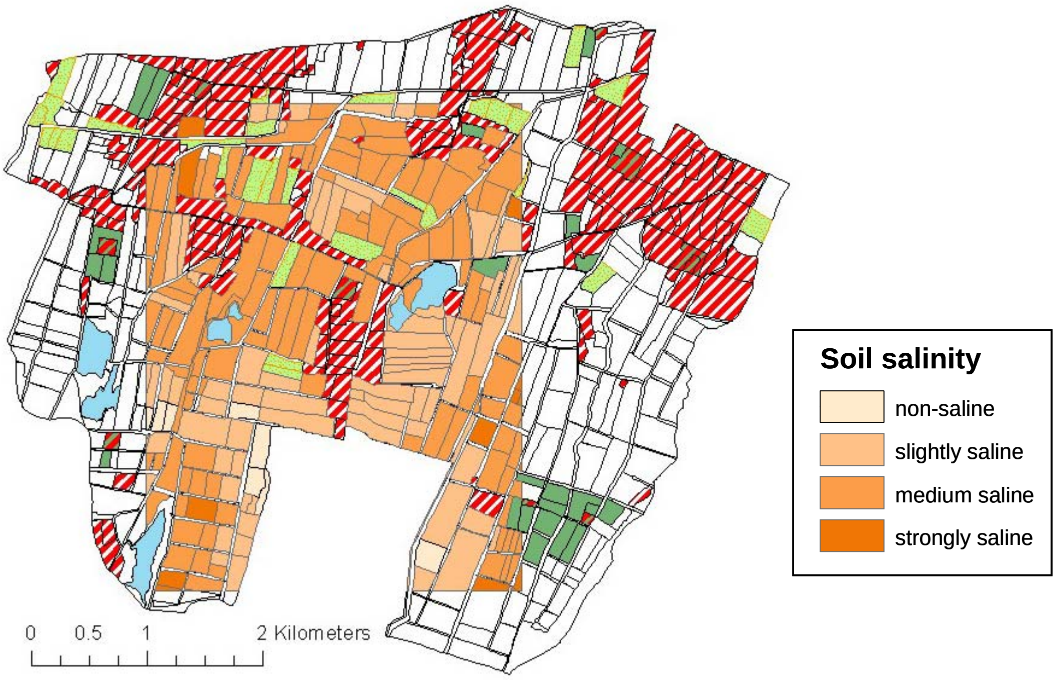


Figure 18: Spatial distribution of soil salinity (0-30 cm) at the PM-WUA; data basis: measured TDS (Akramkhanov, 2005)

A spatial pattern in topsoil salinity was not as clearly visible as for SOM. Nevertheless it appeared that the soils in the south of the farm had correspondingly lower topsoil salinity, most likely because capillary rise of groundwater of these comparably lighter soils is lower and so is secondary soil salinization.

According to the classification of soil salinity inTable 12, only 4 % of the fields at PM-WUA had no measurable degree of soil salinity (EC_e < 2 dS m^{-1}) in the topsoil, 34 % were slightly, 56 % medium and 7 % strongly saline.

As salinity in the subsoil was not measured, for simulations in CropSyst it was assumed that vertical distribution of EC_e followed the trend that was observed for Khorezm soils (compare Figure 17). Depending on topsoil salinity, three levels were distinguished (Table 13). The low salinity level also included those fields with no observed salinity.

Table 13: Levels and vertical distribution of ECe as used in the CropSyst simulations (initial conditions); same data for all soil textures

Soil layer	Low	Medium	High
	EC_e (dS m^{-1})		
1. layer	5	9	30
2. layer	4	7.7	15
3. layer	3	6.5	10
4-6. layer	2	5	8

4.1.3.6 Groundwater dynamics and salinity

Khorezm

Ibrakhimov (2004) provides a comprehensive overview of ten years (1990-2000) of monthly measurement of groundwater and groundwater salinity dynamics in Khorezm.
There is no simple explanation for spatial and temporal patterns of groundwater in Khorezm and underlying causes. In general, groundwater table is lowest in winter. It rises in spring with the start of cropping activities (pre-season leaching) with a first peak in April and a second one in July-August, when irrigation water requirement (for cotton and rice) and accompanying system losses are highest. Groundwater slowly drops thereafter, with some delay, when either a second summer crop like maize or sunflower is cropped.

PM-WUA

The above-mentioned trend was also observed from 1990 till 2000 at the four official measuring wells (no. 195, 196, 199 and 201) located in the center of PM-WUA (Tischbein, personal communication; Figure 19).

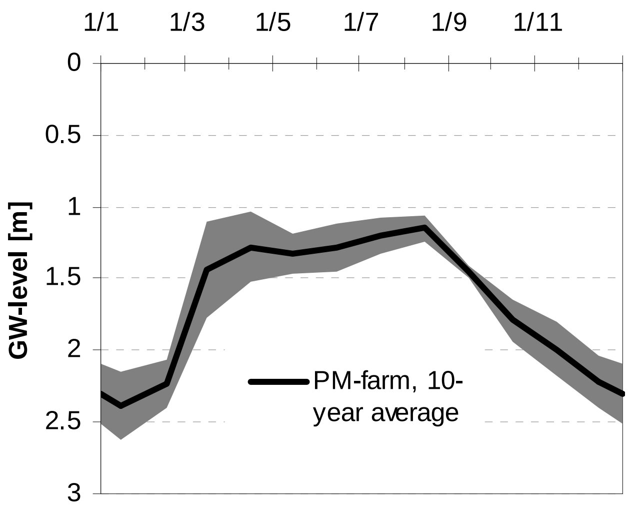


Figure 19: Average monthly groundwater table depth from 1990 to 2000 at PM-WUA; gray-shaded area: standard deviation of n=4 measuring wells

Akramkhanov (2005) interpolated groundwater table depths observed in July (averages from 1990 to 2002) over PM-WUA (Figure 20). Therefore, in addition to the data from the four wells in the center of PM-WUA he used data from another 45 wells surrounding this area and 14 wells installed by the ZEF-Uzbekistan Project south of PM-WUA.

Ibrakhimov (2004) provided thresholds of critical groundwater depths. According to those, groundwater depths > 1.6 m of medium textured soils with a groundwater salinity < 3 dS m^{-1} in July are to be considered uncritical, respectively could be called "deep". We extended this classification and furthermore divided groundwater depths in July into critical ("mean"), when groundwater was deeper than 1 but shallower than 1.6 m, and highly critical ("shallow"), when it was shallower than 1 m. This classification took into account that root depth in July would allow cotton to tap directly into groundwater (no capillary rise necessary) only when it was shallow, thus providing for a completely water-stress free growth during this period.

Following this classification, in July 80.2 % of the fields at PM-WUA had a mean, and 19.8 % a shallow groundwater level. None of the fields were drained to such an extent that groundwater levels in July were uncritical (> 1.6 m).

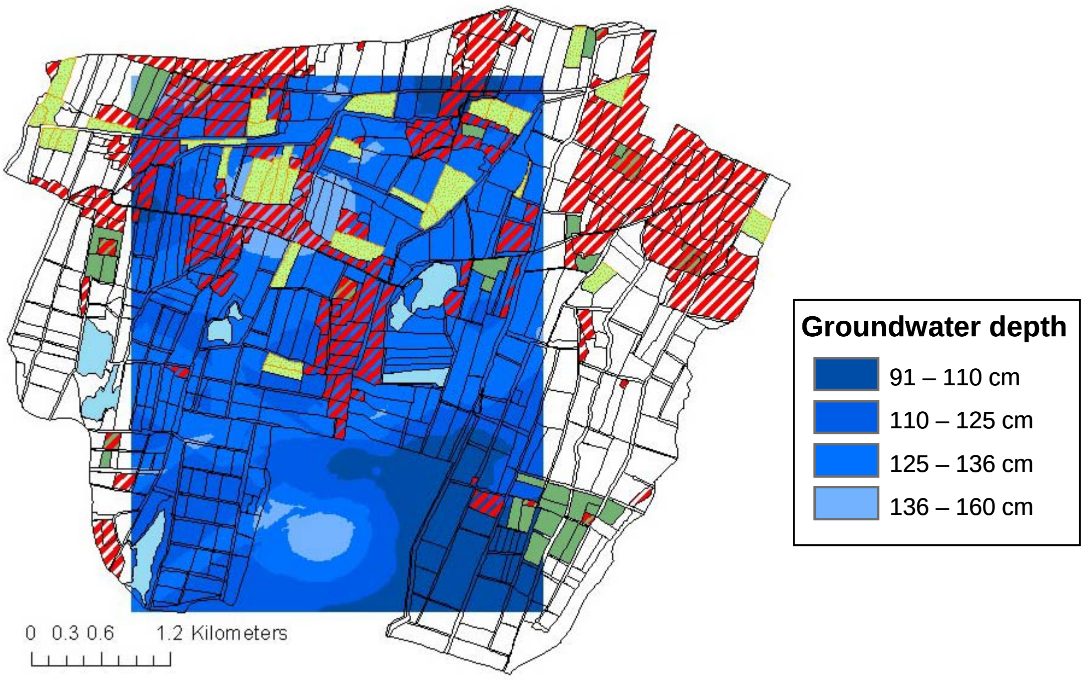


Figure 20: Average groundwater table depths in July at PM-WUA (Akramkhanov, 2005)

Combining the 10-year groundwater trend observed at PM-WUA (Figure 19) with the thresholds for critical depths in July, three different levels of GW-dynamics were derived for cotton simulations in CropSyst (Figure 21).

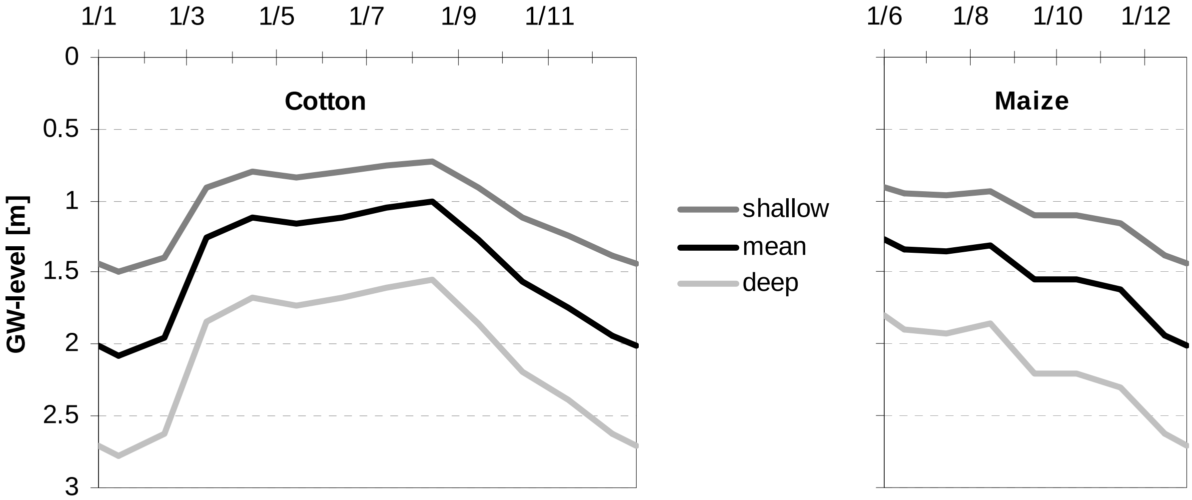


Figure 21: Groundwater dynamics under cotton and maize classified into shallow, mean and deep following threshold of Ibrakhimov (2004)

Consequently, the constructed deep, mean and shallow annual groundwater dynamics under cotton reached 1.60 m, 1.05 m and 0.75 m in July, respectively. For the deep groundwater level we assumed a slightly faster drop in autumn.

Groundwater levels and dynamics of maize (right hand side of Figure 21) were established analogously, providing however for a slower drop in autumn in response to the, as compared to cotton, prolonged irrigation season.

Groundwater under winter wheat was not fully derived from general long-year trends. Instead, for the main growing season (spring and early summer) we used data from detailed field observations in 2006 (Djumaniyazova et al., 2010). We assumed that levels from September till the end of the year would equal those under cotton.

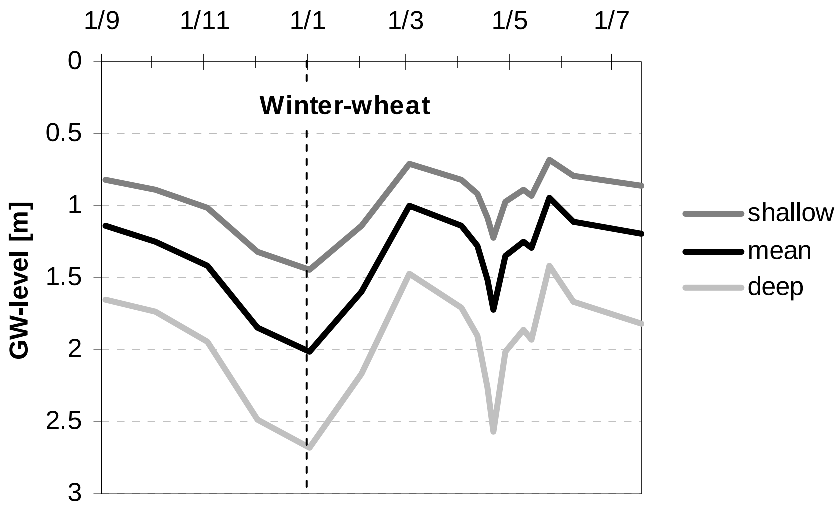


Figure 22: Groundwater dynamics under winter-wheat classified into shallow, mean and deep; mean levels from March till June observed by Djumaniyazova et al. (2010) in 2006.

Akramkhanov (2005) also assessed the salinity of groundwater on PM-WUA by measuring the electrical conductivity, EC_w. Field were classified into low, medium and highly saline groundwater according to the levels in given inTable 14.

Table 14: Groundwater salinity, EC_w, at PM-WUA

Level	EC_w [dS m^{-1}]	% of fields
low	0 - 2	14
medium	2 - 4	82
high	> 4	4

EC_w of only 4 % of the fields exceeded 4 dS m^{-1}, with a maximum of 5.1 dS m^{-1}. To reduce the number of simulation runs necessary we decided to include these 4 % into the medium EC_w class.

Detailed analyses and discussion of groundwater salinity in Khorezm can be found in Ibrakhimov (2004).

4.1.4 Simulation scenarios

Based on the different agronomic management scenarios and the potential differences in field/soil attributes, CropSyst simulation scenario files (*.scn) were established, each of which covering one of the multitude of possible combinations.

The amount of possible combinations can be calculated by multiplying the number of levels defined for each management and field/soil attribute, as there are for each crop:

Management

- 3 planting dates (cotton only; maize and wheat one planting date only)
- 3 irrigation levels
- 4 fertilization levels

Field attributes

- 4 soil textures
- 3 levels of soil organic matter
- 3 levels of initial soil mineral N
- 3 levels of soil salinity
- 3 groundwater levels
- 2 groundwater-salinity levels

Altogether, thus, for cotton 23,328 combinations had to be simulated, for winter wheat and maize these amounted to 7,776. Since sands and loamy sands never had high levels of SOM and N_{min}, these combinations *a priori* were ruled out, and the number simulations therefore decreased to 16,200 for cotton and 5,400 for winter wheat and maize. For the creation of the 16200 simulation-scenario files a small program was written to automatically create these scenario files of the feasible combinations, reading-in the necessary data from a MS-Excel spreadsheet.

To model the growth of cotton, a full year (1/Jan/ - 31/Dec/2005) was simulated. Winter wheat simulations comprised ten months (1/Sept/05 - 31 July/06) and maize simulations six months (1Jun/ - 1 Dec/06). A single simulation run of cotton, winter wheat and maize required around 30, 25 and 15 seconds of CPU time (Intel Pentium-IV 2.5 GHz, Microsoft XP-Professional OS), respectively. Each of these simulations created about 2.6 MB of results. To compile all necessary results for the completed input-output table 195 hours of CPU-time and 69 GB of hard-drive storage capacity were required.

4.1.5 Biophysical classification of PM-WUA

The center-part of PM-WUA that was considered in the simulations comprised 227 distinct fields covering 812 ha. Regarding the above-mentioned biophysical field attributes and classifications, 45 actually differing field types could be distinguished. For instance, the most abundant field type was a sand with a low level of soil organic matter, medium soil salinity, mean groundwater table, and medium groundwater salinity. This field type occupied 10.6 % (85.5 ha) of the total area and 11.9 % (27) of all fields. Altogether, the ten most abundant field types covered 495 ha, i.e. 61 % (Table 15). The rest of the field types, on average, only comprise 2.7 fields, and each of them covered in total less than 9 ha.

Table 15: The ten most abundant field types at PM-WUA distinguished according to soil texture, soil organic matter (SOM) and mineral N (N_{min}), soil salinity, groundwater (GW)-table and groundwater salinity level, and its corresponding covered area and number of fields

Soil texture	SOM & N_{min}	Soil salinity	GW-table	GW-salinity	Area (ha)	% of area	No. of fields	% of fields
Sand	low	medium	mean	medium	85.5	10.6	27	11.9
Sandy Loam	medium	medium	mean	medium	84.6	10.5	18	7.9
Sand	low	low	mean	medium	69.7	8.6	17	7.5
Loam	medium	high	mean	medium	51.6	6.4	12	5.3
Loam	medium	medium	mean	medium	45.6	5.6	14	6.2
Loam	medium	medium	shallow	medium	35.3	4.4	9	4.0
Sand	low	high	mean	medium	35.2	4.3	11	4.8
Loam	medium	medium	shallow	low	31.6	3.9	7	3.1
Sandy Loam	medium	medium	mean	low	28.5	3.5	9	4.0
Loam	medium	high	mean	low	27.0	3.3	10	4.4
Sum					**494.6**	**61.1%**	**134**	**59.0%**

4.1.6 Irrigation network water losses

Even though fields could be grouped in view of their biophysical attributes, each field eventually was unique regarding its location within the irrigation channel network. Understandably, irrigation of each individual field should provoke a unique amount of seepage loss in the channels. To quantify these losses on field-level, we calculated the lengths of first (Dist1) and second (Dist2) order channels from the main inlet of PM-WUA in the northwest to each field. To account for these losses, i.e. to make sure that the required amount of water would reach the individual fields, we then applied the following equation, which was developed on empirical grounds (Tischbein, personal communication):

$$\text{Water\_requir}_{\text{inlet}} = \text{Field\_Irrig} \cdot \frac{1}{0.99 \cdot e^{\alpha_1 \cdot \text{Dist1}}} \cdot \frac{1}{0.99 \cdot e^{\alpha_2 \cdot \text{Dist2}}}$$

where Water_requirinlet is the irrigation water requirement at the inlet of PM-WUA depending on the distance of fields to canals, Field_Irrig is the field irrigation level according to CropSyst settings (see chapter 4.1.1.3), and $\alpha 1$ and $\alpha 2$ is the slope of an exponential seepage function for first and second order channels. We assumed that first order channels would conduct water more efficiently than second order channels. Thus $\alpha 1$ was set to -0.0001 and $\alpha 2$ to -0.0002. Figure 23 shows the percentage single and absolute combined effect of this approach on irrigation water requirements.

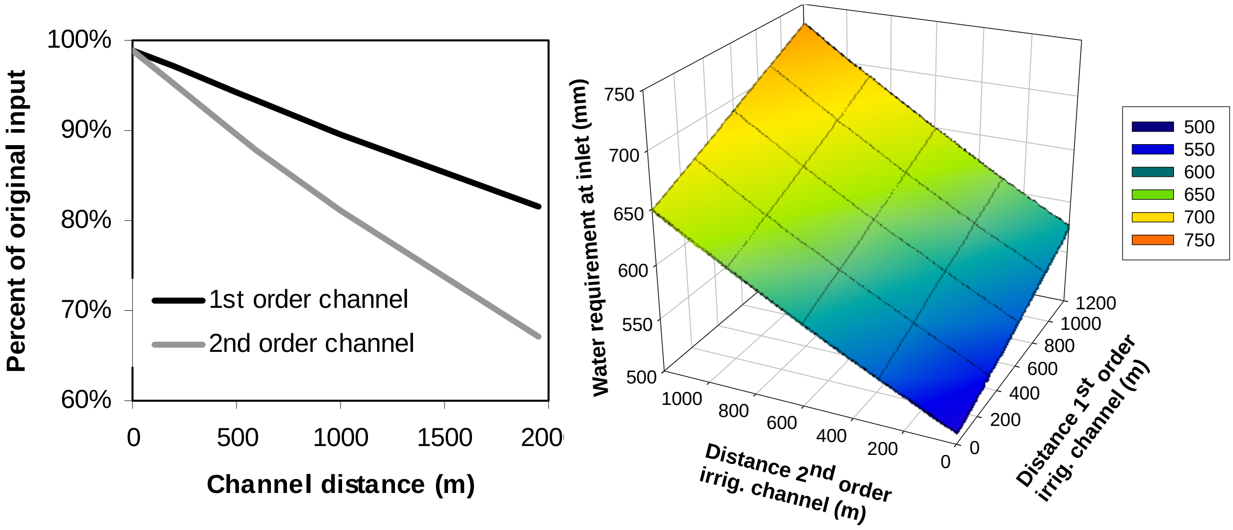


Figure 23: Loss of irrigation water by seepage as a function of channel length, left: individual percentage losses for first and second order channels, right, combined absolute effect assuming exemplarily a field irrigation requirement of 500 mm.

The applied function is a distance-based equation, excluding individual conditions of channels, or their slopes, material, surrounding GW table, etc. Once these are available, however, they can be used to extend the current approach. This procedure supports a truly spatial optimization of water allocation in so far as it penalizes non-productive use of water by seepage over longer conveyance distances. If saving irrigation water is a goal, water demanding crops like rice would therefore theoretically better be grouped closer to the main water inlet.

In the next version of FLEOM a similar scheme will be developed for farm-field distances and access to land by machinery. The first, for instance would penalize distant-farming by increased requirements for diesel and labor-time (for merely reaching the field), the second could be used to decide whether e.g. machine harvest of winter-wheat is at all possible, or whether it has to be substituted by manual harvesting.

4.1.7 Calibration of CropSyst

Crop model calibration was completed for cotton, winter wheat and maize. Besides gathering field data for this purpose, model calibration was the most labor- and time-intensive part. In the following, a brief summary of the CropSyst model calibration is provided. Details of this calibration and the biophysical routines used in CropSyst can be found in Kienzler (2010), Djumaniyazova et al. (2010) and Sommer et al. (2008).

CropSyst calibration was done step-wise. It started with the calibration of optimal crop growth. Subsequently the potentially yield limiting factors water, salt and nitrogen were included.

After successful calibration, optimal growth of cotton in 2005 (Kienzler, 2010), i.e. aboveground biomass (AGB) and leaf area index (LAI) development could be reproduced with a root mean square error (RMSE) between simulated and observed LAI and AGB of 0.34 m^2 m^{-2} and 0.95 Mg ha^{-1}, respectively (n=5; Sommer et al., 2008;Figure 24).

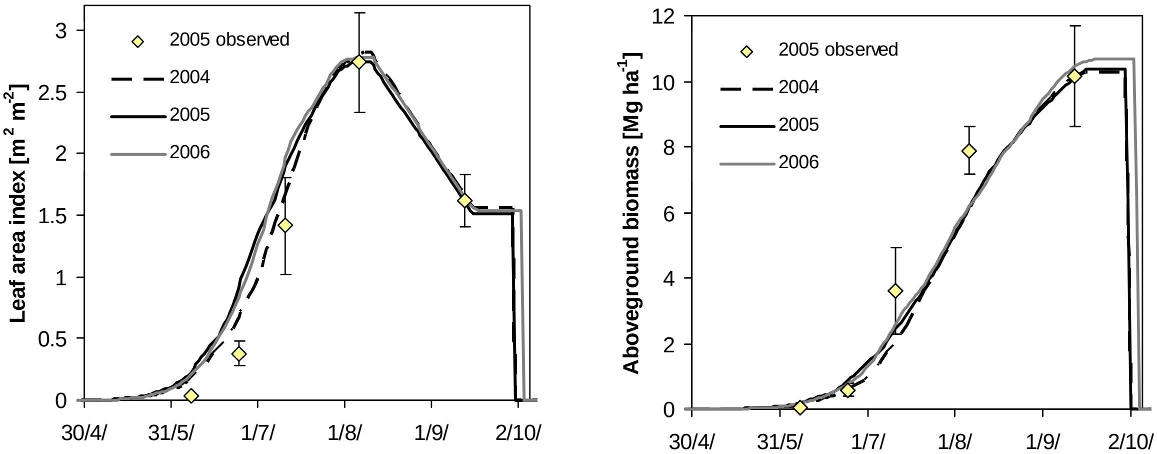


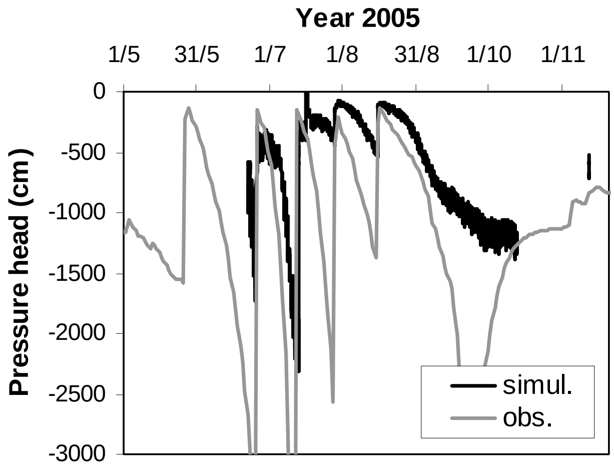
Figure 24: Observed (points) and simulated (lines) leaf area index (left) and aboveground biomass (right) in 2005, as well as simulated LAI and AGB in 2004 and 2006; bars denote the standard deviation

Simulation of optimal growth of winter wheat (2005-06 data set) achieved RMSEs of 0.37 m^2 m^{-2} for LAI and 2.6 Mg ha^{-1} for AGB (n=4; figure not shown). The latter was rather high, because the mid-season rapid increase of AGB could not be predicted sufficiently. However, simulated AGB at maturity (12.0 Mg ha^{-1}) closely matched observed AGB (12.2 Mg ha^{-1}). The same was true for yield.

Similarly to winter wheat, simulations of optimal growth of maize yielded a RMSE of 0.45 m^2 m^{-2} and 2.0 Mg ha^{-1} (n=8) for LAI and biomass, respectively. Again, despite some deviations of observed and simulated AGB during rapid growth, AGB at maturity as well as yield was well predicted.

Soil water dynamics under cotton and wheat were studied by simultaneous automated measurements of soil moisture and soil pressure head at different depths. These data sets served for the calibration of soil hydraulic properties in Hydrus-1D (Forkutsa et al., 2009). Transfer of these parameters from Hydrus-1D followed the procedures as described in Sommer and Stockle (2010). With these optimized soil hydraulic parameters (compare loam inTable 8) simulated soil moisture and pressure head under cotton matched observations reasonably well (Figure 25).

a)



b)

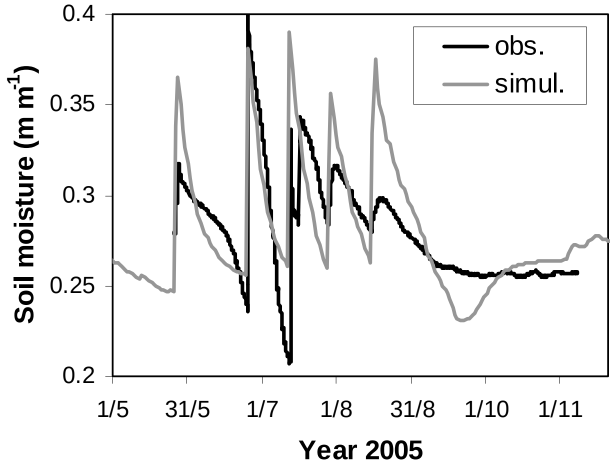


Figure 25: Observed and simulated pressure head (a) and volumetric soil moisture (b) at 20 cm depth under cotton in 2005

In CropSyst, the influence of soil salinity on crop growth is considered by the variables describing the soil solution osmotic potential for 50 % yield reduction and the Van-Genuchten salinity tolerance exponent. No own specific data were available to adjust these two parameters. However, crop response to salinity was well described for a number of crops by Abrol et al. (1988). The Van-Genuchten exponent describes the steepness of the salinity response curves. Thus together with the osmotic potential for 50 % yield reduction it could be manually adjusted so that the salinity response curve of each of the crops would match the Maas andHoffmann (1977) yield-salinity-curves, on which Abrol et al. (1988) based their assessments.

Kienzler (2010) and Djumaniyazova et al. (2010) studied the response of cotton and winter wheat growth to N-fertilization. Both applied CropSyst for simulating this response. Cotton response to N-fertilization was weak, but yet significant. Zero-N application resulted in a higher yield than the application of 42 kg N ha^{-1}; a phenomenon that could neither be well explained nor simulated correctly (Figure 26).

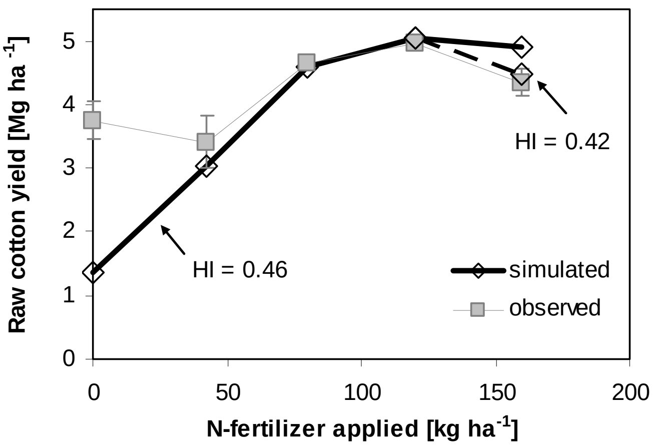


Figure 26: Observed (Kienzler, 2010) and simulated raw cotton yield in response to different levels of N-fertilizer applications and for 160 kg N ha^{-1} with two different harvest indices (HI); bars denote the standard error of the mean

The actual fertilizer response, however, was very well predicted. Merely yield at highest N-level (160 kg ha^{-1}) was overestimated, because *in-situ* harvest index (HI) dropped from 0.46 to 0.42 at that level. Simulated yield would approximate observed yield when this was manually corrected in the model. The RMSE between observed and simulated yield was 1.1 Mg ha^{-1} if the zero-N level and a fixed HI of 0.46 was included, and only 0.04 Mg ha^{-1} without zero-N and a HI of 0.42 at highest N-level.

Similarly, irrigation and fertilizer response of winter wheat was simulated with CropSyst using data of two seasons comprising three different irrigation levels and four levels of N-fertilization (Djumaniyazova et al., 2010). The RMSE between observed and simulated yield of winter wheat across all irrigation and fertilizer levels was 0.61 Mg ha^{-1} (Figure 27).

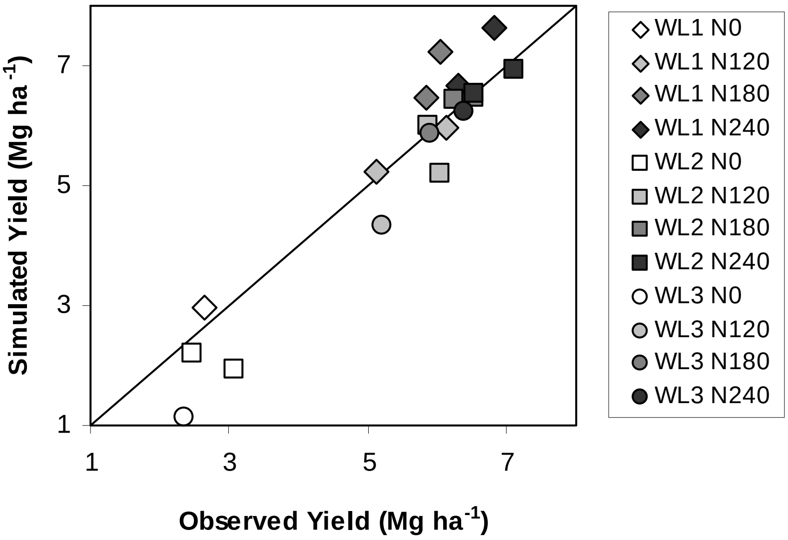


Figure 27: Simulated yield plotted against observed yield (Djumaniyazova et al., 2010)

The optimized CropSyst settings for cotton and winter wheat to N-response were used for simulating the four different fertilization levels as defined in chapter 4.1.1.4. For maize CropSyst standards were used.

Table 16 provides a comprehensive overview of all important CropSyst parameters. The last four parameters in Table 16 are agro-ecosystem-specific, are largely unrelated to the actual crop grown, but they drive the soil N_{min} cycle and simulate how much NH_4, NO_3, nitrous oxide and N_2 is produced. CropSyst default for the first three parameters is 0.8. Those have been developed for soils in the temperate climate of northern USA. In the course of calibrating SOM decomposition and matching simulated and observed NO_3 and NH_4 concentration in a soil under cotton cultivation, they have been optimized. The results show that in Khorezm:

(i) the readily decomposable SOM fraction (light fraction) constitutes only an insignificant part to SOM and consequently the overall mineralization rate of SOM is low;

(ii) the nitrification (conversion of NH_4 into NO_3) occurs comparably faster, i.e. the high soil temperatures in combination with favorable soil moisture stir a faster nitrification than accounted for by the moisture-temperature nitrification function of CropSyst; and

(iii) analogously, denitrification rate (conversion of NO_3 into nitrous oxide or N_2) is considerably higher than under comparable conditions in temperate regions.

Table 16: CropSyst model settings for cotton, winter-wheat and maize; C = calibrated parameters, D = model default, O = observed data

Characteristic	Cotton		Winter-wheat		Maize	
	Value	Source	Value	Source	Value	Source
Life cycle, photosynthetic pathway, land use	Annual C3 row crop		Annual C3 row crop		Annual C4 row crop	
Harvested biomass	Seed¶		Seed		Seed	
Biomass-transpiration coefficient (kg m^{-2} kPa m^{-1})	8.2	C	10.5	C	16	C
Radiation use efficiency (g MJ^{-1})	2.3	C	3.0	C	3.0	C
Act. to pot. transpiration ratio that limits leaf area growth	0.8	C	0.95	D	0.9	D
Act. to pot. transpiration ratio that limits root growth	0.5	D	0.5	D	0.7	D
Optimum mean daily temperature for growth	25	C	20	D	25	D
Initial green leaf area index (m^2 m^{-2})	0.011	D/C$	0.011	D/C	0.02	C
Expected maximum LAI (m^2 m^{-2})	3	O	6	C	3	C
Specific leaf area, SLA (m^2 kg^{-1})	13.0	O	17	C	20	C
Leaf/stem partition coefficient, SLP	2.6	C	2.5	C	8	C
Leaf duration (°C day)	1000	C	520	C	730	C
Leaf duration sensitivity to water stress	1	D	1	D	1	D
Fraction of maximum LAI at physiological maturity	0.55	O	0.8	C	0.85	C
Maximum rooting depth (m)	0.9	O	1.1	C	1	C
Root length per unit root mass (km kg^{-1})	90	D	90	D	90	D
Surface root density (cm cm^{-3})	6.0	D	6	C	6	C
Curvature of root density distribution	0.5	C	1	C	1	C
Extinction coefficient for solar radiation	0.9	(Ko et al., 2005)	0.7	D	0.7	D
ET crop coefficient at full canopy	1.1	D/C	1.1	D/C	1.2	D/C
Maximum water uptake (mm d^{-1})	14	C	10	D	14	D
Leaf water pot. at the onset of stomatal closure (J kg^{-1})	-1000	C	-1300	D	-800	D
Wilting leaf water potential (J kg^{-1})	-1500	C	-2000	D	-1300	D
Accumulated growing degree days from seeding						
to emergence (°C day)	110	O	100	C	150	C
to maximum rooting depth (°C day)		O	350	C	1040	C
to end of vegetative growth (°C day)		O	345	C	1150	C
to begin flowering (°C day)		C	420	C	665	C
to beginning grain filling (°C day)		C	500	C	757	C
to maturity (°C day)	1630	C	750	C	1260	C
Adjustment factor phenologic response to water stress	1	D	1	D	1	D
Base temperature at daily resolution (°C)	8	C	5	C	8	C
Cutoff temperature at daily resolution (°C)	20	C	28	C	30	C
Unstressed harvest index	0.46	O	0.46	O	0.46	O
Sensitivity to water and N stress during flowering	0.7	C	0.6	C	0.8	D
Sensitivity to water and N stress during grain filling	0.5	C	0.4	C	0.6	D
Translocation to yield factor	0.4	C	0.3	D	0.3	D
Nitrogen demand adjustment	1	D	0.8	C	1	D
Max. N concentration of chaff and stubble (kg N kg^{-1})	0.008	O	0.006	O	0.007	D
Standard root N concentration	0.007	O	0.006	O	0.007	D
Max. N uptake during rapid linear growth (kg ha^{-1} d^{-1})	6.5	C	5	D	5	D
Residual N not available for uptake (mg kg^{-1})	4.0	C	4	C	4	C
Soil N conc. at which uptake starts decreasing (mg kg^{-1})	13.0	C	12	C	12	C
PAW at which uptake starts decreasing	0.5	D	0.5	D	0.7	D
Soil solution osmotic pot. for 50 % yield reduction (kPa)	-623.4	(Abrol et al., 1988)	-504	(Abrol et al., 1988)	-216	(Abrol et al., 1988)
Salinity tolerance exponent (Van-Genuchten)	4	C	3	C	3	C
Soil N transformation (single SOM pool model):						
Mineralization rate adjustment	0.2	C	0.2	C	0.2	C
Nitrification rate adjustment	2	C	2	C	2	C
Denitrification rate adjustment	6	C	6	C	6	C
Maximum transformation depth	0.5	D/C	0.5	D/C	0.5	D/C

¶ assumed to include cotton lint

$ calibrated, but default turned out to be optimal

4.2 Socio-economy and GAMS-based LP

The optimization LP module of FLEOM is designed to economically evaluate technological advancements and innovations or other changes within or outside a single farm, a group of farms or a farm association as exist in Uzbekistan. The model optimizes at each of these options production activities at the level of a farm field, as the smallest unit, using the constraints defined at a farm level for a one-year period. The LP module allows for effects within a year rotation taking into account the soil attributes of each field.

4.2.1 LP structure of FLEOM

The LP model within FLEOM is deterministic and uses the general characteristics of a simple farm model presented by Hazel and Norton (1986) and Kingwell (1987) for evaluating the impact of external shocks on cropping patterns in selected fields and farms. The present version of FLEOM is a static model, and assumes that the adaptation in the cropping pattern in response to the intervention occurs instantaneous without a time lag. Results obtained after implementing an exogenous shock in scenario simulations are compared with the base-run results.

Similar to the model itself, the solution comparisons are also static. The model is linear and in its base-run solution it does not replicate the cropping patterns of selected fields observed in the base year 2007. The model is not yet calibrated to replicate the observed situation. This is anticipated in the future after introducing the non-linear cost terms of the positive mathematical programming approach as advocated by Heckelei (2002).

The activities and constraints of the LP module of FLEOM are shown in a simplified and grouped form in Table 17. The groups of activities are shown at the top of the table under eight headings which represent cropping activities, output selling on market and to state organization, purchase of fertilizer and diesel, labor hiring, credit borrowing, and fodder purchasing. The rows of the matrix indicate the type and form of the constraints included such as total land availability, labor, fertilizer, and fuel endowments in each farm, the livestock feeding requirements, product balance calculations, state order regulations, crop rotation, and environmental restrictions.

The model endogenously determines cropping activities based on producer preferences, which in turn are shaped by production technologies. The major dimensions of cf^{th} cropping activities are as follows: (1) three alternative water application practices in combination with (2) four nitrogen fertilizer applications are simulated for (3) start of crop production at three different planting dates (see sections 4.1.1.2, 4.1.1.3 and 4.1.1.4). The model aggregates each cf^{th} cropping activity into c^{th} crop groups.

The objective function maximizes the profit of cropping activities, i.e. total return from crop selling activities minus variable costs including fertilizer, diesel and fodder purchases, labor hiring, payments for credits and fixed crop production costs. The inclusion of a profit maximizing objective function instead of an objective function that minimizes the risk is motivated by the purpose of the farm model, which is to predict or evaluate change at the farm level. In this regard it is more important to accurately represent the physical and biological relationships of inputs and outputs, rather than develop risk determinants in the model (Kingwell 2000). The output of the model will indicate the corresponding optimal cropping pattern. Additionally, the model results will show how much labor to use and hire, amounts of fertilizer and diesel to purchase and the amount of credit to borrow. Since FLEOM incorporates biophysical and economic parameters, its results can demonstrate the effects of optimal crop and soil management on soil quality. The model produce information for researchers and policy makers in form of dual values, e.g. shadow prices of land, water and procurement tasks.

In the following, upper case letters denote variables and lower case letters denote parameters and sets presented in Table 17.

Table 17: Outline of the LP structure of FLEOM

Activities / *Constraints*	$Xlevl_{d,cf}$	$Xmsale_{f,c}$	$Xssale_{f,c}$	$FertF_{f,j}$	$DislF_f$	$LabrF_f$	$Credit_f$	$FodrF_{f,n}$		*Right-hand side*	
Land use	$+caln_{c,m}$								<=	$land\_b_{d,m}$	Available land (ha)
Nitrogen fertilizer requirements	$+nitr_{cf}$			$-nitrC_j$					<=	$fert\_b_{f,j}$	Available fertilizer in farm (kg)
Diesel requirements	$+disl_c$				-1				<=	$disl\_b_f$	Available diesel in farm (kg)
Labour requirements	$+labr_c$					-1			<=	$labr\_b_f$	Available fixed labor in farm (wh)
Water requirements	$+watr_{cf}$								<=	$watr\_b_h$	Available water in irrigation network (m^3)
Animal feeding requirements	$+feedR_{cf,n}$							$-feedN_{a,n}$	=>	$anim\_b_{f,a}$	Livestock and poultry heads in farms (head)
Cash-flow requirements	$-fixC_c$	$+mkP_c$	$+soP_c$	$-fertP_j$	-dislP	-labrP	-1	$-fodrP_n$	<=	$cash\_b_f$	Annual cash available in farms (UZS)
Production	$-yild_{cf}$	+1	+1						<=	0	Production balance (kg)
Credit availability							+1		<=	$credit\_b_f$	Maximum level of credits available to farms (UZS)
State order tasks for land allocation	+1								=>	$sord\_b_{f,c}$	Minimum area required for cotton cultivation (ha)
State order tasks for output			+1						=>	$stask\_b_{f,c}$	Minimum output to be sold by farms to state organization (kg)
Rotation restrictions	+1								<=	$rotat\_b_{d,c}$	Maximum level of crop rotation
Soil salinity restriction	$+soilS_{cf}$								<=	$soilsal\_b_d$	Maximum level of soil salinity allowed after crop production (ds ha^{-1})
Maximum nitrogen leaching restriction	$+leacM_{cf}$								<=	$maxleach\_b_d$	Maximum level of nitrogen leached after crop production (kg ha^{-1})
Objective function	$-fixC_c$	$+mkP_c$	$+soPr_c$	$-fertP_j$	-dislP	-labrP	-credP	$-fodrP_n$	=	Profit	Total whole-farm profut (UZS)

where the sets are as follows:

Code	**Description**
cf	Crops
c	Aggregated crop groups
d	Farm fields used for alternative cropping activities
f	Aggregated farm groups
h	Irrigation network location
m	Periods of field use by aggregated crops
j	Fertilizer type
n	Fodder type
a	Animal type

The model variables are:

Code	Indices	Description
Profit	*f*	Total whole-farm profit to be maximized
Xlevl	*d,cf*	Production activity levels in farm fields
Xmsale	*f,c*	Commodity marketing by farms
Xssale	*f,c*	Commodity sale to state organization by farms
FertF	*f,j*	Fertilizer purchasing by farms
DislF	*f*	Diesel purchasing by farms
LabrF	*f*	Labor hiring by farms
Credit	*f*	Credit borrowing by farms
FodrF	*f,n*	Fodder purchasing by farms

The model parameters are:

Code	Indices	Description
caln	*c,m*	Cropping calendar
watr	*cf*	Water application for cropping activity
nitr	*cf*	Nitrogen application for cropping activity
nitrC	*j*	Nitrogen content in fertilizers
dies	*c*	Diesel application for cropping activity
labr	*c*	Labor application for cropping activity
yild	*cf*	Crop yield
fertP	*j*	Fertilizer prices
dislP		Diesel price
mkP	*c*	Market price of commodity
soP	*c*	State price of commodity
labrP		Wage for hired labor
fodrP	*n*	Fodder prices
credP		Interest rate for credit
fixC	*c*	Fixed costs of cropping activity
land_b	*d*	Area of farm field
fert_b	*f,j*	Annual fertilizer endowments in farms
disl_b	*f*	Annual diesel endowments in farms
labr_b	*f*	Annual permanent workers in farms
watr_b	*h*	Annual water availability in irrigation network
anim_b	*f,a*	Livestock and poultry heads in farms
cash_b	*f*	Annual cash available in farms
credit_b	*f*	Maximum level of credits available to farms
sord_b	*f,c*	Minimum area required for cotton cultivation
stask_b	*f,c*	Minimum output to be sold by farms to state organization
rotat_b	*d,c*	Maximum level of crop rotation

soilsal_b	*d*	Maximum level of soil salinity allowed after crop production
maxleach_b	*d*	Maximum level of nitrogen leached after crop production

The variations in gross-margins within cf^{th} cropping activity are based on variations in crop yields ($yild_{cf}$) and application rates of fertilizer ($nitr_{cf}$) and water ($watr_{cf}$), assuming all other costs as fixed among different crop cultivation practices. The fixed costs ($fixC_c$) of cf^{th} cropping activities are calculated separately from the LP model and contain the costs of inputs which may directly affect producer decisions such as costs of seeds, pesticides, full payments for permanent labor and machinery costs. These are valued at their observed market prices. The production technologies are initially specified in fixed proportions of size of farm fields, labor, diesel fuel, nitrogen fertilizer, and water. Other inputs are not yet included.

The constraints in FLEOM can be classified into three groups such as resources, state policies and environment. It is assumed that resources can be purchased from the markets, but cannot be traded between *f* farm aggregates. The constraints in FLEOM are:

1. The land constraint ($land\_b_{d,m}$): This is specified for d^{th} fields that are aggregated into f^{th} farms. The number of m^{th} time periods is kept at a minimum to cover the basic cropping schedule options. The cropping calendar ($caln_{c,m}$) covers the regional agriculture characteristic of a double cropping schedule, according to which two crops can be grown and harvested from the same location during the assumed agricultural period of 12 months.
2. The fertilizer constraint is presented as the annual nitrogen (since N is the main limiting factor for cop growth in the study region) required for cropping activity. The values of each nitrogen application technology ($nitr_{cf}$) are generated in CropSyst. It is assumed that f^{th} farm has a specified amount of fertilizer ($fert\_b_{f,j}$) and can buy additional amounts ($FertF_{f,j}$). The purchased amount of fertilizer is transferred into elementary nitrogen according to the nitrogen content ($nitrC_j$) in the j^{th} fertilizer. Unused fertilizer is assumed being stored in farm.
3. The irrigation water requirement ($watr_{cf}$), for the cf^{th} alternative cropping activity is generated by the CropSyst simulations. The water endowments ($watr\_b_h$) are fixed at annual volumes of water in h^{th} irrigation network. According to this, the d^{th} field is aggregated into h^{th} irrigation network area.
4. Diesel, required for crop production, indicates fuel costs for machine field operations and water pumping. Similar to fertilizers, f^{th} farm has a specified amount of diesel ($disl\_b_f$) and can buy ($DislF_f$) additional amounts. The diesel requirements ($disl_c$) for c^{th} crop production include diesel used for output trading to market ($Xmsale_{f,c}$) and state organization ($Xssale_{f,c}$), as well as for irrigation.
5. Although labor is not reported as a constraint in the agricultural production in Khorezm (in fact there is a relatively high rural underemployment in the agricultural sector), the significance of including labor as a restraint in this study is to analyze the potential employment creation by agricultural production constraints in each farm aggregate. The annual amount of available working hours per person is assumed to be 2,400 h. The values of labor endowment ($labr\_b_f$) in f^{th} farm was formed by summing the total annual hours of permanent and family workers per hectare of an average farm in Khorezm in 2003. The units are in terms of adult working hours with weights of 1 for males and females between 15 and

65 years old, 0.8 for males and females over 65, and 0.5 for children aged less than 15. Apart from fixed farm labour (*$labr\_b_f$*), hiring additional labor (*$LabrF_f$*) is made possible The labor requirements (*$labr_c$*) for c^{th} cropping activity include labor used for all operations in the field and proportional to the amount of water (*$watr_{cf}$*) and nitrogen fertilizer (*$nitr_{cf}$*) application rates and harvested yield (*$yild_{cf}$*).

6. The cropping activities (*$Xlevl_{d,cf}$*) are also restricted by n^{th} fodder produced by cf^{th} crop growing activities. Fodder production has to match the amount required for feeding the number of a^{th} livestock in f^{th} farm, whereas additional fodder can be purchased (*$FordF_{f,n}$*) on the market. It was assumed that the feeding technology (*$feedN_{a,n}$*) does not vary across farms.
7. Cash-flow constraints define that total amount of funds available (*$cash\_b_f$*) to f^{th} farm, amount of credit borrowed from banks (*$Credit_f$*) and total value of crop sold on markets (*$Xmsale_{f,c}$*) and to state organization (*$Xssale_{f,c}$*) is not less than the costs generated during the agricultural activities such as cropping (*$Xlevl_{d,cf}$*), input purchasing (*$FertF_{f,j}$* and *$DislF_f$*), labor hiring (*$LabrF_f$*), and fodder purchasing (*$FodrF_{f,n}$*). Additionally, a maximum credit constraint is imposed according to which there is a specific amount of money (*$credit\_b_f$*) which f^{th} farm can borrow from banks at unified (*credP*) interest rate.
8. FLEOM features commodity balance equation for each farm aggregate, which guarantee that the amount of crop traded by f^{th} farm to markets (*$Xmsale_{f,c}$*) and to state organization (*$Xssale_{f,c}$*) is not greater than the amount produced by the f^{th} farm.
9. Policy instrument constraints relate to government policy objectives for regional and national development and are similar to target variables. The state policy instrument constraint of the model requires that c^{th} activity levels for cotton production in f^{th} farm aggregate are not less than the assigned area (*$sord\_b_{f,c}$*) by the state. Additionally, a minimum level constraint is imposed for the amount of grains which is required to be delivered to state organizations (*$stask\_b_{f,c}$*).
10. Rotation constraints are related to the maximum number of c^{th} crops in d^{th} field. For agronomic reasons rotation restrictions (*$rotat\_b_{f,c}$*) were set for individual crops as for groups of crops. In this way, cotton cannot be cultivated in fields, which are smaller than 0.1 hectare.
11. Two environmental issues are included through constraints for soil parameters, namely (i) the maximum level of nitrogen leached (*$maxleach\_b_d$*) and (ii) the maximum level of soil salinity (*$soilsal\_b_d$*). The soil fertility of fields depends on cropping activities of a farm. These constraints depict the levels of specific soil parameters of d^{th} field modified after cf^{th} crop production activities. For various reasons the maximum levels can be adjusted by a user depending on his environmental strategy, such as to improve, maintain or ignore care about soil quality of modeled fields.

Compared to the depiction of the farm model presented in Hazel and Norton (1986), FLEOM has a number of simplifications: First, the model omits commodity processing activities. Secondly, it omits the inter-farm product and input trading activities. To simplify the features of the regional farm, several assumptions for the model were therefore formulated:

- The selected area is small enough so that production will not affect the regional commodity prices;
- Products within each commodity type are homogeneous;
- Relationships between inputs and outputs are linear in form of single Leontieff technologies.

The model solves for the optimal values of cropping activities using LP CONOPT solver in GAMS (General Algebraic Modeling System).

4.2.2 Socio-economic date sources

The necessary dataset was compiled from 2007 values and consists of several categories such as social and policy conditions of the region, regional input and output prices, production pattern, input-output coefficients, resource and input endowments. The micro-level data represent distributional impacts of agricultural systems in either economic or environmental terms (Brown, 2000; Antle et al., 2004c). Although, the model allows capturing *f* group of farms, each of them must be described by the relevant database. During the base simulation by FLEOM, the same dataset is used for all farms. To distinguish socio-economic parameters for each farm, it is recommended to interview managers of each modeled farm.

The technical input–output coefficients such as yield, water application and fertilization rates are derived from the agroecological simulation approach using CropSyst. The data on diesel use, working hours of combine harvesters and commodity transportation costs is based on norms developed by the Ministry of Agriculture and Water Resources of Uzbekistan (MAWR) in 1997. Farm and household surveys conducted in 2003 and 2004 (Djanibekov, 2008b) provided information for structuring relevant activities and constraints of each farm aggregate and establishing proper cropping calendar of the modeled crops. Information on input and output prices were obtained from farm interviews conducted in 2007. Resource endowments such as total labor supply, and available real elementary nitrogen, were derived from official reports of OblStat. The total values of water use for crop production in 2007 were calculated from the average water use per hectare reported by Department of Agriculture and Water Resources of Khorezm Region (*OblSelVodKhoz*). Data on animal feeding requirements and recommendations, as well as nutrient content of crops were acquired from secondary sources on animal keeping in Khorezm region and Uzbekistan from Abdolniyozov (2000) and Dalakyan Rakhmanova (1986).

4.3 GIS and data base

4.3.1 GIS

One of the advantages of FLEOM is the visualization of maps based on GIS methodologies.

BBN Technologies' OpenMap ™ package – an open-source toolkit based on JavaBeans – was used as a base for the visualization component of FLEOM. OpenMap provides the means to allow users to see and manipulate geospatial information. The facilities provided by OpenMap package include (among others) the following:

- Visualization of “Shape”-files
- Panning, zoom-in/zoom-out
- Arranging multiple layers on a map
- Selection of individual elements from a layer
- Drawing all layer elements using the same (uniform) symbology
- Customization of layer symbology

These assets were complemented with features of OpenMap such as:

- Selection of multiple elements of a layer
  Selection of multiple elements of a layer can be controlled in several ways:
  - Selection/de-selection of all layer elements
  - Adding/removal of individual (selected) element to/from current selection
  - Selecting multiple elements based on a query, such as “Select all polygons with area larger than *N* hectares”
- More flexible layer symbology
  The visualization of layer elements was improved by using different symbology to different classes of layer elements. Visualization options provided in ESRI ArcGIS software package was used as a template in this case:
  - **Category**-based classification – layer elements are categorized based on a certain attribute field value and each category is displayed differently. For example, areas with shallow ground water level can be colorized differently than areas with deep ground water level.
  - **Quantity**-based classification – layer elements are split into several quantity classes based on a certain attribute field value and each class is displayed differently. For example, field area can be used as a classification quantity to display larger fields with darker colors and smaller fields with lighter colors.
- Map legend
  Legend provides information about the symbology used by each layer of the map

This set of GIS functionality responded to the present demands of FLEOM. A full-fledged GIS analysis in FLEOM is not included. However, if desired, FLEOM results can be exported and analyzed in external GIS software.

4.3.2 Database

All of the data used by FLEOM is stored in a Microsoft Access database. Note that FLEOM does not require that Microsoft Access DBMS software is installed on the computer – when FLEOM is installed, the database is configured on the system as an ODBC (“Open Database Connectivity”) data source using standard Microsoft Access driver for ODBC found on most systems. A standard JDBC ("Java Database Connectivity") driver supplied with Java Runtime Environment connects the database from within the FLEOM application.

The database acts as a data exchange point for the components of FLEOM:

- GIS component uses CropSyst simulation data as well as the optimization results stored in the database for visualization – it does so by performing a "JOIN" operation on the database table(s) with the shape files' attribute tables.
- GIS component also stores information about the fields selected by the users in the database.
- Optimization component (GAMS) retrieves information about the fields selected by the user, as well as various input parameters entered by the user from the database before performing optimization, and then stores the results back into the database.
- GUI provides means of viewing the data produced by GAMS in tabular as well as chart form.

Tables found in the database include:

- **Categories_econ** – contains information about the different categories of economic parameters
- **Crops** – contains information about the major crops used in the optimization
- **Dictionary** – contains translations of all terms used in FLEOM
- **Farms** – contains basic information about farms for which the optimization is performed
- **GUI_params_common** – contains information about the different parameters that can be changed using FLEOM GUI
- **Input_params_gams** – contains information about the different GAMS input parameters for which the user can update the values
- **Input_prices_gams** – contains information about the different GAMS input prices for which the user can update the values
- **IN_input_params** – contains the values for different GAMS input parameters entered by the user and which are passed on to the GAMS optimization
- **IN_input_prices** – contains the values for different GAMS input prices entered by the user and which are passed on to the GAMS optimization
- **IN_selected_fields** – contains information about the fields selected by the user for optimization
- **OUT_*** - several tables with prefix "OUT_" contain data produced by GAMS optimization
- **Params_econ** – contains information about the different economic parameters

4.4 GUI

The Graphical User Interface (GUI) is the main means of interaction between the user and the application.

FLEOM GUI was developed using Java's Swing package, which allows building various GUI forms (windows) and dialog boxes consisting of different kinds of standard GUI elements, such as command buttons, checkboxes, scrollbars, etc.

Some of the GUI elements are provided by the OpenMap package – these include map navigation/zoom panels, layer order arrangement forms, (uniform) symbology editing forms, and some others.

The following list describes the main forms of the FLEOM GUI:

- **Main form** – the "entry point" to the application, which is displayed when the application is launched and contains buttons used guide the user through the FLEOM optimization process.
- **Settings** – used to set the parameters that control various aspects of the application, such as the path to the GIS layers ("shape"-files), ODBC username and password, etc.
- **Visualization (GIS)** – contains the maps of the area, as well as means of controlling how the map is displayed and of selecting fields for optimization.
- **Input/Output Prices** – contains fields where the user can enter values for various input/output prices used in the optimization.
- **Farm Parameters** – contains fields where the user can enter values for various farm parameters used in the optimization.
- **Optimization Process** – contains information about the stages of optimization being performed.
- **Table Viewer** – allows the user view and analyze the data produced by GAMS optimization in tabular form.
- **Chart Viewer** – allows the user view and analyze the data produced by GAMS optimization in form of charts.
- **Map Viewer** – allows the user view and analyze the input data and data produced by GAMS optimization in forms of maps.
- **Save/Export** – this dialog box prompts for a file name to save the optimization description to.

Some of these forms contain buttons that, when clicked on, launch other forms or dialog boxes. Figure 4.5.1 contains the summary of all the forms used in the FLEOM GUI.

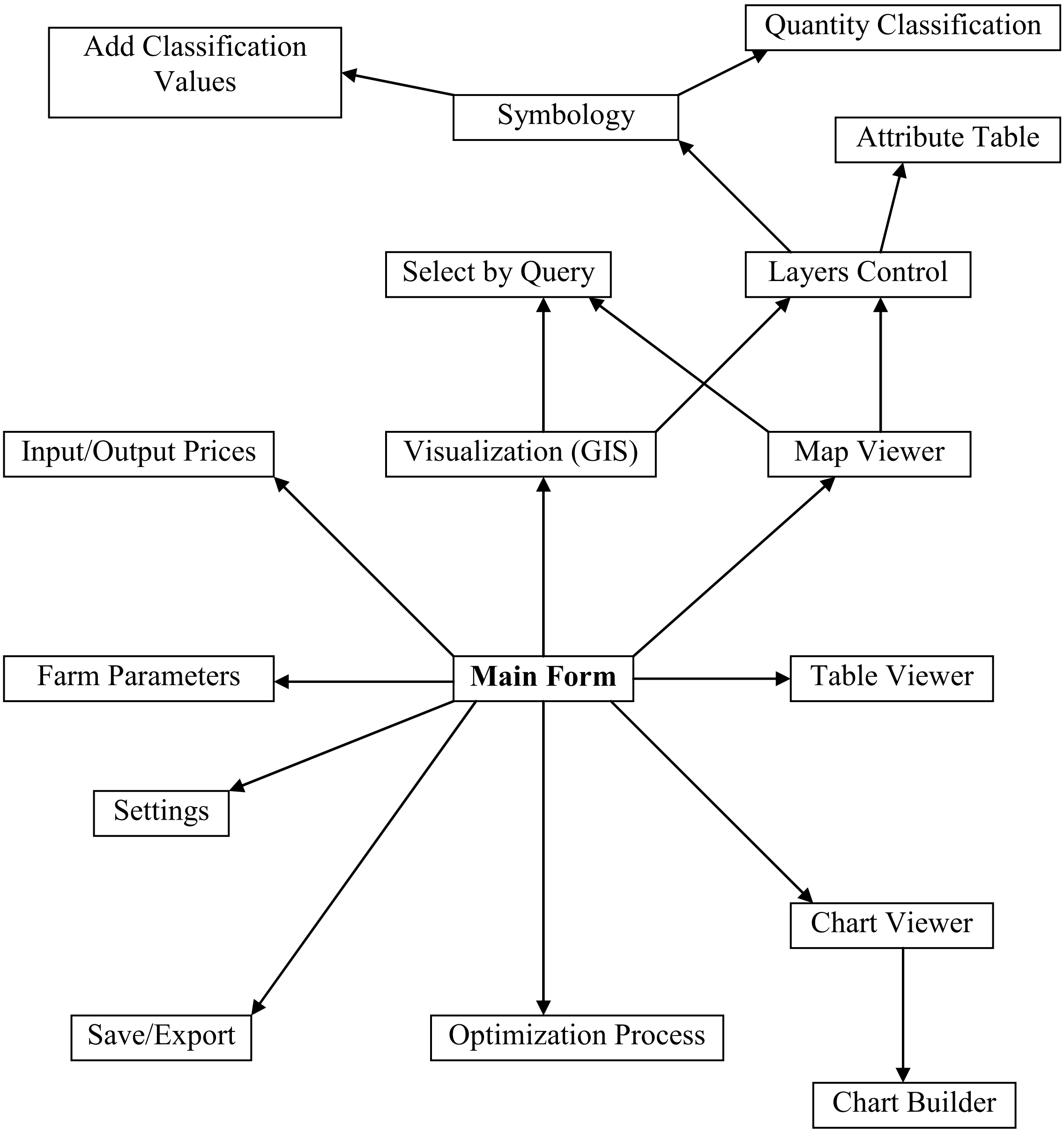


Figure 28: FLEOM GUI forms

5 Test application

The test application of FLEOM is based on four scenarios (henceforth called scenarios 1 through 4) each with different sets of assumptions relating to changes in socio-economic conditions. The scenarios were set up to demonstrate possibilities to simulate and optimize land use with FLEOM on the basis of economic and agro-ecological land-use drivers or constraints. The subsequent discussion focuses on the plausibility of results and general trends. Simulated quantities (of resource use, costs, profits, etc.) are assessed vis-à-vis this goal rather than to describe production potentials, constraints and possibilities in the very detail.

Pakhlavan-Makhmud Water User Association (PM-WUA) with its fields, soils, groundwater-levels and irrigation network as described in chapter 4, served as the test area[1] for the simulations. In reality (status 2008), around 100 individual private farms constitute the PM-WUA. However, to keep the FLEOM test application simple, and to highlight the generic sub-regional land use planning-tool character of FLEOM, the area of PM-WUA was arbitrarily divided into seven modeled farms (Figure 29).

[1]FLEOM is generic and can be used to simulate any WUA in Khorezm, provided that the agro-ecological framework conditions (field boundaries, irrigation network, soils, etc.) are parameterized in FLEOM's MS-Access database and in GIS shape files.

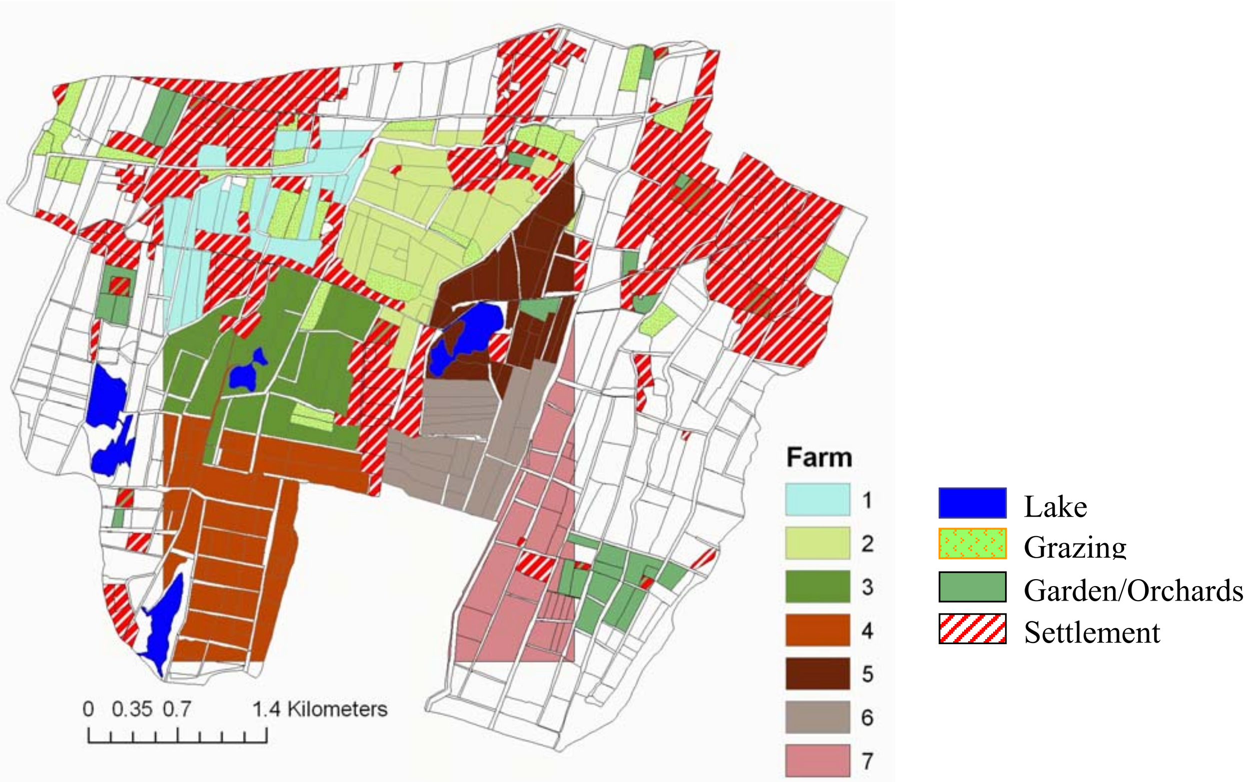


Figure 29: PM-WUA and its seven modeled farms

The individual farm size in terms of arable land ranged between 83 and 161 ha (Table 18)

Table 18: Size of the PM-WUA modeled farms

Farm	Size (ha)
1	90
2	121
3	135
4	161
5	83
6	84
7	147

5.1 Scenario description

Four scenarios were simulated:

1. "Business-as-usual"
2. "Relaxation of state order"
3. "Ecological market liberalization"
4. "Dry year"

In all four scenarios, the four crops cotton, wheat, rice and maize entered the simulations, and also livestock-production was considered. For the sake of simplicity, identical resource endowments were assigned to all seven modeled farms in the test WUA.[2]

The basic framework conditions of the scenarios are summarized in Table 19. Further agro-economic factors such as conversion rates or labor-requirements for the four simulated crops are provided in the Appendix.

Scenario 1 describes the situation under business-as-usual. Here the state-set price for raw cotton was 370 UZS (= 28 US cents[3)]) per kilogram, which is slightly below the world market price. The state imposes that at least 55 % of each individual farm area must be allocated to cotton production and one ton of wheat and rice must be sold for a price prescribed by the government. Total available water for irrigation is defined by multiplying the farm size with 18,000 m^3 ha^{-1}, the average volume of irrigation in a normal year. Consequently, maximum water use per farm is not greater than the total available water for irrigation. The amount of 18,000 m^3 ha^{-1} was chosen as to ensure that water should not constrain production in the scenario 1. This value corresponds to the average crop water use in the region (Mueller 2006); additionally it is assumed that water is sufficiently available in all crop growth stages.

Scenario 2 describes the relaxation of state order where area-based state order tasks for cotton as well as for the mandatory delivery of a certain amount of wheat and rice to the state agencies have been abolished. In this scenario, the price for raw cotton is raised to that at the world market (440 UZS kg^{-1} in 2007). All other parameters are identical to scenario 1.

Scenario 3 follows scenario 2, but in view of the fact that unconstrained water use and costless availability would trigger irrational use, a water price of 20 UZS (= 1.5 US cents) per cubic meter of water is introduced.

Scenario 4 finally assesses the potentially optimal production under conditions of water scarcity in a dry year. Similar to the real situation in the years 2000/2001, two pronounced dry years, actual water availability is reduced to 30 % of the availability in a normal year (such as in 2007).

Since the crop and input prices are fixed over all scenarios, the farm profits per hectare are solely defined by the changes in the crop yields, which in turn are subject to the input and resource availability, e.g. of water.

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[2] This does not mean, however, that all seven farms are equal. Given the different sizes of the farms, the distinct geographic location within the WUA and differences in soils, farms differed notably.

[3] At an exchange rate of 1 USD = 1319 UZS

Table 19: Costs, resource availability and assets of all seven modeled farms of PM-WUA for the four different scenarios; 1 USD = 1319 UZS

Parameter	Scenario 1 Business-as-usual	Scenario 2 relaxation of state order	Scenario 3 Eco-liberalization	Scenario 4 Dry year
Product prices (UZS kg^{-1})				
Raw cotton	370	440	440	370
Cottonseed cake		210		
Wheat, grains		400		
Wheat straw		70		
Rice, grains		900		
Rice straw		75		
Maize, grains		350		
Maize stem		80		
Cottonseed hull		180		
Fertilizer prices (UZS kg^{-1})				
Ammonium-Nitrate		200		
Ammonium-Phosphate		405		
Potassium-Chloride		730		
Ammonium-Sulfate		180		
Diesel price (UZS litre^{-1})		730		
Seed prices (UZS kg^{-1})				
Cotton		970		
Wheat		450		
Rice		900		
Maize		350		
Inter-farm canal efficiency (0-1)$^{\Pi}$		0		
Field-canal efficiency (0-1)$^{\Pi}$		0		
Max. availability of irrig. water (m^3 ha^{-1})	18,000	18,000	18,000	5400
Interest rate for credit (%)		25		
Water price (UZS m^{-3}) for				
Cotton	0	0	20	0
Wheat	0	0	20	0
Rice	0	0	20	0
Maize	0	0	20	0
Max. leaching of Nitrate (kg N ha^{-1})		Unconstraint		
Max. seasonal increase in soil salinity (dS m^{-1})		Unconstraint		
Share of farm land allocated for cotton according to state procurement task (%)	55	0	0	55
Wheat to be sold according to state procurement task (tons)	1	0	0	1
Rice to be sold according to state procurement task (tons)	1	0	0	0
Money in farm (Million UZS)		100		
Credit available for farm (Million UZS)		200		
(Family) working hours available (h)		12,000		
Number of cows		20		
Number of calves		20		
Number of bulls		15		
Number of poultry		40		

$^{\Pi}$ 0= unchanged, i.e. as current, 1 = lined, lossless canal

5.2 Results

5.2.1 Scenario 1 "business-as-usual"

Given the state order to produce cotton on 55 % of the land in scenario 1, land allocation to cotton dominated at PM-WUA in this simulation (Figure 30a). However, cotton under the defined production conditions could not compete with wheat-rice or wheat-maize (double) cropping, and thus cotton was not grown above the level defined by the state order. On the other hand, on all farms all available land was cultivated – no field was left fallow – and the land use rate with 145 % was at maximum (see line in Figure 32a). Rice was the most profitable crop and, by occupying between 32 % and 37 % of the land in the model farms, dominated as summer crop in this scenario. Maize was produced for fodder for own livestock production and occupied 8-13 % of the model farm land.

Even though rice ranked only third in area coverage in this scenario, total water use for this crop was highest (Figure 31a). This was due to the fact that rice fields are kept continuously inundated during the cropping season until about one week before rice maturity, and hence per-hectare water use is various times higher than for cotton wheat or maize. On average, between 27,325 m^3 ha^{-1} (farm 5) and 39,212 m^3 ha^{-1} (farm 4) of water was applied to produce between 5.0 and 6.6 t ha^{-1} rice. Total irrigation water use for the other three crops followed overall crop abundance, with cotton production consuming more water than wheat or maize (Figure 31a).

Constant farm costs, which account for land tax, salaries of permanent labor, transportation expenditures, and costs for diesel (for field operations) were the type of expenditures that ranked highest in this scenario 1; the absolute quantity depending on the modeled farm size (Figure 32a). These costs were followed by expenses for fertilizers and repaying credits and interests. The latter ranged between 5,222 USD for the smallest farm 5 and 33,189 USD for the largest farm 4.

All byproducts used for livestock keeping were produced on-farm, and thus no purchasing costs occurred. The same was true for irrigation water, as this was provided free of charge and abundantly in this scenario. Basically, cotton byproducts can be purchased by a farmer at the subsidized below-market prices subject to the quantity of raw cotton produced.

Under the assumptions in scenario 1, total farm profits ranged between 94,729 USD and 151,306 USD (Figure 33). Larger farms tended to make more profits than smaller farms, however also the location, i.e. the differences in the natural resource basis, influenced this trend. In fact, farms below 100 ha in size had the highest profit on a per-hectare basis (Figure 34). As expected, with 940 and 995 USD ha^{-1} profit was lowest for farms 4 and 7, respectively, located in the south of PM-WUA where the comparably less productive sandy soils were most abundant.

5.2.2 Scenario 2 "Relaxation of state order"

Given the higher profitability of double cropping (wheat-rice or wheat-maize) as compared to cotton growing only, the land use rate was at, or close to, the maximum of 200 % throughout (see line in Figure 32b). Also, cotton almost disappeared at PM-WUA when state order was abolished for this crop (Figure 30b). Cotton was only produced on farm 4 on 23 ha, on farm 7 on 27 ha, and on farm 1 on as little as 1 ha.

The reason for the decline in rice production in scenario 2 as compared to scenario 1 (farm 1, 4 and 7) lies in model specifications. The model optimizes the whole WUA using the collective scarce resource, i.e. water for irrigation. In scenario 2, when additional land is released via the abolishment of the state order, 18,000 m^3 ha^{-1} maximum water availability (on average for the whole WUA) constraints maximizing profits and a shift takes place in favor of less water intensive crops, i.e. from rice towards maize. This occurred in particular on farms with predominantly lighter, mostly sandy soils with high water percolation losses and accompanying leaching of fertilizers, which means a comparably lower fertilizer use efficiency and higher fertilization costs. Under these conditions, maize cultivation dominated over rice production.

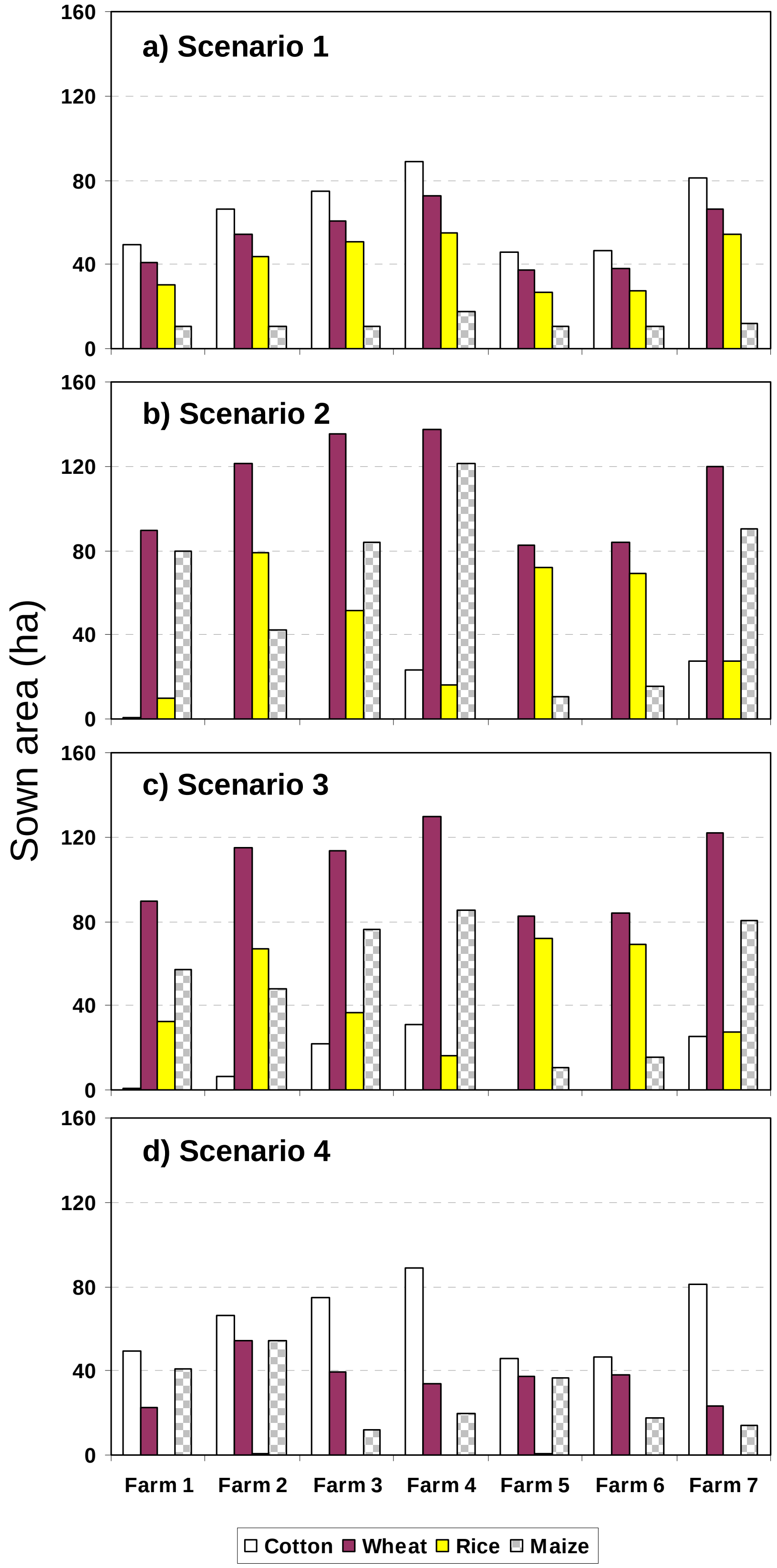

Figure 30: Farm crop allocation for the four scenarios

Except for the farms where maize cropping dominated as summer crop, total water use increased under scenario 2 as compared to the business-as-usual scenario (Figure 31b). The higher water use was related to increased land use and not to an increased use of water per hectare and higher per hectare production. Rather the contrary, the yield of maize, now at an average of 4.9 t ha^{-1}, had slightly decreased as compared to scenario 1 (5.1 t ha^{-1}). This finding indicates that spreading rather than concentrating crop production inputs is a more viable option under the assumptions of scenario 2.

Production costs under scenario 2 increased due to increased land use (Figure 32b), but relative distribution across the individual costs remained as observed in scenario 1. Byproducts appeared as additional costs under scenario 2, because cotton seed husk was no longer produced in sufficient quantities and had to be acquired as "feed" from outside the farm.

Total profits were higher on all farms under scenario 2 as compared to scenario 1 (Figure 33). This meant that state order for cotton damps farm profitability when water is provided free of charge. Profits on farms 2, 3, 5 and 6 which had comparably more area under rice, increased the most. These were also the farms that had the highest profits per hectare of farm land (Figure 34). In this regard, differences between farms related to the productivity of land (less productive soils in the south of PM-WUA) played out more strongly as compared to scenario 1. For instance, the farm profit per hectare of farm land with 2191 USD ha^{-1} of farm 5 (located in the north) was for instance almost double that of farm 4 (located in the south) that could only achieve 1120 USD ha^{-1}.

5.2.3 Scenario 3 "Ecological market liberalization"

A price for water, as simulated in scenario 2, is often discussed as a possible steering instrument to promote the rational and more eco-friendly use of irrigation water. Additionally the state income from water pricing could substitute for the income losses from abolishing state order for cotton (and state governed cotton exports).

With a water price incurred at the level of 1.5 US cents m^{-3} on top of the settings of scenario 2, land use rate of four out of the seven modeled farms decreased by 7 to 16 % (Figure 32c). As compared to scenario 2, relative crop allocation remained unchanged for farms 5 and 6 that maintained the maximum (200 %) land use rate (Figure 31c). Land use rate was also at 200 % for farm 1, but relative crop allocation changed. Since farm 1 (together with farm 2) was the closest to the main irrigation canals, it had less water conveyance losses and the additional costs formed by water pricing were smallest. Consequently, rice cultivation in farm 1 increased from 10 ha (scenario 2) to now 33 ha, whilst for the farms 2,3,4 and 7 the area under rice, which is the most water consuming crop, decreased slightly. Again, the optimization rule applied that FLEOM optimizes total WUA profits using the common resource water as one constraining parameter. Reducing rice production on the latter farms while increasing it on farm 1, is a particular result of this rule.

With the exception of farm 1, the total water consumption under scenario 3 was reduced (Figure 31c) as compared to scenario 2. However, a water price of 1.5 US cents m^{-3} only triggered water savings by between 1 and 16 %.

Total farm profits decreased on all farms (Figure 33), which was expected since the imposed water price adds to the production costs. Profits of four out of the seven farms were still higher than under scenario 1, which means that the increase in profits due to the abolishment of state order for cotton dominates over the increase in costs due to the introduction of water prices. This was concurrently the case for profits per hectare of farm land (Figure 35).

In total 14.67 million cubic meter of water were used by PM-WUA for irrigation in scenario 3. Therewith, the state income from payments for irrigation water – 1.5 US cents per cubic meter – amounted to 220,080 USD for PM-WUA with a total size of 812 ha arable land.

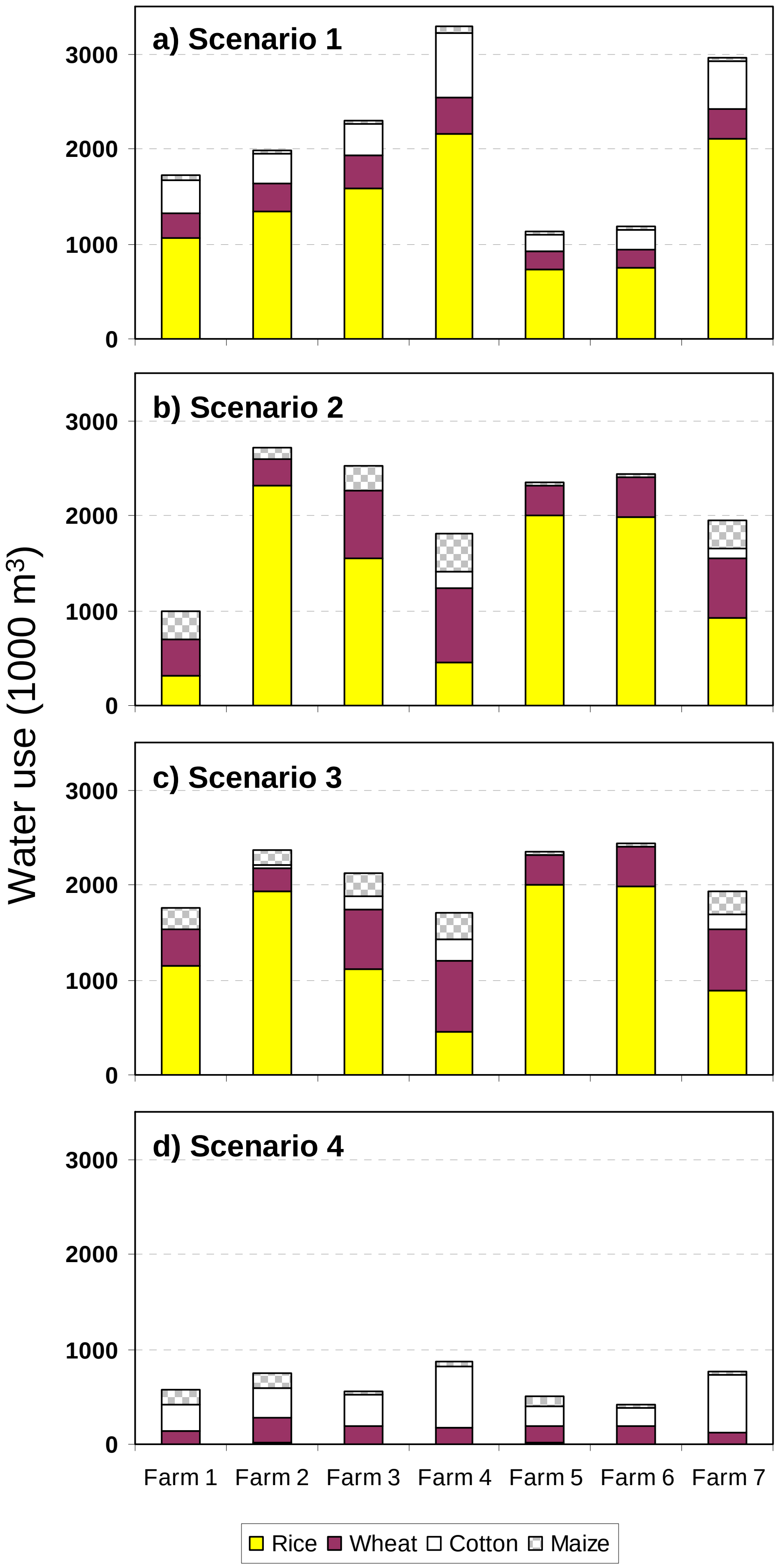

Figure 31: Total water use by crop of the seven modeled farms for the four scenarios

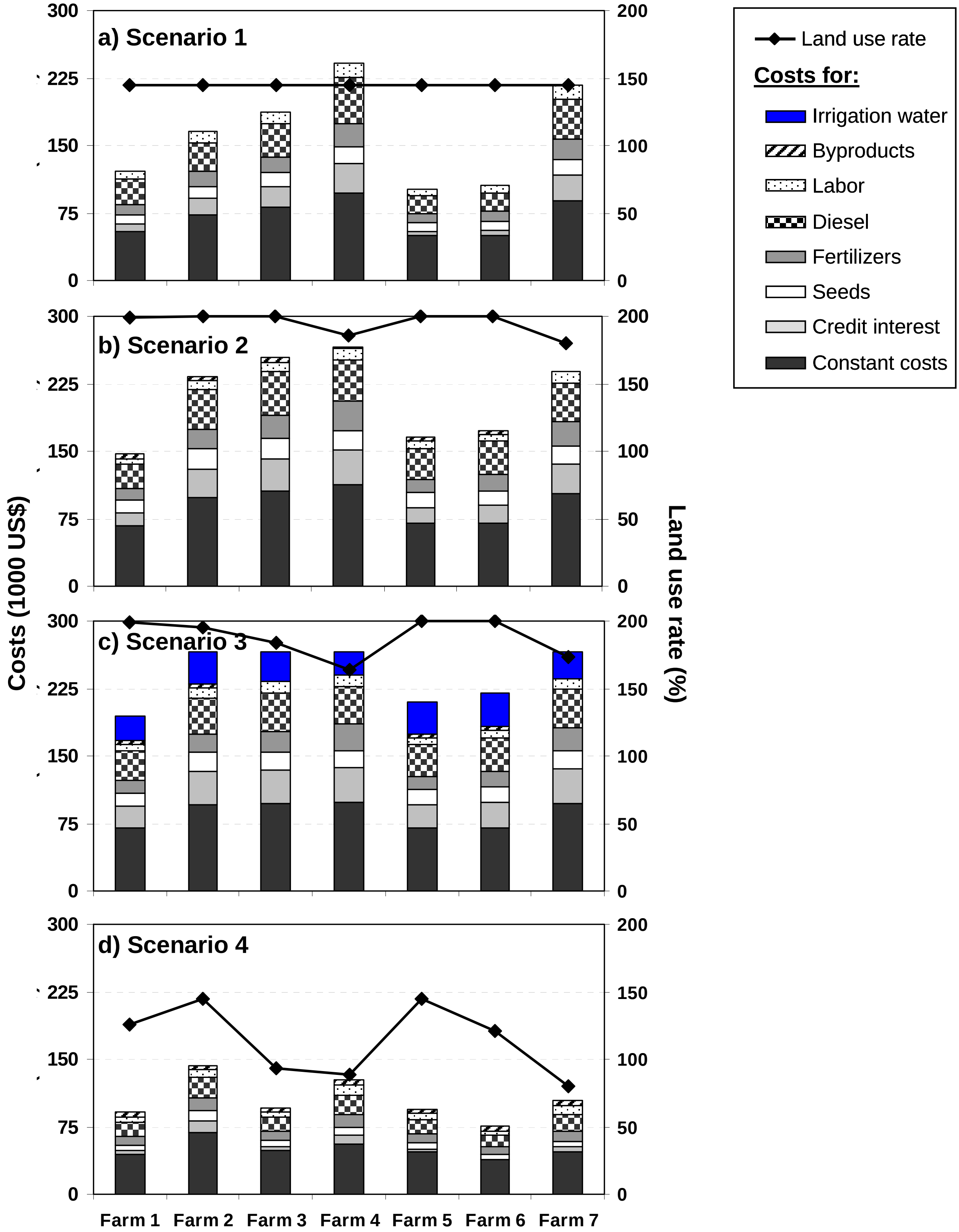

Figure 32: Farm operation costs (left axis) and land use rate (line, right axis) of the seven modeled farms for the four scenarios

5.2.4 Scenario 4 "Dry year"

Land use (rate) decreased considerably under conditions of water scarcity as simulated in scenario 4 (Figure 30d and line in Figure 32d). As expected, this mostly affected rice cultivation, but all double-cropping activities were reduced as compared to scenario 1. Rice was only produced in negligible quantities by farm 2 on 1 ha and farm 5 on 0.35 ha. As was the case under scenario 1, the area of cotton cultivation was limited to the imposed sizes to fulfill the state order. The findings showed that holding on to this targeted production in dry years where water availability is down to 30 % as compared to a normal year, farm profits are substantially reduced (Figure 33).

In the "Dry year" situation, farms now cultivated crops using less water and achieving lower yields. As result, total water consumption in scenario 4 reduced by 55 to 76 % as compared to scenario 1 (Figure 31d). Costs (Figure32d) but also profits (Figure 33) were largely reduced due to the increased water scarcity, as was the case for profits per hectare (Figure 34).

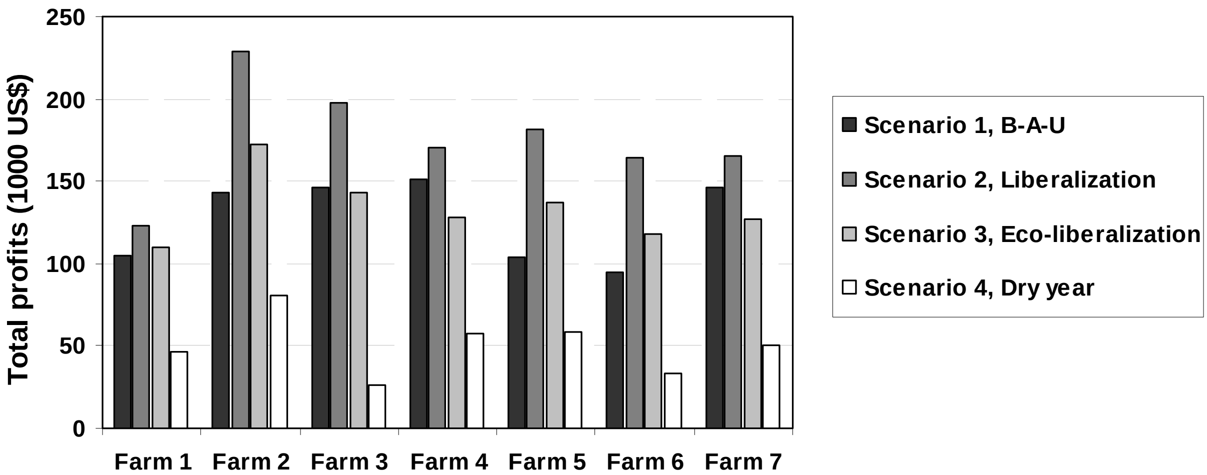

Figure 33: Total profits of the seven modeled farms of PM-WUA for the four scenarios

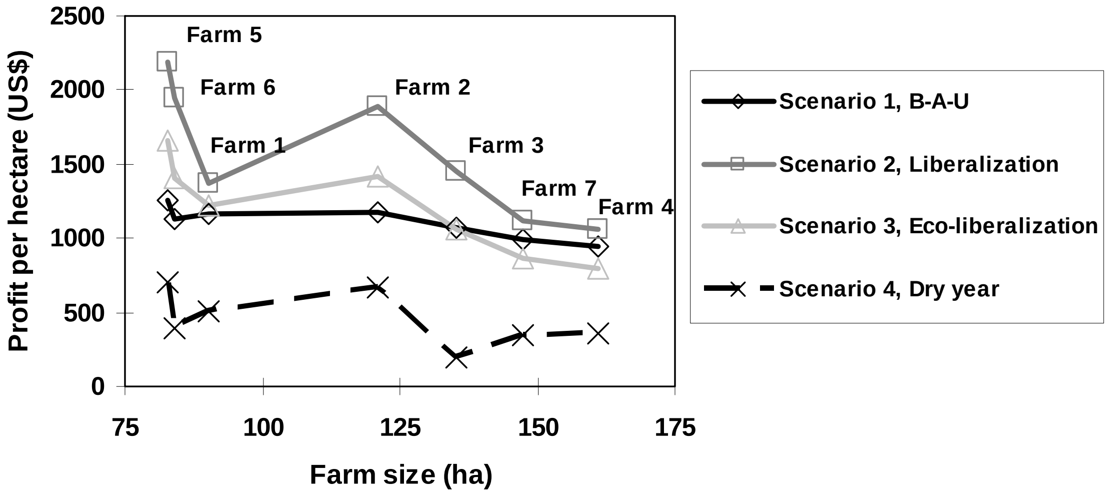

Figure 34: Farm profits per hectare of farm land in relationship to farm size of the seven modeled farms of PM-WUA for the four scenarios

Finally, Figure 35 shows the farm profits per hectare for the four crops averaged over the seven farms of PM for the four scenarios. Maize, rice and wheat per-hectare profits remain rather stable across scenarios. Only the cotton per-hectare-profits increase significantly from the business-as-usual to relaxation of state order or ecological market liberalization scenario, because for the latter two higher farm-gate raw-cotton prices would be realized. In a dry year with state order for cotton (scenario 4), profit maximization during the simulation favors crops other than cotton, and consequently, cotton receives little water and inputs and cotton per-hectare profits are the lowest overall.

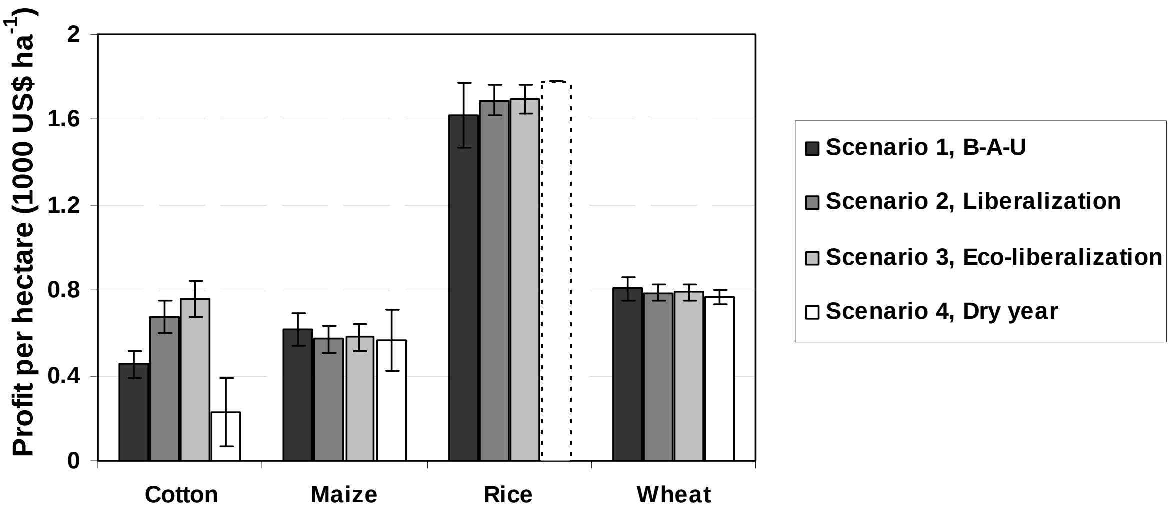

Figure 35: Per-hectare profits disentangled by crops averaged over the seven farms of PM-WUA for the four scenarios; bars denote the standard deviation; rice under scenario 4 only cropped by farm 2 and 5 on one field each

5.2.5 Spatial assessment of cropping patterns and yield differences

Even though results in the previous chapter were presented in an aggregated form, FLEOM optimizations are carried out in a spatially explicit from. This was introduced due to the fact that farmer's fields are uniquely defined by soil properties, salinity status, groundwater table depth as well as their individual distance to the WUA's main water inlet expressed via the length of the first and second-order irrigation canals (see chapters 4.1 for details).

FLEOM offers the possibility to describe various agro-ecological features, such as the impact of specific management scenarios on field-level water use (actual evapotranspiration), conveyance losses, soil salinity, nitrate leaching, etc. For the sake of conciseness, in the following only cropping patterns and crop yields as a consequence of the first (business-as-usual) and fourth scenario (dry year) are discussed.

Given the obligation of each *individual* farm to fulfill the state order for cotton, no clear WUA-wide spatial cropping pattern could be identified, neither for the business-as-usual (Figure 36, a) nor for the dry year scenario (Figure 36, a). The differences in yields, however, between the two scenarios (1 and 4), with lower yields in a dry year, are clearly visible. Similarly, the shift from rice to maize as summer crop, as the more profitable alternative in a dry year is also obvious (Figure 37). Lighter soil texture, with lower water holding capacity and potential for capillary rise of groundwater is the major factor for lower maize yields in a dry year for fields in the southern part of PM-WUA. This spatial gradient can also be identified, though less pronouncedly, for rice-dominated summer cultivation in a normal year.

a)

b)

Figure 36: Cotton (red) and wheat (green) crop allocation and yield at PM-WUA under scenario 1 "business-as-usual" (a) and 4 "dry year" (b); for the sake of clarity communal grazing areas, gardens, orchards and settlements are not shown (see Figure 29 for such details)

a)

b)

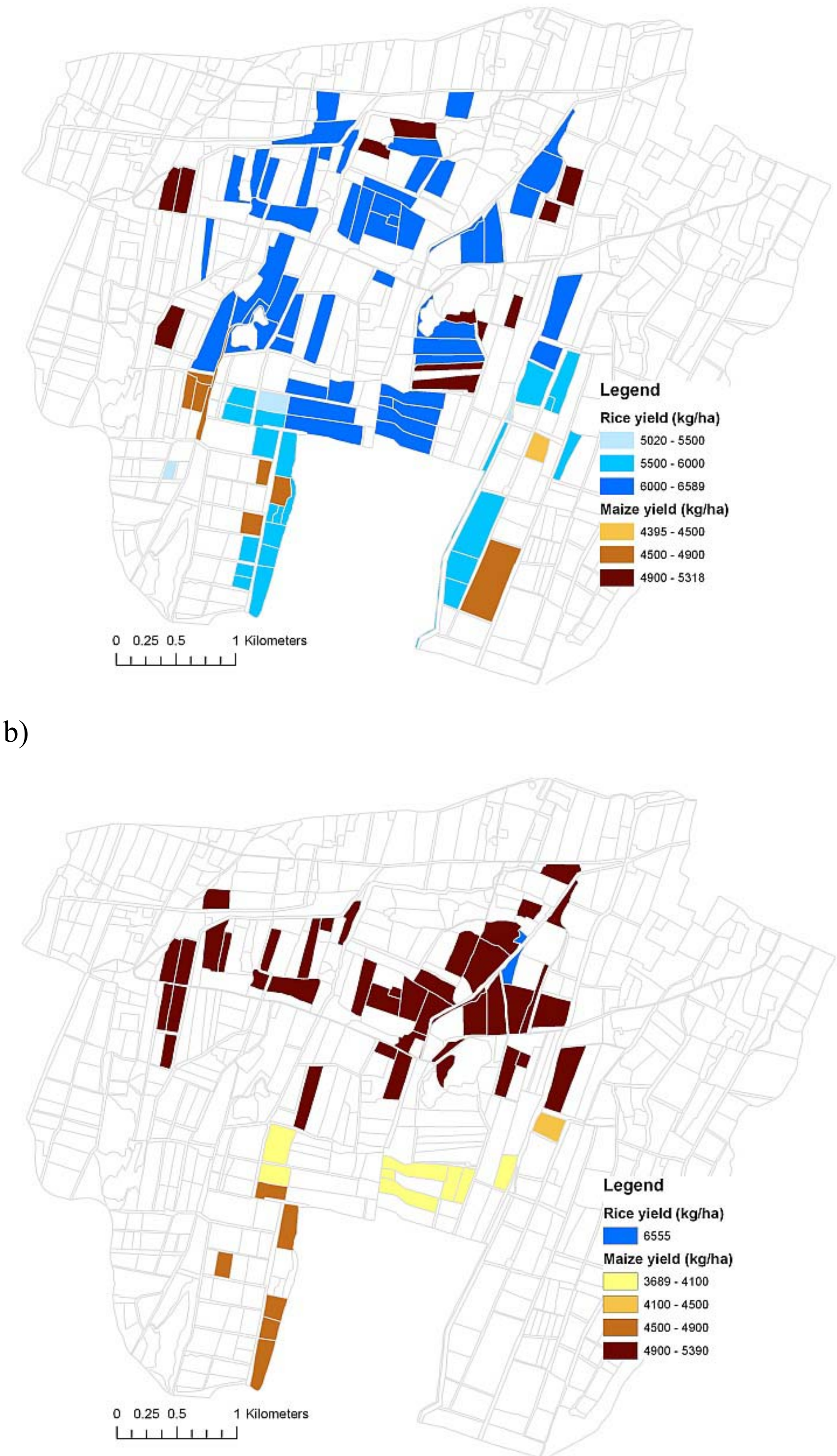

Figure 37: Rice (blue) and maize (brown) crop allocation and yield at PM-WUA under scenario 1 "business-as-usual" (a) and 4 "dry year" (b); for the sake of clarity cotton fields, communal grazing areas, gardens, orchards and settlements are not shown (see Figure 29 for such details)

5.3 Discussion

Double cropping of wheat and rice or maize as summer crop was the most profitable cropping strategy in all four scenarios, and is only constrained by the availability of water or the obligation for state order production of cotton. This is not surprising considering alone the superior market price for rice grain. Further simulations with varying market prices for rice and cotton as well as with varying prices for irrigation water could demonstrate under which conditions cotton production would be equally lucrative for farmers.

A relaxation of state order as simulated in scenario 2 increases farmer's profits. Water use reached the specified maximum amount of 18,000 m^3 ha^{-1}, and would have been even higher if this constraint had been eliminated (data not shown). Cotton completely disappeared in this scenario, and with it the state income from cotton exports. This means, on one hand, that the state order of cotton seems to indirectly mitigate excessive use of irrigation water and that without state order system the scarcity and conflicts over irrigation water even in normal years would be the consequence. On the other hand, scenario 2 also demonstrates that, if the state was furthermore to be responsible for the maintenance of the irrigation system, as is currently the case, alternative income sources for the state would have to be generated, as for instance via water pricing.

In response to the introduction of a price for water (scenario 3) irrigation water consumption did not drop as notably as was expected. It could be argued that apparently the water price with 1.5 US cents per cubic meter was too low to reduce consumption. To be able to prove this, further simulations are necessary to demonstrate the dependency between a price for water and the impact on its (rational) use.

The state income generated from the introduced water price is significant. For PM-WUA alone, 220,080 USD were generated for one season for an area of 821 ha arable land. Scaling up this income to whole Khorezm (~200,000 ha), annually more than 50 million USD could be set aside for the urgently needed consolidation of irrigation and drainage infrastructure. These investments would eventually trigger a boost in crop-production by an improved provision and a more efficient use of irrigation water.

The outcomes of the dry-year simulation realized in scenario 4 showed that the current state order for producing cotton on 55 % of the land during a dry year should be re-assessed. Lowering this target could help sustaining farmer's income and livelihood, and at the same time might be an efficient way of saving labor and machinery, as during a dry year concentrating irrigation on less land is more profitable (see low land use rate in Figure 32 for this scenario).

The spatial distribution of crops was heterogeneous in all scenario results because of the single-farm structure and state order at single-farm level (as opposed e.g. to a WUA-wide state procurement) in Khorezm. It should be noted however, that FLEOM could be used to simulate optimal spatial WUA-wide crop allocation, to follow-up for instance on the hypothesis that a clustering of crops would be economically and ecologically beneficial. To accomplish this, individual farm boundaries would simply have to be neglected and PM-WUA (or any other larger land unit) simulated as one single entity.

Compared to yield ranges observed in reality (see for instance Shi et al., 2007), the yields produced by FLEOM simulations are less heterogeneous. For instance, raw cotton yields were never below 1.95 Mg ha^{-1}, whereas in reality – especially in a dry year – much lower yields can be expected. At first sight, this seems a flaw. However FLEOM is not meant to be a tool for mimicking real cropping patterns and yields. Instead it rather optimizes land-use in an economic-ecological way in response to the given constraints. It is thus not surprising, but rather logical that yield variation under optimized conditions is comparably low. The same characteristic is detectable when for instance comparing temporal and spatial distribution of grain yields of developing countries with those of developed countries where production conditions are close to optimal.

6 General discussion and conclusions

The question might arise why was another integrated model built from scratch instead of using an already existing model building framework for this task? We had three reasons: (1) this option was explored but we could not find a modeling framework that sufficiently covered all required aspects; (2) we intended to using GAMS and CropSyst, as these two tools were intensively used for the integrated modeling work in this project; and (3) the model components (GUI, GAMS) should read from the same file format (e.g. in our case Microsoft mdb-files).

Great care was given to the detailed setup and description of the bio-physical settings for the multiple CropSyst simulation that build the basis of the input-output table. Also bio-physical model calibration and validation received special attention. The importance of these underlying data sets cannot be overestimated, as all further integrated simulations do rely thereon. We observed that often in integrated modeling studies, in favor of a fast presentation of the "big picture", underlying model details are too hastily and carelessly compiled, with unclear impact on the overall quality of results.

A current bottleneck still is computing time: processing a single simulation takes between 5-10 minutes depending on CPU power. This limits fast and multiple assessment of the effect of single (and groups of) factors. However, the fast progress in computing power in general, but also the possibility to simplify some GAMS routines – which is currently looked into – will most likely alleviate this bottleneck.

The developed version of the model has a flexible and user-friendly interface and allows for one-click scenario formulation. However, up-to-dateness of integrated simulation models is a constant concern, especially when development of such a tools takes several years as in our case. This is even more so true for the current situation of agriculture and farm enterprises in Uzbekistan that underwent considerable institutional change in the past and most likely will experience further changes in the near future. Of major concern for a tool like FLEOM are the level of ownership and accountability (farm versus WUA) as well as farming obligation such as state order or access to water (maximum allowance of withdrawal). Some cases – such as an institutional change of the production framework conditions – could be coped with by the user him/herself via adjusting settings in the graphical user-interface (e.g. merging small farms to larger enterprises), but other cases (e.g. maximum allowance introduced for water use for a particular crop) might require changes in the GAMS code. This might require some experience with GAMS, however the code is written in an understandable form and the explanation for each equation is given in the GAMS files. The model operates with the compiled database in a way that a user can add additional crops in the model via properly updating the database tables. The GUI is programmed in a way to automatically include such new crops.

In that respect, probably one of the biggest advantages of FLEOM is the possibility for a user to modify all input parameters. This allows for a multitude of possible scenario analyses, including the simulation of some possible changes in the production environment including those mentioned above. The results of the model stored in the mdb-database can be easily transferred to other software for further analysis.

Furthermore, equally important is FLEOM's generic character that allows simulating any farming environment (single farm, farmer's association, WUA) for which bio-physical data and maps are available. Surely, our experience shows that putting together all necessary data for a single WUA requires considerable time, and thus the decision to "move" should not be taken lightly.

It might anyway be the educational aspect of FLEOM, i.e. the new theoretical insights into the dynamics of the simulated agricultural system, that might be of utmost interest for a user, rather than the exact quantities produced for parameters x,y,z under some specific situation.

FLEOM scenario evaluation demonstrated that the model produces consistent and logical outputs, and that it can be used for quite complex scenario simulations. This complexity however creates completely new challenges. The present experiences with the model showed that simulation results were sometimes difficult to comprehend at first sight, and that multi-disciplinary team discussions were necessary for a complete understanding of causalities (and to rule out errors in model-coding during model development).

7 Outlook

From an agronomic point of view, crop rotation, i.e. considering a period of 3-5 cropping seasons at once, is of special importance. Here, to maintain soil health and to suppress soil borne pests and diseases, a rotation of cotton with wheat-rice or wheat-maize, or even some further, yet unaccounted crops, is desirable. Multi-year simulations are not yet covered by FLEOM, but it is planned to introduce such a feature in the near future. The multi-year simulations would also allow incorporating the soil fertility dynamics such as changes in soil salinity and groundwater tables due to alternative field/crop management. Particularly, the continuous crop-yield response functions and dynamic salt balance relations are interesting as soil salinity is a severe problem in Khorezm. These functions can be estimated using the existing data generated by CropSyst simulations to replicate the explicit relationships between quantity and salinity of applied irrigation water and salt accumulation in the soils, to be able to accommodate new soil salinity management practices outside the current modeling frame. Ways have to be discussed, how sustainable crop-rotations could be appropriately valuated in FLEOM.

In addition, we intend to introduce tree growth and livestock rearing models as joint components of FLEOM with multi-year dimension. All this will largely expand the applicability of FLEOM for end users to simulate the environmentally friendly development and assess its impacts on farm incomes, land and water use.

Apart from the irrational use of irrigation water, FLEOM also allows setting limits to other environmental damage, such as the pollution of groundwater by excessive nitrate leaching or the deterioration of land by secondary soil salinization. The resulting cropping patterns can be used as concepts for defining the fields with the lowest probability of receiving high farm revenues that could then be considered for alternative uses, such as tree plantations.

A dependency of the modeled area on fertilizer and water, intensity of land use and labor employment can be evaluated such as to characterize the socio-economic impacts of the analyzed policies. With this respect, FLEOM allows for spatial analysis to evaluate the vulnerability of each farmer to such policy effects.

From a hydrologic point of view the explicit representation of the network of surface water flows in the modeled area will narrow the gap between modeled situation and reality. For this, the properties and characteristics of the irrigation canals, pumps and water distributing schedules need to follow the detailed quantitative and qualitative studies.

Quantitative impacts of other changes could be analyzed using FLEOM. For instance, instead ofa full relaxation of state order, a scenario where the (current) area-based mechanism for setting the state order of cotton is replaced by a quantity-based one, would be interesting. The optimal cropping pattern in the scenario of a dry year to ensure the irrigation water sufficiency for downstream users can be of particular relevance for water management in Khorezm. In this regard, considering the WUA-wide salt dynamics can increase the scope of the model simulations from investments into water saving technologies to soil conservation methods.

The four simulated scenarios in the last chapter, thus, only provide a humble insight of the potentials of FLEOM to assess the production systems of farms in a single WUA of Khorezm.

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Appendix

Strengths and weaknesses of FLEOM

1. Strengths

1. The user-interface is user friendly and allows operating the model by click&select exercises. This means a user can enter the input and output prices according to the observed situation without the necessity to change the database file (and corresponding database management knowledge).
2. FLEOM allows for building various policy scenarios relevant to the studied region simply by entering the required values at relevant places on the user interface.
3. The results of optimization process are visualized in form of maps, tables and figures with relevant legends easily understandable for users;
4. FLEOM is spatially explicit and thus field-specific (soil properties of single fields are considered).
5. Farm fields are small enough to be treated as individual heterogeneous components.
6. A user can chose the scale of optimization from a single field, to number of fields, a farm, group of farms and/or the entire WUA.
7. FLEOM utilizes the agronomic database on crop response and secondary effects on soil attributes generated by the cropping system simulation model, CropSyst, using field experience and knowledge of a range of agronomic and hydrological studies, rather than relying solely on quantitative farm surveys or expert knowledge only.
8. The utilized database is recognized by each component of FLEOM and flexible for further extension, e.g. addition of new crops.
9. FLEOM considers four main crops of Uzbekistan which are competing for the same resources.
10. FLEOM's LP module is coded in GAMS in a simple algebraic form which is understandable in case a user with a moderate level of GAMS knowledge would like to reprogram the model specification.

2. Weaknesses

1. Currently only four crops are included into FLEOM. Extending the number of crops would increase the flexibility towards simulating/achieving maximum water use efficiency or soil conservation practices.

2. The database generated by CropSyst is valid for specific crop varieties. This means that new varieties that are considerably different from the current ones do require renewed (crop) model calibration.
3. The optimization process is done in GAMS which requires purchasing a (rather expensive) user license. (The same is basically true for using Microsoft Access mdb-database format, but certainly this software is much more widespread than GAMS and thus more easily available.)
4. The model does not include continuous response functions for crop yields but is based on manifold input-output points. The yield response function and dynamic salt response functions will be included into newer version of FLEOM using the existing agronomic database.
5. The model is yet one-year static. Dynamic features, e.g. soil fertility build-up or deterioration, are omitted.
6. The LP model solves towards profit maximization and thus has limitation in projecting other priorities at farm/household level that are partly based on the currently prevailing uncertainties of availability of irrigation water in Khorezm.
7. At this level of specification, the model does also not include the behavioral characteristics of farmers or past observations. The introduction of non-linear cost terms via calibrating the model via positive mathematical programming to the observed situation would solve this problem. However, to do so additional information needs to be generated.
8. The water distribution and conveyance losses are given implicitly. The introduction of surface water flow component will extend the capability of the model to tackle the scenarios related to water availability and water distribution policies.