Development of a spatial planning support system for agricultural policy formulation related to land and water resources in Borkhar & Meymeh district, Iran

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To my wife, *Arezou*
and my daughter, *Ghazal*

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1 Introduction

1.1 Planning and planning support systems

According to Sharifi (2003), planning is a continuous process that involves decisions, or choices, about alternative ways of using available resources, with the aim of achieving particular goals at some time in the future (Conyers and Hills, 1986). Sharifi and Rodriguez (2002) extended Simon's model (Simon, 1960) and developed a framework for the planning and decision-making process, consisting of three phases (Figure 1.1):

Phase 1 (Intelligence phase): This phase deals with identification of the problem, understanding the behavior of the system, and defining the objectives of actions intended to solve the problem. Identifying the problem is conceptually defined as finding the difference between the current situation and some desired state. This can be implemented through different types of models such as explanatory and process models. Intelligence is carried out in four stages: (1) the system has to be described, (2) system behavior has to be understood and described, (3) the current situation has to be assessed, (4) the objectives of the actions/decisions that are aiming at improving the current situation have to be formulated. The result of this phase is definition of the problem in such a way that the design and choice phases operate on the appropriate problem.

Phase 2 (Design phase): A significant component of the planning and decision-making process is the generation of alternatives to be considered in the choice phase. The design phase involves generating, developing, and analyzing possible courses of action. In this phase, mostly a model of the system is being developed, calibrated and validated. Modeling involves conceptualization of the problem and its abstraction into a quantitative and/or qualitative form.

In model development (Figure 1.1; stage 5), first the relevant aspects of the problem are identified. As a result, a conceptual model of the system, as perceived by the decision maker, is developed and subsequently improved to arrive at a model that corresponds as closely as possible to the real system (empirical model). After verification and validation, followed by correspondence and consistency checks, the model is complete to the extent that the decision maker thinks is relevant.

Using the planning model developed in stage 5, alternative solutions can be simulated and tested for their feasibility. This can be achieved through appropriate introduction of changes to either one or a combination of driving force(s), pressure(s) and/or state(s) of the environment. In modeling practice, continuation of the current situation is defined as the base or current scenario. The number of alternatives to develop depends on the case and selected scenarios.

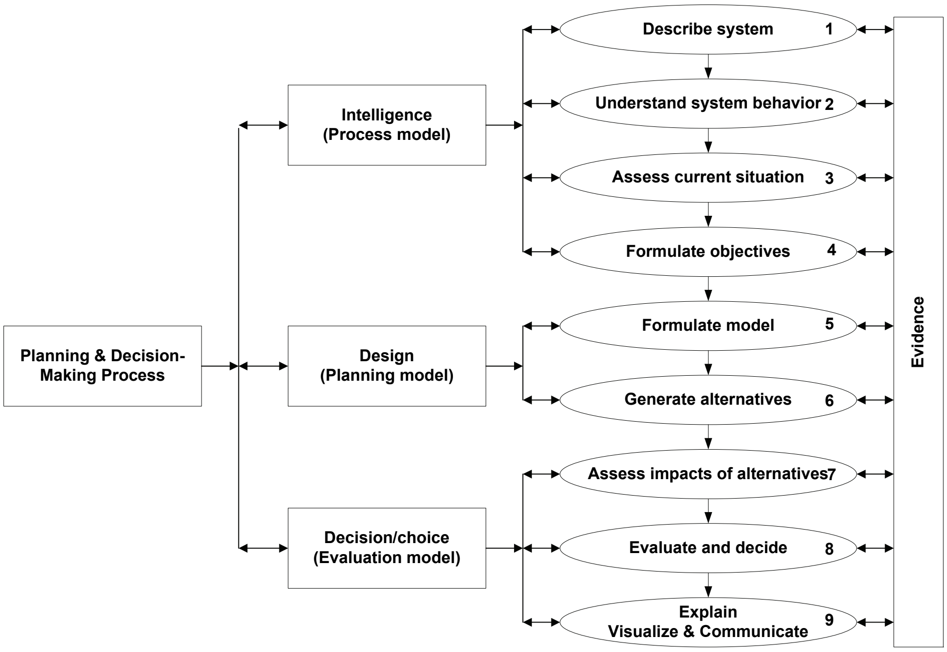

Figure 1.1. Framework for the planning and decision-making process (Sharifi and Rodriguez, 2002)

Phase 3 (Choice phase): This is the most important phase of the decision-making process that starts with a set of alternative options and ends with a decision. This phase includes an evaluation model which includes assessment of the impacts of alternatives, evaluation and selection of the acceptable one, and explanation of the choice.

The required information, such as facts, values, knowledge and/or experiences that must be considered during the analysis is collected, evaluated for inaccuracies, biases and other characteristics (e.g., value judgment).

Planning Support Systems (PSSs) as defined by Sharifi (2003) are a specific class of (geo-)information systems, composed of data/information, models, and visualization tools, that are primarily developed to support different phases of the planning and decision-making process. PSSs focus particularly on the design phase that leads to the generation of options and plans. PSSs are rationalizing planning and related decision-making processes by providing necessary support to systematically structure and formulate the alternative policies, scenarios, and plans, to assess and evaluate their impacts (considering objectives of the relevant stakeholders), and to guide the selection of a proper policy, scenario, or plan. The overall architecture of a planning support system is presented in Figure 1.2 (Sharifi, 2003).

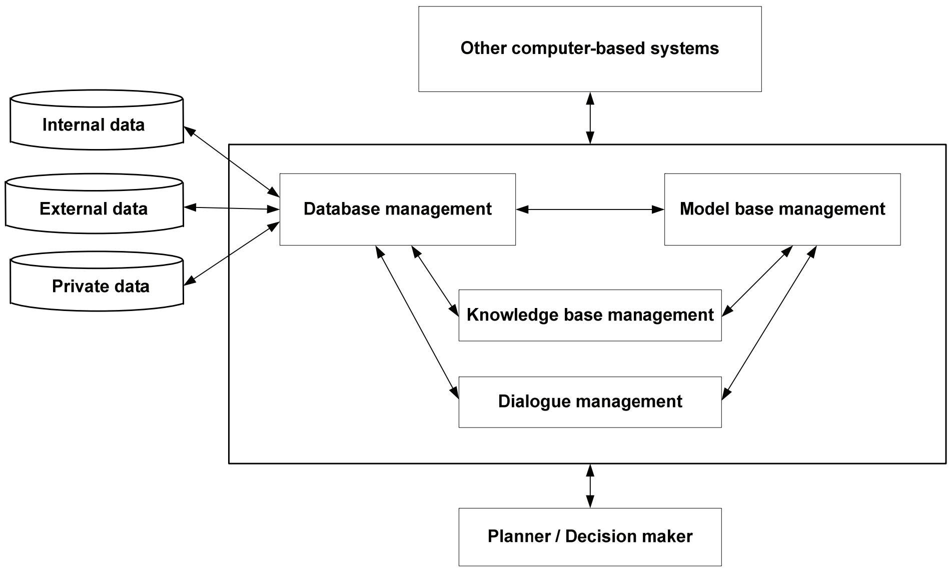

Figure 1.2. Overall architecture of a planning support system (Sharifi, 2003)

Planning support systems include the following main components:

1. **A database management system.** This system includes databases designed to accommodate and organize the basic spatial and thematic data, provide facilities for selection and manipulation of data, as well as interrelating data from various sources. It can include different types of databases, i.e. biophysical, socio-economical, internal data generated by the organization, data from external sources, and private data that are specific to the decision maker.
2. **A model base management system.** This system includes quantitative and qualitative models that support resource analyses, i.e. assessment of the potentials and capacities of resources at different levels of management. This is the most important component of the planning support system, and thus forms the foundation of model-based planning support. It includes three classes of models that make use of existing data, information and knowledge for problem identification and for formulation, evaluation and selection of the appropriate solution(s). These models are:
   - A *process/behavioral model* describing the current functional and structural relationships among elements of the planning environment to help analyzing and assessing the actual state of the system and identify existing problems or opportunities. This model also supports resource

analysis, which clarifies the fundamental characteristics of land and other resources and helps in understanding the process through which they are allocated and utilized (Sharifi and Van Keulen, 1994; Sharifi and Rodriguez, 2002; Sharifi, 2003).

- A *planning model* that integrates the potentials and capacities of the resources (biophysical), socio-economic information, goals, objectives, and concerns of the different stakeholders to simulate the behavior of the system. Conducting experimentation with such a model helps in understanding the behavior of the system and allows generation of alternative options/solutions to address the existing problems.
- An *evaluation model* that allows evaluation of impacts of various options/solutions and supports selection of the solution that is acceptable to all stakeholders, and improves the management and operation of the system.

3. **A knowledge base management system.** This system provides information on data and existing processing capacity and models that can be used to identify the problem, to generate solutions, test their feasibilities, evaluate and appraise their performances, and finally to communicate the results to the decision makers.
4. **A Dialogue management.** This system includes a user friendly interface that allows smooth and easy communication with the system, visualization and communication of the results of the analyses to the decision makers in a manageable and understandable form.

1.2 Agricultural development and agricultural policy formulation[1]

Challenges facing agriculture in developing countries are immense. The debate about development of the agricultural sector has often centered on the question of how to achieve adequate food security, while simultaneously providing sufficient income for food producers. A growing concern about environmental sustainability issues has entered the debate (Lee et al., 2006). Development of an agricultural sector that preserves natural resources and at the same time can feed a rapidly growing population and provides sufficient income for producers is one of the challenges facing agriculture in developing countries. Agricultural sector development is strongly related to land use. The way land is used has obvious implications for food security, economic development and the environment. Land in developing countries is increasingly subject to population pressure, soil degradation and pollution (Lal, 2009). Policies aimed at changing

[1] - Part of this section is extracted from the CSPSS (Collaborative Spatial Planning Support System for food security and agricultural development with a special reference to Iran) project proposal (Sharifi et al., 2002).

land use in a predefined direction form strong instruments to alleviate all these problems.
The issues and dimensions involved in land use policy analysis are complex. Evidently, solving land use problems requires contributions from various disciplines and involves several levels of aggregation. Tensions between aggregation levels and also between disciplines frequently occur (Rabbinge and Van Ittersum, 1994). Moreover, land use problems deal with multi-purpose use of land, trade-offs between different functions of the land, and conflicting interests among different categories of stakeholders and between individual and collective goals and needs (Van Diepen et al., 1991). Under these conditions, designing policy interventions supporting successful land resource management for agricultural development, to satisfy changing human needs, while maintaining or improving the quality of the environment and conserving natural resources in developing countries, presents an enormous challenge to all those concerned (Fresco et al., 1992). What is needed is a strong call for a basic redirection in the concepts of land use, in which the notion of inter-disciplinarity will play an ever-increasing role (Fresco, 1994).

Usually, policy makers have different objectives for agricultural development that in some cases may be conflicting. Increasing the food self-sufficiency index, increasing the value of agricultural exports, decreasing the value of agricultural imports, increasing net income of farmers, providing high-quality food for consumers at a low price, attaining parity income of the agricultural and industrial sectors, protection of the environment and increasing employment in the agricultural sector are among the objectives of agricultural policy makers. Moreover, the relative importance of these objectives is different for different policy makers and may even vary in different stages of agricultural development and/or in different parts of the country. On the other hand, farmers, as the final decision makers in the agricultural planning process, may have objectives that are different from those of policy makers. Objectives may also vary among farmers, and may be different in various stages of their life.

Agricultural policy instruments (measures) are tools that are used for stimulating farmers to change their behavior for achieving the objectives of policy makers. The most appropriate policy instrument(s) depend(s) among others on the gap between the goal(s) pursued and the current situation. Policy makers can intervene through different types of policy instruments such as:

- Incentive policies
    - Import/export policies (tax on imports, export subsidy)
    - Commodity pricing policies (promotion incentives)
    - Input subsidies
    - Infrastructure support

  - Production support (capital, machinery, leveling, irrigation, …)
  - Research and development (extension …)
  - Marketing and export support (transport, processing, storage, …)
  - Support of the private sector
  - Support low income group
- Regulating policies
  - Land zoning
- Liberalization policies
  - Removal of subsidies
  - Reduction of unnecessary government interference
  - Removal of controlling instruments

Land use decisions are made at the farm level, influenced by policy decisions at the national level, and to a lesser extent at the regional and sub-regional levels (Schipper, 1996). Analyzing the effects of specific policies on the agricultural sector or a region always relies implicitly or explicitly on decision making at the farm household level (Kruseman, 2000). It can be expected that different farmers respond differentially to specific policy instrument(s), because of differences in their biophysical resources and socio-economic situations. For example, providing low-interest loans to change irrigation systems from surface to pressurized systems to increase water productivity in agriculture can be an incentive for farmers with medium and large farm sizes, while it is not for smallholders, because of the high installation costs per ha of this type of irrigation system that increase with decreasing farm size.

Ex-ante assessment of the effects of agrarian policies on agricultural sustainability and objectives of different stakeholders is important for decision makers and agricultural planners. The objectives of various stakeholders are different and sometimes they are in conflict. Some policy instruments may have positive effects on attainment of the objectives of some stakeholders, while having negative effects on attainment of the objectives of other stakeholders or no effects on others. For example, increasing the price of products may increase farmers' income and increase the use of fertilizers and pesticides, and as a result increase environmental hazards.

On the other hand, available resources are limited, implying that not *everything* can be realized and therefore choices have to be made in a complex and dynamic socio-economic environment. There is a need therefore, for a tool to support policy makers in the analysis and selection of appropriate policy instruments. Such a tool, called a planning support system, can support policy makers in the analysis, for example through comparison of the impacts of various policy instruments on the degree of attainment of objectives of different stakeholders, including policy makers. Such a planning support system should help in estimating the impacts of policy instruments on a set of indicators, representing the objectives of different stakeholders, in support of the policy debate. The final selection of the most appropriate policy instrument(s) could be supported by an analysis of predetermined indicators, negotiation between stakeholders, trade-off analysis or multi-criteria analysis.

In most developing countries, methodologies that are capable of simultaneously addressing the various dimensions of land use are lacking, thus seriously hampering informed decision-making. The main challenge in development of such methodologies is in the integration of socio-economic and agro-ecological information. Lack of a sound methodology for integration is one of the main reasons for not being able to select proper and effective interventions. This also can be a reason that land use planning efforts have often not lived up to expectations (Stomph et al., 1994; Mohamed et al., 2000). Although the importance of integration of biophysical and socio-economic information and incorporation of the aims and aspirations of the different stakeholders in planning for sustainable land use is well recognized (Fresco et al., 1992; Stomph et al., 1994; Bouman et al., 1998; Mohamed, 1999; Aggarwal et al., 2001; Louhichi et al., 2005; Janssen and Van Ittersum, 2007), the problem has not been solved and thus more research is required.

A review of studies in the integration of biophysical and socio-economic disciplines and developing tools for decision support in agricultural planning and decision making showed that the main issue are related to (Mohamed, 1999):

- Aggregation problem and difficulty of integration of different scales
- Difficulty of finding an integrated unit of analysis because of:
    - Different nature and focus of disciplines
    - Different units of analysis
    - Different hierarchical levels of analysis
    - Difficulty of spatial linking of disciplines
- Insufficient attention to quantitative socio-economic analysis
- Multi-objective nature of land use problems

1.3 Bio-economic (agro-economic) models for agricultural policy analysis

Bio-economic modelling is defined by Kruseman (2000) as "a quantitative methodology that adequately accounts for biophysical and socio-economic processes and combines knowledge in such a way that results are relevant to both social and biophysical sciences". In recent years, with the rapid developments in computer technology, different types of bio-economic farm models have been developed for agricultural systems and farm management to support the analysis of the potential impacts of agrarian policies on changes in land use, (sustainable) resource management and farmers' welfare (Andersen et al., 2006; Laborte, 2006; Bartolini et al., 2007). These models are different in terms of modelling approach (mechanistic or empirical, static or dynamic, lumped or distributed), objective function of farmers (single or multi objective), incorporation of risk, agricultural activities and method of estimation of input/output (I/O) coefficients of activities, level of analysis, aspects considered in modelling (social, economic, environmental) and model evaluation (Janssen and Van Ittersum, 2007). Most of these models are demanding extensive data and knowledge and are therefore, more appropriate for developed countries.

Modelling is quite new in Iran. Many studies have been carried out during the last decade on various aspects of bio-economic models, but rarely have biophysical and socio-economic analyses been integrated. For example, crop growth simulation models have been used by agricultural researchers (Kiani et al., 2003; Kiani et al., 2004; Soltani et al., 2005; Majnoni Haris et al., 2006; Sepaskhah et al., 2006) and optimization models for agricultural planning by economists (Torkmani and Khosravi, 2001; Asadpour et al., 2005; Solimanipouri et al., 2005).

In the following, some of the bio-economic models that have been developed during the last decade to integrate biophysical and socio-economic aspects of agricultural production systems and support agricultural policy formulation are briefly reviewed:

Kruseman (2000) developed a farm household model to assess the effects of technology change and policy interventions on household welfare and sustainability indicators in the Cercle de Koutiala, Mali. In this study, four major farm household types were distinguished based on initial resource endowments of land, labour, livestock and equipment. Both cropping and livestock activities were considered. The crop growth simulation model WOFOST (Boogaard et al., 1998) was used for estimation of potential crop production in different regions of the study area, based on historical weather data. A technical coefficient generator (TCG) (Hengsdijk and Van Ittersum, 2003) was used for generation of I/O coefficients of current and alternative activities. Using the TCG for each unique and feasible combination of the production systems as defined by environmental and management conditions, I/O coefficients were determined for crop, livestock, pasture and fallow activities. The farm household was assumed to maximize the utility function, defined as a combination of consumption and income. Results were aggregated to regional level by using a weighted (representing the number of households of each type in the study region) sum of the farm household models and used for analysis of household reactions to policy incentives. Prices were assumed exogenous in the farm household models, whereas they were endogenous in the regional model.

Mohamed (1999) developed a model for analysis of policy impacts on the behavior of farmers in Amol, Iran. Farms are classified based on data from the agricultural census such as farm size, groundwater availability, labor availability and geographical coordinates. In fact, in this study, villages were classified and each ‘farm type’ consists of several villages, located close to each other and similar in variables used for farm type classification. Land was classified into homogenous units in terms of their biophysical characteristics the so-called land units. By overlaying these two spatial units, farm type-land units were created and a model was developed for each farm type-land unit. The model maximized total net income of each farm type-land unit. This study considered only cropping activities. I/O coefficients were derived from analysis of available local data and farm surveys (crop yield, pesticide inputs, labour requirement, and machinery requirement) or from available agro-ecological models (water requirement). Constraints on the resources were considered at farm type-land unit level. Aggregation of the farm type-land units to regional level was carried out by addition of all farm type-land units.

Laborte (2006) developed models for agricultural policy analysis in Ilocos Norte province, Philippines at different spatial scales (farm household, municipality and province). In this study, farms were grouped into four farm types on the basis of a cluster analysis of 150 surveyed farm households. Clustering was based on farm size, ownership, labour force and value of farm assets. Farm land was classified into eight land unit classes, based on availability of surface irrigation, soil fertility and topography. Crop and animal production activities were included in the model. Maximizing discretionary income, defined as total income derived from sale of agricultural activities (crop and animals) and off-farm activities minus expenses for self-sufficiency in food was defined as the objective of farmers. In the farm household analysis, each farm type was maximizing its objective function without consideration of other farm types. Price risk was considered in this model. Two types of models were developed to simulate the agricultural sector at municipal level. In one, aggregation was based on the number of each of the farm types in the municipality, with the objective function defined as total discretionary income of all farm types. In the other model, the municipality was considered as one large farm, with maximization of net income as objective function. Technical coefficients for current activities were derived from a farm household survey, and for alternative activities they were calculated following the target-oriented approach using TechnoGin (Ponsioen et al., 2006).

In the model developed by Bartolini et al. (2007) for analysis of agricultural and water policy impacts on irrigated farming systems in Italy, farming systems were modeled. Farming systems were selected as representative of the main Italian irrigated crops, considering specialization (extensive and intensive), geographical coordinates and climatic conditions. Farms in each farming system were classified into relatively homogenous groups using cluster analysis. A linear programming model, with a multi-objective function was developed for each farm type in each farming system. Maximizing net income, maximizing profit, maximizing crop diversification and minimizing labour use (family, hired or total) were defined as the potential objectives of farmers. Weights of the objectives were determined for each farm type in each farming system in the process of model calibration and validation as those minimizing the sum of the distances between actual and simulated crop mix. I/O coefficients were estimated through interviews with local experts. Resource availability was estimated as the average for each farm type, determined in the process of farm type classification. Aggregation to farming system level was performed by summing the weighted results of each farm type. Weights of each farm type were determined according to the share of usable agricultural area belonging to that farm type.

A linear programming model was developed by Solimanipouri et al. (2005) to support regional agricultural planning in Esfahan province, Iran. The objective function of the model was defined as maximizing total gross margin at provincial scale. Constraints of land, water, capital, minimum level of crop production, and minimum and maximum area under cultivation of different crops were specified at district scale (administrative unit). Total income at provincial scale was calculated by summation of the income of all farmers in the different districts. Available resources in each district were determined from current databases. Technical (input/output) coefficients were defined as averages for each district based on the related surveys. The only linkage between the districts was in the definition of the objective function.

FSSIM (Farm System SIMulator) (Louhichi et al., 2005) is a bio-economic farm model developed in the framework of SEAMLESS[1] to analyse the integrated agricultural, environmental and socio-economic aspects of farming systems in the European Union (EU). The model was developed to assess the response of major farm types in the EU to policies and agro-technological development (Van Ittersum et al., 2008). Farms in each region (approximately 300) in the EU-25 were classified into different farm types based on an extended farm typology (Andersen et al., 2007). The model is considering both crop and livestock activities. Another model in this project was developed to generate feasible production enterprises within each farm type based on soil, climate, slope and rotation constraints. Feasible agricultural activities are identified as specific combinations of production enterprise and feasible production techniques (e.g., water management, nutrient management, pesticide management and landscape and biodiversity management). Biophysical

1 - SEAMLESS stands for “System for Environmental and Agricultural Modelling; Linking European Science and Society” (http://www.seamless-ip.org/)

technical coefficients of agricultural activities were generated using APES[1] (Agricultural Production and Externalities Simulator; (SEAMLESS Consortium, 2007)) and socio-economic technical coefficients were derived from statistical databases. FSSIM is maximizing a utility function (expected income minus some measure of risk) of each farm type, subject to land, labour, equipment, water, animal, policy, investment, cash flow and environmental constraints. Prices are exogenous and are derived from an agricultural sector model. Aggregation of farm types to higher scales such as country or EU level is carried out by another model.

Classification of farms or farmers to define homogenous groups is an essential component of this type of studies as they aim at analyzing behavior. Hence, groups are required that are homogenous in *all* characteristics that affect behavior. In actual practice, in farm household models 'representative' farmers are modeled. Review of previous studies shows that different variables are used for farm type classification, justified by model purpose and data availability.

This review has shown that:

- The basic 'model unit' should be homogenous in terms of biophysical and socio-economic characteristics to reduce aggregation error. In the above mentioned studies, no unique "basic planning unit" was defined. In some of the studies, the focus was on socio-economic aspects, therefore only representative farms or farming systems were modeled. In some others, farming systems or farm households were defined in a large region, which could hardly be assumed homogenous in terms of biophysical and socio-economic conditions. Clustering of farms or farmers was based on different sets of variables, depending on data availability, scale of the study and purpose of the model. There is a need to define a basic planning unit that characterizes the integrated relevant biophysical and socio-economic conditions.

- Different methods were used for aggregation of the results to higher spatial scales. In most cases, aggregation was carried out by 'simply' calculating a weighted sum of the results at lower scales (e.g., farm household, farm type, farm type-land unit, farming system and district), without consideration of the interactions between basic planning units. However, in the model developed by Laborte (2006), some of the constraints were modified when the model was used at a higher level of aggregation. Another method used was to aggregate all *resources*, and treat the entire region as one large farm. That assumes mobility of resources throughout the entire region which is far from reality. In all studies reviewed, prices at the farm household scale were

1 - Information on this model is available at: http://www.apesimulator.it/

assumed exogenous ('farm households are price takers'), and became endogenous in some regional models.

- For the farmers, different objectives were defined. Income was always considered as one of their objectives. In some of the studies, price or crop production risk was considered explicitly in the utility function. In the study of Bartolini et al. (2007), different objectives with different relative importance (expressed in their weights) were defined for the various farming systems and for the different farm types in each farming system. So, across the studies, no unique set of objectives of farmers could be identified. Objectives of various groups of farmers in a specific region could be determined through consultation of local experts and farmers.

- In all models, linear programming was used and agricultural activities were described according to a Leontief production function (Leontief, 1986), characterized by fixed I/O coefficients (Van Ittersum et al., 2008). This is one of the advantages of bio-economic farm models compared to econometric methods, using continuous production functions (Janssen and Van Ittersum, 2007). Socio-economic I/O coefficients for each activity per modelling unit (farm type, farming system, farm household, etc.) were derived from available databases, field surveys and/or interviews with local experts. Different approaches were used for estimation of biophysical I/O coefficients (crop yield, water and fertilizer requirement, nitrogen loss, etc.). In most of the studies, average values for the whole region were used, which would lead to higher aggregation bias (Day, 1963). Variations in biophysical I/O coefficients caused by variation in biophysical characteristics (soil and weather) were considered in some of the studies. For that purpose, the study area was divided in different homogenous (agro-climatological) units and for each unit biophysical I/Os were determined, using local data or crop growth simulation models. Although crop growth simulation models were used in some of the studies to estimate biophysical I/O coefficients, they were not adequately regionalized, mostly considering a large area (e.g., in the SEAMLESS project or the Cercle de Koutiala study) that can hardly be assumed homogenous in terms of biophysical characteristics.

  Integration of agro-ecological models with geographical information system (GIS) and remote sensing (RS) techniques provides an opportunity to generate site-specific biophysical I/O coefficients of agricultural activities. However, this integration is not yet well established and used in planning models (Jansen et al., 2005).

  Application of crop growth simulation models to estimate biophysical I/O coefficients for bio-economic models needs more research. I/O coefficients for potential production situations (Van Ittersum and Rabbinge, 1997) can be determined for each biophysically homogenous unit by integration of agro-ecological models with GIS (and remote sensing) technique(s). Modification of these coefficients to estimate biophysical I/O coefficients for each farm type or farm household in each biophysically homogenous land unit needs more investigation. This issue is addressed in the current study.

- Different sets of constraints were considered in the reviewed models at different spatial scales. All models considered resource (land, labour, water) constraints. Environmental and policy constraints are considered only in the FFSIM model. Types of constraints which are used in the models of different spatial scales were not essentially the same. This issue (different set of constraints) is illustrated in the different models developed by Laborte (2006) for policy impact analysis in Ilocos Norte province, Philippines.

- One of the weaknesses of current bio-economic models is that they are not generic and rarely can be applied in other regions (Laborte, 2006; Janssen and Van Ittersum, 2007). Assumptions made during model development are often location-specific and dependent on the purpose of the model. Complex models, such as FFSIM that were developed for existing farm types in the EU cannot be applied directly in developing countries. Development of a site-specific model for each country, taking into account data availability and socio-economic conditions could be an option to cope with this difficulty.

1.4 Agricultural planning in Iran

Agriculture is one of the most important sectors of the Iranian economy, as it is the major source of employment and the main land and water user. More than 17 million hectares of land are cultivated and about 94% of all available water in Iran is used for agricultural production (Alizadeh and Keshavarz, 2005). The contribution of the agricultural sector in the value of non-oil exports (year 2005) and total employment (year 2006) was around 22 and 18% respectively (SCI, 2006; IRICA, 2007). The sector provides a substantial proportion of the food to the country’s 70 millions habitants (SCI, 2006). One of the challenges for the agricultural sector is the sustainable use of existing resources, e.g., land, water and labour for increasing production and the prosperity of farmers.

Increasing the level of self-sufficiency in the production of strategic crops (e.g., oil-seed crops, wheat, rice, maize, sugar beet) is one of the objectives of Iranian policy makers (MPO, 2005). Currently, Iran is importing a significant part of its national requirements for these crops. For economic and social reasons, increasing national production and the level of self-sufficiency is urgently needed. The current production levels of most agricultural crops are far below the potential set by environmental conditions, mainly because of problems and constraints in production techniques, resource allocation to various activities, and government production and support policies. Food demand in the (near) future will continue to increase because of the current population growth rate. Increased agricultural production should be stimulated through the formulation and implementation of proper government policies that lead to introduction of more productive and sustainable land use activities, that are technically feasible, environmentally sustainable, economically viable and socially acceptable.

In Iran, over the past two decades, Agricultural Planning and Economic Research Institute (APERI), responsible for preparation of agricultural development plans, has initiated and completed studies covering almost all the catchments and sub-catchments in the country. These studies, carried out at a scale of 1:250,000 have resulted in large amounts of detailed data on the existing natural resources and the socio-economic setting of the areas concerned. In a follow-up study, the results have been scaled-up from catchment to provincial levels, as planning is carried out at the level of administrative units. In a subsequent program, the agricultural potentials of lands located in the foothills of the catchments have been identified (over 600 plains) and studied at a scale of 1:50,000.

Many other data are being collected by different organizations. For example, every ten years (sometimes 5 years), an agricultural census is carried out and very detailed data about farmers and agricultural activities are collected. Updated information on the population in the rural area is available from the health service centers in the villages. Each year, agricultural production costs and production volumes are estimated in each district from samples of farmers in each sub-district. Also the local branches of the Ministry of Jihad-e-Agriculture collect routinely information at sub-district level. Hourly and daily weather data are collected by a network of weather stations. Information on the land resources is available spatially in digital format. Many studies are carried out in the agricultural and agro-meteorological research centres and agricultural faculties on different agricultural subjects. In addition, many temporally and spatially high-resolution satellite images are becoming available that can support research and development in various fields.

This wealth of data and information has been accumulated without being effectively and efficiently used to increase agricultural production, improve food security and raise prosperity. As a result, the data and information lie idle and will gradually loose their value. Now the question is how one can best make use of this information in support of better management of the resources. To answer that question, the Iranian Ministry of Jihad-e-Agriculture has been seeking support from national and international research institutions to support development of (a) proper methodology(y)ies. In this context, a joint research project was formulated by the Iranian Agricultural Planning and Economic Research Institute (APERI) and the International Institute for Geo-information Science and Earth Observation (ITC) (Sharifi et al., 2002). The research project, "Development of a Collaborative Spatial Planning Support System (CSPSS) for food security and agricultural development with a special reference to Iran" includes three sub-projects, Goal formulation, Policy formulation and Plan formulation. The current study deals with the policy formulation sub-project of the CSPSS project.

Agricultural planning and policy formulation in Iran is carried out as part of national development planning. Three planning horizons can be distinguished: General directions for national development are formulated based on long-term visions (20-years); medium-term plans (5-years) are formulated to move towards the set visions (objectives of long-term plans) and in the same way annual plans are formulated to achieve goals and targets of the 5-years plans. Long-term plans are mainly qualitative, and annual plans are operational. The most important activity in this process is the formulation of five-year plans. Since 1948, nine medium-term plans have been formulated. Although there is ample experience in plan formulation, an appropriate planning support system that can make use of available data and information to integrate biophysical and socio-economic information in the planning and policy formulation process is missing. Given the advances in geo-information technology, use of regional averages of agricultural production or expert estimates in the planning process is not the most appropriate procedure, as it lacks site-specificity and may lead to unrealistic plans. This issue was raised at various occasions by the national and provincial agricultural planners in the CSPSS workshop in Tehran in the year 2005. Therefore, there is a need to develop a system to integrate biophysical and socio-economic data and aggregate them from lower to higher spatial scales to support agricultural planning and policy formulation. This system should provide a base for analysis at different spatial scales and negotiations among various stakeholders, including agricultural planners at different positions in the hierarchy. As planning is a dynamic process and this process is becoming more important than the plan itself (Sharifi, 2003), such a system should predominantly support the planning process.

1.5 Research objectives

This study aims at development and evaluation of an appropriate spatial planning support system to formulate and assess the impact and effectiveness of possible policy instruments. The system will make use of all relevant socio-economic, biophysical, research and development data.

The specific research objectives are:
1. To develop a model for land resource analysis
2. To develop a planning model that integrates biophysical and socio-economic information to support agricultural policy formulation
3. To develop a model to support policy impact analysis

The philosophy behind this study is that a concept should be developed that can be implemented for policy formulation at national level. Therefore, the study has focused on methodology development, using one of the districts of Esfahan province as a case study. Following extensive discussion with policy makers on the usefulness and effectivity of the methodology, it might be extended to other regions in the country.

1.6 Conceptual framework of a planning support system for agricultural policy formulation

The conceptual framework of the planning support system for agricultural policy formulation is presented in Figure 1.3. It comprises three main components that are briefly described in the following.

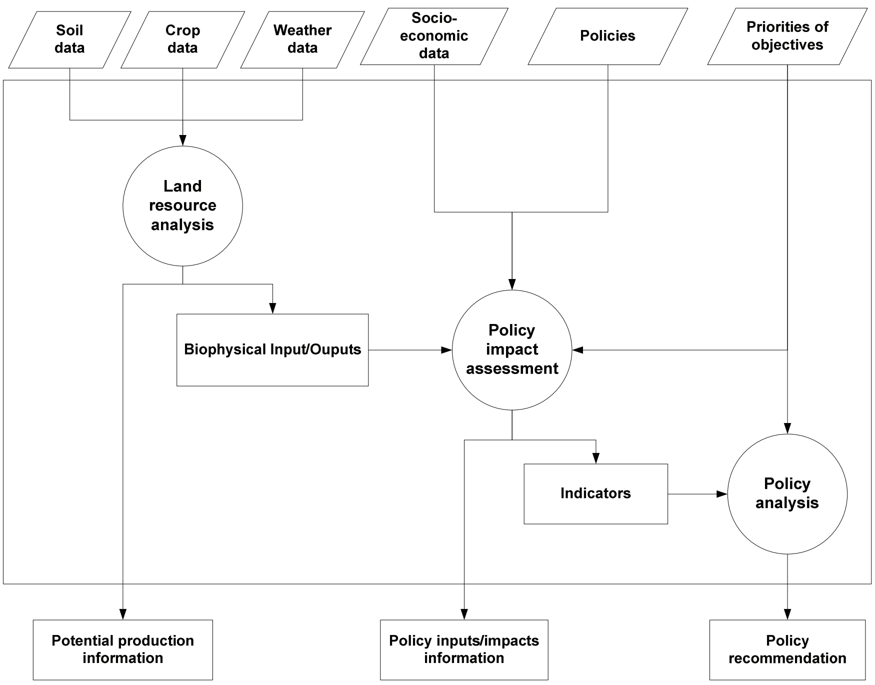

Figure 1.3. Conceptual framework of planning support system for agricultural policy formulation

1.6.1 Land resource analysis

Analysis of the land resources is the first step in the proposed framework of agricultural planning and policy analysis. Resource analysis is the process of thorough understanding of the fundamental characteristics of resources and the processes through which they are allocated and utilized (Sharifi and Van Keulen, 1994). In this process, the gap between the potentials of the resources and their current use is determined and used to explore the opportunities and constraints for further development. The potentials of land resources can be derived from dynamic simulation modeling, taking into account the main growth controlling factors and processes, or from empirical models or from experimental data.

1.6.2 Policy impact assessment

Policy formulation is a process composed of identification of policy objectives and policy instruments, policy impact assessment, analysis of impacts and selection of policy instruments. The aim of this sub-system (policy impact assessment) is to support the policy making process by exploring the reaction of farmers to various policy instruments and assess the impacts on the objectives of the various stakeholders.

1.6.3 Policy analysis

Policy analysis comprises assessment of the impacts of policies from the perspectives of the various stakeholders and selecting the most favorable policy instrument in view of the degree of realization of their objectives. The purpose of this evaluation is to answer the question: which policy instrument(s) is/are suitable (or preferable) for achieving development objective(s), taking into account different perspectives of stakeholders' priorities. It is meant to provide the policy makers with a menu of policy options, with their consequences for development objectives, under different assumptions with respect to desired development directions and priorities.

1.7 Study area

1.7.1 Administrative units

The study area is Borkhar & Meymeh district in Esfahan province, Iran (Figure 1.4). It comprises three sub-districts (Bakhshs), six Dehestans, nine cities (Table 1.1) and 31 residential villages. One of the most important arguments for selection of this area was availability of data and information from previous studies.

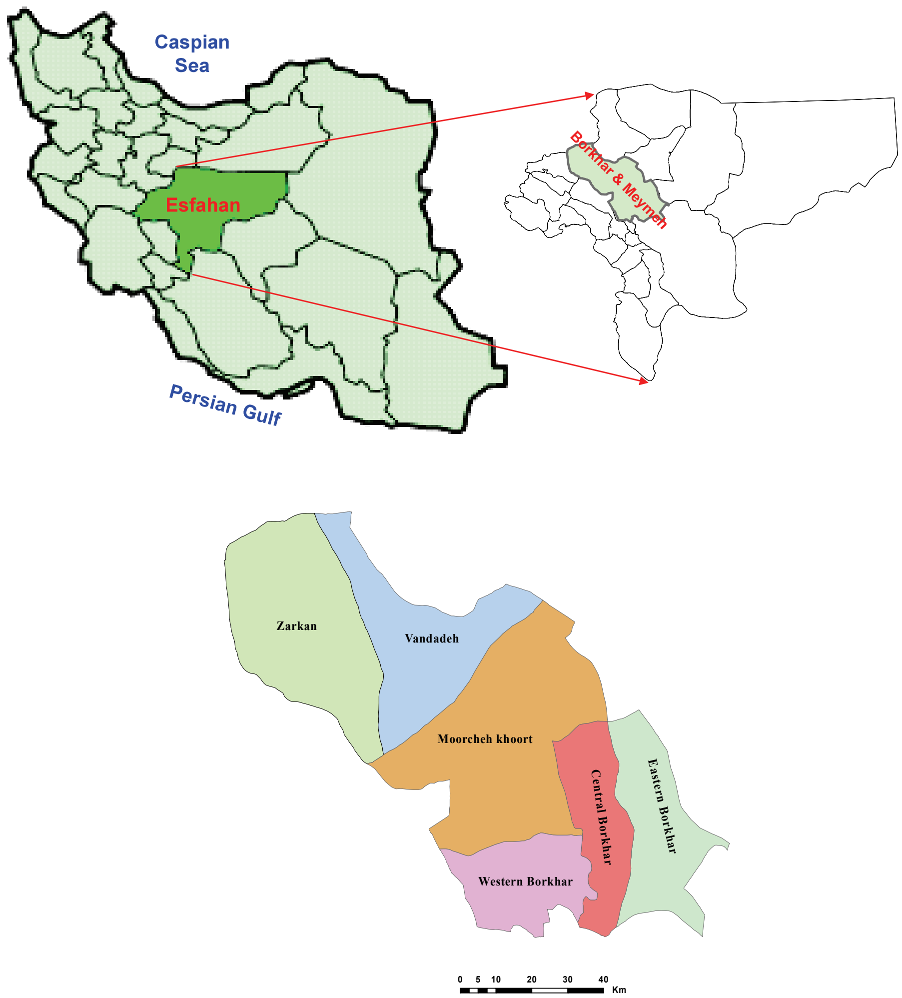

Figure 1.4. Location of Esfahan province in Iran (Top-Left) and Borkhar & Meymeh district in Esfahan province (Top-Right) and Dehestans in Borkhar & Meymeh district

Table 1.1. Sub-districts, Dehestans and cities in Borkhar & Meymeh district

Bakhshs (Sub-districts)	Dehestans	Cities
Borkhar	Eastern Borkhar	Habib Abad, Komshecheh
	Central Borkhar	Khorzough, Dastgerd, Dawlat Abad
Central	Western Borkhar	Shahin Shahr, Gaz
	Moorcheh khoort	-
Meymeh	Zarkan	-
	Vandadeh	Meymeh, Vazvan

1.7.2 Climate

Average daily temperature in the district varies between -2°C in winter and 30°C in summer. Annual precipitation varies between 100 and 300 mm over the district, concentrated in the winter and spring months from December to April, and average annual potential evapotranspiration is around 1400 mm.

1.7.3 Water resources

Water is the most limiting factor for agricultural development in Borkhar & Meymeh district, located mainly in the sub-catchments of Esfahan-Borkhar, Moorcheh khoort, Meymeh and Mooteh (Figure 1.5). Figure 1.5 shows the location of the agricultural water resources in Borkhar and Meymeh sub-catchments (no map of the water resources in Mooteh sub-catchment was available, but in this sub-catchment only groundwater is used). Groundwater (wells and qanats[1]) is the main source of water for irrigation in most of the district. Groundwater quality in the region is low. An irrigation network has been constructed and is in operation since the year 2002 in the Borkhar plain (Figure 1.6).

1.7.4 Agricultural land

The district covers total area of 762,500 hectares, of which about 37, 000 is cultivated (on average: 22000 ha cropped, 2000 ha fruit trees and 13000 ha fallow). Surface irrigation system is the common irrigation system and less than 1000 ha were under pressurized irrigation systems (sprinkler and drip irrigation systems) in the year 2006.

The total area under cultivation has increased since the year 2002 (Table 1.2), as the result of the opening of a new irrigation network in the Borkhar plain[2]. Most of the agricultural area is located in the southern part of the district, which is part of Borkhar plain.

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1 - Qanat is an ancient type of water-supply system developed and still used in arid regions of the world. A qanāt taps underground mountain water sources trapped in and beneath the upper reaches of alluvial fans and channels the water downhill through a series of tunnels, often several kilometers long, to the places where it is needed for irrigation and domestic use (Source: Encyclopedia Britannica) .

2 - Borkhar plain is a hydrological unit, while Borkhar & Meymeh district is an administrative unit. Part of Borkhar plain is located in Borkhar & Meymeh district.

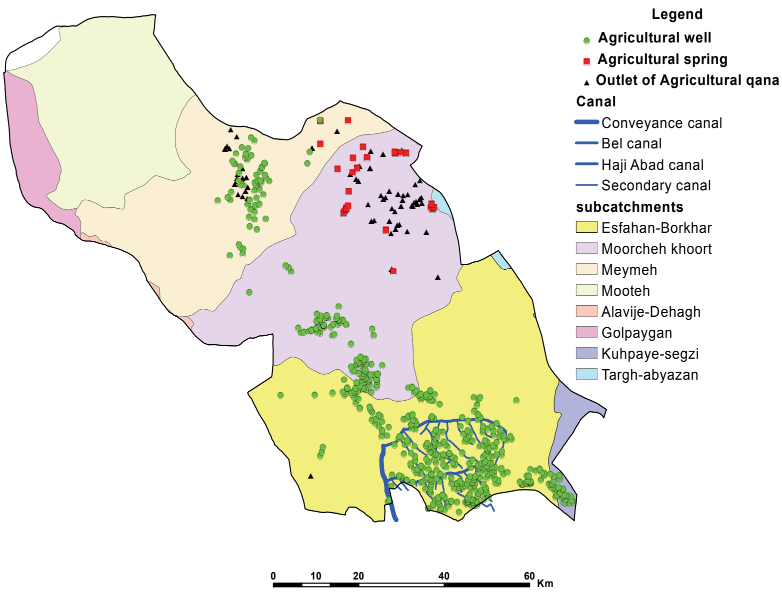

Figure 1.5. Agricultural water resources (wells, springs, qanats and canals) in the sub-catchments of Borkhar & Meymeh district

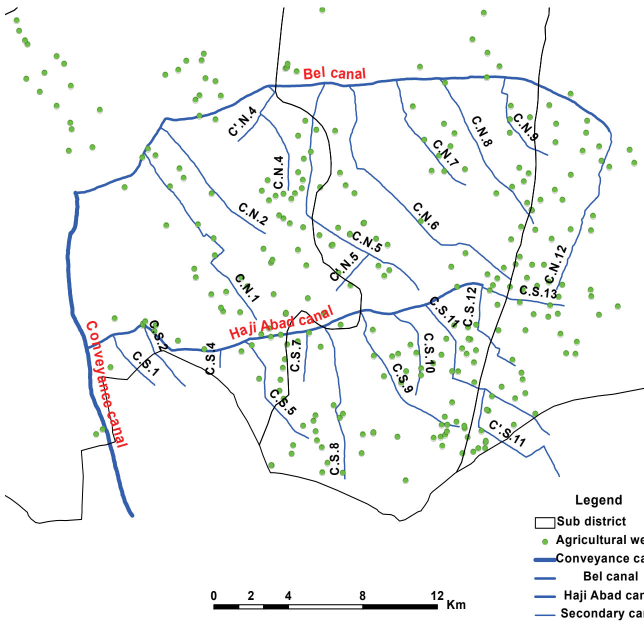

Figure 1.6. Location of agricultural wells and Borkhar irrigation network in the southern part of the study area

Table 1.2. Cultivated area of main crops in the Borkhar & Meymeh district during the years 2002-2005 (Esfahanian Agricultural Jihad Organization, 2007)

	cultivated area (ha)			Percentage of cultivated area (%)		
Crop	2002-2003	2003-2004	2004-2005	2002-2003	2003-2004	2004-2005
Winter wheat	10290	11000	11450	52.6	48.8	47.4
Winter Barley	2160	2300	2500	11.0	10.2	10.3
Silage maize	880	3700	3520	4.5	16.4	14.6
Sugar beet	1500	1050	900	7.7	4.7	3.7
Sunflower	1000	713	1196	5.1	3.2	5.0
Potato	310	320	310	1.6	1.4	1.3
Alfalfa	1300	1500	1440	6.6	6.7	6.0
Watermelon	15	75	594	0.1	0.3	2.5
Mellon	807	770	899	4.1	3.4	3.7
Other crops	1293	1112	1371	6.6	4.9	5.7
Total	19555	22540	24180			

1.7.5 Agricultural production systems

Agricultural production system in the study area are different in terms of ownership, management and objectives (APERI, 2002d).

Farm size is one of the limiting factors for farm mechanization. Most of the farms belong to traditional agricultural production systems with less than 2 hectares of land. Farm size will become smaller in each generation, because of heritage law that by death of a person, his/her land will be split between his/her inheritors.

Table 1.3. Agricultural production systems in Borkhar& Meymeh district, Iran (APERI, 2002d)

Main system	Sub-system
Traditional	Sharing system Leasing (Rent) system Hired labour Family type
Cooperative	Rural production cooperatives
Agro-industrial	Agro-industrial units

1.7.6 Population

The number of households and the population of the villages and cities in Borkhar & Meymeh district in the year 2006 is presented in Table 1.4 (SCI, 2008b). Analysis of the census data shows that 54 and 51% of the males in the rural and urban area, respectively were between 20 and 60 years of age. In general, agricultural activities in the district are carried out by males, although in some villages farm households are female-headed.

Table 1.4. Number of households and population of the villages and cities in Borkhar & Meymeh district in the year 2006 (SCI, 2008b)

Bakhsh	Dehestan	Name	Village/city	Household	Population	
					Male	Female
Borkhar	Eastern Borkhar	Habib Abad	City	2403	4689	4389
		Komshecheh	City	1072	2276	2119
		Ali Abad	Village	676	1405	1297
		Ali Abadchi	Village	32	65	48
		Donbai	Village	32	49	65
		Margh	Village	69	128	123
		Parvaneh	Village	53	114	88
		Shoorcheh	Village	12	16	16
	Central Borkhar	Dastgerd	City	4038	7976	7564
		Dawlat Abad	City	8661	17661	16280
		Khorzough	City	5478	10532	9769
		Mohsen Abad	Village	781	1599	1475
		Shahpour Abad	Village	1312	2693	2479
Meymeh	Zarkan	Hasan robat paein	Village	362	877	885
		Laibid	Village	510	982	1004
		Loshab	Village	113	163	179
		Mooteh	Village	242	463	445
	Vandadeh	Meymeh	City	1790	2953	2780
		Vazvan	City	1413	2315	2346
		Azan	Village	731	1283	1295
		Ghasem Abad	Village	7	8	7
		Khosro Abad	Village	115	170	170
		Maravand	Village	10	10	6
		Robat agha kamal	Village	5	7	3
		Vandadeh	Village	422	583	680
		Ziad Abad	Village	442	743	744
Central	Western Borkhar	Gaz	City	5704	10547	9885
		Shahin Shahr	City	33515	62868	63202
		Gorghab	Village	1400	3055	2589
		Jafar Abad	Village	20	60	0
		Jehad abad	Village	368	732	690
		Mojtameh karkhaneh ha	Village	48	224	0
		Noor Abad	Village	7	12	7
		Sin	Village	1066	2192	1955
	Moorcheh khoort	Bagh miran	Village	14	9	15
		Bidashk	Village	37	46	56
		Kalahrood	Village	128	146	149
		Khal sefid	Village	5	17	0
		Moorcheh khoort	Village	470	904	723
		Soh	Village	141	193	210

1.8 Structure of the thesis

Following this introduction, land resource analyses, using agro-ecological models, are performed in Chapters 2-4. In Chapter 2, the crop growth simulation model WOFOST is described and calibrated for winter barley, based on available field data from Kaboutar Abad agro-meteorological research center. This model has been implemented in CGMS, which is discussed in Chapter 4. Solar radiation is one of the important weather characteristics used in crop growth simulation models. As solar radiation is not recorded in all weather stations, in this study it is estimated by empirical formulas. The sensitivity of solar radiation to method of estimation and its impacts on the outputs of crop growth simulation models is evaluated in Chapter 3. Potential crop yields and input requirements (water and fertilizer) for their realization are determined spatially per land unit in Chapter 4. These characteristics are used in the generation of biophysical I/O coefficients for the distributed linear programming model developed in Chapter 5 to simulate the reaction of various farm types in the different villages of Borkhar & Meymeh district to policy instruments. The model is validated for Borkhar Sub-district. The model is used in Chapter 6 to determine the impacts of some of the possible policy instruments, which are assessed from various perspectives considering various policy objectives, using a multi-criteria evaluation technique. The thesis is completed with a general discussion is the last part of this thesis.

2 Point-based simulation of barley production using the crop growth simulation model WOFOST

Abstract

WOFOST is one of the crop growth simulation models that are used to support agricultural decision-making and learning processes. In this chapter, calibration and validation of WOFOST for barley (cv. Karoon dar Kavir) based on studies at the agro-meteorological station in Kaboutar Abad, Iran is carried out. Each year, phenological stages, irrigation dates, crop growth situation, total aboveground production and grain yield were reported in barley bulletins. However, the purpose of those studies was different from that of the current study hence, not all required data for model calibration were reported. In the calibration process, first phenological stages were fixed by comparison of total heat sums (in degree-days) from emergence until flowering (TSUM1) and from flowering to maturity (TSUM2) in different years. Total aboveground production and grain yield in experiments without water stress were used for calibration of crop parameters in the potential production situation. Review of the reports revealed uncertainty and contradictions in the available data. Uncertainty analysis has been performed on some of the main model parameters such as TSUM1, TSUM2, partitioning of dry matter among different organs, soil water holding capacity (in the water-limited production situation) and emergence date. Finally, it is concluded that calibration of WOFOST is possible on the basis of historical and on-going studies at agricultural research centers, agricultural faculties and agro-meteorological stations, as long as they report all the recorded parameters.

Keywords: Calibration, Validation, Uncertainty analysis

2.1 Introduction

Agricultural policy makers can make use of planning support tools to formulate appropriate policies. Crop growth simulation models have become increasingly important as major components of agriculture-related learning and decision-support systems (Van Ittersum et al., 2003; Park et al., 2005)

Many crop growth simulation models have been developed during the last three decades, among others by the School of De Wit in Wageningen, such as SUCROS (Van Laar et al., 1997), ORYZA2000 (Bouman and Van Laar, 2004), WOFOST (Boogaard et al., 1998), SWAP (Kroes et al., 2000), LINTUL (Spitters and Schapendonk, 1990) and ROTASK (Jongschaap, 1996). STICS (Brisson et al., 2003) and CropSyst (Stockle et al., 2003) are examples of other crop models. Crop models vary in terms of production situation (potential, water-limited, and nutrient-limited), application domains (research, education, and decision support), objectives and degree of detail.

Crop growth simulation models have been used in different studies and projects. For example, to determine input/output coefficients for a number of pre-defined cropping systems within the European Community (EC) to support strategic policy-making (De Koning et al., 1995). Ruben and Van Ruijven (2001) used agro-ecological simulation models to estimate input/output coefficients for alternative land use activities to analyse impacts of agrarian policies on changes in land use in Mali. Donaldson et al. (1995) combined an agronomic crop growth simulation model (Erosion Productivity Impact Calculator, EPIC) with a linear programming model to estimate the effects of Common Agricultural Policy (CAP) price changes on model farm types in southeast England and southwest France.

WOFOST (WOrld FOod STudies) is a generic crop model that can be applied to a range of crops through combination with crop-specific data files (Boogaard et al., 1998). This model has been applied for determination of crop yields and for generation of input/output coefficients of agricultural activities (De Koning et al., 1995; Hengsdijk et al., 2005; Roetter et al., 2005; Wu et al., 2006). WOFOST is one of the models that are used in the CGMS (Crop Growth Monitoring System) (Van Diepen et al., 2004) in the framework of the MARS (Monitoring Agriculture with Remote Sensing) project. Also, WOFOST has been used in combination with the SWAP (Soil Water Atmosphere Plant) model (Kroes and Van Dam, 2003).

WOFOST is a generic crop growth simulation model, but (some of) the crop parameters in the model are variety-specific and should be calibrated. Van Dam and Malik (2003) calibrated WOFOST for wheat, rice and cotton in India by comparing the results of the model for total aboveground dry matter and leaf area index (LAI) with measured data. Wu et al. (2006) used two-year field experiments for calibration of WOFOST for wheat in the North China Plain. Crop phenological characteristics, leaf area index at emergence, specific leaf area, maximum assimilation rate, and light-use efficiency were modified in the calibration procedure.

It has been shown that application of a crop growth simulation model outside the domain for which it was developed and calibrated often leads to disappointing results (Kabat et al., 1995). Therefore, (a) field experiment(s) is (are) necessary for calibration of WOFOST for each crop in each region, hence calibration for different crops in different regions (variable in soil and weather conditions and even management) is time- and labour-demanding. On the other hand, each year many experiments are being carried out for different purposes in agricultural research centers, agricultural faculties and agro-meteorological stations in Iran. In some of these, most of the required data for calibration of WOFOST such as phenological stages, growing situation, management, yield, etc. are being recorded.

The aim of this study was to test the possibility of calibration and validation of crop parameters based on available data and information from one of these studies. For this purpose, available data from the barley bulletins of Kaboutar Abad agro-meteorological research center were used. Studies on barley are being carried out in the Kaboutar Abad (one of the cities in Esfahan province, Iran) branch of the Iranian Agro-meteorological Research Center, in which phenological stages and other crop characteristics are being recorded. Barley bulletins of the 1999-2000, 2000-01, 2002-03 and 2003-04 seasons were accessible for this study. Review of the available information showed inconsistencies, indicating uncertainty in the quality of the data. Therefore, in the calibration we deal with uncertainty, in the model as well as in the available data.

Barley is the second winter crop in terms of cultivated area, after wheat in Esfahan province, and was cultivated on about 44 thousand hectare of irrigated land in the 2003-2004 growing season. Table 2.1 shows the cultivated area (irrigated) and average grain yield of barley in Esfahan province for the period 1996-2003 (Esfahanian Agricultural Jihad Organization, 2007).

Table 2.1. Cultivated area (irrigated) and average grain yield of barley in Esfahan province in the period 1996-1997 until 2003-2004

	1996	1997	1998	1999	2000	2001	2002	2003
Area (ha)	64230	58690	53160	44385	32431	42076	42924	44186
Yield (kg/ha)	4010	4300	3650	3500	3420	3904	4142	4281

WOFOST and the data required for using the model are introduced in the first part of the chapter. After that, available data for calibration and validation of the model in Kaboutar Abad are analyzed. Crop parameters are calibrated based on available data in the barley bulletins for different years. Finally, an uncertainty analysis on some of the major crop parameters is performed.

2.2 Study site

The agro-meteorological research center in Kaboutar Abad is located at 32.52 ^{o}N, 51.85 ^{o}E, at an altitude of 1545 meters above sea level, 22 km to the south-west of Esfahan city, Iran. Mean annual precipitation and average temperature during the years 1987 until 2003, was 103.8 mm and 17.2 ^{o}C, respectively (IRIMO, 2007a).

Salemi et al. (2005) who carried out a study in this research center, reported average soil characteristics of this field for 100 cm soil depth as in Table 2.2.

Table 2.2. Soil characteristics of the study site (Salemi et al., 2005)

Clay %	Silt %	Sand %	K (ppm)	P (ppm)	N (ppm)	Organic Carbon (%)	pH	Soil salinity (%)
35.4	42.2	22.4	310	30.2	0.11	0.93	7.2	0.42

2.3 WOFOST

WOFOST simulates daily crop growth rate, based on climatic conditions (i.e. solar radiation, temperature, relative humidity, wind speed, and rainfall), soil properties (i.e. soil depth, water holding capacity and infiltration capacity) and crop characteristics (i.e. length of growing cycle, photosynthetic characteristics and distribution of dry matter) (Boogaard et al., 1998). It is a tool for quantitative analysis of growth and production of annual field crops. In principle, WOFOST can simulate the growth of any annual crop growing at any location. It is capable to simulate crop growth in three production situations: Potential, water-limited and nutrient-limited (Van Ittersum and Rabbinge, 1997).

In the potential production situation, crop growth rate is determined by climate conditions and crop characteristics. The water-limited production level takes into account the effect of periods of soil moisture deficit on crop growth, and the water-limited yield represents the maximum yield that can be obtained under rainfed[1] conditions. The yield-limiting effect of drought depends on soil moisture availability as determined by rainfall and evapotranspiration, and their distribution over the growing season, soil type, soil depth and groundwater influence. The difference between potential and water-limited production indicates the production increase that could be achieved by irrigation. WOFOST uses the QUEFTS approach (Janssen et al., 1990) for nutrient-limited production (Boogaard et al., 1998).

WOFOST calculates daily potential gross photosynthesis of the canopy from the prevailing level of incoming solar radiation, leaf area of the crop and photosynthetic characteristics of individual leaves, taking into account ambient temperature. Part of the daily production of assimilates is used for maintenance and growth respiration of the crop, the remainder is converted into structural dry matter for leaves, stems, roots and storage organs. Leaf area index of the crop is calculated by multiplying leaf weight by the specific leaf area. Phenological

[1] - As the study area has a dry climate and rainfed crops are not cultivated, we have added irrigation amount to precipitation. In this paper, the water-limited production situation refers to irrigated crops, but under water stress.

development rate is defined as a function of temperature and, for some crops, day length.

WOFOST needs three types of data: weather, crop and soil

2.3.1 Weather data

Two different types of weather files can be used in WOFOST, i.e. files in WOFOST-format and in CABO-format. The WOFOST-format files contain either long-term monthly averages or time-series of monthly averages of the relevant meteorological variables, while files in CABO-format contain daily weather data (Boogaard et al., 1998).

A CABO-format file has been used for calibration of the model in this study. Daily weather data required for this file are:

- Irradiation ($kJ \cdot m^{-2} \cdot d^{-1}$)
- Minimum temperature (°C)
- Maximum temperature (°C)
- Early morning vapor pressure (kPa)
- Mean wind speed at 2 m above ground ($m \cdot s^{-1}$)
- Precipitation ($mm \cdot d^{-1}$)

Daily weather data have been measured in a synoptic weather station in the agro-meteorological research station in Kaboutar Abad. Weather characteristics have been recorded since 1978 (except in the years 1991 and 1992). Daily weather data for the years 1996 until 2004 were supplied by the Islamic Republic of Iran Meteorological Organization (IRIMO). For each year, a weather file was created in CABO format.

Minimum temperature, maximum temperature, vapor pressure, and precipitation have been taken directly from recorded data in the station. Analysis of recorded solar radiation data showed errors in measured data for the years 1999 and 2000. In addition, this analysis showed that for other years about 15% of the data were missing or outside the acceptable range. Therefore, solar radiation was calculated based on sunshine hours reported in the station by the Ångstrom formula (Allen et al., 1998). Wind speed measured at 10 m above ground surface has been transformed to 2 m, by multiplying by 0.75 (Allen et al., 1998).

2.3.2 Soil data

Two types of soil files can be used in WOFOST. Files with extension “NEW” can be used in simulation of water-limited crop growth with free drainage as well as with groundwater influence, while soil files with the extension “AWC” can only be used for simulation with free drainage. The soil file in WOFOST contains information on soil physical characteristics (Boogaard et al., 1998).

There is no influence of groundwater in the study area, therefore we have used the AWC soil file. Physical soil characteristics have been estimated based on soil texture and organic carbon content (Saxton and Rawls, 2006).

- Soil texture: clay loam
- Organic carbon: 0.92%
- Field capacity: 0.365 $cm^3.cm^{-3}$
- Permanent wilting point: 0.220 $cm^3.cm^{-3}$
- Saturation moisture content: 0.465 $cm^3.cm^{-3}$
- Bulk density: 1.42 $g.cm^{-3}$
- Total available water: 145 $mm.m^{-1}$
- Saturated hydraulic conductivity: 7 $cm.d^{-1}$

2.3.3 Crop data

For each crop or cultivar, a crop file with a set of specific parameters is necessary for crop growth simulation. These parameters include phenological, assimilation and respiration characteristics, and partitioning of assimilates to plant organs (Boogaard et al., 1998).

Different cultivars of barley are cultivated in Esfahan province, but mainly "Karoon dar Kavir", also in agro-meteorological and agricultural research stations. This cultivar is cold-tolerant and its average yield is about 7000 kg/ha in Kaboutar Abad agricultural research station (Mahlooji et al., 2003) . Average height is about 100 cm.

There is an ongoing research program in the agro-meteorological station of Kaboutar Abad on wheat (cultivar MB73-18) and barley[1] (cultivar Karoon dar Kavir). In this research program, planting date, seed rate, irrigation system, irrigation dates, growth situation, weed situation, soil temperature and several crop characteristics such as phenological stages, and crop height were recorded. In addition, harvest date, and straw and grain yields were recorded.

Results of field experiments in the agro-metrological station in Kaboutar Abad in the agricultural years 1999-2000, 2000-2001, 2002-2003 and 2003-2004 are published in annual barley bulletins (Kaboutar Abad agro-meteorological research center, 2000; 2001; 2003; 2004). Timing of important phenological stages based on available barley bulletins in Kaboutar Abad agro-meteorological research station for different years is given in Table 2.3.

A number of crop physiological parameters in WOFOST are defined as a function of development stage (DVS). DVS is a dimensionless state variable

1 - This research program stopped for barley in the season 2005-2006.

that for most annual crops is set to 0 at emergence, 1 at flowering and 2 at maturity (Boogaard et al., 1998). DVS changes with accumulated degree-days between these phenological stages. Total degree-days required for completion of phenological phases (emergence-flowering and flowering-physiological maturity) can be calculated based on the base temperature and average daily temperature. TSUM1 and TSUM2 are total degree-days from emergence until flowering and from flowering until maturity, respectively.

Dates of emergence, flowering and maturity in the experiments in the seasons 1999-2000, 2000-2001, 2002-2003 and 2003-2004 in Kaboutar Abad research station were taken into account for determination of development stages. In this station, phenological stages were recorded every other day, except after irrigation, when observations were discontinued for a week, because of high soil moisture. Total degree-days from sowing until emergence (TEME), from emergence to flowering (TSUM1) and from flowering to maturity (TSUM2) were calculated based on daily average temperature, calculated as the average of maximum temperature (Tmax) and minimum temperature (Tmin), and recorded phenological data. Table 2.4 shows accumulated degree-days from sowing until various phenological events for barley cultivar "Karoon dar Kavir" in experimental station Kaboutar Abad.

Review of the daily reports in the barley bulletins shows that in the 1999-2000 season, experimental fields were irrigated at flowering and full maturity. As a result, they did not observe exact dates of flowering and full maturity. As we did not trust these important dates, values of these parameters for the year 1999-2000 were not taken into account in calculating average values for TSUM1 and TSUM2.

Table 2.5 shows the variation in TEME, TSUM1 and TSUM2 for the three seasons and the averages of these parameters based on the 2000-01, 2002-03 and 2003-04 seasons.

Table 2.3. Timing of important phenological stages based on available reports in Kaboutar Abad agro-meteorological research station

Phenological stage		1999-2000	2000-2001	2002-2003	2003-2004
Sowing		8/11/1999	6/11/2000	8/11/2002	2/12/2003
Emergence		6/12/1999	8/12/2000	30/11/2002	14/1/2004
Third leaf		10/1/2000	10/1/2001	20/12/2002	1/2/2004
Tillering		8/2/2000	24/1/2001	8/1/2003	16/2/2004
Stem extension		26/3/2000	20/3/2001	6/3/2003	28/3/2004
Heading		12/4/2000	10/4/2001	22/4/2003	24/4/2004
Flowering		24/4/2000	19/4/2001	27/4/2003	9/5/2004
Ripeness	Milk	28/4/2000	30/4/2001	2/5/2003	22/5/2004
	Dough	6/5/2000	11/5/2001	31/5/2003	1/6/2004
	Physiological	22/5/2000	24/5/2001	2/6/2003	10/6/2004
Harvest		12/6/2000	10/6/2000	10/6/2003	18/6/2004
Sowing – Emergence (days)		28	32	22	43
Emergence – Flowering (days)		139	133	148	115
Flowering – Maturity (days)		28	35	36	32

Table 2.4. Accumulated degree-days (^{0}C.d) from sowing until various phenological events for barley cultivar "Karoon dar Kavir" in experimental station Kaboutar Abad

Phenological stage	1999-2000	2000-2001	2002-2003	2003-2004
Sowing	0	0	0	0
Emergence	222	212	185	219
Third Leaf	407	362	294	296
Tillering	476	414	347	398
Stem Extension	826	788	642	834
Heading	1063	1117	1259	1198
Flowering	1296	1266	1342	1449
Milk ripeness	1366	1468	1423	1706
Dough ripeness	1527	1669	1985	1920
Physiological ripeness (Maturity)	1872	1969	2030	2135

Table 2.5. TEME, TSUM1 and TSUM2 during the years and averages of these parameters based on years 2000, 2002 and 2003 (^{o}C.d)

Year	2000-2001	2002-2003	2003-2004	Average
TEME	212	185	219	205
TSUM1	1054	1157	1229	1147
TSUM2	704	689	687	693

2.4 Calibration and validation of WOFOST

For calibration of the model, available barley bulletins have been used that report values of four plots of 1 m^2 each. Table 2.6 shows average values at harvest time of the four replicates.

Table 2.6. Average crop characteristics at harvest time in four replicates

Year	1999-2000	2000-2001	2002-2003	2003-2004
Number of plants per m^2	192.0	359.5	235.3	202.0
Total number of stems per m^2	576.3	580.5	705.8	606.5
Number of productive stems per m^2	552.5	527.8	665.8	570.0
Number of non-productive stems per m^2	23.8	27.8	40.0	34.3
Mean height of plants (cm)	83.1	72.2	94.5	117.8
Mean weight of straw per m^2 (g)	726.6	505.9	780.0	770.2
Mean weight of grains per m^2 (g)	721.5*	659.1	854.4	919.9
Mean weight of grains in one ear (g)	1.2	1.7	2.1	1.8
Mean weight of 1000 grains (g)	44.9	42.6	38.6	48.7
Shrunken grains (%)	2.5	2.5	8.0	7.3
Harvest Index	0.50	0.57	0.52	0.54

* Data in the Table did not match with text. (Table: 721.5 g; Text: 744.4 g)

Reported grain yields are fresh yield (sun-dried) with about 13 percent moisture content. Therefore, measured yields were converted to dry matter by dividing by 1.13.
Irrigation dates for the four study years are listed in Table 2.7. First irrigation was after sowing.

Table 2.7. Irrigation dates for barley in the four study years in the research plots

Irrigation Number	1999-2000	2000-2001*	2002-2003	2003-2004
1	14-11-1999	09-11-2000	10-11-2002	04-12-2003
2	8-12-1999 & 16-12-1999	30-12-2000	20-03-2003	20-03-2004
3	29-02-2000	30-03-2001	08-04-2003	07-04-2004
4	07-04-2000	28-04-2001	05-05-2003	28-04-2004
5	24-04-2000		20-05-2003	10-05-2004
6	05-05-2000			18-05-2004
7	18-05-2000			2-06-2004

- Because of water limitation, replicates were not irrigated at the same time

2.4.1 Potential production situation

Review of the bulletins for the seasons 1999-2000, 2002-2003 and 2003-2004 showed that in these years barley did not experience water stress, fertilizers were applied based on analysis of soil fertility and the crop was in good

condition. Therefore, we expected that yields would be close to potential during these years. However, in the year 2000-2001, not enough water was available and the crop experienced water stress.
As Table 2.5 shows, TEME, TSUM1 and TSUM2 varied during the four years. Theses variations may be due to errors in data recording, or some stress during the growing periods in different years. TSUM1 varied between 1054 and 1229 with an average of 1147 degree-days. TSUM2 varied between 575 and 704 with an average of 693 degree-days. For model runs, phenological events (flowering and full maturity) have been defined as the average values.

Initial partitioning and other parameters were derived from literature (Table 2.8).

Table 2.8. Source of initial crop parameters used for model calibration

Parameter	Reference
Extinction coefficient for diffuse visible light	(Van Heemst, 1988)
Efficiency of conversion of assimilation into leaves, stems, roots and storage organs	(Van Heemst, 1988)
Maintenance respiration factors of leaves, stems, roots and storage organs	(Van Heemst, 1988)
Partitioning: fraction of total dry matter to roots (FR), fraction of above-ground dry matter to leaves (FL), stems (FS) and storage organs (FO) as function of DVS	(Boons-Prins et al., 1993)
Leaf area index at emergence	(Boons-Prins et al., 1993)
Daily increase in TSUM as function of average temperature	(Boons-Prins et al., 1993)
Maximum leaf CO_2 assimilation as function of DVS	(Boons-Prins et al., 1993)
Specific leaf area	(Boons-Prins et al., 1993)

Only grain and straw yield have been used for calibration and validation of the model. There were significant differences in yields among replicates and averages in different years. Maximum and average yields reported for barley in the year 2002-2003 were close to yields reported for high-yielding producers (best farmer: 8500 kg/ha) (APERI, 2002c). Therefore, WOFOST was calibrated based on this year. Crop parameters have been established through trial and error. Subsequently, the model has been run for the other years for validation. The calibrated crop file is given in Annex 1. Table 2.9 and Figure 2.1 show simulated potential total aboveground dry weight (TAGP) and total dry weight of storage organs (TWSO) of the calibrated model for the years 1999-2000, 2000-2001, 2002-2003, and 2003-2004. Maximum leaf area index (LAIM) and harvest index (HI) are presented in Table 2.10.Simulated potential grain yields (dry matter) varied between 6480 and 8364 kg/ha, which is comparable to the 8500 kg/ha (dry matter: 7522 kg/ha), the highest yield recorded in the study area.

Table 2.9. Results of the model in the potential situation

Season	Grain yield (kg DM/ha) Simulated	Grain yield Measured Max	Grain yield Measured Average	Total aboveground production (kg DM/ha) Simulated	Total aboveground production Measured Max	Total aboveground production Measured Average
1999-2000	6480	9161	6385	11893	17699	12814
2000-2001	7398	6174	5833	15106	11062	10310
2002-2003*	8364	8205	7561	15335	15788	14464
2003-2004	8085	9455	8140	18018	19027	14956

* Calibration was based on the season 2002-2003

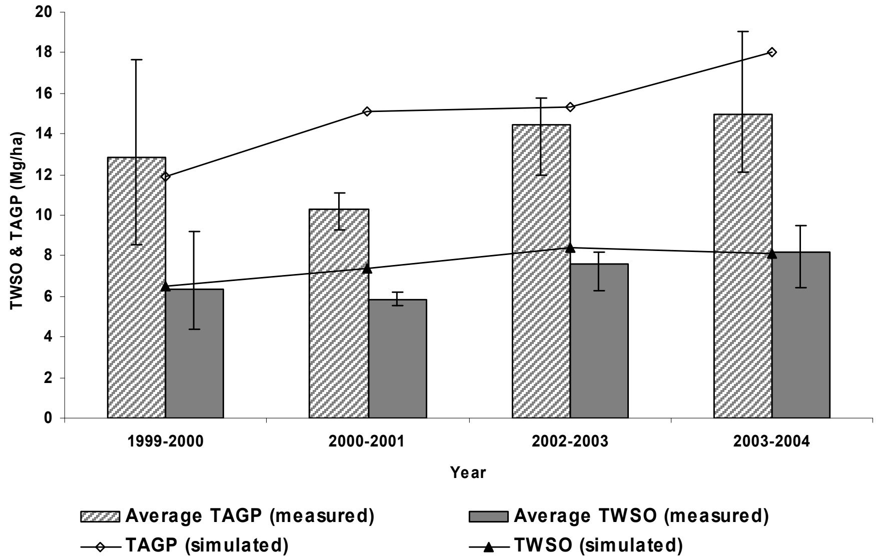

Figure 2.1. Results of the model in the potential situation (TWSO is grain yield; TAGP is total aboveground production)

Table 2.10. Simulated maximum leaf area index (LAIM) and harvest index (HI) and measured HI in different seasons

Season	simulated LAIM	simulated HI	Measured HI
1999-2000	3.17	0.54	0.50
2000-2001	4.94	0.49	0.57
2002-2003	4.22	0.55	0.52
2003-2004	6.85	0.45	0.54

2.4.2 Water-limited

Review of the barley bulletins showed that there was water-stress during the 2000-2001 season. Crop, weather, soil and irrigation data are required for simulation of crop growth in the case of water-stress. Irrigation dates were known, but irrigation depths were not reported. It is assumed that irrigation refilled the soil profile to field capacity. Irrigation depth is considered as precipitation and added irrigation to rainfall. The calibrated model has been run in the water-limited situation. Figure 2.2 shows simulated soil moisture content in the root zone, for the different seasons. Periods with soil moisture content below the critical soil moisture (50% depletion of total available soil water in the root zone) are considered as water-stressed.

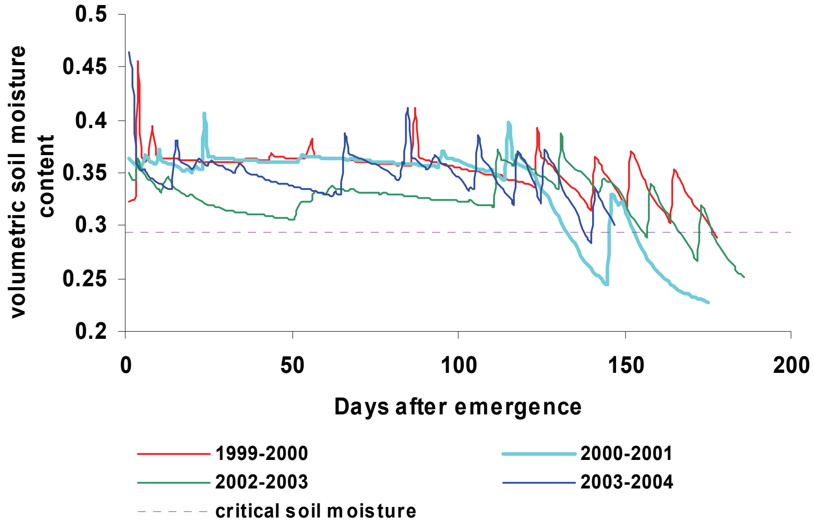

Figure 2.2. Simulated soil moisture content ($cm^3.cm^{-3}$) in the root zone, for different seasons

Based on this graph it can be seen that the crop was water-stressed during the season 2000-2001. In addition, there was a short period of water-stress at the end of 2002-2003. Table 2.11 shows the results of the model in the water-limited situation. This Table shows that in the 2000-2001 season, simulated TAGP is close to measured TAGP, while simulated TWSO is lower than measured TWSO. The simulated harvest index in the 2000-2001 season was lower than measured (Table 2.12). Review of the barley bulletin for the 2000-2001 season showed that experimental blocks were not irrigated at the same time. Table 2.13 shows irrigation dates for the different blocks.

Table 2.11. Results of the model in the water-limited production situation

	grain yield (kg DM/ha)			total aboveground production (kg DM/ha)		
Year	Simulated	Measured		Simulated	Measured	
		Max	Average		Max	Average
1999-2000	6480	9161	6385	11893	17699	12814
2000-2001*	3298	6174	5833	9960	11062	10310
2002-2003**	7811	8205	7561	14762	15788	14464
2003-2004	8056	9455	8140	17987	19027	14956

* Severe water stress in the 2000-2001 season
** Slight water stress in the 2002-2003 season

Table 2.12. Simulated maximum leaf area index (LAIM) and harvest index (HI) and measured HI in the water-limited situation

Year	simulated		Measured HI
	LAIM	HI	
1999-2000	3.17	0.54	0.50
2000-2001	4.50	0.33	0.57
2002-2003	4.22	0.53	0.52
2003-2004	6.85	0.45	0.54

Table 2.13. Irrigation dates of different replicates during the 2000-2001 season

Block No.	First Irrigation	Second Irrigation	Third Irrigation	Fourth Irrigation
1	10/12/2000	30/12/2000	30/3/2001	28/4/2001
2	10/12/2000	30/12/2000	30/3/2001	28/4/2001
3	10/12/2000	30/12/2000	8/4/2001	30/4/2001
4	10/12/2000	30/12/2000	30/3/2001	22/4/2001

These blocks are considered as four different treatments and the model has been run for these four treatments. Results of the model for the four treatments are presented in Table 2.14, Figure 2.3 and Figure 2.4. Results of these runs are compared to measured yields, showing that the model satisfactorily simulates TAGP, but there is a problem with TWSO.

Table 2.14. Comparison of simulated grain yield (TWSO) and total aboveground production (TAGP) with measured data in four experimental blocks in the 2000-2001 season

	TWSO (kg DM/ha)		TAGP (kg DM/ha)	
Block No.	Simulated	Measured	Simulated	Measured
1	3449	5513	10241	9292
2	3449	6174	10214	11062
3	3890	5551	11202	10265
4	3208	6093	10492	10619

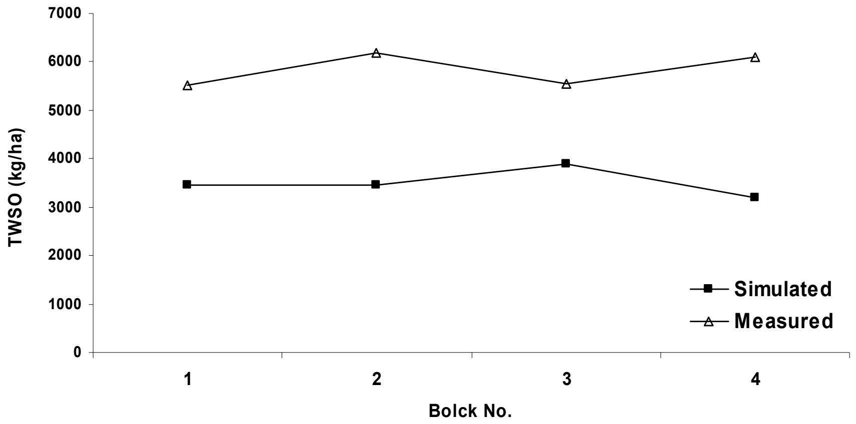

Figure 2.3. Simulated and measured grain yield (TWSO) in different blocks (season: 2000-2001)

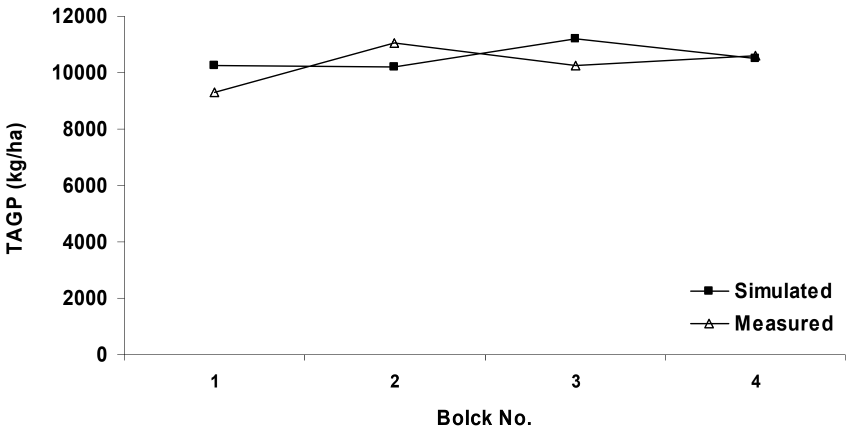

Figure 2.4. Simulated and measured total aboveground production (TAGP) in different blocks (season: 2000-2001)

2.5 Uncertainty analysis of field data

2.5.1 Analysis of TSUM

Average values of TSUM1 and TSUM2 are used in the three seasons for calibration and validation of WOFOST. An uncertainty analysis was performed in a range ± 10% for TSUM1 and TSUM2. Table 2.15 shows the results of the different runs. Figure 2.5 and Figure 2.6 compare simulated potential TWSO and TAGP in different runs with measured data.

Table 2.15. Simulated grain yield (TWSO), total aboveground production (TAGP), maximum leaf area index (LAIM) and harvest index (HI) in the potential and water-limited situations for different combinations of temperature sums in the pre-anthesis (TSUM1) and reproductive (TSUM2) stages

				Potential				Water-limited			
Year	RUN No.	TSUM1 (^{0}C.d)	TSUM2 (^{0}C.d)	TWSO (kg/ha)	TAGP (kg/ha)	LAIM (m^2/m^2)	HI (kg/kg)	TWSO (kg/ha)	TAGP (kg/ha)	LAIM (m^2/m^2)	HI (kg/kg)
	1	1032	624	4966	8594	2.06	0.58	4966	8594	2.06	0.58
	2	1032	693	5420	9095	2.06	0.6	5420	9095	2.06	0.6
	3	1032	728	5621	9320	2.06	0.6	5621	9320	2.06	0.6
	4	1147	624	5944	11300	3.17	0.53	5944	11300	3.17	0.53
1999	5*	1147	693	6480	11893	3.17	0.54	6480	11893	3.17	0.54
	6	1147	728	6693	12135	3.17	0.55	6693	12135	3.17	0.55
	7	1204	624	6254	12511	3.82	0.5	6254	12511	3.82	0.5
	8	1204	693	6702	13020	3.82	0.51	6700	13017	3.82	0.51
	9	1204	728	6974	13321	3.82	0.52	6948	13294	3.82	0.52
	1	1032	624	6417	12167	3.45	0.53	4204	9760	3.45	0.43
	2	1032	693	6981	12791	3.45	0.55	4246	9832	3.45	0.43
	3	1032	728	7249	13089	3.45	0.55	4264	9864	3.45	0.43
	4	1147	624	6748	14391	4.94	0.47	3301	9945	4.5	0.33
2000	5*	1147	693	7398	15106	4.94	0.49	3298	9960	4.5	0.33
	6	1147	728	7705	15446	4.94	0.5	3295	9965	4.5	0.33
	7	1204	624	6777	15228	5.69	0.45	3012	9899	4.88	0.3
	8	1204	693	7390	15906	5.69	0.46	3005	9904	4.88	0.3
	9	1204	728	7718	16265	5.69	0.47	2998	9903	4.88	0.3
	1	1032	624	6766	11748	2.82	0.58	6764	11746	2.82	0.58
	2	1032	693	7375	12419	2.82	0.59	7371	12415	2.82	0.59
	3	1032	728	7674	12749	2.82	0.6	7655	12730	2.82	0.6
	4	1147	624	7683	14582	4.22	0.53	7333	14219	4.22	0.52
2002	5*	1147	693	8358	15329	4.22	0.55	7811	14762	4.22	0.53
	6	1147	728	8580	15586	4.22	0.55	7964	14945	4.22	0.53
	7	1204	624	7817	15889	5.05	0.49	6984	15018	5.05	0.47
	8	1204	693	8144	16282	5.05	0.5	7185	15272	5.05	0.47
	9	1204	728	8216	16383	5.05	0.5	7231	15340	5.05	0.47
	1	1032	624	7716	15978	5.31	0.48	7704	15966	5.31	0.48
	2	1032	693	8415	16750	5.31	0.5	8399	16734	5.31	0.5
	3	1032	728	8747	17118	5.31	0.51	8730	17101	5.31	0.51
	4	1147	624	7458	17321	6.85	0.43	7431	17293	6.85	0.43
2003	5*	1147	693	8085	18018	6.85	0.45	8056	17987	6.85	0.45
	6	1147	728	8380	18348	6.85	0.46	8351	18318	6.85	0.46
	7	1204	624	6948	17895	7.4	0.39	6917	17862	7.4	0.39
	8	1204	693	7524	18537	7.4	0.41	7494	18505	7.4	0.4
	9	1204	728	7796	18842	7.4	0.41	7766	18810	7.4	0.41

* TSUM1 and TSUM2 in this run are the averages values of TSUM1 and TSUM2 that have been used in the calibration and validation process

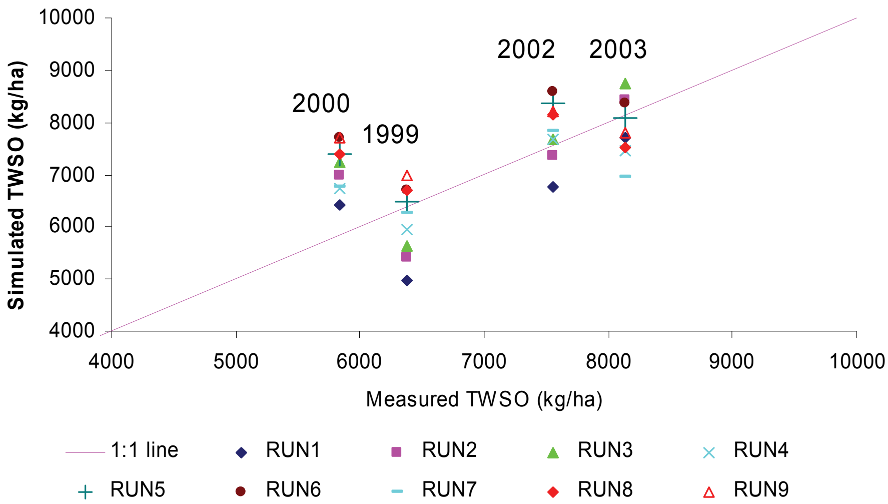

Figure 2.5. Comparison of simulated potential grain yield (TWSO) in different runs with measured data in the four years

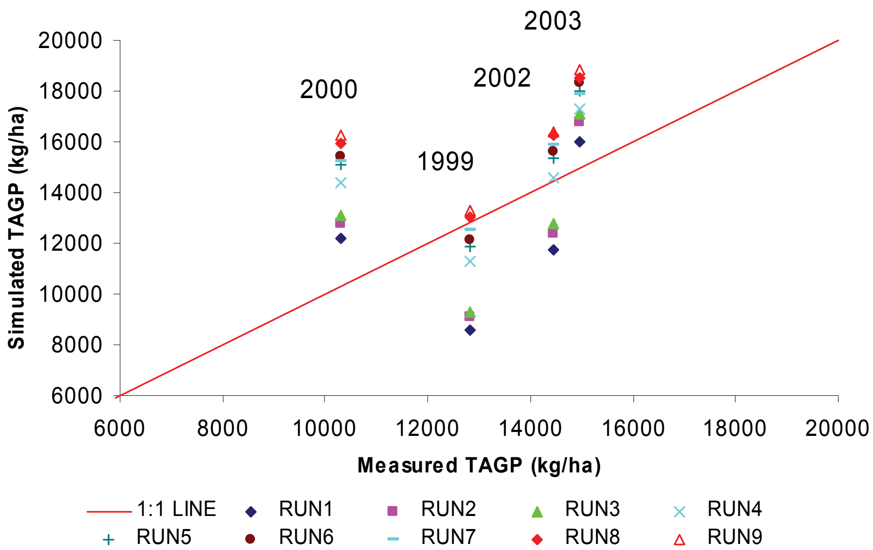

Figure 2.6. Comparison of simulated potential total aboveground production (TAGP) in different runs with measured data in the four years

Statistical analysis has been performed by SPSS software (SPSS Inc., 2007) to analyze the effects of changes in TSUM1 and TSUM2 on TAGP and TWSO in both the potential and water-limited situations. This analysis shows that by 10% changes in TSUM1, only differences in simulated TAGP in the potential situation (TAGP_POT) among the analyzed characteristics (TAGP_POT, TAGP_WL, TWSO_POT and TWSO_WL) are significant at the 5% level (Table 2.16). The same analysis with TSUM2 shows only significant differences at the 5% level in TWSO_POT (Table 2.17).

Table 2.16. Comparison of total aboveground production (TAGP) and grain yield (TWSO) in the potential and water-limited situations for different values of the pre-anthesis temperature sum (TSUM1)

TSUM1	TAGP_POT	TAGP_WL	TWSO_POT	TWSO_WL
1032	a	a	a	a
1147	b	a	a	a
1204	b	a	a	a

Table 2.17. Comparison of total aboveground production (TAGP) and grain yield (TWSO) in potential and water-limited situations with different values of the reproductive temperature sum (TSUM2)

TSUM2	TAGP_POT	TAGP_WL	TWSO_POT	TWSO_WL
624	a	a	a	a
693	a	a	ab	a
728	a	a	b	a

2.5.2 Uncertainty analysis on partitioning

Partitioning of total dry matter among the different crop organs is one of the main crop characteristics that was calibrated in this study. Calibration was based on grain and straw yields, because of lack of other data. Therefore, an uncertainty in partitioning was expected. An uncertainty analysis on partitioning was performed (Table 2.18). The model has been run for the potential and water-limited situations for each partitioning and for four years. Figure 2.7 shows simulated TWSO and TAGP for both the potential and water-limited situations with different partitioning.

Table 2.18. Different dry matter partitioning factors used in the uncertainty analysis on partitioning

	Partitioning 1 (P1)		Partitioning 2 * (P2)		Partitioning 3 (P3)		Partitioning 4 (P4)	
DVS**	FL	FS	FL	FS	FL	FS	FL	FS
0	0.75	0.25	0.8	0.2	0.9	0.1	0.8	0.2
0.33	0.75	0.25	0.8	0.2	0.9	0.1	0.8	0.2
0.8	0.4	0.6	0.4	0.6	0.4	0.6	0.3	0.7
1	0.1	0.9	0.1	0.9	0.1	0.9	0	1
1.01	0	0.15	0	0.15	0	0.15	0	0
2	0	0	0	0	0	0	0	0

* calibrated partitioning as a reference
** DVS: development stage; FL, FS: Fraction to Leaves and Stems, respectively

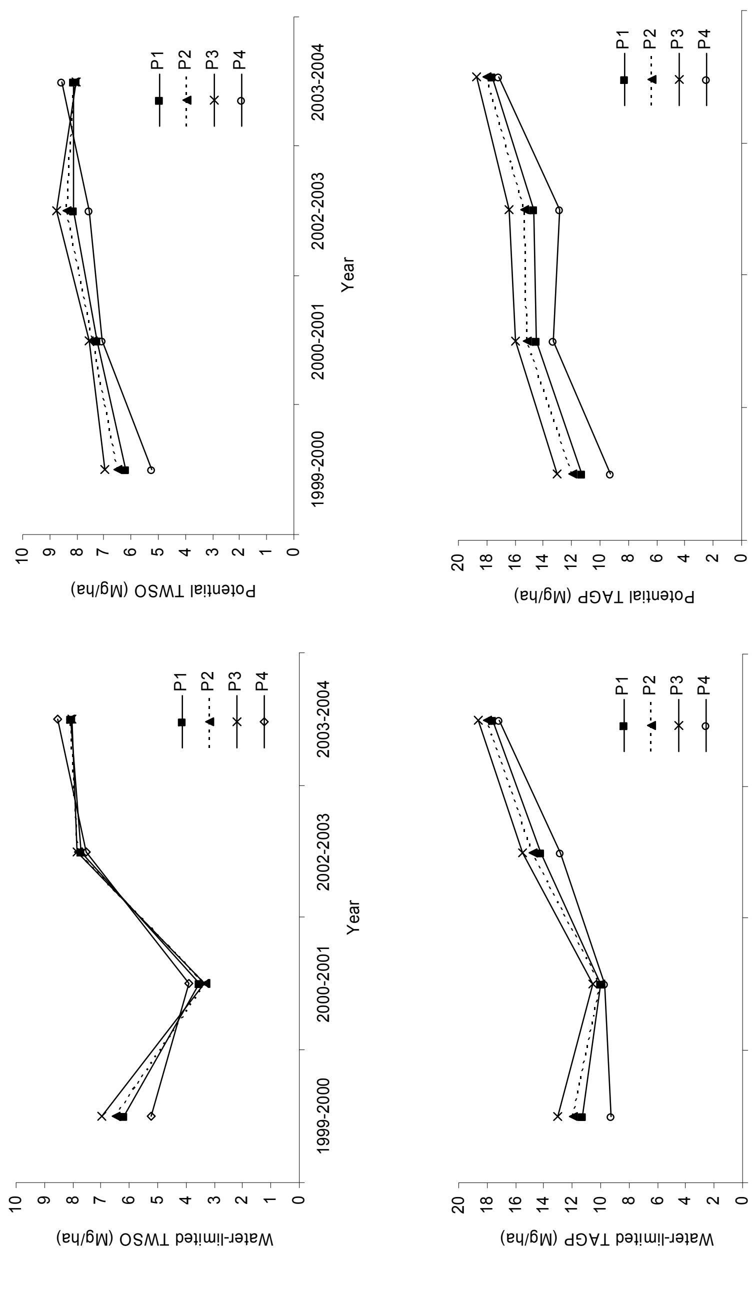

Figure 2.7. Simulated grain yield (TWSO) and total aboveground production (TAGP) in the potential and water-limited situations with different partitioning factors

2.5.3 Sensitivity of estimated potential yield to emergence date

Model calibration was based on the emergence date at the research station in the specific years. Review of available bulletins showed that there were 22-35 days difference in emergence date of different plants in the blocks (Table 2.19). Therefore, a sensitivity analysis was performed on emergence date. The calibrated model was run for emergence dates between 25th November (Julian day 330) and 10th January (Julian day 10). In all years, later emergence leads to higher TAGP (Table 2.21), while the results are variable for TWSO (Table 2.20 and Table 2.21).

Table 2.19. Emergence dates (Julian calendar day) of different plants in the experimental blocks in different years

Year	sowing	Emergence			Duration
		Start	50% *	End	
1999	312	332	340	2	35
2000	310	338	342	360	22
2002	312	328	334	350	22
2003	336	N.A.**	14	N.A.	N.A.

* 50% of the plants have emerged
** N.A. – not available

Table 2.20. Comparison of simulated grain yield (TWSO, kg/ha) in different years for different emergence dates

	Emergence date (Julian calendar day)				
year	330	340	350	360	10
1999-2000	6367	6480	6705	6914	7104
2000-2001	7194	7397	7413	7416	7268
2002-2003	8210	8484	8272	8146	7860
2003-2004	7901	8250	8370	8373	8168

Table 2.21. Comparison of total aboveground production (TAGP, kg/ha) in different years for different emergence dates

	Emergence date (Julian calendar day)				
year	330	340	350	360	10
1999-2000	11436	11893	12819	13572	14774
2000-2001	13539	14916	15691	16053	16598
2002-2003	14960	15916	16601	17016	17480
2003-2004	13993	15584	16121	17298	18096

2.5.4 Uncertainty analysis on soil water holding capacity

Water holding capacity is an important soil physical characteristic used in WOFOST for crop growth simulation in the water-limited situation. This characteristic can be determined by measuring field capacity and permanent wilting point, but in this study, it was estimated based on soil texture. In addition, WOFOST cannot deal with variations in soil characteristics in vertical direction in the soil profile, and one average value is used for these characteristics for the root zone. A sensitivity analysis on soil water holding capacity was performed in the range of 115 to 175 mm/m. Model results for TWSO and TAGP for the 2000-2001 season for this range are presented in Table 2.22 and Figure 2.8.

Table 2.22. Simulated grain yield (TWSO) and total aboveground production (TAGP) in the 2000-2001 season, for different values of soil water holding capacity

Water holding capacity (mm/m)	TWSO (kg/ha)	TAGP (kg/ha)
115	3091	9207
130	3256	9730
145*	3494	10214
160	3683	10698
175	3591	10418

* Water holding capacity based on soil texture used in model calibration

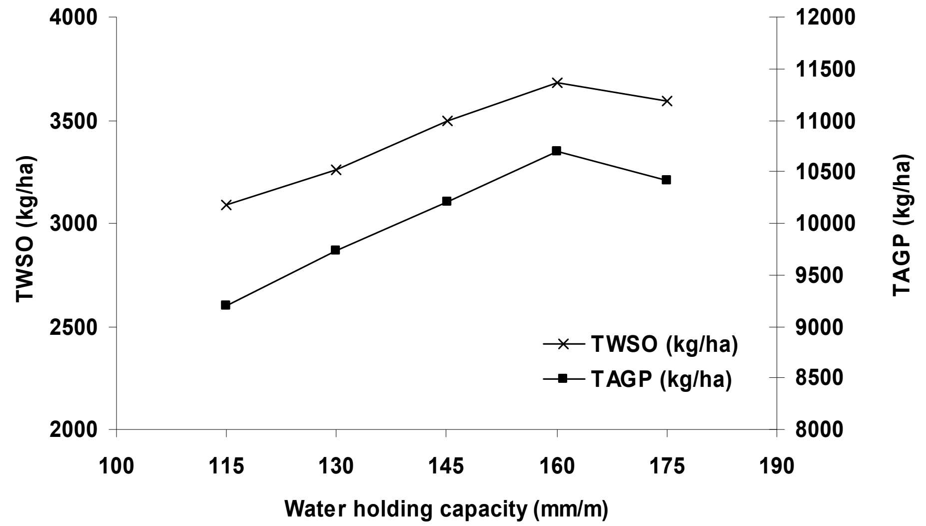

Figure 2.8. Simulated values of TWSO and TAGP for 2000-2001, for different values of soil water holding capacity

2.6 Discussion and conclusion

Phenological development is one of the most important crop characteristics in WOFOST that has to be taken into account in crop growth simulation. The major environmental conditions influencing phenological development are temperature and day length (Van Keulen and Wolf, 1986) . In this study, phenological development was defined based on temperature only. For this purpose, the concept of thermal time was applied. WOFOST determines phenological stages by means of TSUM1 and TSUM2.

In the agro-meteorological research center of Kaboutar Abad, phenological stages were recorded every other day, except after irrigation, when observations were discontinued for a week, because of high soil moisture. TSUM1 and TSUM2 for each year were calculated based on phenological events and daily weather data (Table 2.5). Values of these parameters vary among years, while it was assumed that they are crop-characteristic and should be constant. Differences in TSUM2 were small, but TSUM1 showed more variation among years. These variations may be due to different reasons.

Some of these differences are due to observation error. For example, in the 1999-2000 season, irrigation was applied at the beginning of flowering and during maturation and no observations were recorded during those important stages. As a result, exact dates of those stages were not recorded. Table 2.5 shows that there are slight differences between TSUM2 in this year and in the other years. Review of the barley bulletins in this year showed that there is uncertainty in the reported dates for flowering and maturity. Therefore, TSUM1 and TSUM2 in the 1999-2000 season did not take into account in the analysis.

Another source of variation in TSUM in different years is related to the assumption that crop development is influenced only by temperature. The effects of day length on development rate and development stage did not take into account, while Mahfoozi et al. (2001) showed that phenological development of winter cereals is sensitive to day length.

Average values of TSUM1 and TSUM2 for the seasons 2000-2001, 2002-2003 and 2003-2004 have been used for calibration of WOFOST. Although there is a tool (FSEOPT) in WOFOST for calibration of crop parameters, in this study crop parameters were calibrated manually for the 2002-2003 season. FSEOPT can calibrate crop parameters based on TAGP, TWSO or LAI in the course of the growing season, which these data was not available for this study. Crop parameters were calibrated only based on grain and straw yields in the 2002-2003 season. Data of the 2003-2004 season have been used for validation of the model. After calibration and validation, the model has been run for other years. Table 2.9 and Figure 2.1 compare simulated potential yields and measured yields. Results show that there is satisfactory agreement between simulated yields and measured yields in the years without water-stress, and with slight water-stress. However, simulated TWSO was far from the measured yield in the 2000-2001 season in which the crop experienced severe water-stress. As only data for one year with severe water-stress were available, it cannot conclude whether the problem originates in the model or in the available data.

Although the field was small (one hectare) and under unique management, differences in yields among experimental plots were identified. For example, total harvested aboveground production in the 1999-2000 season varied between 12 and 20 Mg/ha in different plots. Although heterogeneity is characteristic in field experiments, such huge variation is abnormal and suggests errors in measurements in the field experiment. Therefore, TSUM, partitioning of dry matter among different organs, emergence date, and soil water holding capacity have been selected for uncertainty analysis.

Table 2.15 shows model results for experimental years with different TSUM1 and TSUM2. Potential TAGP and water-limited TWSO were significantly different at the 5% level for different values of TSUM1 and TSUM2, respectively.

Partitioning of total dry matter increase to different organs was calibrated in the potential production situation, based on grain yields and total dry matter production at maturity. The uncertainty analysis showed that model results are sensitive to partitioning.

Emergence date is the starting point for crop growth simulation. Emergence depends on sowing depth and (soil) temperature. For example, in experimental fields in the 1999-2000 season, emergence started on 30 November 1999 and was completed on 2 January 2000. In the current study, emergence date and other phenological stages were defined as the moment that 50% of the plants passed that stage. Results of the uncertainty analysis showed that later emergence results in higher TAGP, while grain yield showed variable results.

Soil water holding capacity is one of the soil physical characteristics used in WOFOST for crop growth simulation in the water-limited situation. Results of the uncertainty analysis showed that both, TWSO and TAGP increase with increasing soil water holding capacity up to a value of 160 mm/m, followed by a decrease with a further increase to 175 mm (Figure 2.8).

Each year many studies are carried out in agricultural research centers, agricultural faculties and agro-meteorological centers on different crops in different regions in Iran. Although in most of these studies data required for calibration of WOFOST are being recorded (or easily could be recorded), researchers think that they are not important and they are not reported. Author believes that crop growth simulation models can be calibrated based on available data of these studies.

Acknowledgments

Most of the data used in this chapter have been derived from on-going studies in the Agro-meteorological station of Kaboutar Abad, Iran. Many thanks are due to the staff of this station, especially Dr. H. Yazdanpanah for providing these data.

3 Sensitivity analysis of performance of crop growth simulation models to daily solar radiation estimation methods

Abstract

Solar radiation is the single most important environmental factor driving canopy photosynthesis and transpiration. This weather characteristic is measured only in a limited number of weather stations. Hence, in many situations it has to be estimated from other weather characteristics such as sunshine duration and temperature using empirical relations. In this study, the Ångstrom and Hargreaves formulas have been used for solar radiation estimation, based on monthly and annual weather data for three weather stations in Esfahan province, Iran. Deviations of estimated solar radiation from measured values (both absolute and relative) varied with month of the year and with estimation method. Estimated and measured radiation values were used in a crop growth simulation model to explore sensitivity of simulated production with respect to radiation estimation method. Maximum deviation for winter barley and silage maize was around 9%.

Keywords: WOFOST, Ångstrom, Hargreaves, Barley, Maize

3.1 Introduction

Crop growth simulation models are computer programs that integrate information on daily weather, crop characteristics, soil characteristics, and management to calculate crop growth and yield (Batchelor and Paz, 1999). They are used, among others, to support agricultural decision-making and learning processes (Van Ittersum et al., 2003; Park et al., 2005).

Solar radiation provides energy for photosynthesis and (evapo)transpiration of crops and soils (Supit and van Kappel, 1998; Donatelli et al., 2003; Pohlert, 2004). Daily solar radiation is therefore one of the major inputs in crop growth simulation models (Williams et al., 1989; Boogaard et al., 1998; Brisson et al., 2003), required for calculation of daily gross CO_2 assimilation, the basis for dry matter production and yield.

In spite of the importance of solar radiation for crop growth, it is not routinely measured at all meteorological stations, probably because of the cost and the maintenance and calibration requirements of the measuring equipment (Nonhebel, 1994a; Almorox and Hontoria, 2004; Podesta et al., 2004). A number of empirical relations of varying complexity have been developed to estimate solar radiation at a given location from other climatic characteristics that are measured more frequently (Mubiru et al., 2007). Relations have been established with sunshine duration (Hargreaves et al., 1985; Bahel et al., 1987; Yorukoglu and Celik, 2006), air temperature (Bristow and Campbell, 1984; Allen, 1997; Paulescu et al., 2006), cloud cover (Supit and van Kappel, 1998; Ehnberg and Bollen, 2005) and combinations of different weather characteristics (Sabbagh et al., 1977; Menges et al., 2006). Results of these studies have shown that sunshine-based models are more accurate than temperature-based models for estimation of daily solar radiation (Chen et al., 2004; Mubiru et al., 2007; Trnka et al., 2007).

Crop growth simulation models have been tested for sensitivity of simulated crop yields to inaccuracies in solar radiation estimates (Nonhebel, 1994a; Nonhebel, 1994b; Fodor and Kovacs, 2005). These analyses have included use of (10-day, monthly and seasonal) average weather data instead of daily data (Nonhebel, 1994c), using radiation from nearby stations (Xie et al., 2003), estimation of daily solar radiation from monthly means (Soltani et al., 2004), exploration of climate change effects on solar radiation (Kalra et al., 2007), and filling missing data of radiation by values generated by different methods of solar radiation estimation (Pohlert, 2004). Fodor and Kovacs (2005), using crop growth simulation model 4M (Fodor et al., 2003) to analyze the sensitivity of yield to inaccuracies in measurements of weather characteristics, found that 2% error in solar radiation caused 3.7 and 2.3% error in simulated grain yield and biomass of maize, respectively. They also showed significantly larger inaccuracies in calculated yield due to errors in measured radiation in years with low yields than in years with high yields. Nonhebel (1994a; 1994b) showed deviations of 5-10% in the simulated yield of spring wheat in both, the water-limited and potential production situations (Van Ittersum and Rabbinge, 1997) with 10% inaccuracy in solar radiation. Water-limited production appeared less sensitive to inaccuracies in solar radiation than potential production. The analysis also showed that randomly replacing 10% of the solar radiation data by average values did not significantly affect simulated water-limited and potential yields of spring wheat. Xie et al. (2003), in analyzing the sensitivity of sorghum and maize yields to solar radiation, found changes of less than 8% at 10% changes in solar radiation.

Trnka et al. (2007) analyzed the effects of different estimation methods for daily global solar radiation on simulated yields of winter wheat and spring barley in the Czech Republic and Austria, using the WOFOST (Boogaard et al., 1998) and CERES (Godwin et al., 1989; Otter-Nacke et al., 1991) crop growth simulation models. Simulated yields based on solar radiation estimated by the Ångstrom-Prescott (Ångstrom, 1924) and Hargreaves (Hargreaves et al., 1985) formulas deviated more than 10 percent from simulated yields based on measured radiation in 6 and 48% of the cases, respectively (in 1.4 and 16.3% of the cases deviations exceeded 25%). Moreover, the sensitivity varied with soil type. As a result of the model structure, diverging values of solar radiation resulted in many cases in disproportionate diversions in actual transpiration.

Soltani et al. (2004) investigated the sensitivity of simulated yields of wheat, maize and soybean to daily radiation generated by linear interpolation from monthly means. Their results showed around 23% difference from yields simulated on the basis of measured radiation. They concluded that only in specific situations, monthly average radiation data can be used as input in crop growth simulation models.

Pohlert (2004) randomly replaced 4.8% of the measured solar radiation data in two temperate (Wageningen, The Netherlands and Cordoba, Spain) and one tropical location (Los Baños, Philippines) by values estimated by different methods. Yields of maize, simulated with WOFOST with these different sets of radiation data, were not significantly different. Nonhebel (1994c) found that use of average weather data in crop growth simulation models in the water-limited production situation resulted in overestimation of spring wheat yields in wet conditions and underestimation in dry conditions.

In most studies reviewed here, a fixed percentage of error (over- or underestimate), uncertainty or change in solar radiation has been considered. Radiation estimates based on various methods produced different results with different magnitudes of error. Moreover, in most cases, sensitivity analyses of crop yields were based on empirical formulas with annual coefficients. However, it has been shown that these coefficients may show strong temporal variation (Almorox and Hontoria, 2004). Moreover, daily solar radiation estimated with empirical formulas may show much larger deviations from measured values than have been established in earlier work.

The objective of this study was to examine the sensitivity of potential yields and evapotranspiration of a winter crop and a summer crop grown in Iran, simulated by the WOFOST model to radiation estimates by sunshine and temperature-based models with different sets of annual and monthly coefficients for three weather stations.

3.2 Material and Methods

First, radiation is estimated by the Ångstrom and Hargreaves equations, as representative of sunshine-based and temperature-based models, respectively with different sets of annual and monthly coefficients in three weather stations in Esfahan province, Iran. The estimated values are then compared with measured data from those stations. The WOFOST crop simulation model (Boogaard et al., 1998) is used for simulation of potential production and transpiration of winter barley (winter crop) and silage maize (summer crop).

Sensitivity analysis on final yield and total potential transpiration of these crops is carried out with respect to different methods of solar radiation estimation. The process is graphically presented in Figure 3.1.

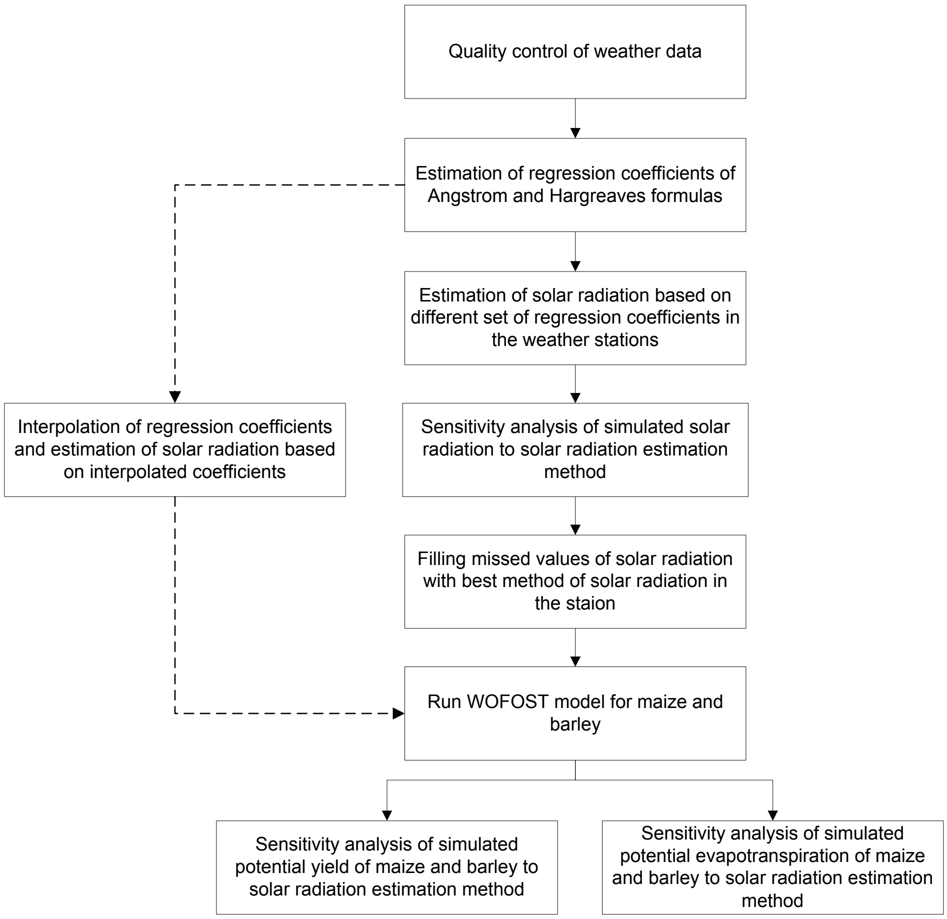

Figure 3.1. Schematic representation of the applied procedure

3.2.1 Data and study area

Daily weather data of the synoptic weather stations of Esfahan (altitude 1550 meter above sea level), Najaf Abad (1641 m asl) and Kaboutar Abad (1545 m asl), established in 1951, 1987 and 2003, respectively, located in Esfahan province, Iran (Figure 3.2), have been collected from the Iranian Meteorological Organization (IRIMO). The distance between Esfahan station and Najaf Abad and Kaboutar Abad stations is 27 and 22 km, respectively, and that between the stations of Kaboutar Abad and Najaf Abad 45 km. Kaboutar Abad is located close to a mountain and Esfahan close to a hill, but no major barriers exist between the weather stations (Figure 3.2). Table 3.1 shows average monthly weather characteristics for Esfahan (1951-2003) and Kaboutar Abad (1987-2003) stations (IRIMO, 2007b). For Najaf Abad, recently established, no average data are available yet.

3.2.2 Calculation of solar radiation

Two approaches for estimation of solar radiation have been selected, the equation of Ångstrom-Prescott and that of Hargreaves.

- ***Ångstrom-Prescott***

The Ångstrom-Prescott equation (Ångstrom, 1924; Prescott, 1940) has been widely used in solar radiation research:

$$\frac{R_s}{R_a} = a + b * \left(\frac{n}{N}\right) \tag{3.1}$$

Where, R_s is total daily global radiation ($MJ.m^{-2}$), R_a is daily extra-terrestrial solar radiation ($MJ.m^{-2}$), n is actual sunshine duration (h), N is potential sunshine duration (h), and a and b are regression coefficients. Coefficient a expresses the fraction extra-terrestrial radiation reaching the earth' surface on fully overcast days (n = 0); (a+b) the fraction reaching the earth' surface on clear days (n = N). Extra-terrestrial solar radiation (R_a) and potential sunshine duration (N) can be calculated from geographical coordinates and Julian calendar date (Allen et al., 1998). Global radiation and actual sunshine duration are measured in weather stations.

Values of the regression coefficients a and b vary in dependence of atmospheric conditions (humidity, dust content, type and thickness of cloud cover and concentration of pollutants) (Almorox and Hontoria, 2004) and of solar declination (latitude and day of year) (Allen et al., 1998). Moreover, the value of coefficient a has been reported to vary with altitude of the station (Rensheng et al., 2006). Values of a and b should be derived therefore, by analyzing actual measurements of both total global radiation and sunshine duration.

Measured data of radiation and sunshine duration from the selected weather stations are used for estimation of Ångstrom coefficients, using linear regression between daily values of (R_s/R_a) and (n/N).

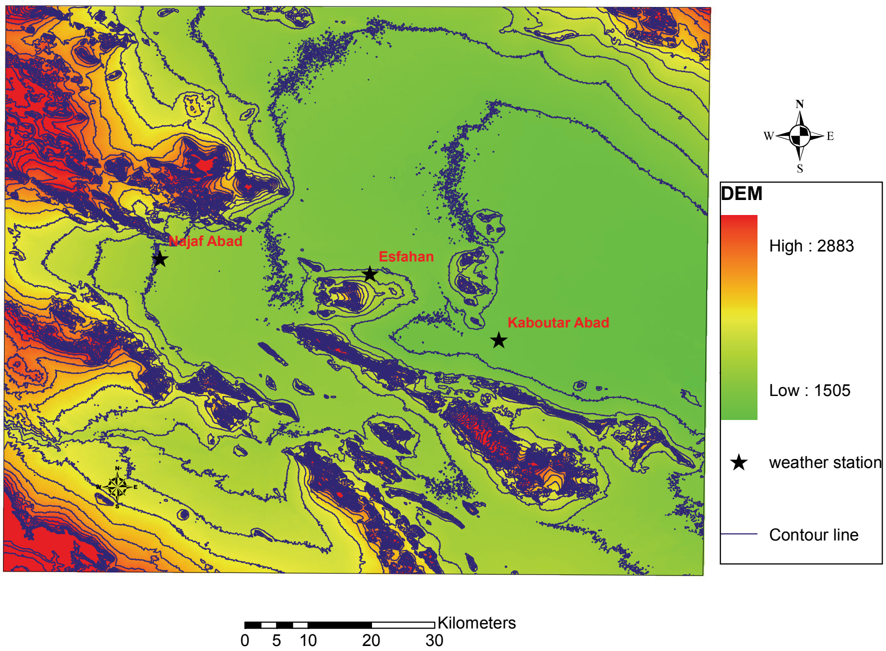

Figure 3.2. Location of the weather stations on DEM

Table 3.1. Average monthly weather characteristics for Esfahan (1951-2003) and Kaboutar Abad (1987-2003) (IRIMO, 2007b)

	Temperature (°C)		Precipitation (mm)		Sunshine duration (h)	
Month	Esfahan	Kaboutar Abad	Esfahan	Kaboutar Abad	Esfahan	Kaboutar Abad
Jan	2.9	3.4	18.3	17.1	203.3	196.1
Feb	5.7	6.4	14.4	12.7	215.1	226.6
Mar	10.3	10.6	22.2	26.9	242.8	237.8
Apr	15.9	17	18.4	11.3	249.1	249.5
May	21.2	22.3	8.8	7.4	307.6	315.6
June	26.8	27.6	1.2	1.5	347.9	345.5
July	29.2	30.5	1.8	2.2	349.7	352.4
Aug	27.7	29.2	0.4	0.2	338.6	350.7
Sep	23.5	25.1	0.1	0	310.6	302.8
Oct	16.8	18.1	4.1	2.9	280.5	271.5
Nov	9.7	10.7	12.2	8.5	224.1	210.9
Dec	4.4	5.7	19.2	13.1	196.9	183.9
Annual	16.2	17.2	121.1	103.8	3266.2	3243.3

- ***Hargreaves***

When only minimum and maximum temperatures are available, Hargreaves equation (Hargreaves et al., 1985) can be used:

$$R_s = a * R_a * \sqrt{T_{\max} - T_{\min}} + b \qquad (3.2)$$

Where, R_s is daily total global radiation ($MJ.m^{-2}$), R_a is daily extra-terrestrial solar radiation ($MJ.m^{-2}$), T_{max} and T_{min} are daily maximum and minimum temperature (^oC), and a and b are regression coefficients.

Again, the regression coefficients vary with geographical location and should be derived by analyzing actual measurements of daily global radiation and minimum and maximum temperatures. Hargreaves coefficients for the selected weather stations are determined using linear regression between daily values of (R_s) and (R_a* $(T_{max}$-$T_{min})^{0.5}$).

- ***Interpolation of regression coefficients***

For situations where actual measurements of solar radiation in a weather station are not available, values for the regression coefficients can be estimated by interpolation of values from nearby stations. Van der Goot et al. (2004) proposed derivation of the coefficients based on simple distance-weighted averages of the three nearest stations, provided the distance to the location of interest is less than 200 km. Moreover, they suggested that these stations should not vary more than 200 m in altitude.

$$a = a_1 * w_1 + a_2 * w_2 + a_3 * w_3 \qquad (3.3\text{-}1)$$

$$b = b_1 * w_1 + b_2 * w_2 + b_3 * w_3 \qquad (3.3\text{-}2)$$

$$w_1 = \frac{D_{2,3}}{(D_{1,2} + D_{1,3} + D_{2,3})} \qquad (3.3\text{-}3)$$

$$w_2 = \frac{D_{1,3}}{(D_{1,2} + D_{1,3} + D_{2,3})} \qquad (3.3\text{-}4)$$

$$w_3 = \frac{D_{1,2}}{(D_{1,2} + D_{1,3} + D_{2,3})} \qquad (3.3\text{-}5)$$

In these equations, subscripts 1, 2 and 3 are the station numbers, *w* is the weight factor for the station and *D* is the distance between two stations.

3.2.3 WOFOST model

WOFOST (Boogaard et al., 1998) is a tool for quantitative analysis of growth and production of annual field crops. It simulates daily crop growth rate, based on climatic conditions (i.e. solar radiation, temperature, relative humidity, wind speed and rainfall), soil properties (i.e. soil depth, water holding capacity and infiltration capacity) and crop characteristics (i.e. length of the growing cycle, photosynthetic characteristics and distribution of dry matter). In principle, WOFOST can simulate the growth of any annual crop growing at any location for three production situations: Potential, water-limited and nutrient-limited (Van Ittersum and Rabbinge, 1997).

WOFOST has been applied for simulation of growth of winter barley and silage maize in the potential production situation, where crop growth rate is determined by climatic conditions and crop characteristics. WOFOST has been calibrated for winter barley (Chapter 2) and silage maize (Vazifedoust et al., 2008) in the study area.

3.3 Results

3.3.1 Calculation of Ångstrom and Hargreaves coefficients

Screening of the available data showed missing values and implausible values. Therefore, the quality of the solar radiation data was checked manually by comparing reported values with extra-terrestrial radiation and sunshine duration in the station, and with measured solar radiation in nearby stations for detecting and removing gross errors. Results showed that 8.5 percent of the data were missing or of doubtful quality (Table 3.2). Figure 3.3 shows daily solar radiation for the three weather stations in the year 2003, after removing unacceptable data.

Table 3.2. Number and percentage of missing data for solar radiation in the three stations after removal of unacceptable data

Station	Total number of records	Number of missing records	Percentage missing records
Esfahan	1827	101	5.5
Kaboutar Abad	1827	205	11.2
Najaf Abad	731	67	9.2
Total	4385	373	8.5

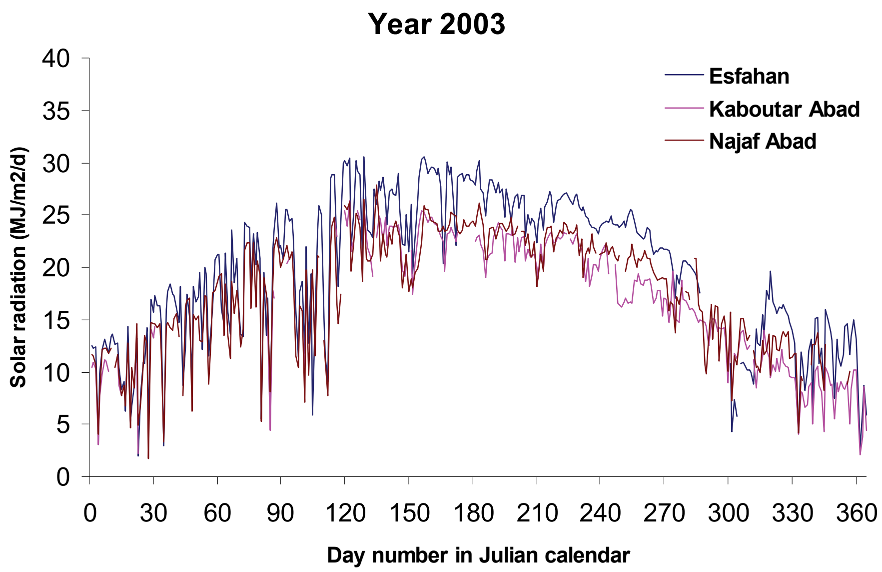

Figure 3.3. Measured daily solar radiation (MJ.m^{-2}) in the weather stations of Esfahan, Kaboutar Abad and Najaf Abad in 2003

Average monthly and annual Ångstrom and Hargreaves coefficients for the three stations have been determined using linear regression of daily measurements of solar radiation, sunshine duration and minimum and maximum temperatures (Figure 3.4 and Figure 3.5). R^2 for the monthly values is higher for the Ångstrom equation than for the Hargreaves equation, whereas the opposite holds for the annual coefficients. Moreover, the correlation coefficients are significantly higher for the winter than for the summer months.

Figure 3.6 shows the annual variation in the Ångstrom coefficients a, b and (a+b) for the three stations. Average annual coefficients vary little over years (except for the years 2003 and 2004 in Kaboutar Abad).

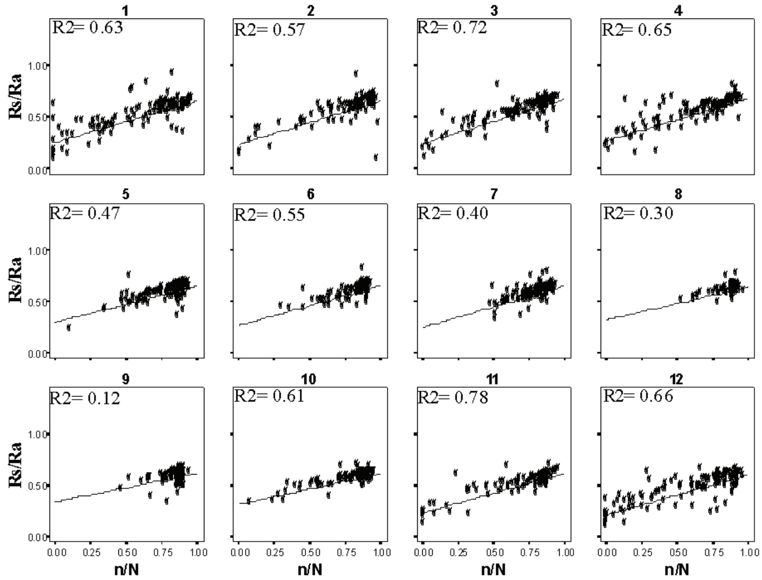

Figure 3.4. Relation between Rs/Ra and n/N for Kaboutar Abad for different months

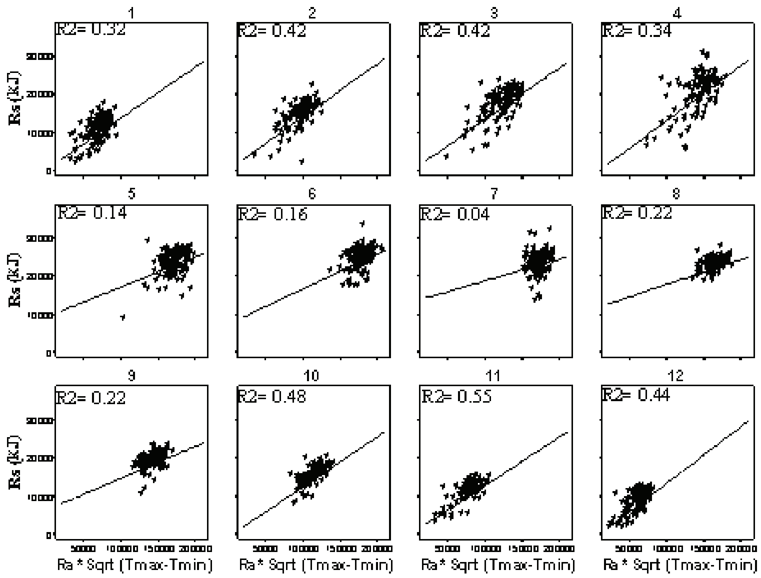

Figure 3.5. Relation between Rs and (Ra* (Tmax-Tmin) $^{0.5}$) for Kaboutar Abad for different months

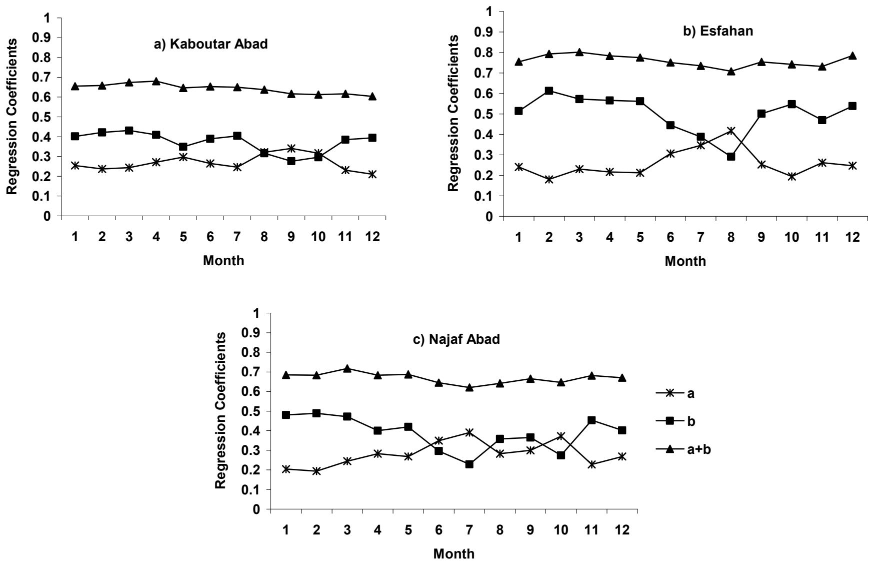

Figure 3.6. Annual variation in Ångstrom coefficients for the three weather stations

3.3.2 Comparison of estimated solar radiation by the Ångstrom and Hargreaves formulas and different sets of coefficients

Solar radiation in the stations has been estimated based on the monthly and annual coefficients of the Ångstrom and Hargreaves formulas. Two sets of coefficients have been used: (i) for each station, coefficients derived from the data of that station (abbreviated as RAM (Radiation _ Ångstrom _ Monthly), RAY (Radiation _ Ångstrom _ Yearly), RHM (Radiation _ Hargreaves _ Monthly) and RHY (Radiation _ Hargreaves _ Yearly), respectively), (ii) coefficients derived from the pooled data of all three stations ((RAMT (Radiation _ Ångstrom _ Monthly _ Total), RAYT (Radiation _ Ångstrom _ Yearly _ Total), RHMT (Radiation _ Hargreaves _ Monthly _ Total), RHYT (Radiation _ Hargreaves _ Yearly _ Total), respectively). Recommended coefficients by FAO (RAF (Radiation _ Ångstrom _ FAO): a = 0.25 and b = 0.50 (Allen et al., 1998)) and by Khalili (1997) (RAK (Radiation _ Ångstrom _ Khalili): a = 0.3 and b = 0.42) have also been used for comparison.

Solar radiation estimated with the coefficients of set (i) showed smaller deviations from measured data than that estimated with the coefficients of set (ii) (Figure 3.7). Largest deviations were observed for RAF and RAK in Kaboutar Abad and Najaf Abad, and RHYT and RHMT in Esfahan. Deviations from measured values varied over time, i.e. solar radiation was underestimated by RAY and RHY in winter and overestimated in summer in Kaboutar Abad and Esfahan. For most methods, absolute deviations from measured radiation were higher in summer than in winter.

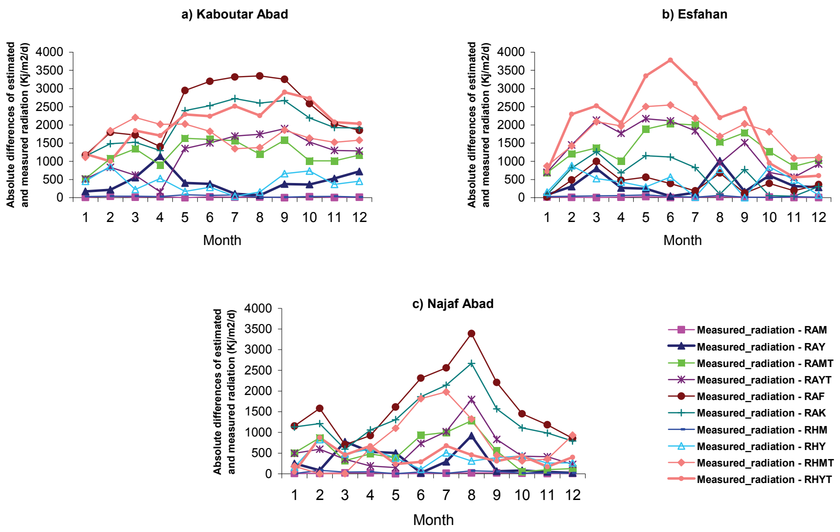

Figure 3.7. Differences between estimated radiation by different methods and measured values

The goodness of fit between daily estimated and measured solar radiation for the three weather stations for the various methods has been tested (t-test) using SPSS 15.0 (SPSS Inc., 2007), separately for the whole year, the growing period of winter crops and the growing period of summer crops. Based on the results of paired samples t-test, the methods have been ranked (Table 3.3). Subsequently, missing values of solar radiation were replaced by values estimated by the best method for each station (RAM for Esfahan and Najaf Abad; RHM for Kaboutar Abad).

3.3.3 Simulation of crop growth for the selected weather stations

As deviations of estimated solar radiation from measured data are different in summer and winter, for sensitivity analysis of crop yields to methods of solar radiation estimation one winter crop (barley) and one summer crop (silage maize) has been selected. Winter barley is sown between September 15 and October 15 in the region. Silage maize is sown in the first half of June, following harvest of winter barley and winter wheat. Although sowing dates of the crops vary among districts, a fixed sowing date has been selected for comparison.

Table 3.3. Ranking of the methods of solar radiation estimation for three weather stations in Iran (annual, growing period of winter crops, and growing period of summer crops)

	Esfahan			Kaboutar Abad			Najaf Abad		
Rank	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer
1	RAM	RAM	RAF	RHM	RHM	RAM	RAM	RAM	RAM
2	RHM	RHM	RAM	RAM	RAM	RHM	RHM	RHM	RHM
3	RAY	RHY	RHM	RHY	RHY	RAY	RHY	RHMT	RHY
4	RHY	RAY	RHY	RAY	RAY	RHY	RAY	RHY	RHYT
5	RAF	RAF	RAY	RAYT	RAYT	RHMT	RHYT	RHYT	RAY
6	RAK	RAK	RAK	RAMT	RAMT	RAMT	RHMT	RAYT	RAMT
7	RHMT	RHMT	RHMT	RHMT	RHYT	RAYT	RAYT	RAY	RAYT
8	RHYT	RAMT	RAYT	RHYT	RHMT	RHYT	RAMT	RAMT	RHMT
9	RAYT	RHYT	RAMT	RAK	RAK	RAK	RAK	RAK	RAK
10	RAMT	RAYT	RHYT	RAF	RAF	RAF	RAF	RAF	RAF

For the simulations, solar radiation values, estimated with different sets of Ångstrom and Hargreaves coefficients have been combined with measured data for the other weather characteristics. Simulated total aboveground dry matter production (TAGP) of silage maize for different runs for the three weather stations is shown in Figure 3.8 and simulated grain yield (TWSO: total weight of storage organ) of barley in Figure 3.9. Over all methods, the maximum deviations, in simulated potential yields from the run based on measured radiation values are observed in Kaboutar Abad: 13.4% in the year 2001 with the RHMT method for TWSO of barley, 19.0% in the year 2001 with the RHYT method for TAGP of barley and 9.0% in the year 2004 with the RHYT method for TAGP of silage maize (Table 3.4).

Table 3.4. Maximum deviation of simulated potential yields with all methods from base run

	Esfahan		Kaboutar Abad		Najaf Abad	
	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)
TAGP silage maize	1260	6.1	1820	9.0	1280	6.3
TAGP barley	1440	9.3	2370	19.0	577	3.6
TWSO barley	380	5.5	920	13.4	400	4.8

The maximum deviation in simulated potential yields from the base run, based on the best methods for solar radiation estimation (RAM for Esfahan and Najaf Abad and RHM for Kaboutar Abad) was less than 9% in all cases (Table 3.5).

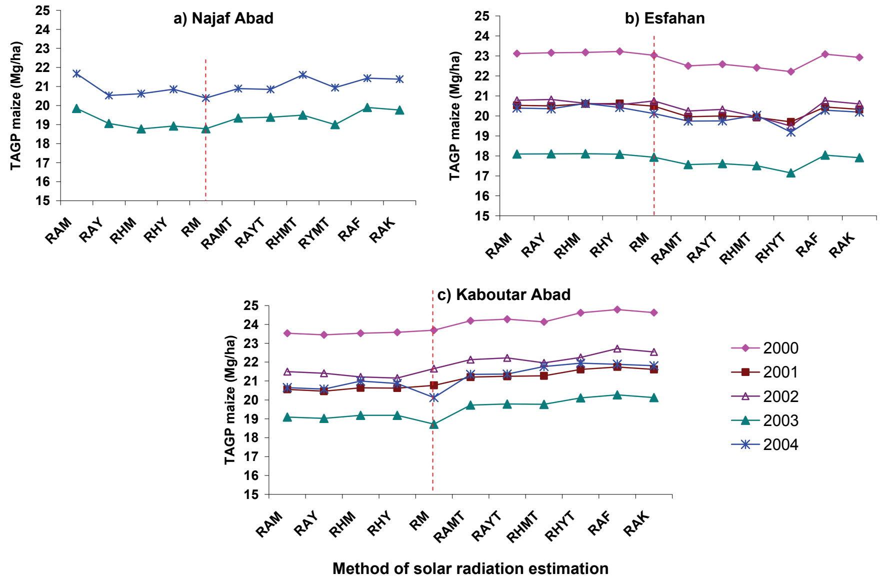

Figure 3.8. Simulated potential total aboveground dry matter production of maize (Mg/ha) based on solar radiation estimates by different methods for three locations in Iran, for the years 2000-2004. Dotted vertical lines represent simulations based on measured radiation

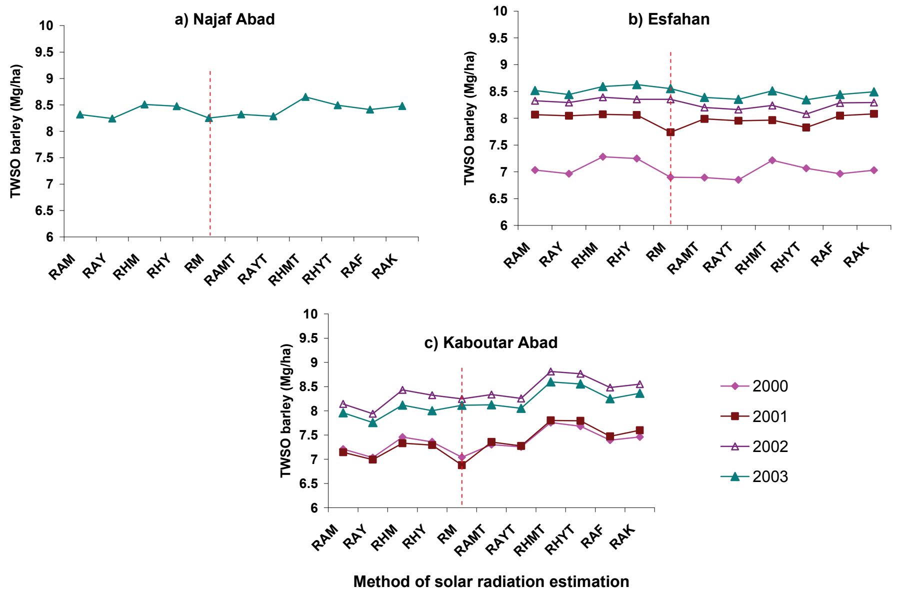

Figure 3.9. Simulated potential grain yield of barley (Mg/ha) based on solar radiation estimates by different methods for three locations in Iran for the years 2000- 2003. Dotted vertical lines represent simulations based on measured radiation

Table 3.5. Maximum deviation of simulated yield from the base run, based on best solar radiation estimation method (RAM for Esfahan and Najaf Abad and RHM for Kaboutar Abad)

	Esfahan		Kaboutar Abad		Najaf Abad	
	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)
TAGP silage maize	500	2.5	870	4.3	1300	6.3
TAGP barley	1130	7.3	1110	8.9	260	1.5
TWSO barley	380	5.5	450	6.6	260	3.1

3.3.4 Interpolation of regression coefficients in Najaf Abad station

The coefficients for Najaf Abad station have also been estimated through weighted interpolation of the regression coefficients of Esfahan (27 km, weight 0.625) and Kaboutar Abad (45 km, weight 0.375) (Table 3.6).

Table 3.6. Interpolated coefficients of Ångstrom and Hargreaves equations for Najaf Abad

Month	Ångstrom coefficients		Hargreaves coefficients	
	a	b	a	b
1	0.246	0.472	0.16	-283
2	0.201	0.541	0.153	994
3	0.235	0.519	0.149	871
4	0.237	0.507	0.193	-5533
5	0.245	0.482	0.121	5607
6	0.29	0.424	0.103	9017
7	0.309	0.394	0.058	15717
8	0.381	0.3	0.059	14702
9	0.286	0.417	0.075	10541
10	0.24	0.453	0.163	-1817
11	0.25	0.438	0.143	418
12	0.233	0.484	0.182	-1905
Annual	0.245	0.473	0.151	242

3.3.5 Simulation of crop growth in Najaf Abad based on interpolated coefficients

The WOFOST model was run with the new set of solar radiation values derived from the interpolated coefficients in Najaf Abad. The maximum deviation associated with the use of interpolated coefficients was 6.3%, comparable with the other methods.

3.3.6 Estimation of potential crop transpiration using the crop growth simulation model WOFOST and different sets of estimated solar radiation

Canopy transpiration is strongly dependent on solar radiation, that provides the energy for vaporization of the water, but is also affected by temperature, vapor pressure, wind speed and crop characteristics. Potential transpiration of silage maize and barley has been estimated using WOFOST for the three weather stations, with radiation estimated by different methods. Results of this analysis showed that transpiration is also sensitive to the method of solar radiation estimation, but less than potential yield. Among all methods of solar radiation estimation, the maximum deviation from the base run of total simulated potential transpiration was 20 mm (6.2%) for silage maize and 43 mm (16.2%) for barley (Table 3.7), while based on the best method for radiation estimation (RAM for Esfahan and Najaf Abad and RHM for Kaboutar Abad), the deviation was less than 19 mm (7.1%) (Table 3.8).

Table 3.7. Maximum deviation of simulated potential transpiration from the base run based on all methods of solar radiation estimation

	silage maize		Barley	
	mm	%	mm	%
Esfahan	17	5.3	22	6.9
Kaboutar Abad	20	6.2	43	16.2
Najaf Abad	19	3.9	10	3.0

Table 3.8. Maximum deviation of simulated potential transpiration from the base run based on the best solar radiation estimation method (RAM for Esfahan and Najaf Abad and RHM for Kaboutar Abad)

	silage maize		Barley	
	mm	%	mm	%
Esfahan	4	1.2	18	5.6
Kaboutar Abad	9	3	19	7.1
Najaf Abad	19	3.9	2	0.5

3.4 Discussion and conclusions

Regression coefficients for the Ångstrom and Hargreaves equations to estimate daily solar radiation from other daily weather data, calculated for three stations in Iran varied with month of the year and station. The coefficient a in Ångstrom's equation was lower in summer than in winter, while the reverse held for coefficient b. The coefficient a in Hargreaves formula showed the same pattern as b in Ångstrom. The seasonal (monthly) variation in the sum of the regression coefficients in Ångstrom's formula was smaller than that in the individual coefficients. Similar variations in the regression coefficients have been reported before (Allen et al., 1998; Almorox and Hontoria, 2004; Menges et al., 2006).

Correlation coefficients between measured and estimated solar radiation for the calibrated models were low in some months, especially in summer for the Hargreaves model. It was almost zero for the months June, July, August, September and October for Hargreaves' formula, when data of all three weather stations were used.

Despite the fact that the three stations are very close (maximum distance between stations was 45 km) and located at more or less the same altitude, solar radiation in Esfahan was slightly higher than in the other two stations (13% and 12% on average, respectively for Kaboutar Abad and Najaf Abad) . Exploring the reason behind this observation was beyond the scope of this paper; however, it is an important issue that should be further studied.

Deviations of estimated solar radiation from measured values (both absolute and relative) varied with month of the year and with estimation method. Deviations were smaller for estimates based on data from individual stations, than for estimates based on data of all three stations. Maximum absolute deviation of solar radiation estimated by different methods was 3.8 ($MJ.m^{-2}.d^{-1}$) in July in Esfahan station, calculated with the RHYT method. Absolute deviations were larger in summer when solar radiation is high, but no consistent pattern was observed for relative deviations. RAM and RHM were the best methods for estimation of solar radiation for all three stations. Maximum relative deviation of average monthly simulated radiation by these methods was less than 0.6%. RAF (the method suggested by FAO) and RAK (a literature method suggested by Khalili (Khalili, 1997) for Iran) were least reliable for Kaboutar Abad and Najaf Abad, but acceptable for Esfahan. Maximum relative deviation for all methods from average measured monthly values was less than 22% in Kaboutar Abad, 15% in Najaf Abad and 14% in Esfahan, values that are higher than those reported by Nonhebel (1994a; 1994b) and Xie et al. (2003).

The variation in performance of the crop growth simulation model WOFOST (expressed in terms of calculated dry matter production) with different methods of solar radiation estimation was very small. The sensitivity of the summer crop (silage maize) was lower than that of the winter crop (barley). These results are contrary to those of Trnka et al. (2007), showing greater sensitivity for the spring crop (spring barley) than for the winter crop (winter wheat). The maximum deviation of simulated potential dry matter production, based on the most reliable methods (RAM and RHM), from the run based on measured solar radiation, was less than 9% in all cases (Table 3.5).

Potential total aboveground dry matter production (TAGP) of barley appeared more sensitive than grain yield. Maximum relative deviation of TAGP for barley in Kaboutar Abad in the year 2001 was 13.4% (with the RHMT method), and 19.0% (with the RHYT method). For silage maize, the maximum relative deviation was 9.0% in the year 2004 (with the RHYT method). Potential yield was less sensitive to estimated solar radiation by the Ångstrom equation, in agreement with Trnka et al. (2007). Deviations in the outputs of the crop growth simulation model did not change significantly when solar radiation in Najaf Abad was estimated on the basis of interpolated coefficients of Esfahan and Kaboutar Abad.

Results of this analysis showed that transpiration is also sensitive to the method of solar radiation estimation, but less than potential yield. Maximum deviation of simulated seasonal potential transpiration from that in the base run for all methods of solar radiation estimation was 20 mm (6.2%) for silage maize and 43 mm (16.2%) for barley (Table 3.7), and based on the best methods (RAM and RHM) less than 19 mm (7.1% of total) in all cases (Table 3.8).

From this study, it may be concluded that lack of measured solar radiation data is not a major constraint for using crop growth simulation models, because it can be sufficiently accurately estimated with empirical formulas such as those of Ångstrom and Hargreaves. The Ångstrom equation yields more accurate results than that of Hargreaves, so that it is preferable in situations where both sunshine duration and temperature are available. However, for use in crop growth simulation models, solar radiation estimates based on Hargreaves' formula are sufficiently accurate. In both, the Ångstrom and Hargreaves approaches regression coefficients vary with time, so that use of monthly regression coefficients leads to more accurate results than use of a single annual set. For situations where no weather station is available, derivation of regression coefficients through interpolation of regression coefficients of neighboring stations is an acceptable procedure. Estimated solar radiation based on interpolated regression coefficients is closer to measured values than estimates based on general values of FAO. The same holds for simulated yield and transpiration.

Acknowledgments

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4 Estimation of regional agricultural production using the crop growth monitoring system[1]

Abstract

The Crop Growth Monitoring System (CGMS), consisting of a crop growth simulation model (WOFOST) combined with GIS facilities, has been applied for spatial biophysical resource analysis of Borkhar & Meymeh district in Esfahan province, Iran. The potentially suitable area for agriculture in the district has been divided into 128 homogeneous land units in terms of soil (physical characteristics), weather and administrative unit. Crop parameters required in the WOFOST simulation model for winter wheat, winter barley, silage maize, sugar beet, sunflower and potato have been calibrated based on experimental data from the study area. The study area has been classified into three cropping calendar zones based on average annual temperature, altitude and latitude. For each zone, a sowing date has been defined per crop as the starting point of crop growth simulation. In one of the zones, two crops (a summer crop after harvesting the winter crop) can be cultivated per year, so two different sowing dates were defined per crop in single and double cropping systems. Growth of these crops has been simulated for the potential and water-limited situation (20 and 40% deficit irrigation) in each land unit for 20 years of historical daily weather data. Daily potential evapotranspiration and irrigation requirements of each crop per land unit have been calculated post-simulation, on the basis of model outputs. Outputs of the model are crop yield (marketable yield and total biomass) and irrigation requirements per decade. A method has been developed for spatial estimation of crop yields and irrigation requirements of the crops colza, melon, watermelon and alfalfa that cannot be simulated by CGMS or for which not enough data were available for calibration. In this method, CGMS outputs of other crops were combined with conventional methods of estimating these parameters. Fertilizer requirements for nitrogen, phosphorus and potassium for each crop and each production situation have been calculated spatially based on crop yields, concentrations of these nutrients in different crop organs and results of soil chemical analyses. Spatial and temporal variation in crop yield, irrigation requirements and fertilizer requirements for all crops for three irrigation regimes (fully irrigated (= potential), 20 and 40% deficit irrigation) have been analyzed. Results show that the spatial variation in crop yield is smaller for winter crops than for summer crops, and the reverse holds for water requirements. The temporal variation in both, crop yield and water requirements is larger than the spatial variation. The maximum variation in 20-year average yield in the different land units in the potential situation (expressed as the coefficient of variation) is 13.5% for sugar beet. The maximum temporal (1985-2004) variation in crop yield for winter

[1] This chapter is written jointly with Mr. Farhag sargordi

wheat, winter barley, silage maize, sugar beet, sunflower and potato was 14.8, 16, 9.9, 16.6, 16.5 and 12.7%, respectively. Fertilizer requirements show the same variation as crop yield. The reduction in crop yields for summer crops under deficit irrigation regimes was stronger than for winter crops.

Keywords: Crop growth simulation, Input-output coefficients, Land evaluation, Spatial yield analysis, Potential yield, Water-limited yield, Water requirement, Nutrient requirement

4.1 Introduction

Sustainable development is one of the concerns of agricultural planners and decision makers. Although there is no unique definition of this concept, there is agreement on some common themes (Sydorovych and Wossink, 2008). Agriculture is considered sustainable if it is economically, socially and environmentally capable of being sustained. This concept should be considered in agricultural planning. Policy makers are interested in methods and instruments that can be used for improving agricultural sustainability.

Biophysical resource analysis is an essential part of agricultural planning and policy formulation. What is the potential of the resources, how they are used and could be used, should be determined in the resource analysis. For this purpose, biophysical resources such as soil and weather have to be analyzed in relation to crop performance. Quantitative analysis of biophysical resources can be carried out at different spatial scales such as plot, farm, regional and global (Van Keulen, 2007) .

In many developing countries, natural resources are overexploited by farmers (Lal, 2009), of which the effects are aggravated by drought and climate change and leads to a decline in their quality and quantity (APERI, 2002a). Therefore, there is a need to identify appropriate land use activities and required inputs for sustainable agricultural production.

In the last decade, different land use models have been developed to support policy makers in agricultural policy formulation at different scales (Kruseman, 1995; Mohamed et al., 2000; Bazzani, 2005a; Laborte, 2006). In general, in constructing these models, principles of quantitative system analysis are applied, they are using economic, social and environmental information and data and take into account different objectives (Hengsdijk et al., 1999). The most important part of these models is the matrix containing quantitative descriptions of the inputs and outputs of land use activities, the so-called technical coefficients (Hengsdijk et al., 1998).

Spatial and temporal variations in the biophysical resources cause variations in crop production and input requirements that are important for agricultural planners and policy makers. For instance, potential crop yields and crop water requirements are dependent on weather and soil characteristics that are variable in time and space. Fertilizer requirements for crop production are related to crop yields, soil chemical properties and weather. Simulation models for crop growth are tools that can be used for estimation of yields, crop water requirements and fertilizer requirements in different situations (Van Ittersum et al., 2003).

Crop growth simulation models quantitatively describe the effects of crop, soil and weather characteristics and management factors and their interactions in a simplified manner. Such models can be used to analyze effects of environmental conditions, such as climate, management, and crop characteristics on crop yield and water productivity (Bessembinder et al., 2005; Richter and Semenov, 2005; Basso et al., 2007; Kalra et al., 2007; Wu, 2008) .

The aim of this chapter is to apply agro-ecological models to determine potential and water-limited yields, and water and fertilizer requirements of various crops under different irrigation regimes for all land units in a certain region. The results are used to quantify the technical coefficients in agricultural planning models that are being developed to support goal and policy formulation for agricultural development in Borkhar & Meymeh district, Iran. At present, statistically derived averages of crop yields and agricultural inputs are being used in the planning procedures in Iran. Combinations of GIS techniques and crop growth simulation models provide opportunities for spatial analyses of biophysical resources and estimation of crop yields (Badini et al., 1997; Bouma, 1997; Wu et al., 2006). In this study, CGMS (Crop Growth Monitoring System) (Van Diepen et al., 2004) is used for spatial and temporal assessment of crop yields. The system includes a spatial crop growth simulation model that calculates potential and water-limited yields at different 'points' in the study area, based on weather, soil properties, and crop characteristics.

In the methodology section, the qualitative land evaluation procedure to identify the potential areas for agriculture, application of the crop growth simulation model to generate input/output coefficients and the spatial estimation methodology for crop yields, water and fertilizer requirements of different crops are explained. Application of the methodology in the study area is described in the implementation section. Results and conclusions are discussed at the end of the chapter.

4.2 Study area

Borkhar & Meymeh district (Figure 4.1) is one of the districts in the northwest of Esfahan province in Iran, comprising three sub-districts (Bakhsh), six Dehestans and nine cities (Table 4.1).

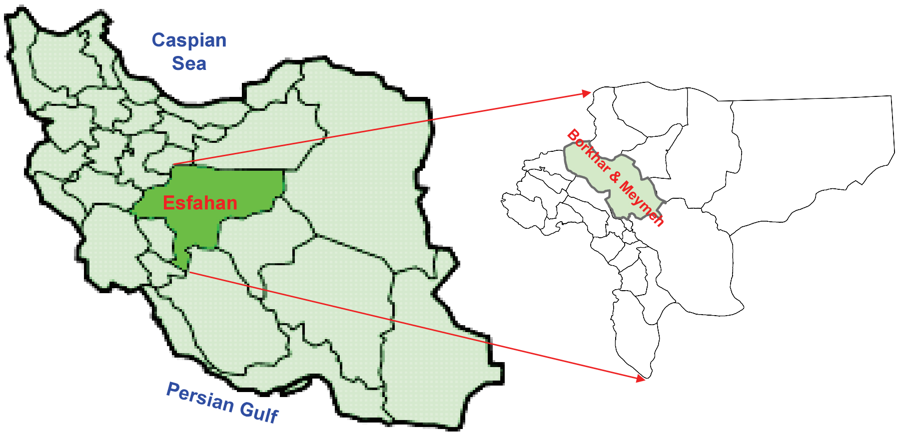


Figure 4.1. Location of Esfahan province within Iran (left) and location of Borkhar & Meymeh district in Esfahan province (right)

Table 4.1. Sub-districts, Dehestans and cities in Borkhar & Meymeh district

Bakhshs (Sub-districts)	Dehestans	Cities
Borkhar	Eastern Borkhar	Habib Abad, Komshecheh
	Central Borkhar	Khorzough, Dastgerd, Dawlat Abad
Central	Western Borkhar	Shahin Shahr, Gaz
	Moorcheh khoort	-
Meymeh	Zarkan	-
	Vandadeh	Meymeh, Vazvan

The district covers a total area of 762 500 hectares, of which about 37 000 is cultivated (on average: 22 000 ha with field crops (Figure 4.2), 2 000 ha fruit trees and 13 000 ha fallow) (Esfahanian Agricultural Jihad Organization, 2007).

Table 4.2 shows the main crops cultivated in the district in the years 2002-2004, illustrating that the total area under cultivation increased from the year 2002 onwards, as a result of the opening of a new irrigation network in Borkhar plain[1]. Most of the agricultural area is located in the southern part of the district, which is part of Borkhar plain.

1 - Borkhar plain is a hydrological unit, while Borkhar & Meymeh district is an administrative unit. Part of Borkhar plain is located in Borkhar & Meymeh district.

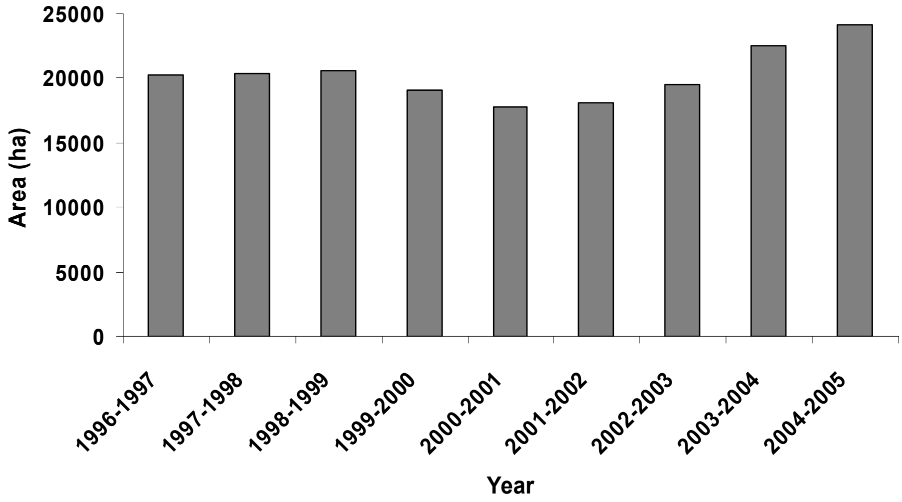


Figure 4.2. Cropped area in Borkhar & Meymeh district in the period 1996-2004 (Esfahanian Agricultural Jihad Organization, 2007)

Table 4.2. Cultivated area of main crops in Borkhar & Meymeh district in the years 2002-2004 (Esfahanian Agricultural Jihad Organization, 2007)

Crop	Cultivated area (ha)			Cultivated area (%)		
	2002-2003	2003-2004	2004-2005	2002-2003	2003-2004	2004-2005
Winter wheat	10290	11000	11450	52.6	48.8	47.3
Winter barley	2160	2300	2500	11.0	10.2	10.3
Silage maize	880	3700	3520	4.5	16.4	14.6
Sugar beet	1500	1050	900	7.7	4.7	3.7
Sunflower	1000	713	1196	5.1	3.2	4.9
Potato	310	320	310	1.6	1.4	1.3
Alfalfa	1300	1500	1440	6.6	6.6	6.0
Watermelon	15	75	594	0.1	0.3	2.5
Melon	807	770	899	4.1	3.4	3.7
Total	19555	22540	24180	93.4	95.1	94.3

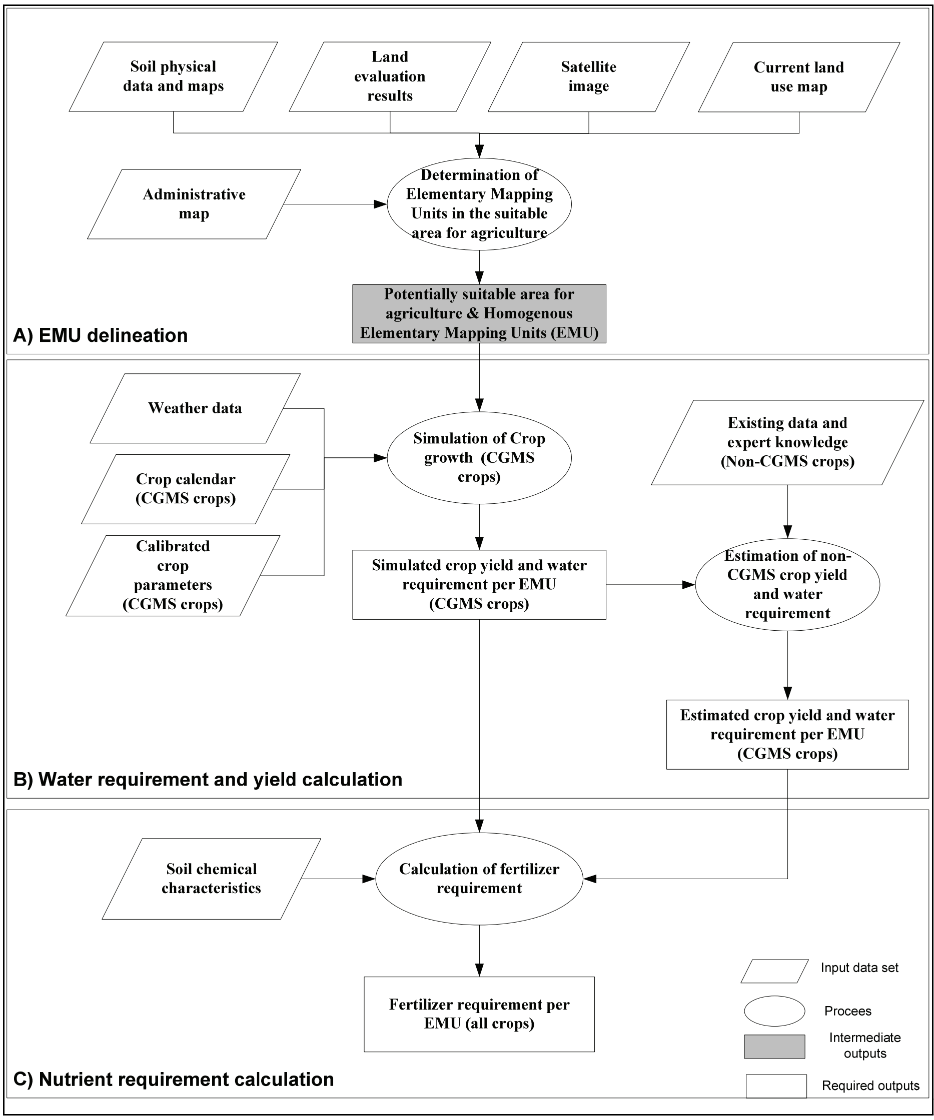
Average daily temperature in the study area varies between -2 ^{o}C in winter and 30 ^{o}C in summer. Annual precipitation varies between 100 and 300 mm over the district, concentrated in the winter months from December to April and average annual potential evapotranspiration is around 1400 mm.

4.3 Methodology

The general outline of the methodology is presented in Figure 4.3. First, the area potentially suitable for agriculture is determined based on the results of the land evaluation study, the current land use map and satellite images. The potential area for agriculture is then classified into homogeneous units (Elementary Mapping Units, EMU) in terms of biophysical conditions and administrative region. Quantitative spatial estimation of yields, water and fertilizer requirements is carried out for the major crops (Table 4.2) in Borkhar & Meymeh district. Colza, introduced recently to the farmers as part of a new national policy, is also included. In this study, crops are distinguished in CGMS and non-CGMS crops. For CGMS crops (winter wheat, winter barley, silage maize, sunflower, sugar beet, and potato), crop parameters could be calibrated on the basis of available experimental data, while non-CGMS crops (alfalfa, colza, melon and watermelon) could either not be simulated by CGMS (non-determinate crops) or not enough data were available for calibration. Crop yields and water requirements of CGMS crops are calculated with a crop growth simulation model, while for non-CGMS crops a calculation procedure is developed, based on yields of best farmers in the region, expert knowledge, and spatial outputs of CGMS crops. Fertilizer requirements for all crops per EMU are estimated based on crop yields and soil chemical characteristics.

4.3.1 Delineation of Elementary Mapping Units (EMU)

Elementary Mapping Units are created by overlaying soil mapping units (SMU), grid weather and an administrative map (Figure 4.4). First, the area suitable for agriculture is identified from the land evaluation study. The potentially suitable area for agriculture is determined by adding currently cultivated land, not included in the suitable area of the land evaluation study. Then, the current land use map and satellite images are used for validation and correction of the potentially suitable area map. In the next step, SMUs are delineated based on soil maps, taking into account soil physical characteristics. A weather grid, either regular or irregular, is defined as a spatial unit assumed to be homogeneous in terms of weather (Buffet et al., 1999; Van der Goot et al., 2004). The village map in the sub-district is determined based on Thiessen polygons (Thiessen and Alter, 1911), as the administrative borders were not identified in the available maps. Weather grids and village polygons (administrative units) are considered identical to reduce the number of units. Hence, weather within a village is assumed constant. This methodology and its implementation in Borkhar & Meymeh district is described in more detail in Section 4.4.



F
igure 4.3. Schematic representation of the applied methodology

4.3.2 Calculation of crop yields and water requirements of CGMS crops

Simulation uses the software package CGMS (Crop Growth Monitoring System), developed in the framework of MARS (Monitoring of Agriculture by Remote Sensing), a project for yield forecasting of major crops in the EU (European Union), based on two point-based crop growth simulation models, WOFOST (Boogaard et al., 1998) and LINGRA (Bouman et al., 1996).

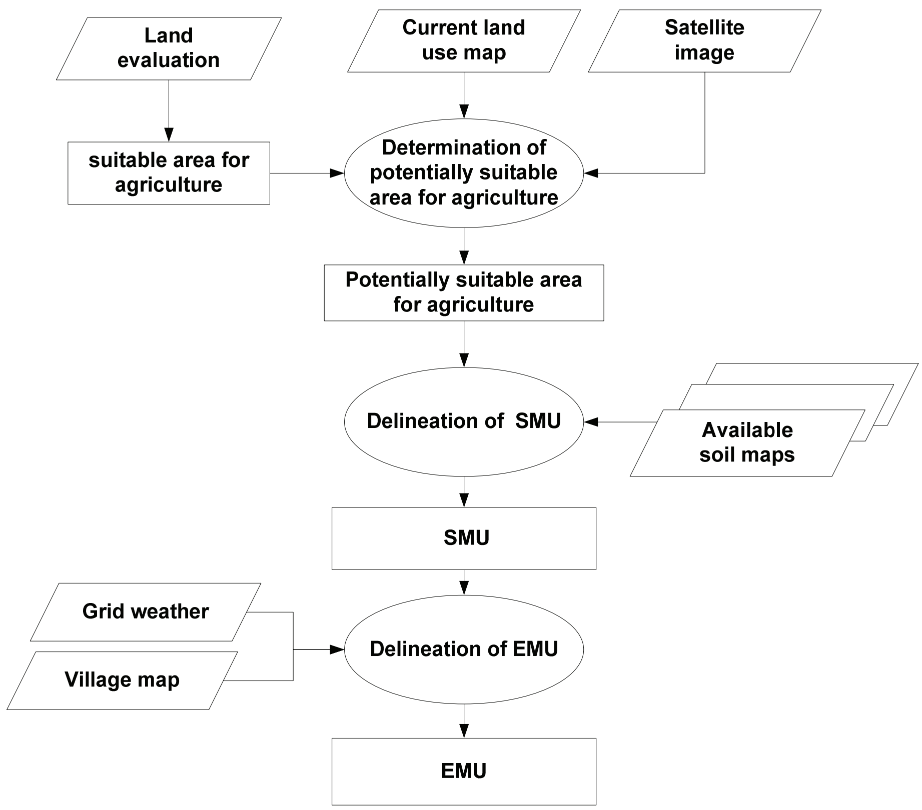


Figure 4.4. Schematic representation of the delineation of Elementary Mapping Units

- ***Data processing***

CGMS comprises four main levels of processing: data preparation (level 0), weather data interpolation (level 1), crop growth simulation (level 2) and statistical evaluation of the results (level 3). Figure 4.5 shows the main inputs/outputs and processes at levels 1 and 2. Yield forecasting can be carried out at level 3 by comparison of outputs of level 2 with statistical data. Level 3 of CGMS has not been used in this study.

At level 0, the required data for crop growth simulation such as soil, weather and crop data and also information on EMUs are stored in the specified formats in a database. Moreover variety-specific crop parameters should be calibrated.

At level 1, required daily grid weather data, i.e. minimum and maximum temperature, wind speed (at 10 m height), vapor pressure, rainfall, and global radiation or sunshine hours, are generated through interpolation of daily weather data from weather stations. Additional environmental characteristics (Van Diepen et al., 2004) such as daily evaporation from a free water surface (E0), evaporation from wet bare soil (ES0) and evapotranspiration for a reference crop (ET0) (Allen et al., 1998) are calculated for each weather station in CGMS. These characteristics are also interpolated during grid weather generation.

- ***Simulation of crop growth and yield***

WOFOST simulates phenological development, leaf area development and aboveground dry matter accumulation of annual field crops from emergence (or sowing) to maturity in daily time steps, based on daily weather data, soil properties and crop characteristics. Crop growth rate depends on daily net CO_2 assimilation rate, calculated as a function of intercepted light, which is determined by the level of incoming radiation and the leaf area of the crop. From absorbed radiation and the photosynthetic characteristics of single leaves, the daily rate of potential gross photosynthesis is calculated. The assimilates, after subtraction of respiration, are partitioned over the various plant organs, i.e. leaves, roots, stems and storage organs. WOFOST simulates crop production in two production situations (potential and water-limited[1] (Van Ittersum and Rabbinge, 1997)), while the nutrient-limited situation is mimicked through calculation of the influence of nitrogen, phosphorus and potassium availability on yield on an annual basis. In CGMS, only the potential and water-limited situations are considered. Potential yield of a crop is only dependent on weather (solar radiation and temperature) and crop characteristics (Boogaard et al., 1998). Water-limited yield is also dependent on weather characteristics (solar radiation, temperature, rainfall, humidity and wind speed), soil physical characteristics and irrigation regime.

CGMS has the capability to apply the crop growth simulation models spatially by their application at different points. For this purpose, the area of interest should be divided into homogeneous units, in this study the EMUs, to each of which WOFOST is applied in the CGMS system.

For application of WOFOST and CGMS to a specific combination of crop (variety) and environment, the model should be calibrated (Van Dam and Malik, 2003). Site-specific experimental field data are necessary for model calibration. Six crops (winter wheat, winter barley, silage maize, sunflower, sugar beet and potato) are simulated by CGMS in this study.

1 - In this paper water-limited refers to situations with deficit-irrigation, while in the WOFOST and CGMS documents it refers to rainfed situations. Rainfed agriculture is not practiced in Borkhar & Meymeh district.

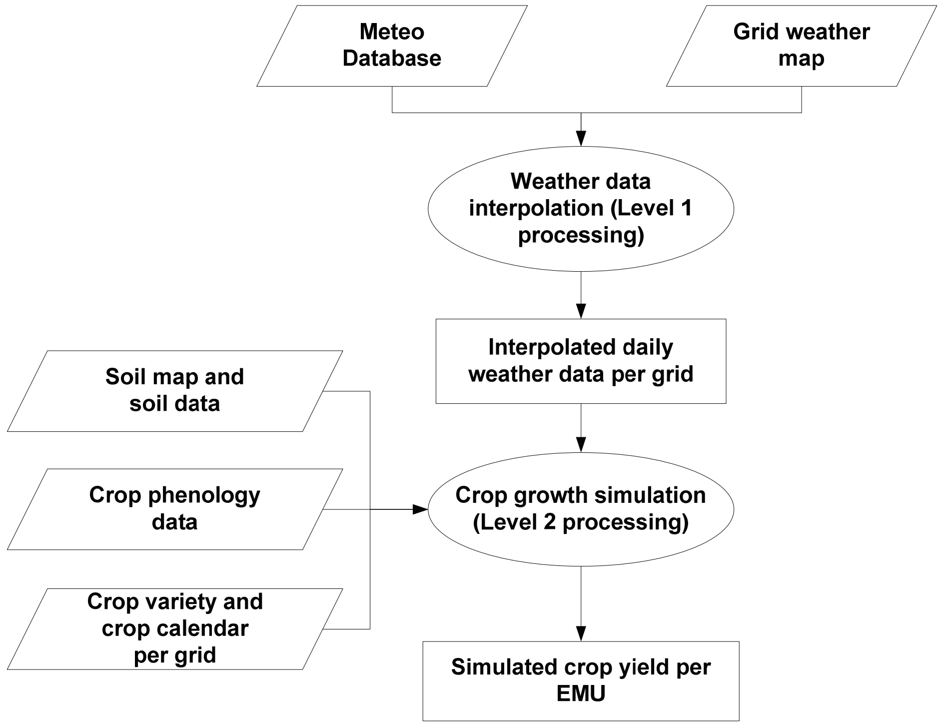


Figure 4.5. Main inputs/outputs and processes at levels 1 and 2 of CGMS (Mahalder and Sharifi, 1998)

Crop growth in each EMU is simulated based on soil parameters, grid weather data, crop characteristics and crop calendar for both, the potential and water-limited situations at level 2. CGMS outputs are presented in a table per EMU and per 10-day period (Table 4.3). CGMS is used for estimation of yields of CGMS crops in both the potential and water-limited situations with 20 years historical daily weather data for the period 1985-2004.

- ***Calculation of water requirements***

In irrigation management, different irrigation regimes can be applied, i.e. with unrestricted water availability during the full crop cycle or during the most sensitive stages to water stress or with controlled water deficits during the complete crop cycle or at specific stages. All these irrigation regimes can be analyzed by crop growth simulation models. In this study, three irrigation regimes are analyzed, i.e. full irrigation, 20% and 40% deficit irrigation at all crop growth stages. Water requirements are defined as the amount of water that should be applied by irrigation to ensure absence of water stress (irrigation efficiency 100%) and equals the difference between potential evapotranspiration and effective rainfall. Effective rainfall has been set to 70% of rainfall.

Table 4.3. Some of the CGMS outputs per EMU and per 10-day period at level 2 (Van Diepen et al., 2004)

Characteristic	Description	Unit	Potential	Water-limited
Biomass yield	Total dry weight of biomass	kg/ha	√	√
Storage organ yield	Total dry weight of storage organs	kg/ha	√	√
Leaf area index	One sided green leaf area per unit ground area	m^2/m^2	√	√
Total water requirement	Sum of potential transpiration	mm	√	
Total water consumption	Sum of water-limited transpiration	mm		√

Potential evapotranspiration, the sum of potential crop transpiration and soil evaporation, is not calculated in CGMS, but can be estimated from the CGMS outputs. Daily potential evapotranspiration (ET_C in mm/d) is calculated based on ES0, ET0 and LAI (Supit and Van der Goot, 2003):

$$EVS_{max} = ES0 * Exp(-0.75 * K_{dif} * LAI) \tag{4.1}$$

$$TRA_{max} = ET0 * (1 - Exp(-0.75 * K_{dif} * LAI)) \tag{4.2}$$

$$ET_C = EVS_{max} + TRA_{max} \tag{4.3}$$

in which,

K_{dif}: Light extinction coefficient of the crop for diffuse visible light (Table 4.4)
ES0: Evaporation rate from wet bare soil (mm/d)
EVS_{max}: Maximum evaporation rate from shaded bare soil (mm/d)
ET0: Potential evapotranspiration rate of reference crop (mm/d)
TRA_{max}: Maximum transpiration rate of crop (mm/d)
LAI: Leaf area index of the crop in the potential production situation (m^2/m^2)

For technical reasons, in CGMS, LAI is available only at ten-day intervals. Daily LAI for each grid cell is calculated by linear interpolation.

Table 4.4. Light extinction coefficient of CGMS crops

	Winter wheat	Winter barley	Silage maize	Sunflower	Sugar beet	Potato
Light extinction coefficient (K_{dif})	0.5	0.55	0.67	0.9	0.67	1.0

CGMS is modified to calculate irrigation application. Irrigation application and irrigation interval for the full irrigation regime are calculated based on daily potential evapotranspiration, effective rainfall, soil physical characteristics and crop rooting depth, assuming:

- 30 mm irrigation application at sowing
- Minimum irrigation application is 30 mm for technical reasons, associated with the design of the irrigation system
- Rooting depth increases from its initial value until maximum rooting depth at a constant rate (e.g., 1.2 cm/d for silage maize)
- 50% of the available soil moisture is considered readily available

Readily available water in the root zone is calculated as:

$$RAW_{Crop,day} = (FC - PWP) * FRAW * RD_{Crop,day} \tag{4.4}$$

in which,

$RAW_{Crop,\,day}$: Readily available water in the root zone (cm)
FC: Volumetric soil moisture content at field capacity ($cm^3.cm^{-3}$)
PWP: Volumetric soil moisture content at permanent wilting point ($cm^3.cm^{-3}$)
FRAW: Fraction of readily available water in soil (0.5)
$RD_{Crop,\,day}$: Rooting depth of the crop (cm)

Irrigation is applied one day before cumulative crop water requirements exceed maximum readily available water.

For the 20% and 40% deficit irrigation regimes, 80% and 60%, respectively of the irrigation applied in the full irrigation regime are applied at the same irrigation interval. Results of CGMS in the water-limited situation represent crop growth under the specified irrigation regime.

4.3.3 Calculation of crop yield and water requirements of non-CGMS crops

- ***Yield Calculation***

The ratio of potential yield in each grid cell and maximum potential yield in the district is an indicator for the variability in weather conditions in the district. Therefore, it could be expected that crops with the same growing period have the same ratio. Based on this assumption, a methodology is developed for calculation of the yield of non-CGMS crops based on simulated yield of the equivalent CGMS crop and maximum yield of the non-CGMS crop in the district:

Reported maximum farmers' yield in the district is set to potential district yield. Potential yield per grid cell is subsequently calculated as:

$$Pot\_Yield_{N\_CGMS\_Crop,\,EMU} = Max\_Yield_{N\_CGMS\_Crop,\,District} * \left(\frac{Pot\_Yield_{E\_CGMS\_Crop,\,EMU}}{Max\_Pot\_Yield_{E\_CGMS\_Crop,\,District}}\right) \quad (4.5)$$

in which,

$Pot\_Yield_{N\_CGMS\_Crop,\,EMU}$: Potential yield of non-CGMS crop per EMU
$Pot\_Yield_{E\_CGMS\_Crop,\,EMU}$: Potential yield of 'equivalent CGMS crop' per EMU
$Max\_Yield_{N\_CGMS\_Crop,\,District}$: Maximum yield of non-CGMS crop in the district
$Max\_Yield_{E\_CGMS\_Crop,\,District}$: Maximum simulated yield of 'equivalent CGMS crop' in the district

In this study, winter barley and silage maize are considered the 'equivalent CGMS crops' for colza (winter crop) and melons (summer crops), respectively. For alfalfa, a perennial crop, the average ratio of barley and silage maize is used.

Yield reduction because of water-stress is dependent on crop characteristics and timing of water-stress. Doorenbos and Kassam (1979) proposed the following equation for estimation of water-limited yield:

$$(1 - \frac{Ya}{Yp}) = Ky * (1 - \frac{ETa}{ETp}) \quad (4.6)$$

in which,

Ya: Actual yield (water-limited)
Yp: Potential yield
Ky: Crop yield response factor to water-stress (Doorenbos and Kassam, 1979)
ETa: Actual evapotranspiration (mm)
ETp: Potential evapotranspiration (mm)

Water-limited yields of non-CGMS crops are calculated spatially by combining Equations (4.5) and (4.6), and assuming the same ratio ETa/ETp for both CGMS and non-CGMS crops:

$$WL\_Yield_{N\_CGMS\_Crop,Irman,EMU} = Max\_Yield_{N\_CGMS\_Crop,District} * \left[\frac{Pot\_Yield_{E\_CGMS\_Crop,EMU}}{Max\_Pot\_Yield_{E\_CGMS\_Crop,District}} + \frac{(WL\_Yield_{E\_CGMS\_Crop,Irman,EMU} - Pot\_Yield_{E\_CGMS\_Crop,EMU}) * (\frac{Ky_{N\_CGMS\_Crop}}{Ky_{E\_CGMS\_Crop}})}{Max\_Pot\_Yield_{E\_CGMS\_Crop,District}}\right] \quad (4.7)$$

in which,

$WL\_Yield_{N\_CGMS\_Crop,\ Irman,\ EMU}$: Water-limited yield of non-CGMS crop per EMU and specified irrigation management
$WL\_Yield_{E\_CGMS\_Crop,\ Irman,\ EMU}$: Water-limited yield of 'equivalent CGMS crop' per EMU and specified irrigation management
$Ky_{N\_CGMS\_Crop}$: Yield response factor to water-stress of non-CGMS crop
$Ky_{E\_CGMS\_Crop}$: Yield response factor to water-stress of 'equivalent CGMS crop'

This method yields total aboveground dry matter production (TAGP) for alfalfa and total dry weight of storage organs (TWSO) for melon, watermelon and colza. TAGP of the latter crops is required for calculation of fertilizer requirements and is calculated from TWSO, using average values of the harvest indices of these crops (Table 4.5).

Table 4.5. Harvest index of non-CGMS crops (Ponsioen et al., 2006)

Crop	Harvest index
Melon	0.6
Watermelon	0.6
Colza	0.35

- ***Calculation of water requirements***

Potential evapotranspiration of non-CGMS crops is calculated as (Allen et al., 1998):

$$ETc = K_c * ET0 \quad (4.8)$$

in which,

K_c: Crop coefficient, i.e. the ratio of actual crop evapotranspiration and evapotranspiration of the reference crop (Allen et al., 1998)

K_c varies in the course of the crop growth period (Figure 4.6).

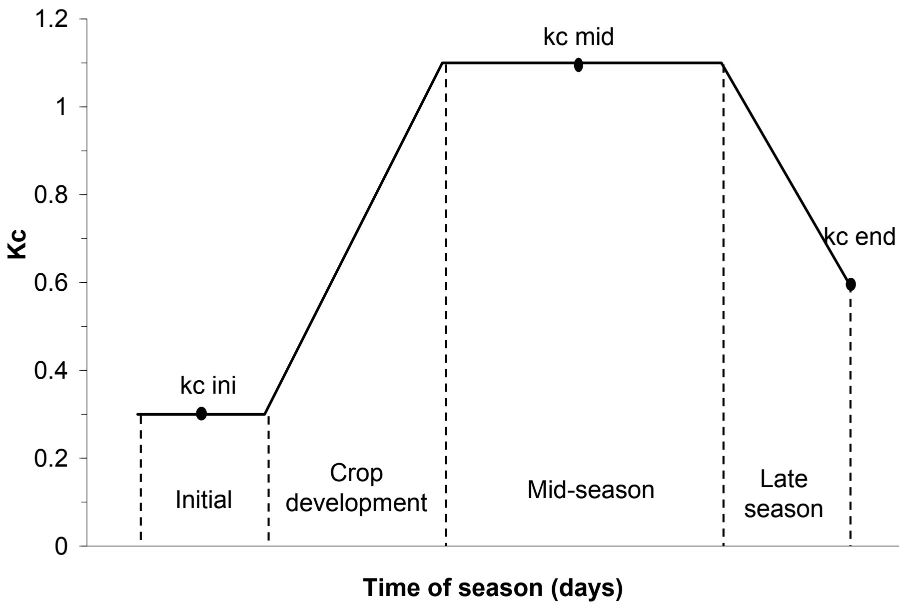


Figure 4.6. Crop coefficient curve (Allen et al., 1998)

For construction of the crop coefficient curve, the following information is required:

- Duration of the initial, crop development, mid-season and late-season stages
- Values of the crop coefficient during the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late-season stage ($K_{c\ end}$)

Information on these crop stages is available in Allen et al. (1998). The duration of the stages shows spatial variation, because of variation in weather conditions, especially air temperature, while $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ are also dependent on climatic conditions. As no information was available for Borkhar & Meymeh district, average values for these parameters were derived from literature (Farshi et al., 1997; Allen et al., 1998). The deficit irrigation regimes are defined as for the CGMS crops.

4.3.4 Calculation of fertilizer requirements

Total external fertilizer requirements for production of the various crops depend on characteristics such as crop yields, concentrations of nutrients in different organs at harvest, soil chemical properties, nutrient recovery fraction and length of the growing period. These fertilizer requirements can be estimated, although not very accurately, using nutrient balances in soil and crop. The procedure applied in this study to calculate fertilizer requirements, is presented in Figure 4.7.

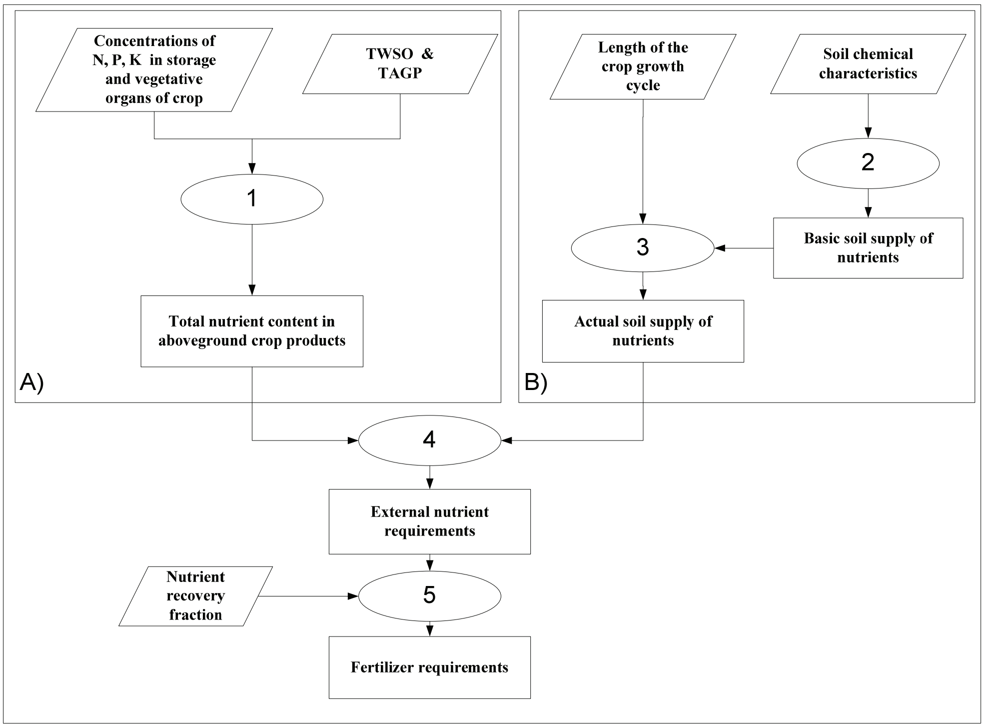


Figure 4.7. Procedure for calculation of nutrient and fertilizer requirements (process are explained in the text)

Total nutrient content (kg/ha) of the crop (process 1, Part A in Figure 4.7) is calculated as (Boogaard et al., 1998):

$$NS = (TWSO * NSO + (TAGP - TWSO) * NVE) * (1 - NFIX) \quad (4.9)$$

$$PS = (TWSO * PSO) + (TAGP - TWSO) * PVE \quad (4.10)$$

$$KS = (TWSO * KSO) + (TAGP - TWSO) * KVE \quad (4.11)$$

in which,

NS, PS and KS are total nitrogen (N), phosphorus (P) and potassium (K) content of the crop at harvest (kg/ha)
TWSO: Total dry weight of storage organs (kg/ha)
TAGP: Total aboveground dry matter production (kg/ha)
NSO, PSO, KSO: Concentrations of N, P, K in the storage organs at harvest (kg/kg)

NVE, PVE, KVE: Concentrations of N, P, K in the vegetative organs at harvest (kg/kg)
NFIX: Fraction of the crop's total nitrogen content at harvest supplied by biological fixation

Concentrations of N, P and K in the storage and vegetative organs of crops have been derived from the literature (Stoorvogel and Smaling, 1990; Boons-Prins et al., 1993; NRCS, 2008).

Part of the nutrient requirements is met by indigenous sources (part B in Figure 4.7). Estimation of the magnitude of indigenous nutrient supply to crops is complex, as it is related to availability of that nutrient, but also to the availability of other nutrients (Janssen et al., 1990). The base supply of a specific soil nutrient is crop-specific and can be determined experimentally, provided all other nutrients are in sufficient supply (Liu et al., 2006), alternatively it can be derived from chemical characteristics of the top soil (Janssen et al., 1990). For a standard crop with growth duration of 120 days, the base supply of the major nutrients, defined as crop uptake when all other nutrients are non-limiting, is calculated as (process 2 in Figure 4.7):

$$\mathrm{NBASE} = 0.25 * (\mathrm{pH} - 3) * 6.8 * \mathrm{OC} = 1.7 * (\mathrm{pH} - 3) * \mathrm{OC} \qquad (4.12)$$

$$\mathrm{PBASE} = 0.35 * (1 - 0.5 * (\mathrm{pH} - 6)^2) * \mathrm{OC} + 0.5 * \mathrm{P\_OLSEN} \qquad (4.13)$$

$$\mathrm{KBASE} = \frac{0.625 * (3.4 - 0.4 * \mathrm{pH}) * 400 * \mathrm{K_{EXCHANGE}}}{2 - 0.9 * \mathrm{OC}} = \frac{250 * (3.4 - 0.4 * \mathrm{pH}) * \mathrm{K_{EXCHANGE}}}{2 - 0.9 * \mathrm{OC}} \qquad (4.14)$$

in which,

NBASE, PBASE and KBASE: Base soil supply of N, P and K for the standard crop (kg/ha)
pH: Soil acidity
OC: Concentration of soil organic carbon (mg/kg)
P_OLSEN: Available soil phosphorus measured by the Olsen method (mg/kg)
$K_{EXCHANGE}$: Exchangeable potassium (mmol/kg)

Soil nutrient supply is subsequently adapted for length of the crop growth cycle (process 3 in Figure 4.7):

$$\mathrm{NBAS} = \mathrm{NABSE} * \alpha \qquad (4.15)$$

$$\mathrm{PBAS} = \mathrm{PABSE} * \alpha \qquad (4.16)$$

$$\mathrm{KBAS} = \mathrm{KABSE} * \alpha \qquad (4.17)$$

in which,

NBAS, PBAS and KBAS: crop-specific base soil supply of N, P and K (kg/ha)
α: Uptake coefficient from soil supply (Figure 4.8)

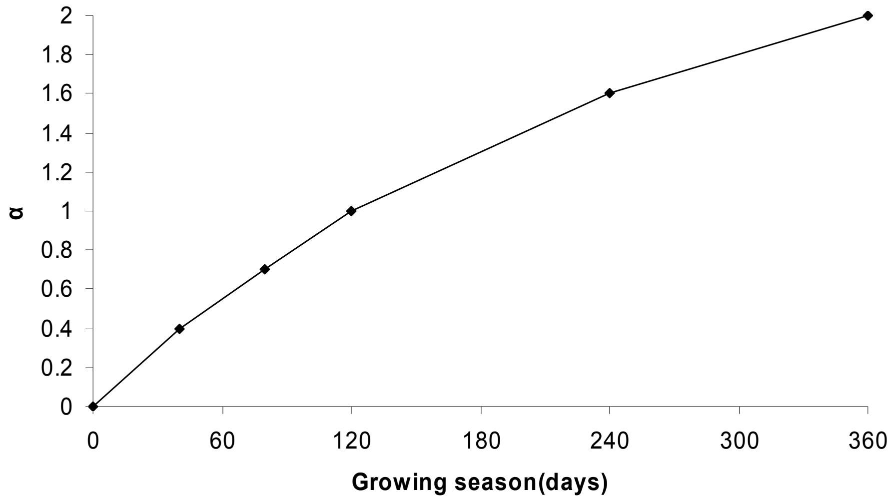


Figure 4.8. Uptake coefficient (α) for indigenous soil nutrient supply

For unrestricted growth, the difference between nutrient requirements and base supply must be supplied from external sources (fertilizer). The quantity of fertilizer required depends on the efficiency of fertilizer uptake (recovery fraction), that can vary strongly in dependence of soil, crop and management factors (Van Keulen and Van Heemst, 1982). In the present study, recovery fractions of 0.6, 0.3 and 0.7 are assumed for N, P and K, respectively. Fertilizer requirements are thus calculated as (processes 4 and 5 in Figure 4.7):

$$NREQ = \frac{NS - NBAS}{N_{REC}} \geq 0 \tag{4.18}$$

$$PREQ = \frac{PS - PBAS}{P_{REC}} \geq 0 \tag{4.19}$$

$$KREQ = \frac{KS - KBAS}{K_{REC}} \geq 0 \tag{4.20}$$

in which,

NREQ, PREQ, KREQ: N, P and K fertilizer requirements (kg/ha)
N_{REC}, P_{REC}, K_{REC}: Recovery fractions of applied N , P and K

P and K requirements are converted to P_2O_5 and K_2O, the form in which the elements are expressed in the fertilizer. P_2O_5 and K_2O contain 44 and 83%, respectively of the elemental form.

This procedure has been applied to all EMUs in Borkhar & Meymeh district for 20 years (1985-2004).

4.4 Implementation

4.4.1 Calibration and validation of crop parameters

Crop parameters of winter wheat and winter barley are calibrated and validated based on field experiments in the years 2000-2001, 2003-2004 and 2004-2005 for winter wheat (cultivar M-73-18) and in 1999-2000, 2000-2001, 2002-2003 and 2003-2004 for barley (cultivar Karoun dar kavir) in the agro-meteorological research center in Kaboutar Abad, close to the study area. Phenological stages, weed infestation, plant density, yield and yield components at harvest time were recorded in these experiments. Calibration has been carried out in two steps (Chapter 2). First, phenological stages (time of flowering and maturity) have been calibrated based on daily weather data. In the second step, some of most sensitive crop parameters (Bessembinder et al., 2003) such as specific leaf area, light use efficiency, maximum relative increase in leaf area index and maximum leaf CO_2 assimilation rate have been calibrated. Different combinations of values, within the acceptable ranges for the parameters, were used iteratively on the basis of comparison of simulated and observed crop yields. Crop parameters from the literature (Van Heemst, 1988; Boons-Prins et al., 1993) were used as initial crop parameters in the calibration process.

For silage maize, sugar beet and sunflower, crop parameters were calibrated in a similar way on yields of the best agricultural producers in the region, starting from values established by Vazifedoust et al. (2008). Initial crop parameters of potato were derived from Van Heemst (1988) and Boons-Prins et al. (1993).

4.4.2 Delineation of Elementary Mapping Units (EMU)

- ***Determination of potential area for agriculture***

The land evaluation study in Borkhar & Meymeh district was carried out by APERI (Agricultural Planning and Economic Research Institute) as part of the Esfahan provincial land evaluation and capability study (APERI, 1999a). The basic maps used in that study were produced by the Iranian Soil and Water Research Institute (ISWRI) at scale 1:250 000 and modified by APERI (1999a). Land was classified into different land types, based on physiographic characteristics, which were subsequently classified into land evaluation units, based on topography, soil acidity and alkalinity, and land cover. In Borkhar & Meymeh district, 10 land types and 22 land units have been identified (Figure

4.9; Table 4.6). More information about the characteristics of the land evaluation units is available in APERI (1999a).

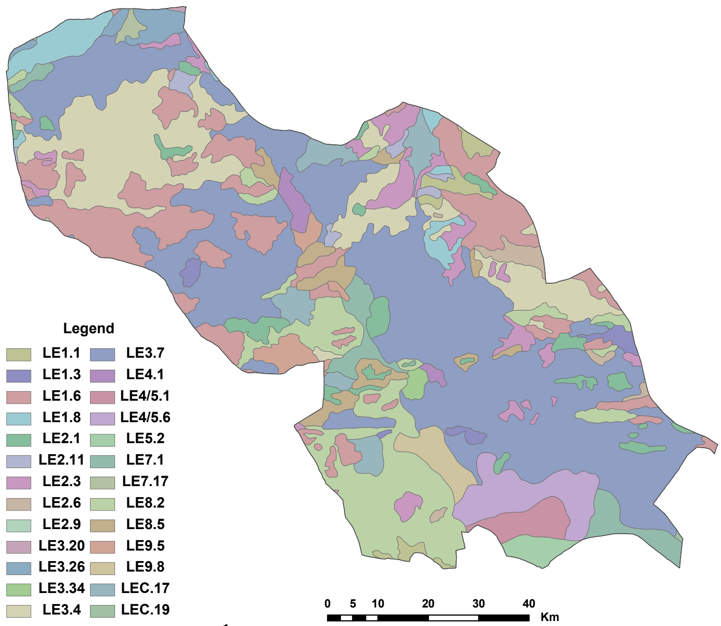


Figure 4.9. Land units[1] in Borkhar & Meymeh district (APERI, 1999a)

A land use suitability assessment was carried out based on the FAO methodology (Mahler, 1970; FAO, 1976) for current and improved situations (Table 4.7), showing that only 43 670 ha (5.7% of the land area) is suitable for agriculture (Figure 4.10;Table 4.8).

Table 4.6. Land types and land evaluation units in Borkhar & Meymeh district (APERI, 1999a)

Land type	Type	Land evaluation units
L1	Mountains	LE1.1; LE1.3; LE1.6; LE1.8
L2	Hills	LE2.1 ; LE2.11 ; LE2.3 ; LE2.6 ; LE2.9
L3	Plateau and upper terraces	LE3.26; LE3.34; LE3.4; LE3.7
L4	Piedmont plains	LE4.1
L45	Alluvial plains	LE4/5.1; LE4/5.6
L5	River alluvial plains	LE5.2
L7	Flood plains	LE7.1; LE7.17
L8	Gravelly colluvial fans	LE8.2; LE8.5
L9	Gravelly alluvial fans	LE9.5; LE9.8
LC	Complex	LEC.17; LEC.19

[1] As the number of units is large, it is difficult to visualize on the paper, but all land units can be differentiated from each other on the screen of the monitor.

Table 4.7. Names and definitions of suitability classes (FAO, 1976)

Class	Suitability	Definition / Description
S1	Highly Suitable	Land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level.
S2	Moderately Suitable	Land having limitations which in aggregate are moderately severe for sustained application of a given use; the limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciably inferior to that expected on class S1 land.
S3	Marginally Suitable	Land having limitations which in aggregate are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified.

Table 4.8. Suitability class of suitable land units for irrigated farming in the current and future situation (after improvements) in Borkhar & Meymeh district (APERI, 1999a)

Land unit	Area (ha)	Present suitability	Future suitability
LE4.1	5280	S2	S1
LE4/5.1	9724	S2	S1
LE4/5.6	22961	S3	S2
LE5.2	5708	S1	S1

On a field visit for verification of the suitable area for agriculture, cultivation was observed in the non-suitable area for agriculture. Current agricultural land use was derived from a Landsat 7 satellite image of August 9, 2002 (Figure 4.11), Google earth images and available land use maps. The potential area for agriculture was defined as the sum of the land currently used for agriculture and the suitable area for agriculture, excluding the urban area from the generated map (Figure 4.12). The potentially suitable area for agriculture (64 000 ha) is different from the suitable area for agriculture identified in the land evaluation study (43 670 ha). It also far exceeds the current agricultural area (37 000 ha), as reported by the Esfahanian Agricultural Jihad Organization (EAJO).

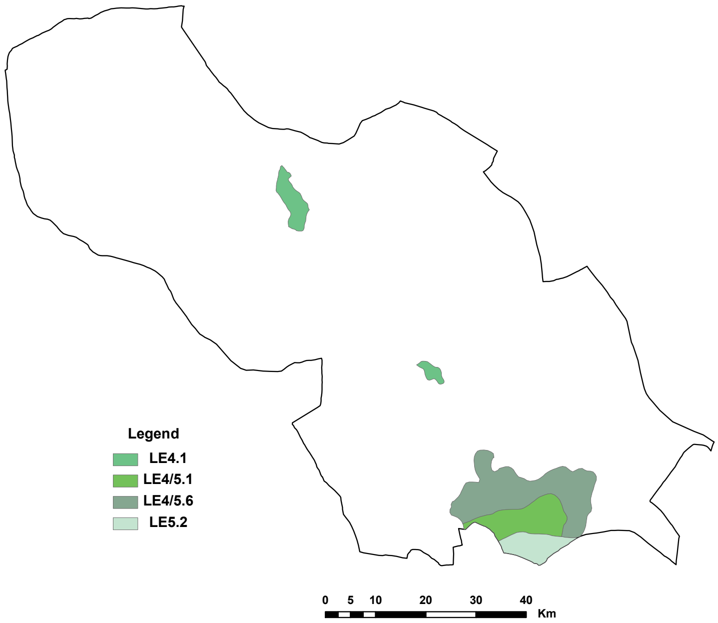


Figure 4.10. Suitable land for irrigated agriculture in Borkhar & Meymeh District (APERI, 1999a)

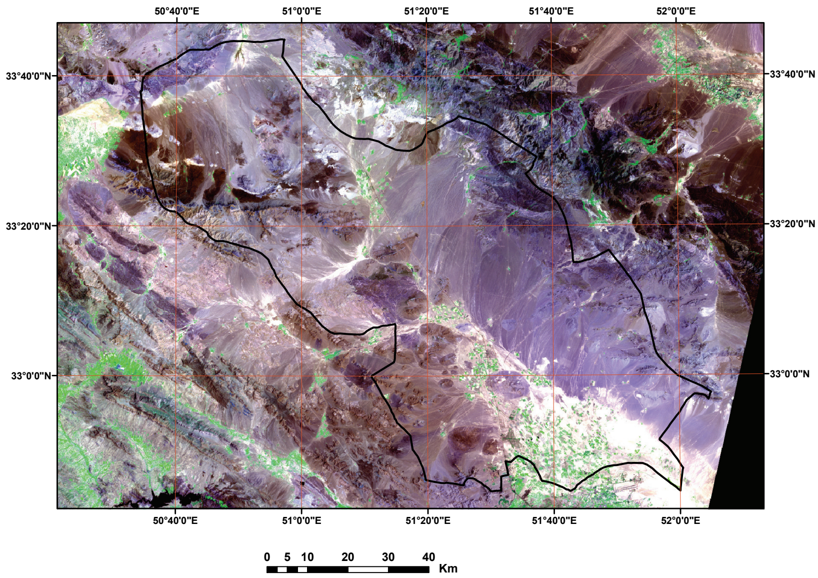


Figure 4.11. Color composite image of the study area based on Landsat 7, 9 August 2002, showing the existing vegetation (green) area

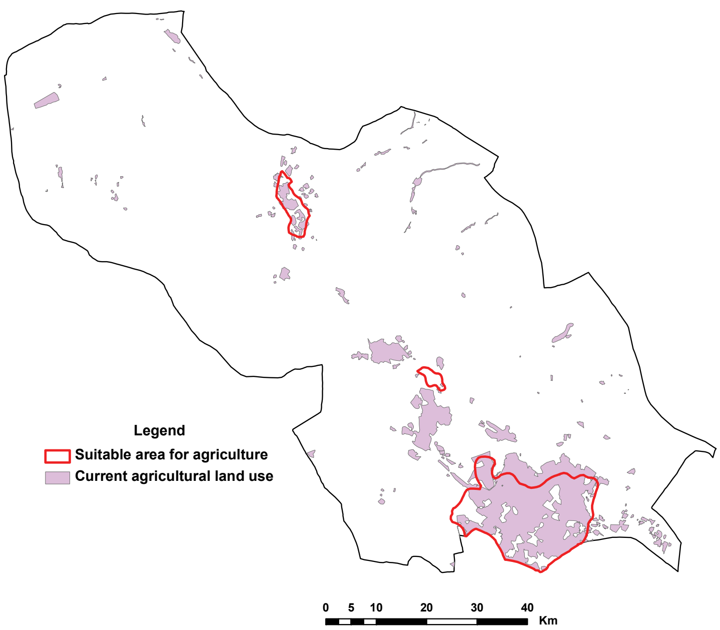


Figure 4.12. Comparison of current agricultural land use with the suitable area for agriculture from the land evaluation study

- ***Delineation of SMUs***

Available soil maps and information produced in earlier studies have been used for soil classification and delineation of SMUs. Soils of Borkhar & Meymeh district have been studied fully or partially in some earlier studies for various purposes and at different scales. Soils in the southern part of Borkhar & Meymeh district have been studied by the Iranian Soil and Water Research Institute (ISWRI) and FAO in the 1960s, aiming at physical and chemical soil characterization (Vakilian, 1968). In that study, soils have been classified into different soil series (Figure 4.13-A; Table 4.9).

Soils of Habib Abad and Komshecheh (Figure 4.13-B; Table 4.10) have been studied in detail by APERI in 1988 (APERI, 2002b).

Soils of Zaman Abad (Figure 4.13-C; Table 4.11) have been studied in detail by the Iranian Agricultural Bank (Agricultural Land Development Company, 1994).

Table 4.9. Average soil physical characteristics of the top 100 cm of soil series in Gaz and Borkhar (Vakilian, 1968)

Soil series	Texture	Organic Carbon content (%)	Average volumetric soil moisture content (cm^3/cm^3)			Permeability (cm/d)
			Saturation	Field Capacity (FC)	Permanent Wilting Point (PWP)	
Golshahr	Sandy clay	0.58	39.8	24.2	15.4	22.1
Homayoun Shahr	Clay loam	0.4	44.1	34.1	22	6.2
Sin	Clay	0.55	50.7	43.5	31	2.2
Haji Abad	Clay	N.A	50	41.6	28.5	3.7
Gorghab	Clay loam	N.A	44	33.9	22.9	6.3
Ashegh Abad	Clay	0.3	50.3	42.3	29.7	3.1
Esfahan	Loam	2.1	41.6	28.6	17.4	13.4

Table 4.10. Average soil physical characteristics of the top 100 cm of soil classes in Habib Abad and Komshecheh (APERI, 2002b)

Soil Clas s	Texture	Organic Carbon content (%)	Average volumetric soil moisture content (cm^3/cm^3)			Permeabilit y (cm/d)
			Saturatio n	Field Capacity (FC)	Permanent Wilting Point (PWP)	
H1	Silty clay loam	0.10	0.39	0.18	0.11	48.2
H2	Clay loam	0.11	0.43	0.33	0.19	6.0

Table 4.11. Average soil physical characteristics of the top 100 cm of soil classes in Zaman Abad (Agricultural Land Development Company, 1994)

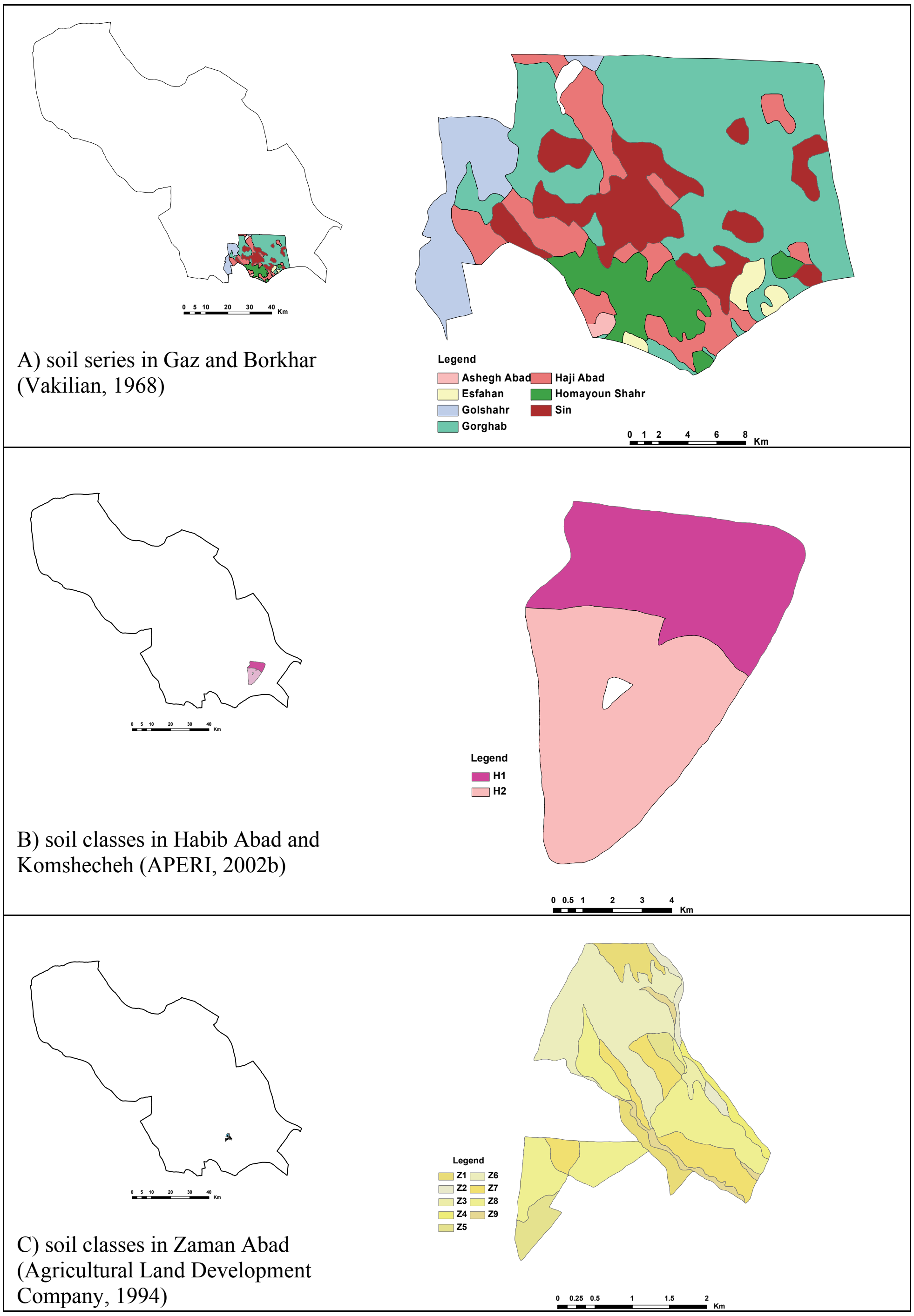
Soil class	Average volumetric soil moisture content (cm^3/cm^3)			Permeability (cm/d)
	Saturation	Field Capacity (FC)	Permanent Wilting Point (PWP)	
Z1	33.4	24.9	10.5	16.7
Z2	27.5	N.A*	N.A	N.A
Z3	35.9	N.A	N.A	N.A
Z4	31.0	20.4	0.9	7.3
Z5	46.8	28.6	13.1	3.8
Z6	43.3	28.0	13.4	8.5
Z7	48.9	29.9	14.8	5.7
Z8	50.2	31.1	14.7	9.8
Z9	27.0	20.0	8.9	19.6
Z10	26.8	17.8	7.6	26.8

* -Soil classes for which no data were available have been merged into other units in the final soil map

For the current study, a soil map of the potential area for agriculture in Borkhar & Meymeh district is constructed by overlaying existing soil maps. This has resulted in identification of 31 SMUs (Figure 4.14b), belonging to 19 different soil physical groups (Table 4.12). Where detailed information for soil groups was not available, soil characteristics have been estimated from land evaluation units.

Table 4.12. Average soil physical characteristics of soil groups suitable for agriculture in the study area

Soil group	Description (identification in original study)	Permeability (cm/d)	Average volumetric soil moisture content (cm^3/cm^3)		
			Saturation	Permanent Wilting Point (PWP)	Field Capacity (FC)
1	Ashegh Abad	3.1	0.5	0.3	0.42
2	Esfahan	13.4	0.42	0.17	0.29
3	Golshahr	22.1	0.4	0.15	0.24
4	Gorghab	6.3	0.44	0.23	0.34
5	Haji Abad	3.7	0.5	0.29	0.42
6	Homayun Shahr	6.2	0.44	0.22	0.34
7	Sin	2.2	51	31	44
8	z6	11.5	0.51	0.31	0.44
9	z7	19	0.41	0.15	0.29
10	z8	24.6	0.4	0.12	0.26
11	H2	6	0.39	0.09	0.25
12	L1	9.7	0.43	0.19	0.33
13	L2	13.7	0.4	0.1	0.16
14	L3	4	0.43	0.18	0.28
15	L4	7	0.44	0.21	0.34
16	L45	7	0.46	0.22	0.35
17	L7	1.5	0.46	0.23	0.35
18	L8	29	0.49	0.31	0.42
19	L9	8.4	0.44	0.13	0.26



A) soil series in Gaz and Borkhar (Vakilian, 1968)

B) soil classes in Habib Abad and Komshecheh (APERI, 2002b)

C) soil classes in Zaman Abad (Agricultural Land Development Company, 1994)

Figure 4.13. Location of existing soil studies in different parts of Borkhar & Meymeh district

▪ ***Delineation of administrative units and grid weather***

The lowest administrative level in this study is the village. Identification of the villages and their locations were based on the Agricultural Census 2003, and the Housing and Population Census (HPC) 2006, both performed by SCI (Statistical Center of Iran), in which the smallest geographical units were Abadi and city. Abadi is defined by SCI (2008a) as a unit comprising a suburban area that is officially registered or traditionally recognized under a specific name, and may be completely or partially under anthropogenic activities. Abadi is perceived as a geographic entity, comprising agricultural and non-agricultural lands with the potential for human activity or residence. Hence, an Abadi can be a village, a farm, a locality, a mining site, or anything similar. The number of units (Abadies plus cities) identified in Borkhar & Meymeh district was 98 and 92 in the Agricultural Census 2003 and HPC 2006, respectively, among which nine cities. Sixty-four units were surveyed in both censuses, of which 40 consisted of more than three households[1]. The units surveyed in HPC 2006 are geo-referenced.

In this study, agricultural administrative units are defined as residential villages and cities exceeding 50 ha in area and establishments such as large agro-industrial units (with more than 200 ha of land), and agricultural production cooperatives. By combining the database of the agricultural census, the list of Abadies in HPC 2006, the digital map of the study area and knowledge of local agricultural experts, Borkhar & Meymeh district was divided into 47 agricultural administrative units, referred to as 'villages'. Borders for each village were determined based on Thiessen polygons, as these borders were not indicated on available maps (Figure 4.14a).

▪ ***Delineation of Elementary Mapping Units (EMU)***

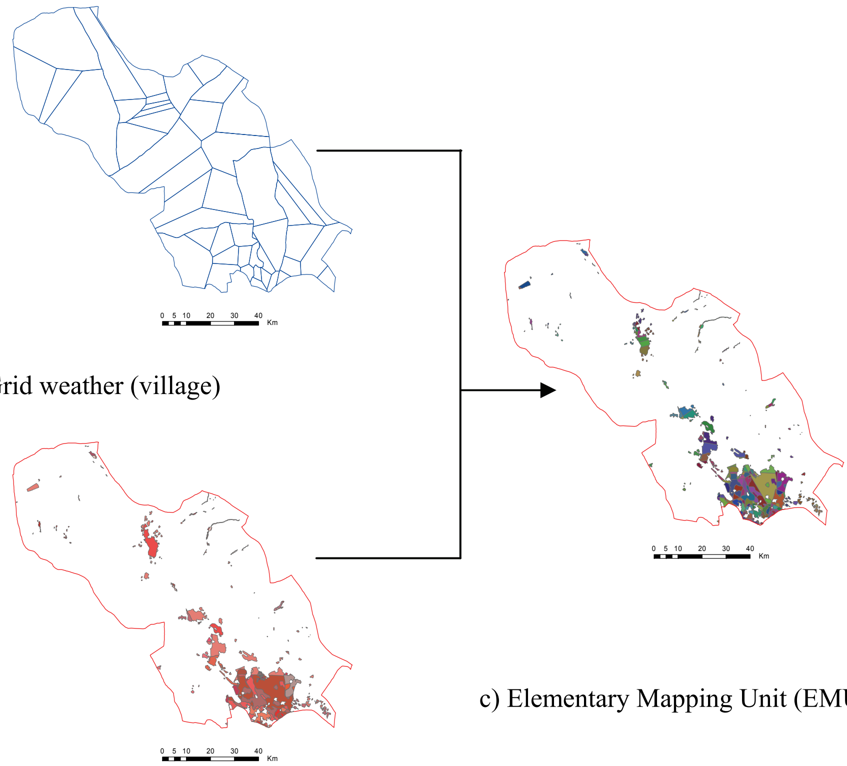
The procedure for generating EMUs results in creation of several very small units (Figure 4.14c). To reduce the number of EMUs to a manageable entity, these small units (less than 50 ha) were merged with larger units, through:

- Merging the unit with the neighboring unit with the longest shared border
- Merging isolated units with the largest unit in the village

In this study, an 8-digit code was assigned to each EMU, composed of a 4-digit code for the village and another 4-digit code for the SMU. The first digit of the village code refers to the Bakhsh, the second digit to the Dehestan in the Bakhsh and the last two digits identify the village in the Dehestan (Figure 4.20; Annex

1 - Information about Abadies with three households or less is not published, because of the privacy policy for census data.

3). The first digit of the SMU code refers to the soil study and the remainder identifies the soil class in the soil study.



b) Soil Mapping Unit (SMU)

Figure 4.14. Grid weather (a), SMU (b) and EMU (c) maps of the district (Colors represent different units)

4.4.3 Weather data preparation and grid weather data generation

Daily weather data of 33 weather stations (Table 4.13 and Table 4.14) in and around the district (Figure 4.15) were used for estimation of daily weather characteristics in the grid cells.

Table 4.13. Type, location and recording period of weather stations in and around Borkhar & Meymeh district

Station Type	Station name	Latitude (^{0} N)	Longitude (^{0} E)	Start	End
Synoptic	Natanz	33.53	51.9	1-1-1992	31-12-2004
	Najaf Abad	32.6	51.38	1-1-2003	31-12-2004
	Esfahan	32.62	51.67	1-1-1961	31-12-2004
	Meymeh	33.43	51.17	1-1-1999	31-12-2004
	Moorcheh khoort	33.08	51.48	1-1-2002	31-12-2004
	Kaboutar Abad	32.52	51.85	1-1-1992	31-12-2004
	Esfahan University	32.7	51.47	1-1-2003	31-12-2004
	Daran	32.97	50.37	7-2-1989	31-12-2004
	Golpaygan	33.47	50.28	1-1-1992	31-12-2004
	Ardestan	33.38	52.37	1-1-1992	31-12-2004
	Delijan	33.98	50.68	1-1-1994	30-12-2004
Climatological	Damaneh Faridan	33.02	50.48	1-3-1965	31-12-2004
	Abadchi	32.72	50.68	1-1-1965	31-12-1984
	Dehagh	33.1	50.48	1-1-2004	31-12-2004
	Khonsar	33.23	50.32	1-1-2004	31-12-2004
	Kordsofla	32.88	50.75	1-1-1976	31-12-1995
	Mahallat	33.9	50.45	1-10-1963	30-11-1975
	Mahyar	32.28	51.78	1-7-1970	31-12-1972
	Natanz	33.53	51.93	1-3-1964	30-9-1991
	Palayeshgah	32.72	51.55	1-1-1984	31-12-2004
	Yazd Abad	32.73	52.75	1-6-1970	30-9-1998
	Abyaneh	33.57	51.58	1-3-1978	30-11-2004
Rain gauge	Kouhpaye	32.72	52.43	1-1-1964	31-12-2001
	Kordeolya	32.92	50.7	20-2-1967	31-12-2001
	Mehdi Abad Shahreza	32.8	50.98	22-2-1967	31-12-1997
	Khomeini shahr	32.68	51.53	13-2-1967	31-12-2001
	Amin Abad	32.77	51.57	1-1-1977	31-12-2002
	Dawlat Abad	32.8	51.67	1-4-1972	30-12-2002
	Zavareh	33.45	52.5	8-3-1966	30-12-2001
	Mahabade Ardestan	33.53	52.23	28-2-1966	30-12-2001
	Mahalat	33.92	50.45	1-1-1986	30-12-2004
	Aran	34.07	51.48	1-4-1964	31-12-2002
	Buyeen gorji	33.08	50.25	24-5-1995	31-12-2002

Table 4.14. Measured weather characteristics in different types of meteorological stations

Type of weather station	Weather parameters
Synoptic	Maximum and minimum temperature, vapor pressure, wind speed, sunshine hours, rainfall, solar radiation
Climatological	Maximum and minimum temperature, rainfall, wind speed and vapor pressure
Rain gauge	Rainfall

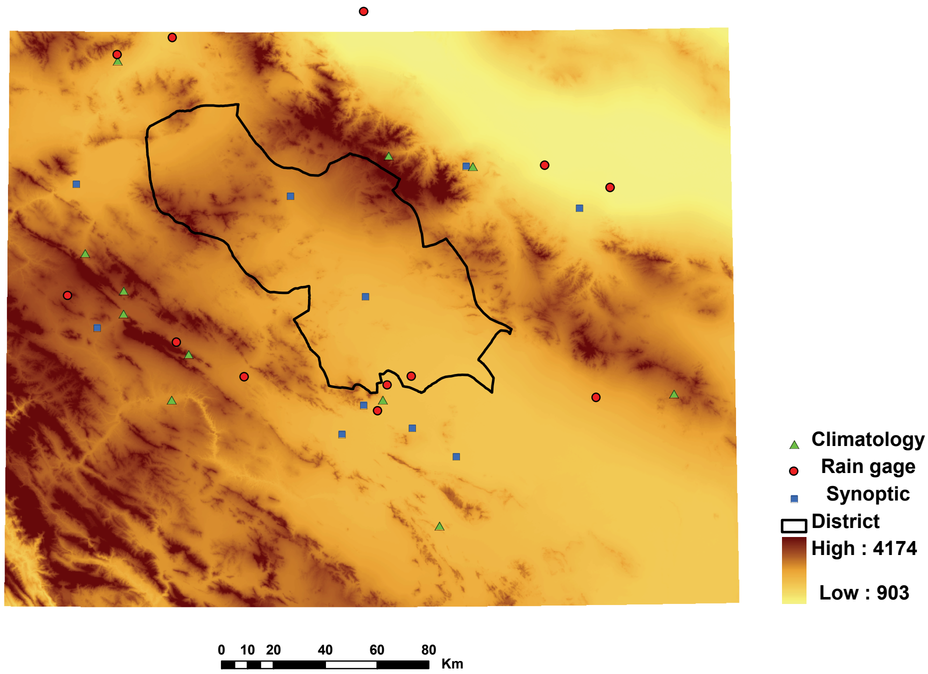


Figure 4.15. Location and type of weather stations in and around Borkhar & Meymeh district on DEM map

In preparing the weather data for use in the CGMS model, the following steps have been taken:

Quality control of weather data: Quality of the daily weather data was checked manually. Wrong or improbable records were removed from the database. Missing values were then replaced by the average values, calculated in the next step.
Calculation of reference weather: Average weather characteristics for each day in each station during the recorded period were calculated by the "ReferenceWeather" package, developed by the Joint Research Center (JRC, 2004). The missing values in the daily weather records of the weather stations were replaced by the calculated average values. CGMS evaluates weather data availability for each station per year and per group of weather characteristics. For this purpose, weather characteristics are classified into three groups: rainfall, temperature and the rest (wind speed, vapor pressure and radiation). If the number of missing values for a specific weather station for each group of weather characteristics is less than a threshold (e.g., 20%), the station is classified as available station for that year and that group of weather characteristic(s). Figure 4.16 shows the number of available weather stations per group of weather characteristics for the years 1985-2004.

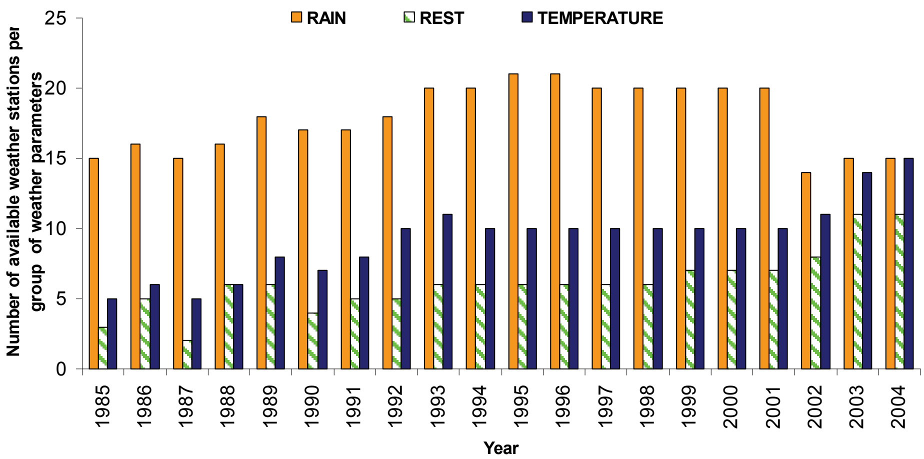


Figure 4.16. Weather data availability in the study area

Calculation of Ångstrom and Hargreaves coefficients: Solar radiation is one of the important weather characteristics in crop growth simulation, as it provides energy for photosynthesis and evapotranspiration (Supit and van Kappel, 1998; Donatelli et al., 2003; Pohlert, 2004). Solar radiation has been measured in only three of the weather stations, used in this analysis, while there were gaps in the records. Ångstrom (1924) and Hargreaves (Hargreaves et al., 1985) coefficients for calculating solar radiation from sunshine duration have been derived for these stations (Chapter 3). The gaps have been filled using the Ångstrom formula and the coefficients of Table 4.15. Coefficients for the other weather stations were estimated through interpolation of the coefficients in these three weather stations, using the "Supit constants" package (JRC, 1997).

Table 4.15. Calculated Ångstrom and Hargreaves coefficients in the weather stations of Esfahan, Najaf Abad, and Kaboutar Abad (Chapter 3)

	Ångstrom coefficients		Hargreaves coefficients	
Station	a	b	a	b
Najaf Abad	0.262	0.41	0.136	1456
Esfahan	0.244	0.517	0.163	342
Kaboutar Abad	0.247	0.399	0.131	76

Calculation of additional environmental characteristics: In this step, daily values of E0, ES0 and ET0 are calculated for all stations. E0 and ES0 are calculated by the Penman equation (Penman, 1948), while ET0 is calculated by the Penman- Monteith equation (Allen et al., 1998). Solar radiation was calculated by either the Ångstrom or the Hargreaves equation, depending on data availability. The Ångstrom equation has been used for the synoptic stations, for which sunshine duration was available. For the climatological stations where sunshine duration was not recorded, Hargreaves' equation has been used. For the rain gauge stations, solar radiation could not be calculated.

Calculation of grid weather data: Daily weather data in the grid cell centers for the period 1985-2004 were generated through interpolation of the daily weather data of the most similar weather stations (Van der Goot et al., 2004). For calculation of the similarity between grid cells and weather stations, the following parameters are determined per grid cell:

- Geographical coordinates of grid cell center and weather station (longitude and latitude)
- Average altitude of the agricultural area in the grid cell
- Distance between grid cell centre and coast

Average elevation of the potentially suitable area in each grid cell/village has been calculated from the DEM (Digital Elevation Model) map (Figure 4.15) that has been generated on the basis of SRTM[1] (Shuttle Radar Topography Mission) data.

The spatial variation in average weather characteristics and other environmental characteristics over the period 1985-2004 in the study area is presented in Figure 4.17, Figure 4.18 and Figure 4.19.

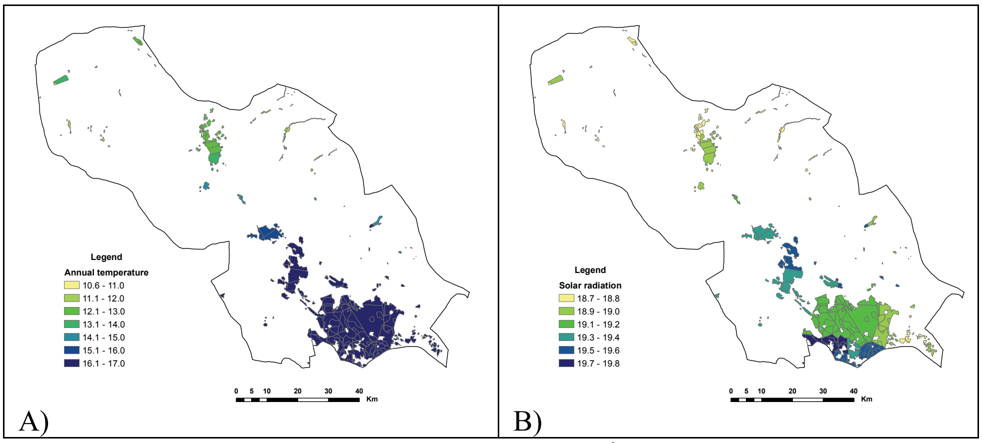


Figure 4.17. Spatial variation in A) annual temperature (^oC) and B) solar radiation ($MJ.m^{-2}.d^{-1}$) in Borkhar & Meymeh district

1 - These data have been extracted from ftp://e0srp01u.ecs.nasa.gov/ (last accessed: 6 June 2008).

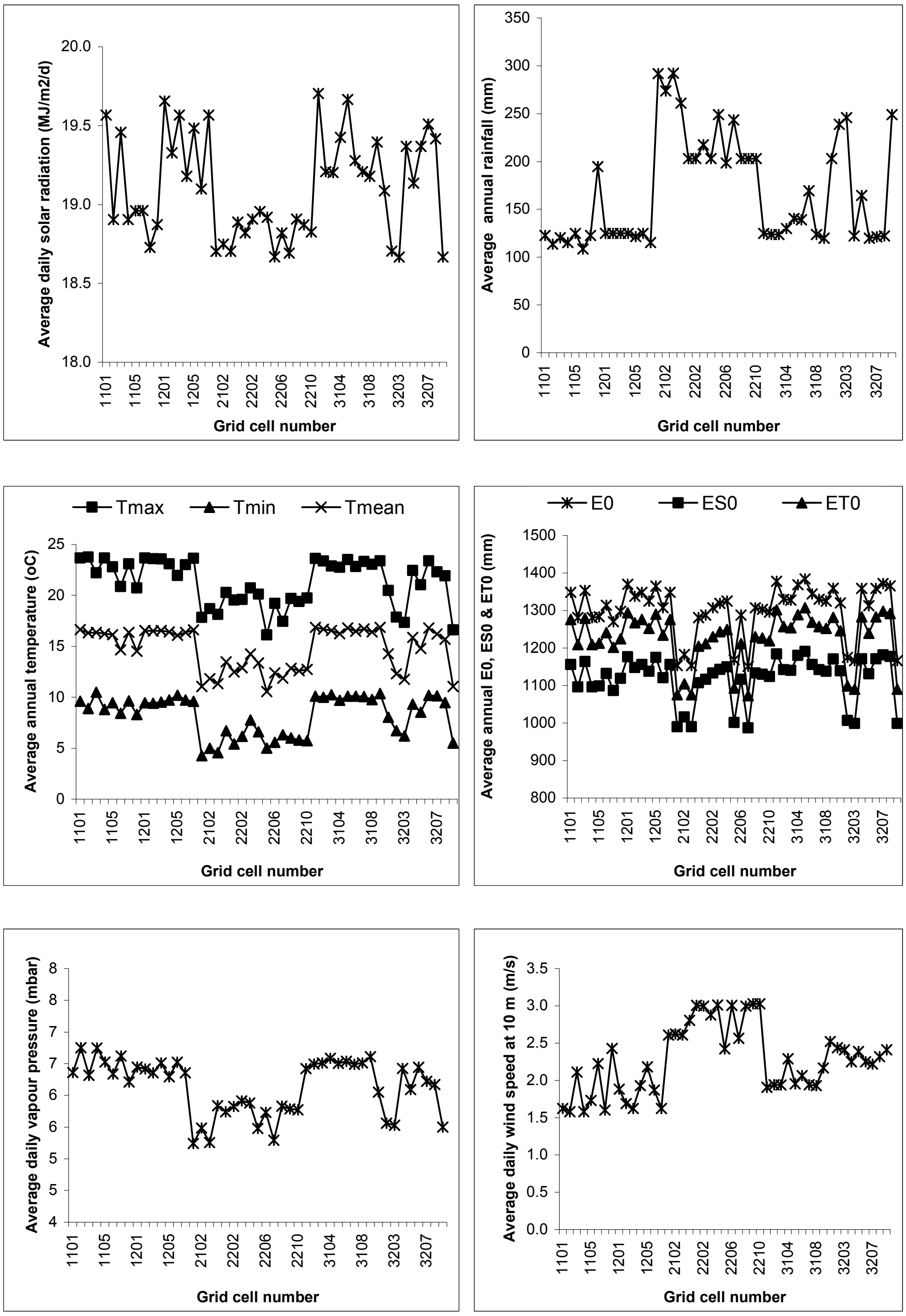


Figure 4.18. Average annual rainfall, temperature, E0 (evaporation from an open water surface), ES0 (evaporation from bare soil), ET0 (crop reference evapotranspiration) and daily solar radiation, wind speed and vapor pressure in different grid cells during the period 1985-2004

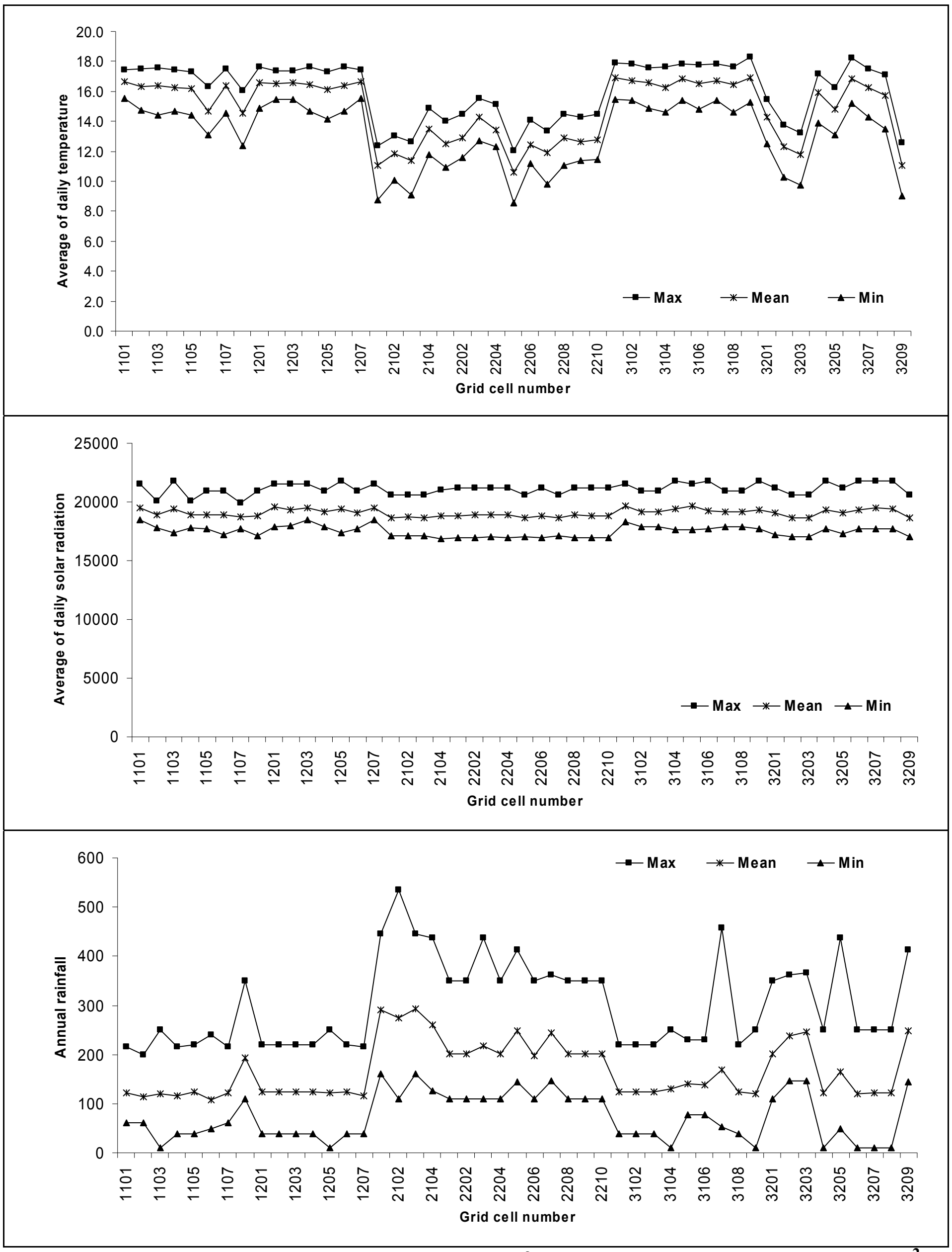


Figure 4.19. Variation in mean daily temperature (°C), mean daily solar radiation ($KJ.m^{-2}.d^{-1}$), and annual rainfall (mm) for all grid cells during the period 1985-2004

The function "Starting campaign month", introduced in CMGS 2.0a to enable simulation of crops whose growth cycle starts in one calendar year and continues in the subsequent year, did not work properly in the current version

(CGMS 2.3). Therefore, an alternative procedure was developed for simulation of winter wheat and winter barley.

4.4.4 Crop calendars

Starting point of crop growth simulation is either sowing or emergence date of the crop, which can vary among grid cells. Sowing date in the region depends on weather, cropping system and availability of agricultural machinery. Winter crops in the study area are sown in October (winter barley and colza) and November (winter wheat), with a variation of some days among grid cells. In grid cells where two crops per year can be cultivated, winter crops are assumed to be sown 20 days earlier than those in grid cells with a single crop. Summer crops in the double cropping system are sown after harvest of the winter crops (or following the last irrigation of winter crops, when the summer crop is cultivated on other parcels). Crop growth duration of winter crops is longer, the lower the temperature in the grid cell. Therefore, in these grid cells, cultivation of a second crop in the year is not possible, because of late harvest of winter crops. To take into account that effect, the region has been classified into three zones (Table 4.16; Figure 4.20), based on average annual temperature, latitude and altitude of the grid cells, using SPSS software (SPSS Inc., 2007). For each zone, a cropping calendar has been defined per crop and cropping system (Table 4.17). Sowing date for colza is set identical to that for winter barley, that for melon and watermelon to that for silage maize.

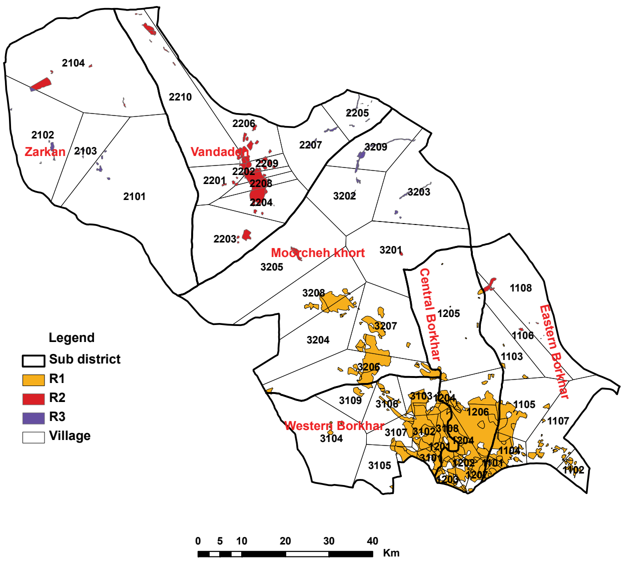


Figure 4.20. Cropping calendar zones (R1-R3), sub-districts, and village (grid cell) numbers in Borkhar & Meymeh district

Table 4.16. Number of villages, average characteristics, and area of the cropping calendar zones in Borkhar & Meymeh district

Zone	Number of villages	Annual temperature (^{0}C)	Altitude (m)	Latitude (^{0}N)	Area of EMUs	
					ha	%
R1	26	16.1	1610	32.91	55269	86.3
R2	13	13.1	1932	33.35	7143	11.2
R3	8	11.1	2277	33.43	1616	2.5
Total	47				64028	100

Table 4.17. Emergence date of CGMS-crops in the single and double cropping systems per cropping calendar zone

Crop	Cropping system	Cropping calendar zone	Emergence date
Winter wheat	Single	R1, R2	21 Nov
Winter wheat	Single	R3	1 Dec
Winter wheat	Double	R1	1 Nov
Winter Barley	Single	R1, R2	11 Nov
Winter Barley	Single	R3	21 Nov
Winter Barley	Double	R1	21 Oct
Silage Maize	Single	R1	11 Apr
Silage Maize	Single	R2	21 Apr
Silage Maize	Single	R3	1 May
Silage Maize	Double	R1	1 July
Sunflower	Single	R1	1 Apr
Sunflower	Single	R2	11 Apr
Sunflower	Single	R3	21 Apr
Sunflower	Double	R1	1 July
Sugar beet	Single	R1, R2	11 May
Potato	Single	R1	11 Mar
Potato	Single	R2	21 Mar
Potato	Single	R3	1 Apr

4.5 Results

Analyses of crop yield, irrigation and fertilizer requirements have been carried out for all CGMS and non-CGMS crops in Borkhar & Meymeh district based on 20 years daily weather data for three irrigation regimes (full irrigation, 20% and 40% deficit irrigation) for 128 EMUs. In the following sections, general results are presented for all crops, detailed results are presented only for one winter CGMS crop (winter wheat), one summer CGMS crop (silage maize) and one non-CGMS crop (melon) in the single cropping system[1] as representatives of major crops in the study area.

4.5.1 Crop Yield

Crop yield (dry matter) of CGMS crops in Borkhar & Meymeh district has been calculated for the period 1985-2004 and three irrigation regimes (full irrigation, 20% and 40% deficit irrigation) for 128 EMUs. Average potential and water-limited yields for these crops for the 20-year period have been calculated per EMU. Average yields of non-CGSM crops have been calculated by Equations (4.5) and (4.7), based on the yield of the equivalent CGMS crop(s) and yields of the best agricultural producers in the region. In addition, the assumption that was made in Equations (4.5) and (4.7) was investigated by calculating the ratio of potential yield in the grid cell and maximum potential yield in the district for the years 1985-2004 for different winter crops (Figure 4.21) and summer crops (Figure 4.22). The analysis shows that the average variation in this ratio is the same for different winter crops and for different summer crops, but different for the two crop types.

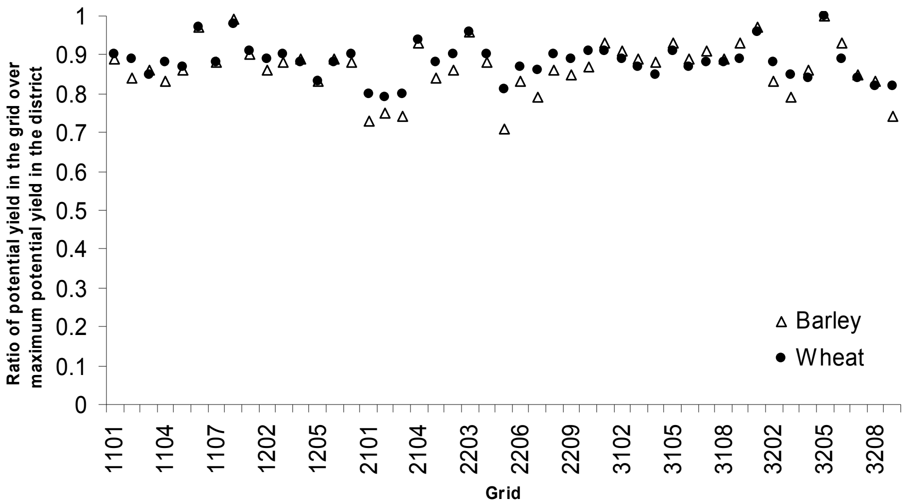


Figure 4.21. Ratio of simulated potential yield (TWSO) of winter wheat and winter barley per grid cell and maximum simulated potential yields in Borkhar & Meymeh district

Average potential grain yields of wheat, total aboveground production of silage maize and fruit weight of melon in both the single and double cropping systems

1 - Single crops are identified by _S and double crops by _D following their names (e.g., wheat_S is wheat single and silage maize_D is silage maize double).

are presented in Figures 4.23 - 4.26 as representatives of winter CGMS crops, summer CGMS crops and non-CGMS crops, respectively.

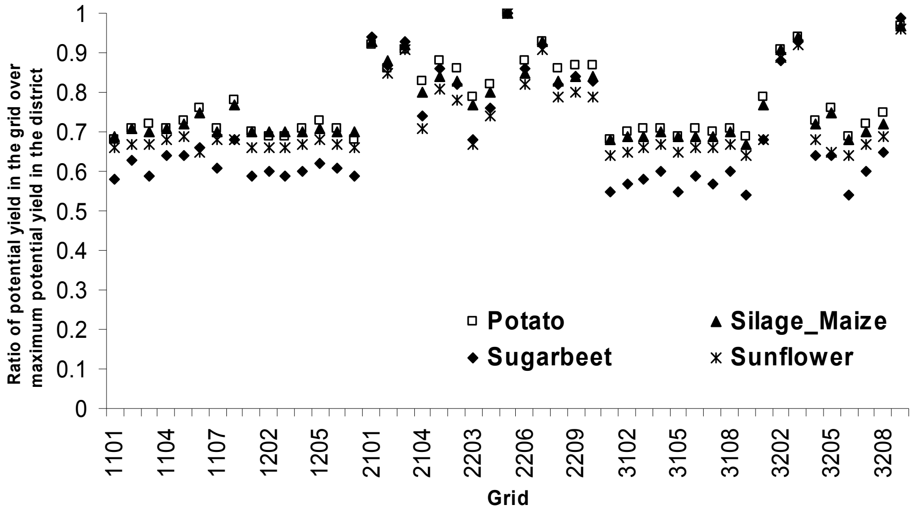


Figure 4.22. Ratio of simulated potential crop production (total aboveground dry matter for silage maize and weight of storage organs for other crops) of summer crops per grid cell and maximum simulated potential crop production in Borkhar & Meymeh district

- ***Spatial variation in crop yield***

Simulated potential crop yields spatially vary, because of spatial variation in weather conditions. The coefficient of variation in the district for the various crops (Table 4.18) varies between 2 (sunflower, double crop) and 13.5% (sugar beet, single crop), while the minimum value for the single crop is 4% (wheat). The maximum coefficient of variation in zone R1, where both single and double crops can be cultivated, is 4.7% for sugar beet (Figure 4.28). For the double cropping systems, the coefficient of variation (CV) is between 2 and 2.9%. The coefficients of variation of simulated potential yields of winter crops are smaller than those for summer crops, except for sunflower (Figure 4.27).

- ***Temporal variation in crop yield***

Average simulated potential yield of crops in grid cells shows inter-annual variation, because of temporal variations in weather conditions. Minimum and maximum coefficients of variation are 4.5 and 16.6% for silage maize and sugar beet, respectively (Figure 4.29).

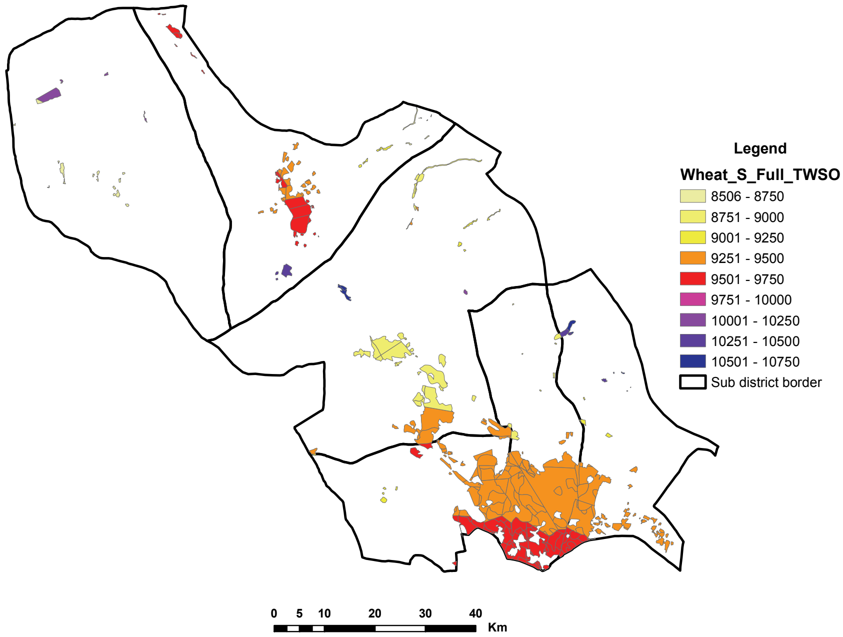


Figure 4.23. Average potential grain yield (TWSO; kg/ha dry matter) of winter wheat (single cropping system) in different EMUs in Borkhar & Meymeh district

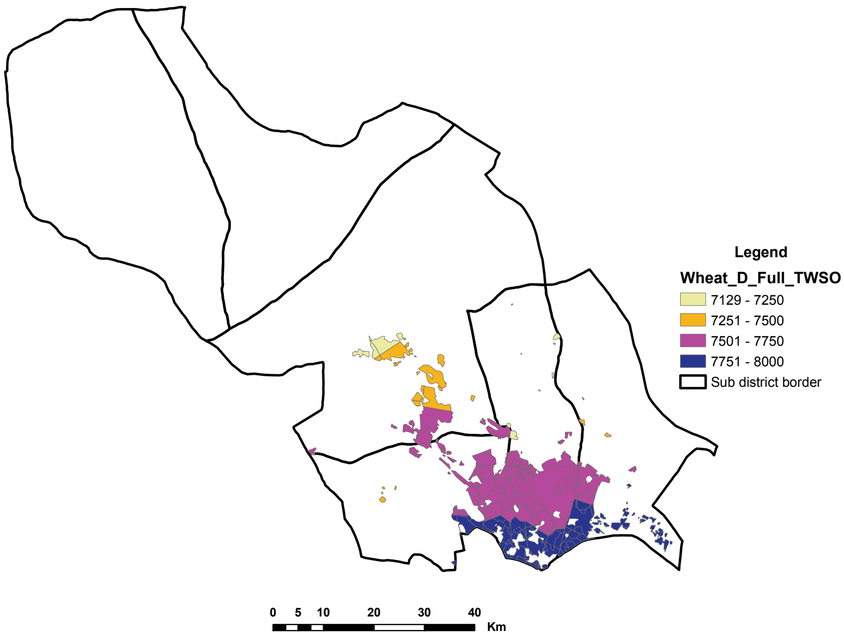


Figure 4.24. Average potential grain yield (TWSO; kg/ha dry matter) of winter wheat (double cropping system) in different EMUs in Borkhar & Meymeh district

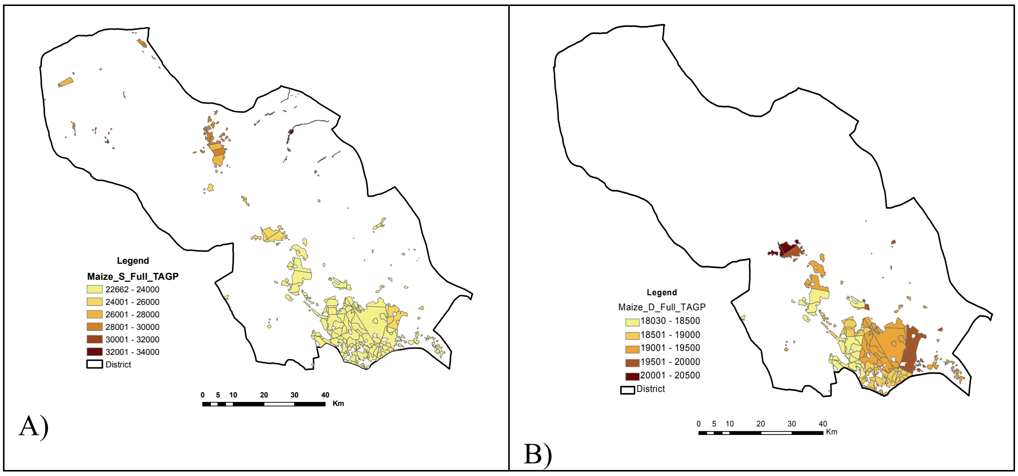


Figure 4.25. Average potential aboveground dry matter yield (TAGP; kg/ha) of silage maize in different EMUs in Borkhar & Meymeh district (A-single, B-double cropping systems)

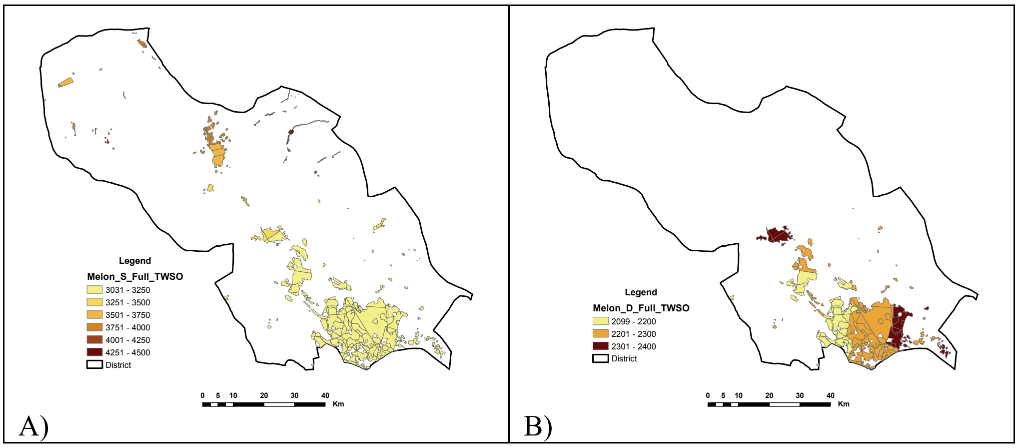


Figure 4.26. Average potential fruit yield (TWSO; kg/ha dry matter) of melon in different EMUs in Borkhar & Meymeh district (A-single, B-double cropping systems)

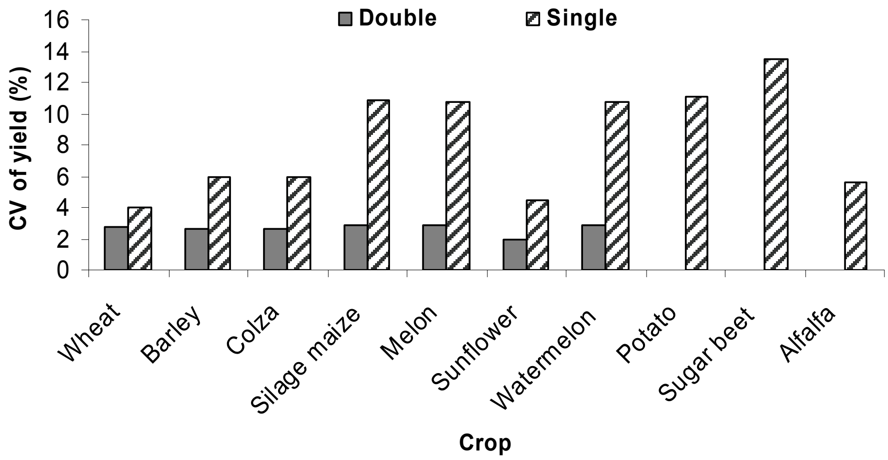


Figure 4.27. Coefficient of variation of simulated potential yield of different crops in single and double cropping systems in Borkhar & Meymeh district (1985-2004)

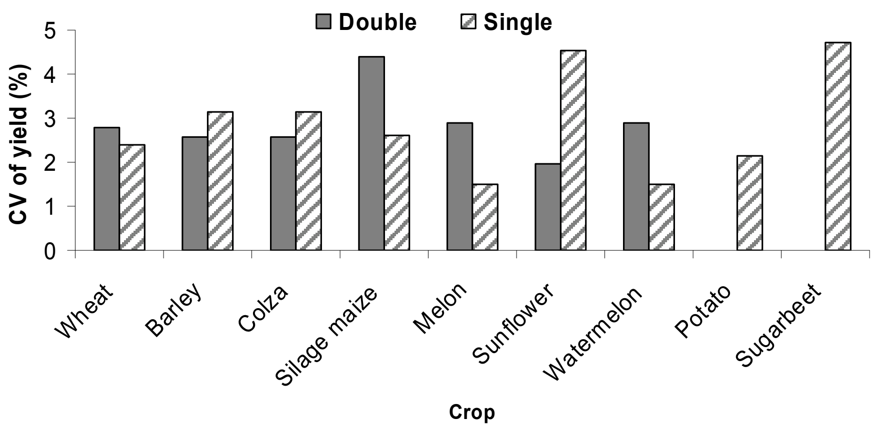


Figure 4.28. Coefficient of variation of simulated potential yield of different crops in single and double cropping systems in zone R1 of Borkhar & Meymeh district (1985-2004)

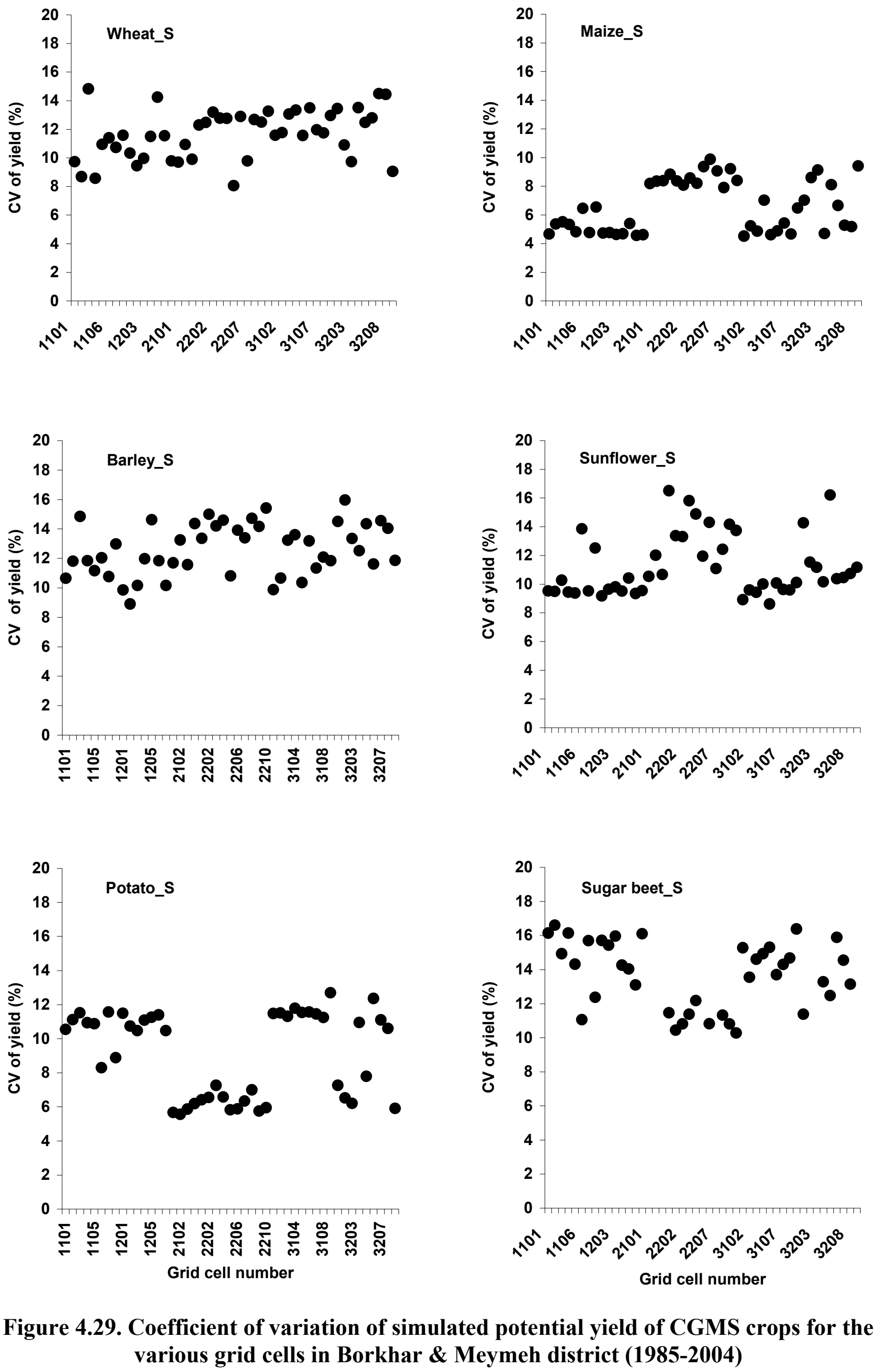


Figure 4.29. Coefficient of variation of simulated potential yield of CGMS crops for the various grid cells in Borkhar & Meymeh district (1985-2004)

Table 4.18. Statistical parameters (minimum, mean, maximum, standard deviation and coefficient of variation) of simulated potential yield of different crops in different grid cells in Borkhar & Meymeh district

Crop	Cropping system	Yield type	Yield (kg/ha)				Coefficient of variation [1] (%)
			Minimum	Mean	Maximum	Standard Deviation	
Wheat	Double	TWSO	7129	7723	7989	217	2.8
Wheat	Single	TWSO	8506	9444	10712	373	4
Barley	Double	TWSO	6784	7360	7610	190	2.6
Barley	Single	TWSO	7669	9365	10726	553	5.9
Colza	Double	TWSO	2564	2781	2876	71	2.6
Colza	Single	TWSO	2603	3178	3640	188	5.9
Potato	Single	TWSO	10033	11019	14683	1228	11.1
Sugar beet	Single	TWSO	12863	15087	20661	2039	13.5
Sunflower	Double	TWSO	4637	4814	5009	94	2
Sunflower	Single	TWSO	4701	5324	7465	661	12.4
Melon	Double	TWSO	2170	2286	2430	58	2.5
Melon	Single	TWSO	3031	3338	4500	362	10.8
Watermelon	Double	TWSO	1157	1219	1296	31	2.5
Watermelon	Single	TWSO	1616	1780	2400	193	10.8
Alfalfa	Single	TAGP	15007	16011	17905	898	5.6
Silage maize	Double	TAGP	18030	18993	20187	482	2.5
Silage maize	Single	TAGP	22662	24959	33648	2708	10.9

[1]Coefficient of variation is the ratio of standard deviation and mean

- ***Irrigation regime and crop yield***

The response of different crops to soil water deficits can vary, depending on crop characteristics, time of water shortage and soil physical characteristics. The reduction in crop yield for each irrigation regime (Yield_Reduction $_{Crop,\ Irman,}$ %) is calculated based on average simulated potential and water-limited yields for that irrigation regime (Equation (4.21)).

$$\text{Yield\_Reduction}_{\text{Crop,Irman}} = \frac{(\text{Ave\_Pot\_yield}_{\text{Crop}}) - (\text{Ave\_WL\_Yield}_{\text{Crop,Irman}})}{\text{Ave\_Pot\_Yield}_{\text{Crop}}} * 100 \quad (4.21)$$

in which,

Ave_Pot_Yield $_{Crop}$: Average simulated potential crop yield (kg/ha) for the years 1985-2004

Ave_WL_Yield$_{Crop,\ Irman,}$: Average simulated water-limited crop yield (kg/ha) for the specified irrigation regime for the years 1985-2004.

Figure 4.30 shows that the yield reduction is smaller for winter crops than for summer crops, because almost all rainfall in this region occurs during the growth period of winter crops. Moreover, the reduction in marketable yield (TWSO) is larger than that in aboveground dry matter production (TAGP). This only holds for CGMS crops, as the applied methodology for non-CGMS crops does not differentiate between total dry matter production and economic yield.

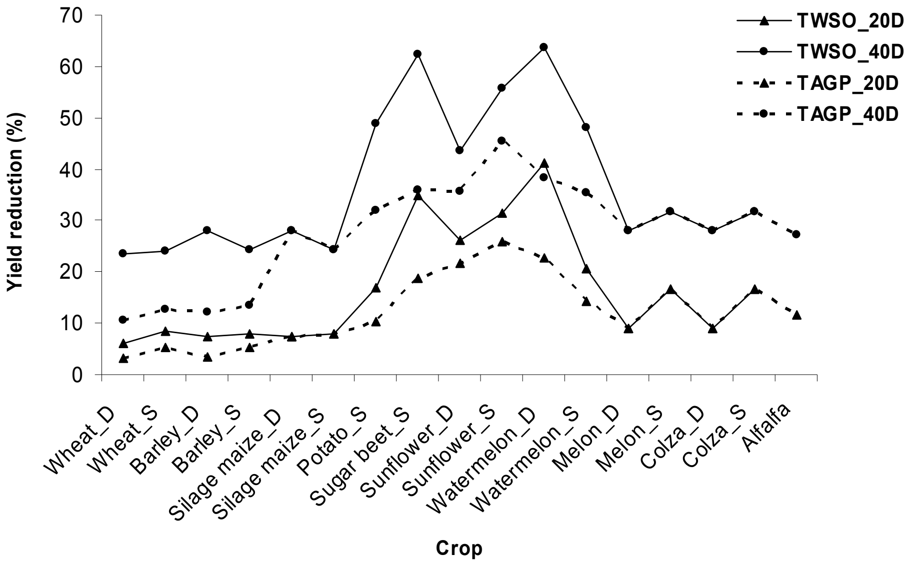


Figure 4.30. Mean simulated yield reduction for different crops under 20% (20D) and 40% (40D) deficit irrigation for the various EMUs during the years 1985-2004

Yield reductions due to water stress also varied among EMUs, because of the variation in weather conditions and soil characteristics. Average TWSO of winter wheat_S, TAGP of silage maize_S and TWSO of melon_S for the three irrigation regimes are presented in Figure 4.31. In some EMUs, strong yield reductions under deficit irrigation coincide with high potential yields (Figure 4.31). These EMUs are located at the higher altitudes, characterized by relatively low temperatures, resulting in long growing cycles and extended periods of reproductive growth, resulting in (relatively) high yield potentials. Strong yield reductions in these EMUs are associated with shallow soils and thus low water holding capacity.

The coefficient of variation of economic yield (TWSO) of crops over all EMUs, averaged over the years 1985-2004, is higher under the 40% than under the 20% deficit irrigation regime (Figure 4.32). The coefficients of variation are highest for winter crops and sugar beet, and are higher for single cropping systems than for double cropping systems. The latter difference is associated with the fact that double crops can be cultivated only in zone R1, while single crops can be cultivated in the entire region.

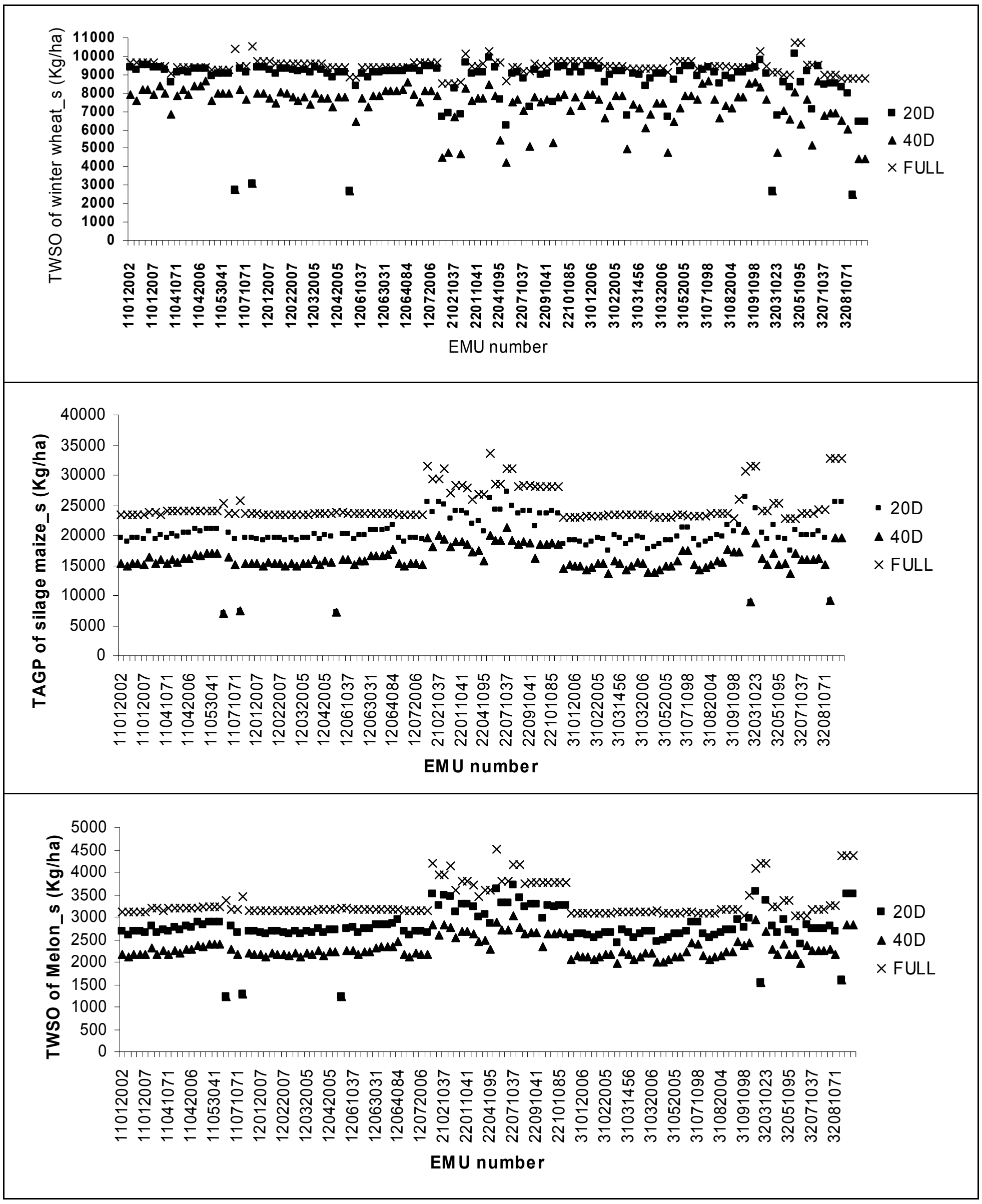


Figure 4.31. Average (1985-2004) grain yield of winter wheat_S, average total aboveground dry matter production of silage maize_S and average fruit yield of melon_S under three irrigation regimes for all EMUs in Borkhar & Meymeh district

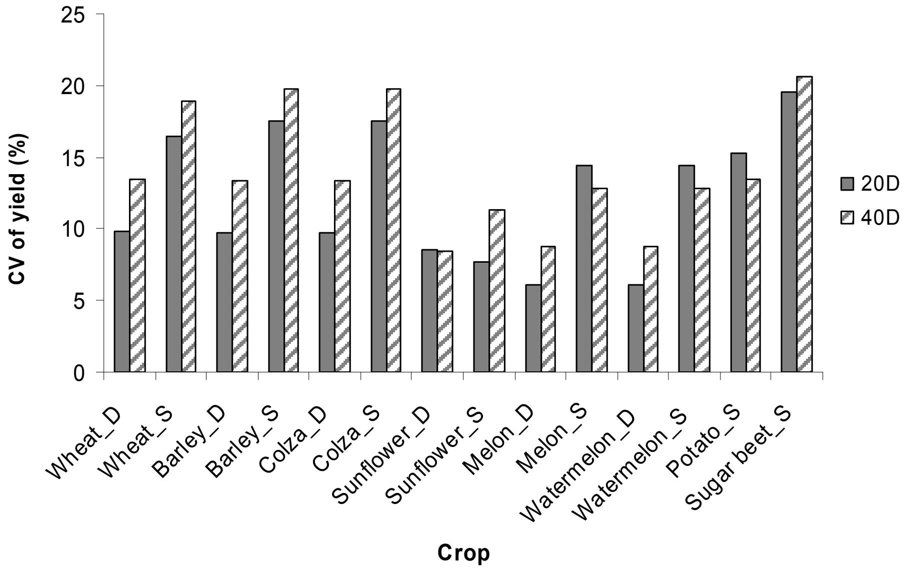


Figure 4.32. Coefficient of variation of simulated crop yield (TWSO) averaged over the years 1985-2004, in different EMUs under 20% and 40% deficit irrigation regimes in Borkhar & Meymeh district

4.5.2 Water requirements

Water requirements per decade of the major crops in the 47 grid cells of Borkhar & Meymeh district have been calculated based on daily weather data for the years 1985-2004 and CGMS outputs in the potential situation. Crop water requirements for the double cropping systems have been calculated only for zone R1, where double cropping is possible. Total crop water requirements per growing season and maximum crop water requirements per decade have been calculated for each crop per grid cell and per year. These characteristics vary both, spatially and temporally, because of spatial and temporal variation in weather conditions.

- ***Spatial variation in crop water requirements in the potential production situation***

As agricultural production in Borkhar & Meymeh district is based on irrigated technologies, water requirements are crucial characteristics of the cropping systems. Average seasonal water requirements of winter wheat, silage maize and melon in the potential situation for the years 1985-2004 were in the range 410-553, 528-634 and 430-574 mm, respectively in different grid cells (Figure 4.33). Crop water requirements are highest in the grid cells at higher latitudes and altitudes, characterized by lower temperatures. Simulated crop cycles are longer in the grid cells located in zones R2 and R3 than in those in zone R1 (Table 4.19). Average seasonal water requirements of crops in zones R2 and R3 exceed those in R1 and in single cropping systems exceed those in double cropping systems (Figure 4.34). The lower variability in crop water requirements in double cropping systems is associated with (i) differences in sowing dates of single and double crops and (ii) the highest crop water requirements in single crops are observed in zones R2 and R3 with longer crop growth cycles. In these zones, double crops cannot be cultivated, hence, the variability for double crops is based on one zone, while that for single crops refers to the entire district (three zones).

Timing and magnitude of maximum water requirements per decade are important criteria for agricultural planners and irrigation designers. As these characteristics vary spatially (i.e. are different for different grid cells), three grid cells (villages) have been analyzed in more detail, each one representative for one of the cropping calendar zones (Figure 4.35; Table 4.20). The villages of Sin and Ghasem Abad are located in the central part of zone 1 and 2, respectively. For zone 3, the village Laibid has been selected randomly, as selecting a village in the center was not possible. Average potential evapotranspiration of the 'reference crop' (ET0), calculated based on generated grid weather data is lower for Laibid than for the other two villages, while in Sin it is higher than in the other two villages in the first half of the year (Figure 4.36). ET0 in the period of January until June is higher in Sin than in Ghasem Abad, while the situation is reverse in the remainder of the year.

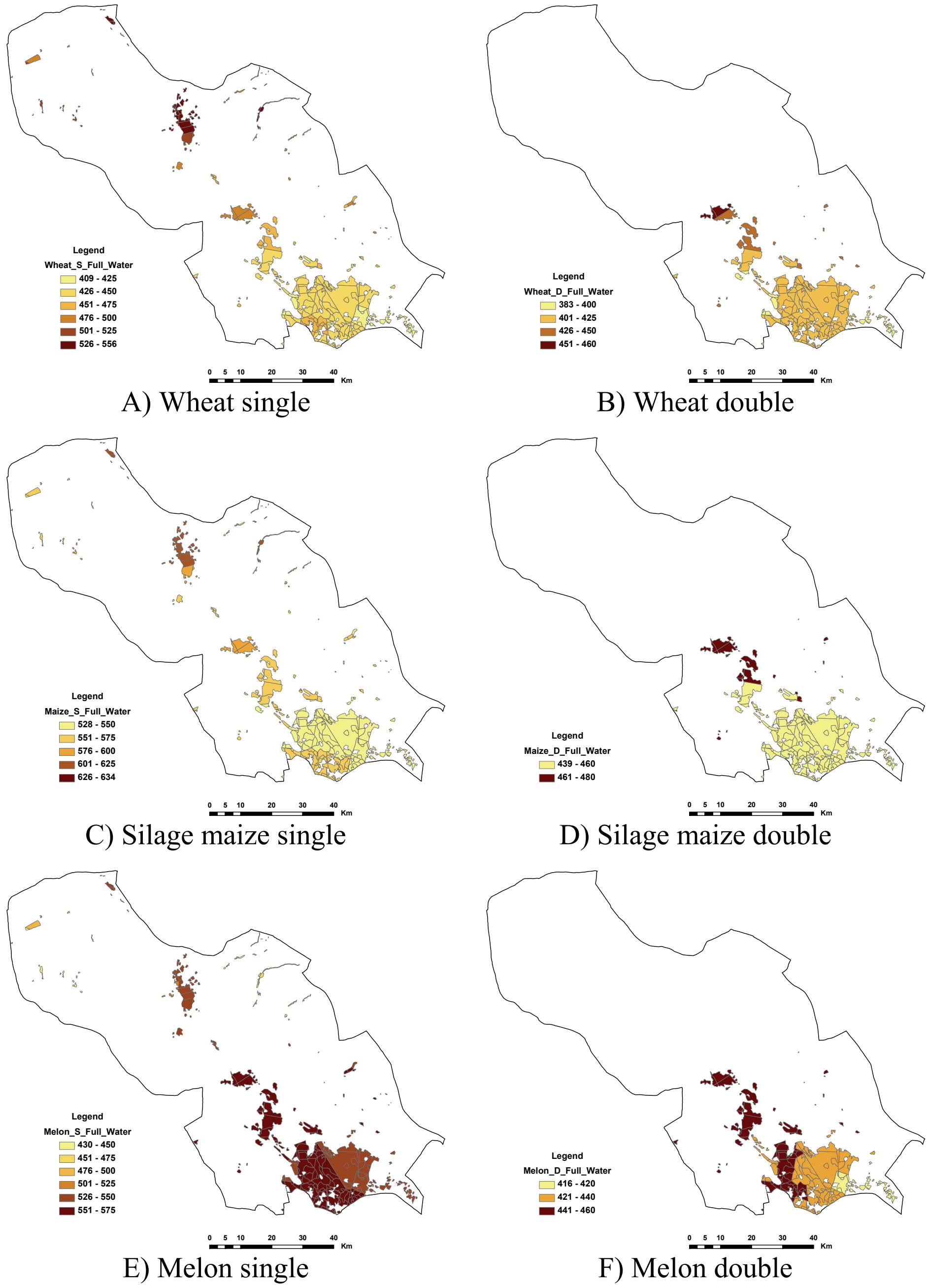


Figure 4.33. Average, for the period 1985-2004, calculated potential seasonal water requirements (mm) for winter wheat, silage maize and melon in the single and double cropping systems in Borkhar & Meymeh district

Table 4.19. Average length of the growing period (days) of CGMS crops in zones R1, R2 and R3

Crop	Cropping system	R1	R2	R3
Wheat	Single	205	227	234
	Double	216	-	-
Barley	Single	203	225	234
	Double	210	-	-
Silage maize	Single	106	113	124
	Double	91	-	-
Sunflower	Single	102	110	117
	Double	80	-	-
Sugar beet	Single	157	168	-
Potato	Single	104	111	114

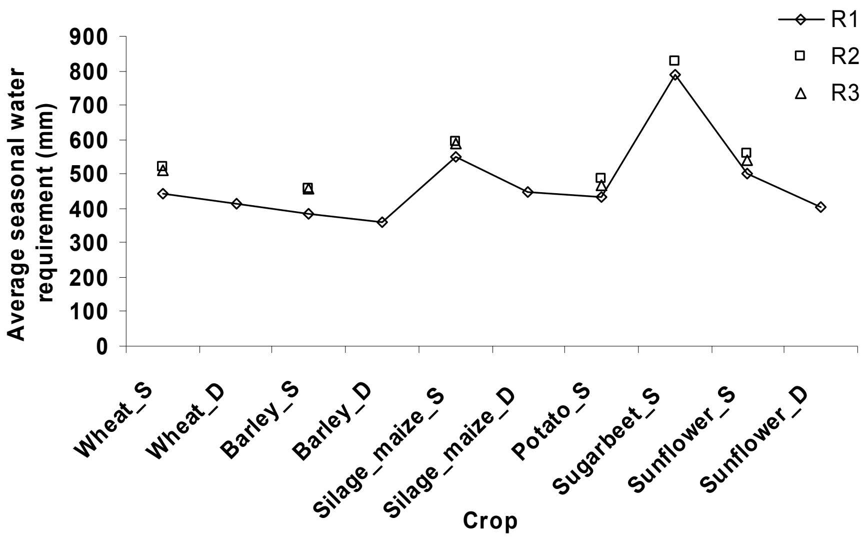


Figure 4.34. Average simulated water requirements in the potential production situation of crops in single and double cropping systems in the three cropping calendar zones

Table 4.20. Selected grid cells (villages) as representatives of the cropping calendar zones

Grid cell number	Village	Zone
3108	Sin	R1
2202	Ghasem Abad	R2
2102	Laibid	R3

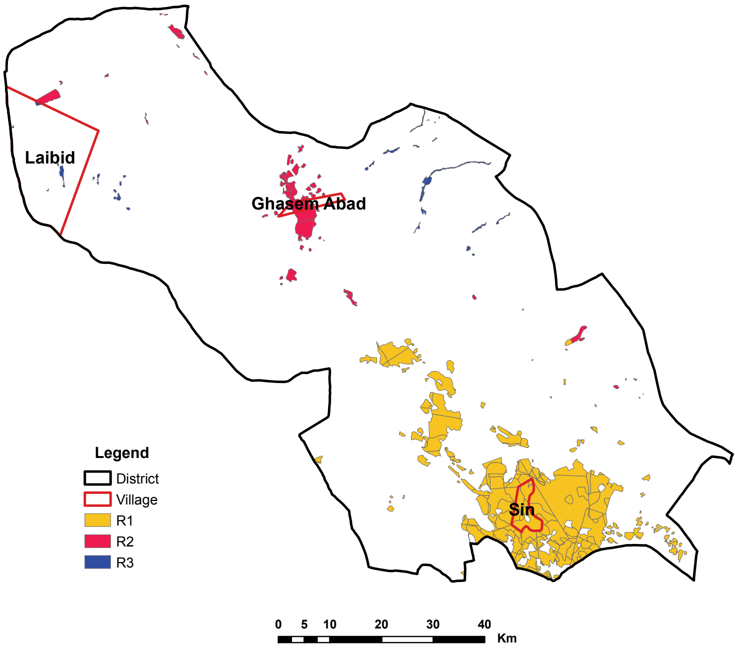


Figure 4.35. Location of selected grid cells/villages in Borkhar & Meymeh district for analysis of water requirements in different cropping zones

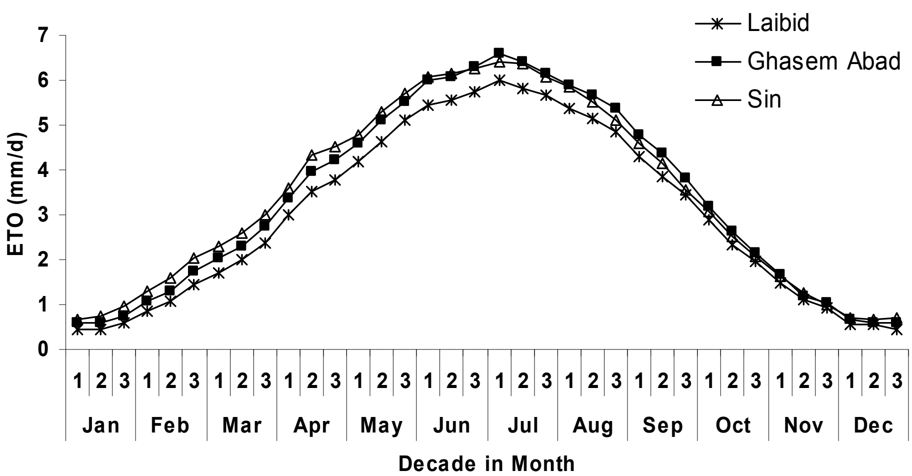


Figure 4.36. Calculated potential evapotranspiration of reference crop in Borkhar & Meymeh district

Maximum water requirements per decade (Figure 4.37) of winter wheat in Sin (last decade of May, 56 mm) are lower than in Ghasem Abad (last decade of June, 66 mm) and in Laibid (last decade of June, 62 mm). Thus, water requirements for wheat are lower in R1 than in R2 and R3, while average temperatures in R1 are higher. The consequence is that the crop cycle is longer in R2 and R3 than in R1. Therefore, the final part of the growing seasons in R2 and R3 is in the warmer period, associated with higher evapotranspiration.

Maximum water requirement of silage maize in Sin is in the first decade of July, compared to the last decade of July in Ghasem Abad and Laibid. Although total seasonal water requirements of silage maize vary among grid cells, differences in the patterns of water requirement are negligible. At the time that ET0 is high, silage maize in all grid cells fully covers the soil and exhibits maximum evapotranspiration.

As there is no rainfall during the growing period of summer crops, water requirements of summer crops are equal to potential evapotranspiration. Potential evapotranspiration of melon has been calculated by Equation (4.8) (Figure 4.37). Because of lack of information on duration of the various growth stages in different grid cells, similar growing periods of melon in all grid cells have been assumed. This assumption leads to underestimation of water requirement in the cooler grid cells and overestimation in the warmer grid cells.

- ***Temporal variation in crop water requirements***

The range in potential evapotranspiration of the reference crop (ET0) per grid cell based on daily weather data in different years is presented in Figure 4.18. The inter-annual variation in ET0 originates from variation in weather conditions, which also causes variations in potential evapotranspiration of other crops. The coefficient of variation of seasonal water requirements over the period 1985-2004 is higher for winter crops than for summer crops (Figure 4.38). Minimum and maximum values for the coefficient of variation in water requirements were 9.8 and 18.3%, respectively for sugar beet_S in zone R2 and barley_S in zone R1 (Figure 4.39). The larger variation in water requirements for winter crops might be associated with the inter-annual variation in contribution of rainfall. Rainfall is quasi-absent during the growth period of summer crops and the variation in water requirements of these crops is related to variation in other weather characteristics. The coefficient of variation in water requirements in zone R3 is smaller than in zones R1 and R2. The temporal variation in crop water requirements is thus substantial, which is the result of the temporal variability in weather conditions (Figure 4.19).

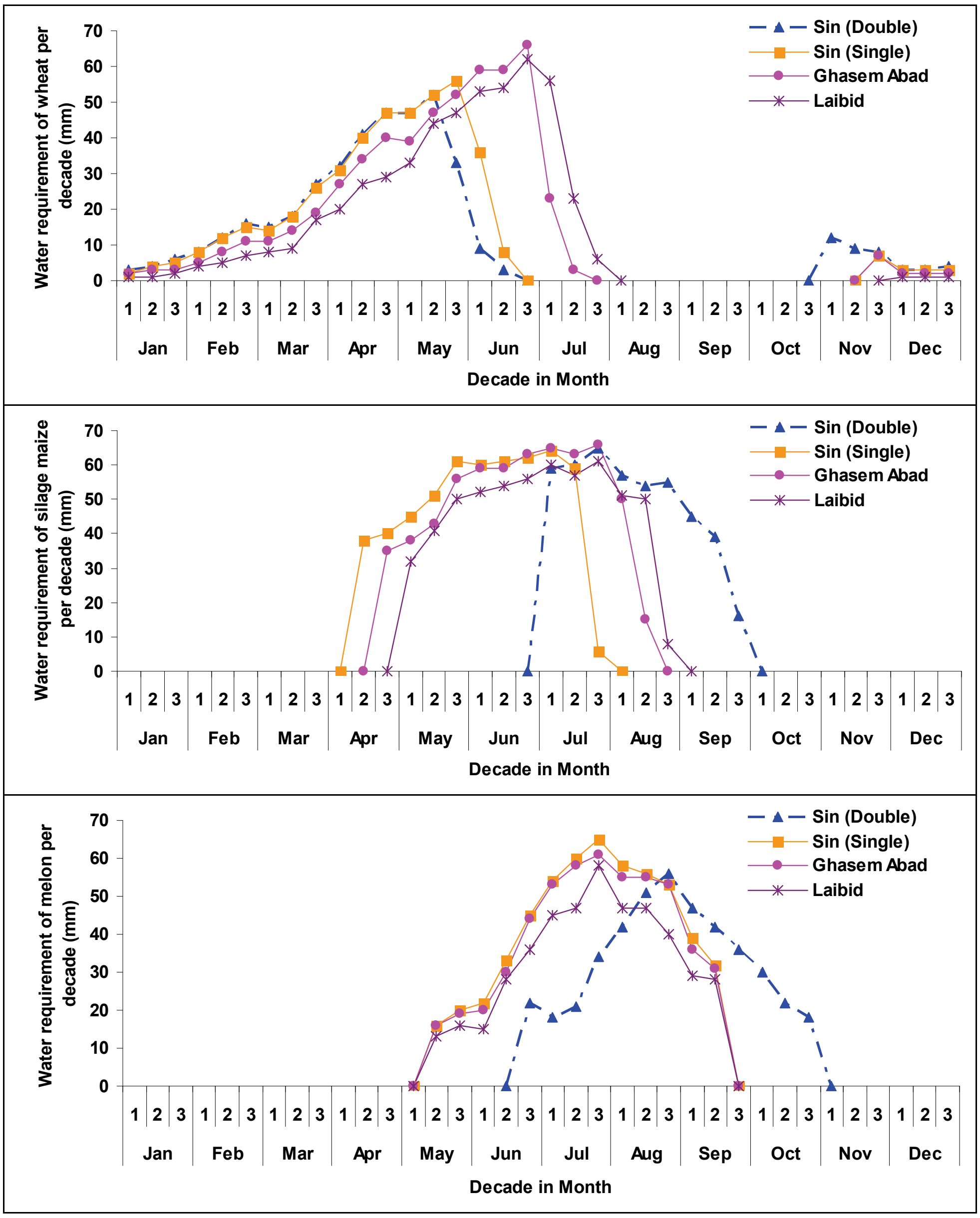


Figure 4.37. Average (1985-2004) simulated water requirements in the potential production situation of winter wheat, silage maize and melon per decade in the villages of Sin (single and double cropping systems), Ghasem Abad and Laibid in Borkhar & Meymeh district

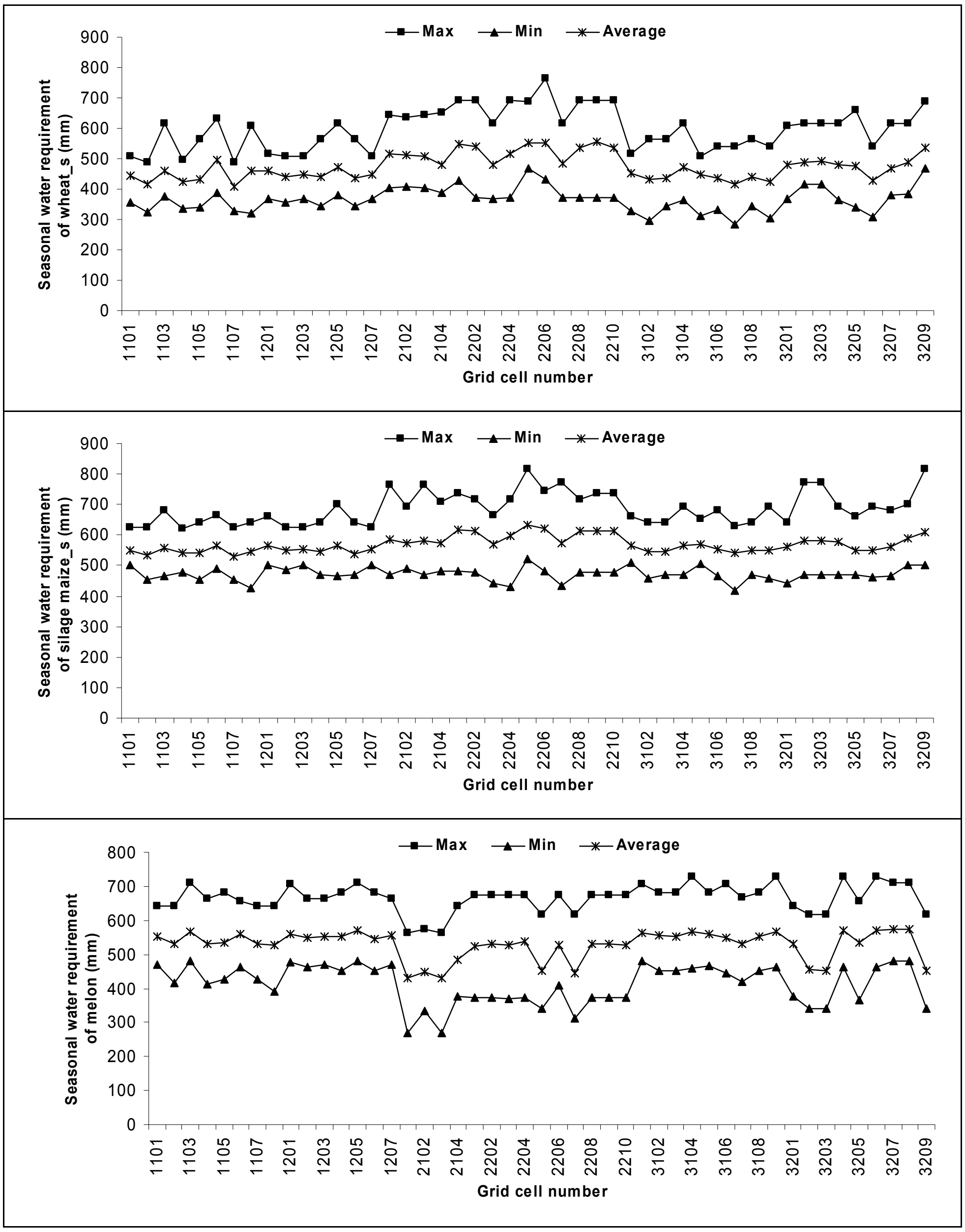


Figure 4.38. Minimum, maximum and average water requirements for the period 1985-2004 of winter wheat, silage maize and melon (in single cropping systems) in different grid cells in Borkhar & Meymeh district

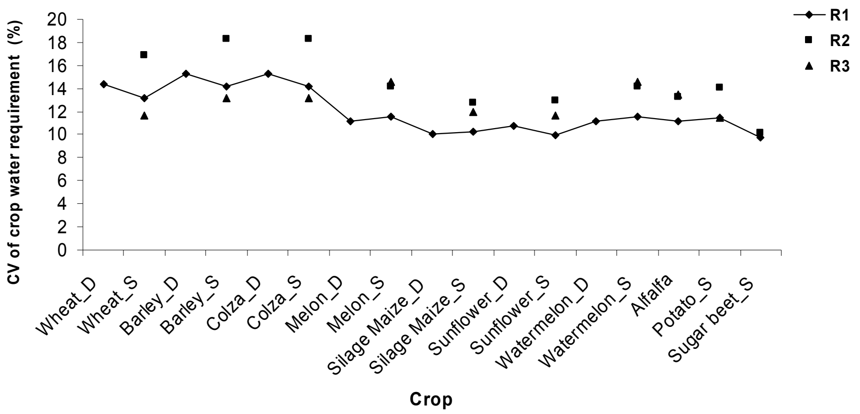


Figure 4.39. Coefficient of variation of crop water requirement for the period 1985-2004 for major crops in crop calendar zones 1, 2 and 3 in Borkhar & Meymeh district

4.5.3 Fertilizer requirements

Average crop macro-nutrient (nitrogen, N, phosphorus, P and potassium, K) requirements have been estimated for all crops (CGMS and non-CGMS crops) in all EMUs under three irrigation regimes. For this purpose, the base soil supply of nutrients (indigenous soil nutrient supply) for each crop has been determined spatially based on results of soil chemical tests. Fertilizer requirements for the major nutrients for each crop per EMU and irrigation regime have been calculated based on simulated average crop yields during 1985-2004.

- ***Base soil supply of nutrients***

The base soil supply of the macronutrients (nitrogen: NBASE, phosphorus: PBASE and potassium: KBASE) for each grid cell has been calculated based on the results of soil tests, available from the local organization of agriculture in Borkhar & Meymeh district. Information required for estimation of the base soil supply is generated as part of the formulation of fertilizer recommendations for different crops in the region. However, no information was available on the exact geographical location of the soil samples, only the name of village. So, average values for soil chemical characteristics and the associated values for NBASE, PBASE and KBASE were calculated per village, based on a variable number of soil samples per village (Figure 4.40; Annex 2). For villages in which no soil samples had been taken, generally because of their limited relevance for agriculture, results from neighboring villages have been used. The spatial distribution of NBASE, PBASE and KBASE is illustrated in Figure 4.40. Indigenous soil macro-nutrient supply is highest in soils in the southeastern part of the district, with the highest values for potassium (Figure 4.40).

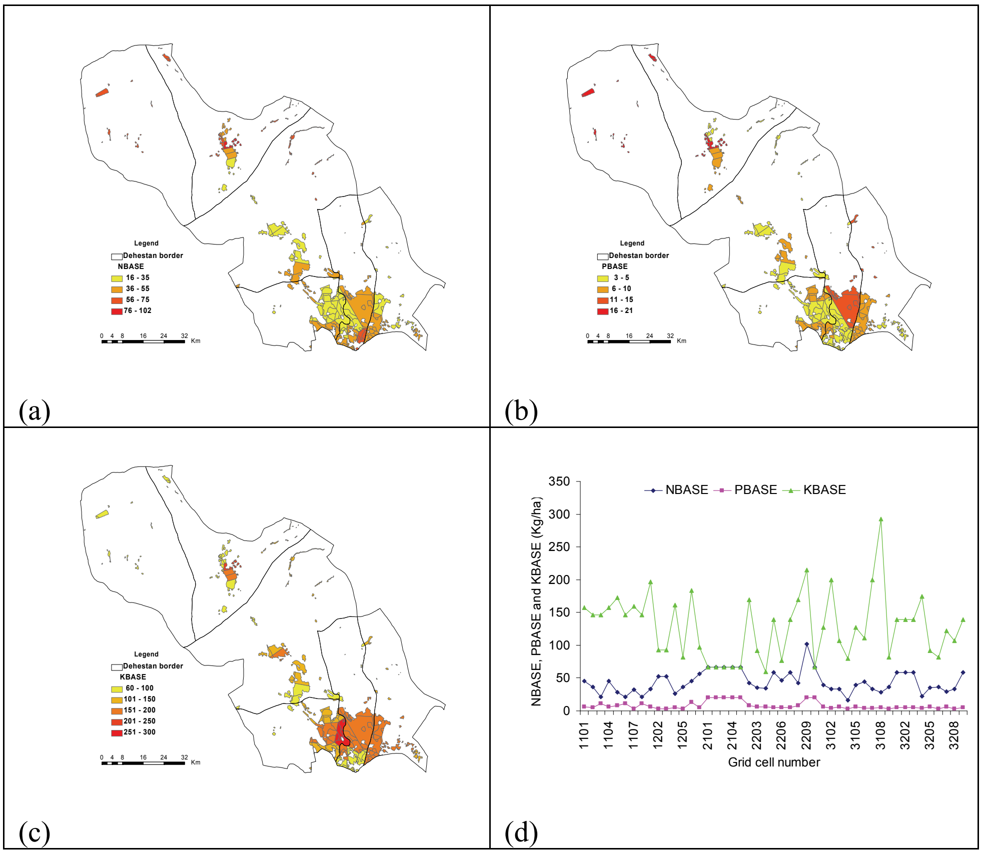


Figure 4.40. Spatial distribution of base soil supply of nitrogen (a), phosphorus (b) and potassium (c) in Borkhar & Meymeh district and in different grid cells (d)

- ***Fertilizer requirements in the potential production situation***

Fertilizer requirements for the three macro-nutrients for realization of the calculated production levels of all crops under the different irrigation regimes are calculated with Equations (4.18), (4.19) and (4.20). In parts of the area, potassium fertilizer is not needed, because of the high indigenous soil supply (Figure 4.41, Figure 4.42, and Figure 4.43).

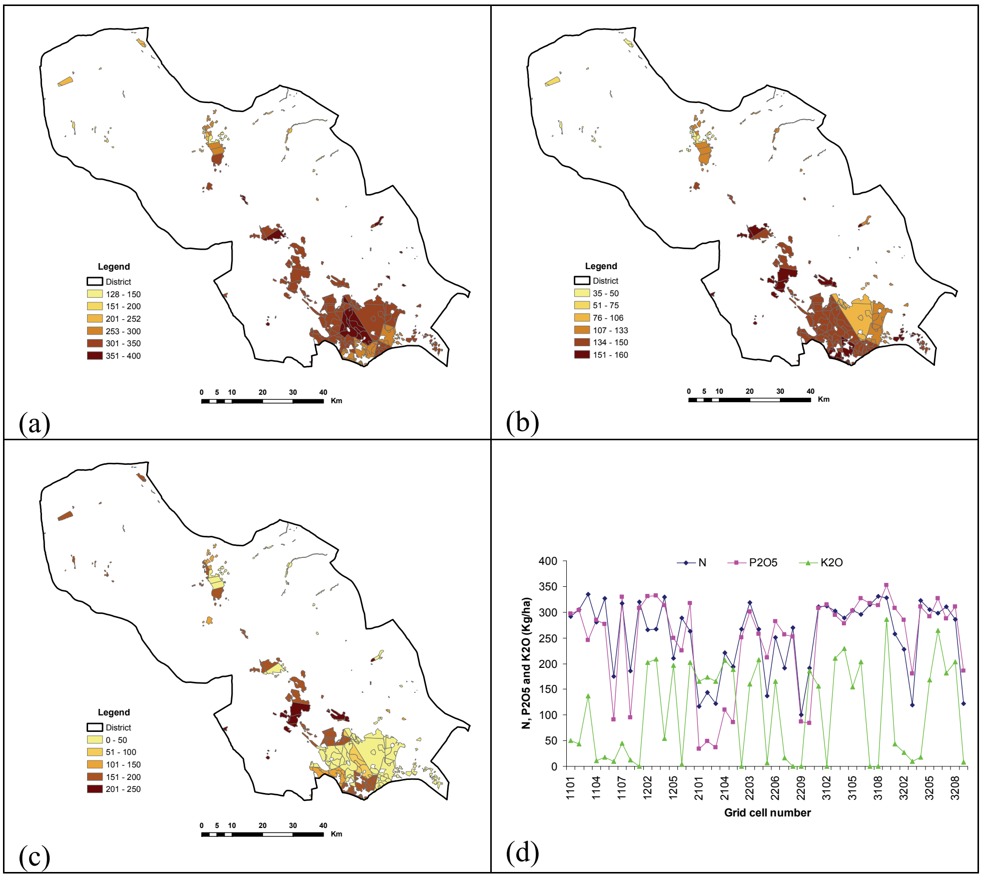


Figure 4.41. Spatial distribution of nitrogen (a), phosphorus (b) and potassium (c) fertilizer requirements for realization of the simulated potential yield of winter wheat in single cropping systems in Borkhar & Meymeh district and these requirements in different grid cells (d)

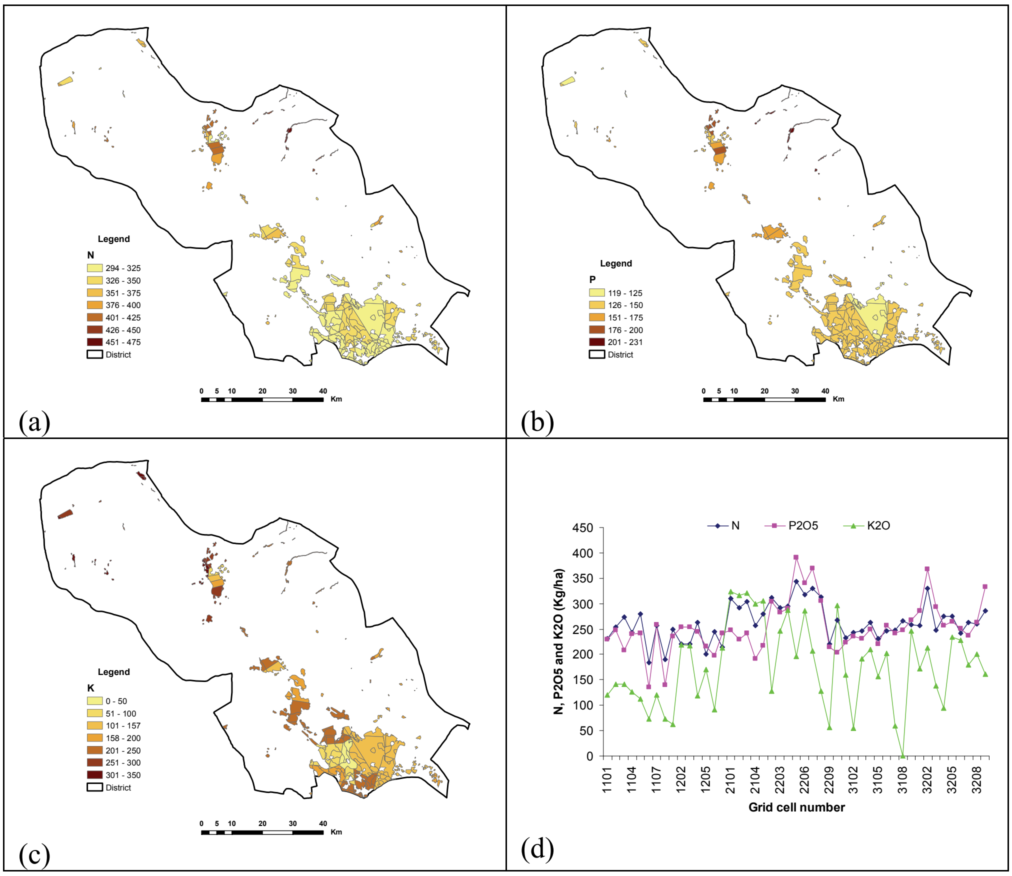


Figure 4.42. Spatial distribution of nitrogen (a), phosphorus (b) and potassium (c) fertilizer requirements for realization of the simulated potential yield of silage maize in single cropping systems in Borkhar & Meymeh district and these requirements in different grid cells (d)

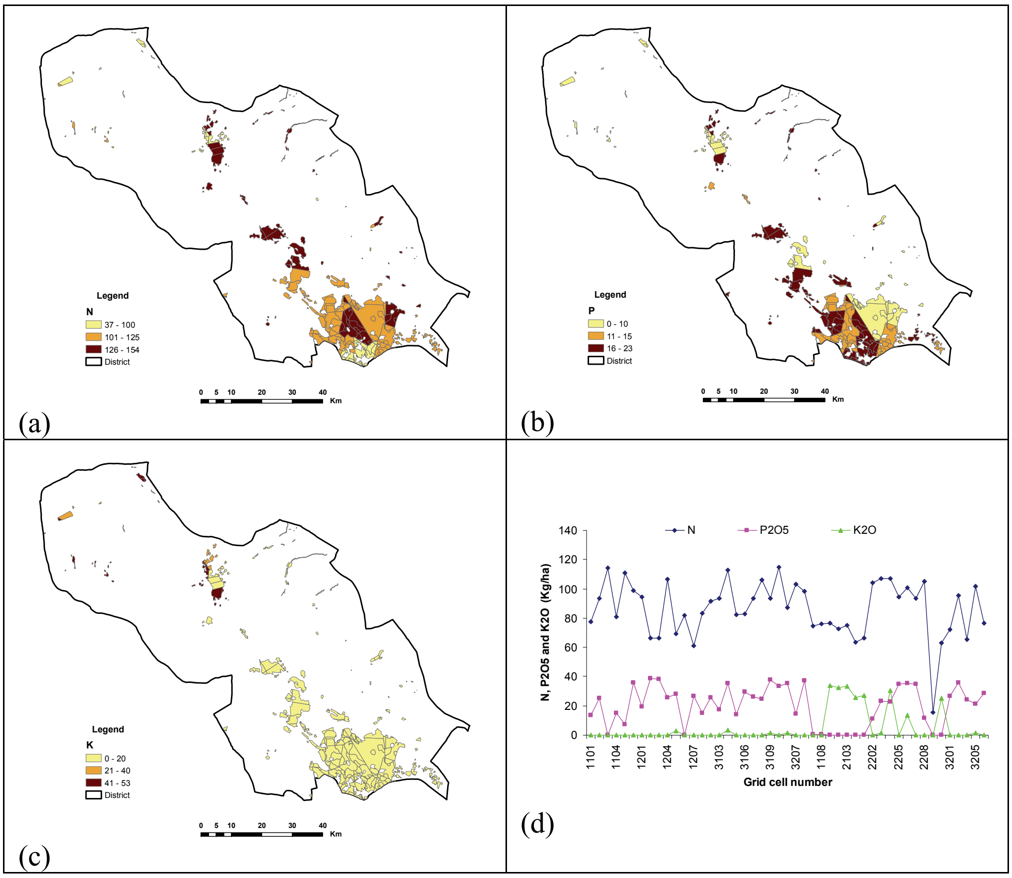


Figure 4.43. Spatial distribution of nitrogen (a), phosphorus (b) and potassium (c) fertilizer requirements for realization of the simulated potential yield of melon in single cropping systems in Borkhar & Meymeh district and these requirements in different grid cells (d)

- ***Irrigation regime and fertilizer requirements***

Fertilizer requirements for crop production under different irrigation regimes (full irrigation, 20% and 40% deficit irrigation) have been calculated based on average yields of all crops in different EMUs (Figure 4.44, Figure 4.45, Figure 4.46). Fertilizer requirements under 40% deficit irrigation are low, because of low crop yields. Differences between the fertilizer requirements of winter wheat under full irrigation and under 20% deficit irrigation are small, because of the winter rainfall in the study area that prevents water stress during the early growing season. However, for silage maize, a summer crop, reduced irrigation leads to crop water stress that negatively influences yield and consequently fertilizer requirements. Fertilizer requirements in the various EMUs show temporal variations, because of variations in weather conditions.

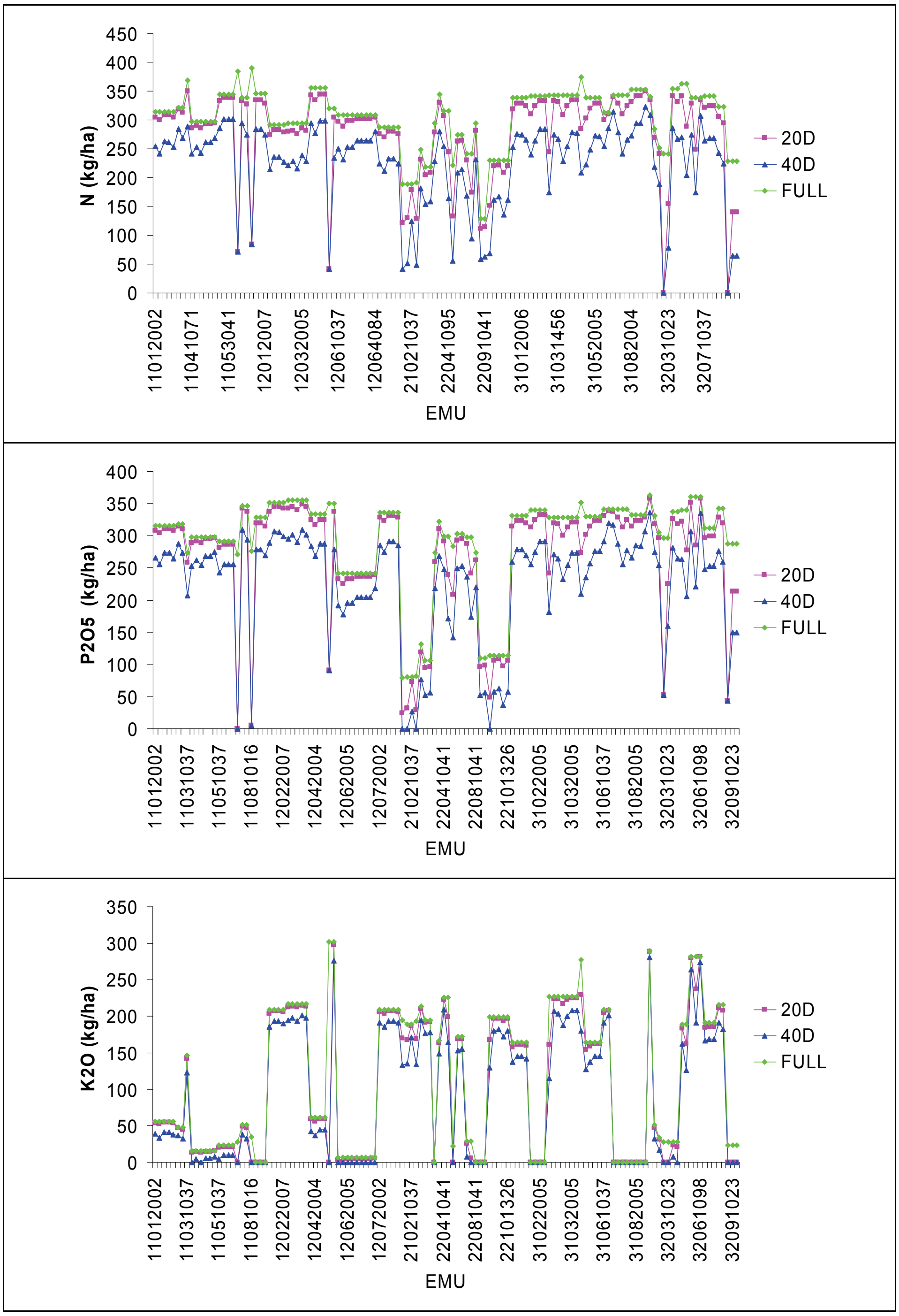


Figure 4.44. N, P and K fertilizer requirements for production of winter wheat_S under different irrigation regimes in all EMUs in Borkhar & Meymeh district

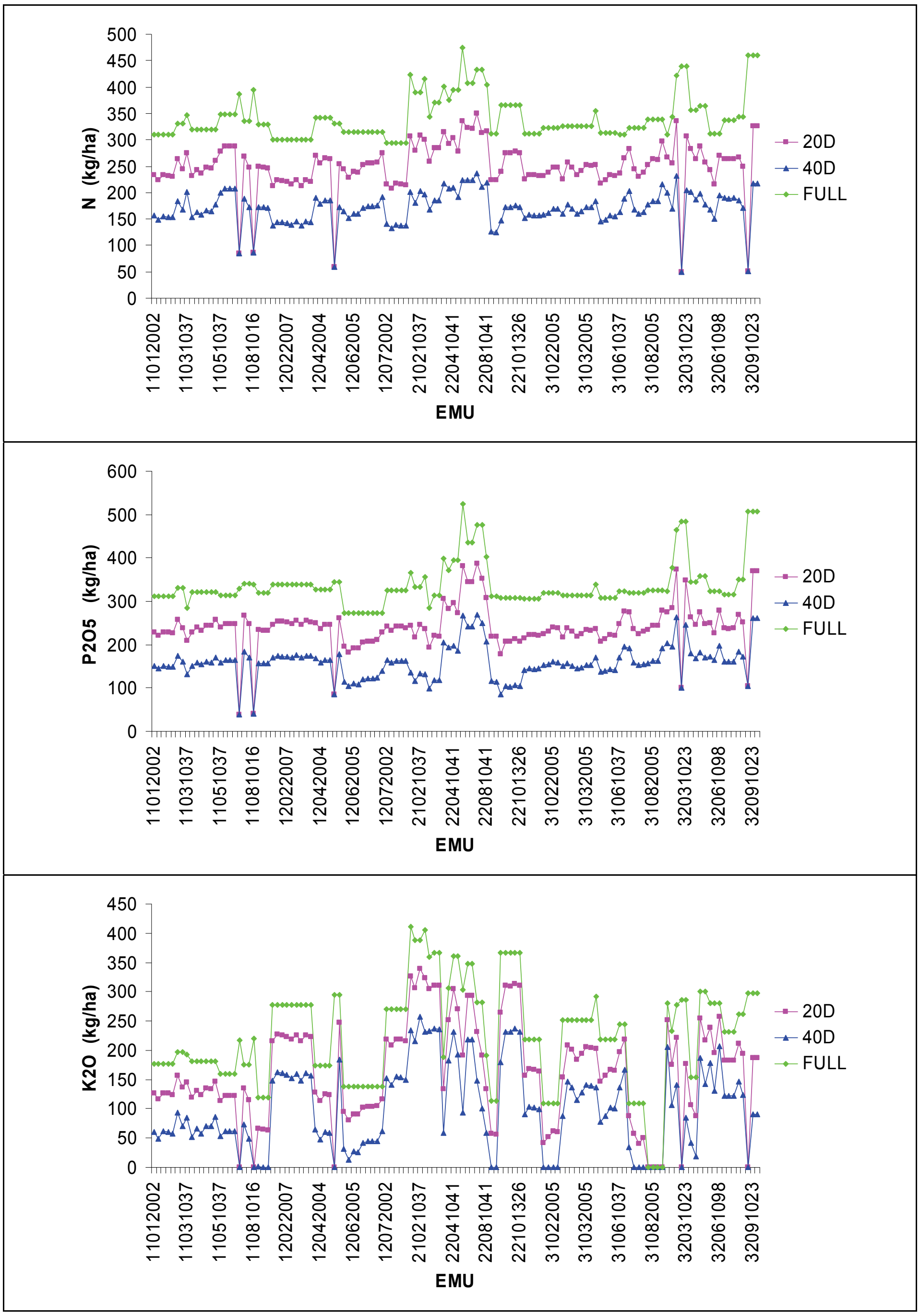


Figure 4.45. N, P and K fertilizer requirements for production of silage maize_S under different irrigation regimes in all EMUs in Borkhar & Meymeh district

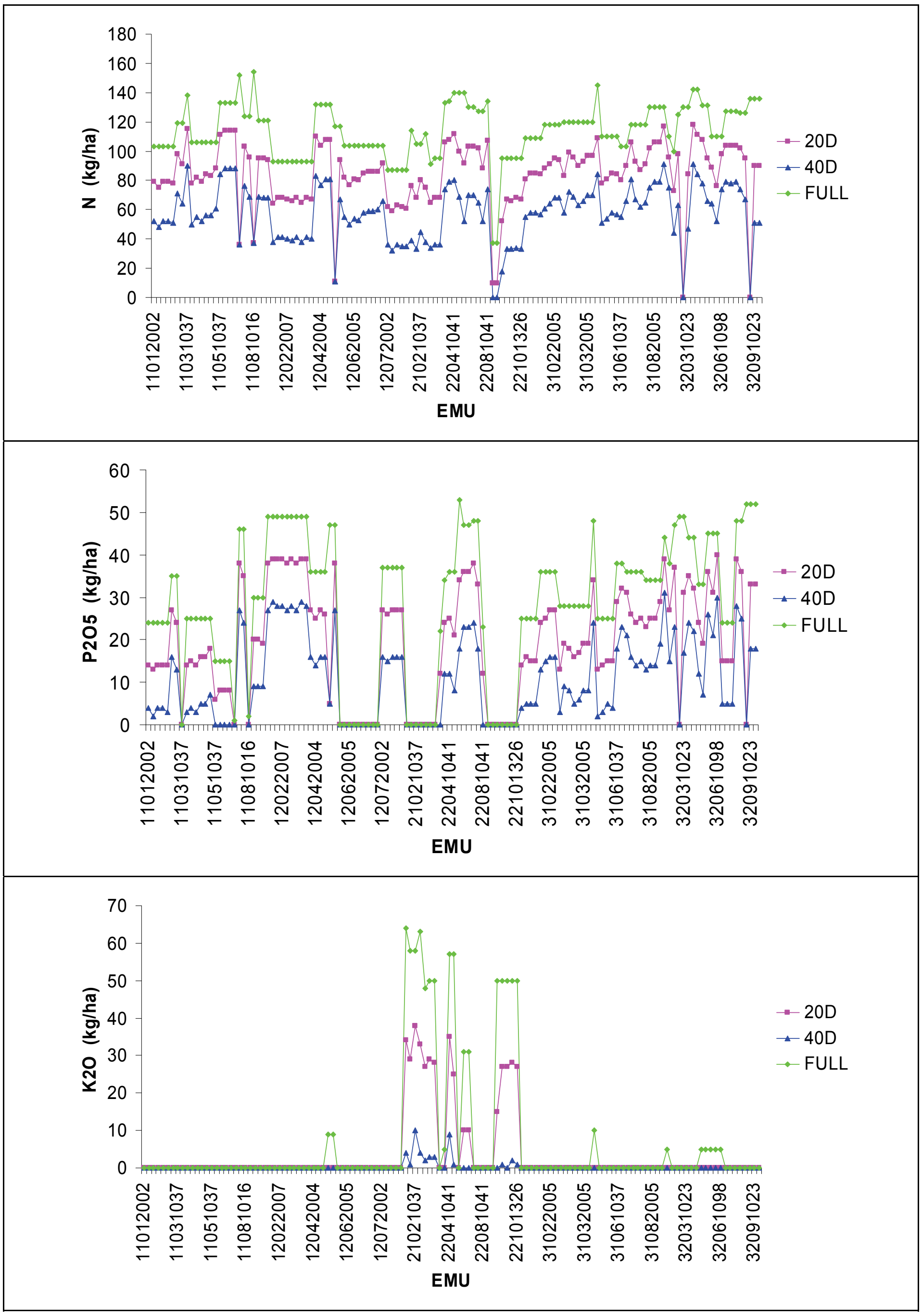


Figure 4.46. N, P and K fertilizer requirements for production of melon under different irrigation regimes in all EMUs in Borkhar & Meymeh district

4.6 Discussion and conclusions

Results of spatial analysis of biophysical resources can be used in regional agricultural planning. Traditionally, agricultural planners in Iran have been using average crop yields and input requirements in their plans, because of lack of an appropriate spatial quantitative tool for estimation of these characteristics. Usually, these averages were estimated based on trend analyses of crop yields and production inputs. This study has shown that dynamic crop growth simulation models combined with GIS can be used to generate spatially explicit yield data and (part of the) input requirements.
Results of this analysis show that yields, water and fertilizer requirements show significant spatial and temporal variation. These characteristics also vary significantly for different irrigation regimes and cropping systems. The methodology applied in this study can be used to generate these coefficients for different combinations of soil, crop, weather and irrigation regime.

4.6.1 Application of the results

The type of analysis that has been carried out in this study can support agricultural planners and decision makers in the following aspects:

- Assessment of the feasibility of double cropping systems in each of the distinguished EMUs

In the current study, a summer crop has been simulated, following maturity of the winter crop, where the two growth cycles could be combined. This analysis has shown that in some parts of the study area a double cropping system can be accommodated, in other parts not (results not shown). The results of this study show that biophysical input/output coefficients of double crops are different from those of single crops, because of differences in sowing date and consequently in growing periods.

- Estimation of fertilizer requirements for specific combinations of crop, soil and irrigation regime

In Iran, overuse of subsidized fertilizers has created problems of soil and water pollution in various places. Results of this type of analyses can be used to formulate more appropriate fertilizer recommendations for farmers.

- Estimation of spatial crop water requirements per decade

Results of the present study have shown that seasonal crop water requirements and maximum water requirements per 10-day period spatially vary in the district. This spatially explicit information can be used in support of allocation of water resources in situations of water shortage. In the present study, three irrigation regimes have been considered, but in general, other specific irrigation regimes can be analyzed using this type of models.

- Determination of the best cultivation period for attainment of maximum crop yields in single and double cropping systems. A sensitivity analysis with the model can be performed on sowing/emergence date.

- Yield gap analysis, by comparing potential yield and actual yield. Yield gap analysis can form the basis for identification of yield-limiting and/or yield-reducing factors in support of identification of appropriate technical and/or policy instruments for each region.

- Generation of biophysical technical coefficients for application in agricultural planning models

  Results of the current study will be used as technical coefficients in distributed linear programming models, developed in support of agricultural policy formulation in Borkhar & Meymeh district.

- Crop yield forecasting

  CGMS is currently used in the MARS project for crop yield forecasting. Efforts are ongoing to link this model to online satellite data for parameterization and validation.

4.6.2 Limitations

The model system applied in the current study has limitations that influence its (potential) applicability.

- Agro-ecological models include many parameters: For simulation of crop growth, WOFOST uses around 45 crop-specific characteristics, some of which are defined as a function of crop development stage. Since our understanding of crop growth and development is partial at best, and moreover part of the crop characteristics are variety-specific, some of these crop characteristics have to be calibrated and validated based on results of site-specific field experiments. Identifying appropriate values for crop characteristics is neither a trivial nor an easy task, even when results of local field experiments are available.

- Field experiments to generate information for calibration and validation of crop parameters are costly and time-consuming. For calibration and validation of CGMS, detailed crop data and other information at different growth stages are required. Calibration and validation of crop parameters for winter wheat and winter barley were based on detailed data and observations from local agro-meteorological research stations. For other crops, calibration and validation have been carried out at a more general level.

- Availability and scale of the soil maps used have influenced model outputs. Available soil maps were prepared with different objectives and at different scales. The composite soil map used in this study, prepared by combining the available soil maps, is a multi-scale map. For part of the study area, detailed information and data were available, while for other parts they have been derived from a general description of land evaluation units. As a result, SMUs and EMUs identified in this study were not homogeneous in terms of information on soil and weather characteristics. In the area for which a detailed soil map was available, smaller SMUs have been delineated.

- The crop growth simulation model WOFOST, implemented in CGMS, also has some limitations:
  1- WOFOST is a purely biophysical model and does not take into account impacts of diseases, pests, crop sequences (crop rotations), and agricultural management on crop growth.
  2- The model does not calculate crop evapotranspiration directly, but that has to be calculated post-model, based on model-calculated potential transpiration, reference crop evapotranspiration and leaf area index.
  3- The model does not consider soil heterogeneity in vertical direction. In the current study, soil physical characteristics averaged over the (potential) rooting depth have been used for simulation of crop growth in water-limited situations.
  4- WOFOST does not include an option for direct inclusion of irrigation. Irrigation dose and date should be calculated outside the model and then added to rainfall in the weather file. In addition, the current version of CGMS that is available does not allow access to the source code, which is a limitation in general, because one has to make additional efforts to introduce modifications in the model, necessary for specific applications.
  5- WOFOST calculates nutrient-limited production in a static procedure, following the dynamic calculations of potential and water-limited yields.

4.6.3 Sources of inaccuracy

- The EMUs are the basic elements for which the input/output relations are described. Some small units (less than 50 ha) generated in the procedure, have been merged with larger units. The area involved is limited, so the overall results are only marginally affected.

- Weather grids and administrative units (village) were considered identical. As a consequence, weather conditions in neighboring land units, located in different villages, are different. However, the spatial variability in weather conditions is small, so this has hardly any effect.

- The accuracy of the generated grid weather data depends on the number and distribution of weather stations within and around the study area. In this study, data of 33 weather stations have been used for generation of grid weather data. However, the spatial distribution of the weather stations was irregular. Moreover, only in three of the weather stations, located in the southwest of the study area, outside Borkhar & Meymeh district, solar radiation was available. Coefficients for the solar radiation estimation model were calibrated for these three weather stations and interpolated for other synoptic and climatological weather stations. In addition, recording periods and data quality in different stations varied. Accuracy of interpolated weather data in different years is different as the number of available weather stations was different among the years (Figure 4.16). The accuracy of the generated weather data is difficult to estimate.

- Indigenous soil nutrient supply was estimated based on empirical equations developed by Janssen et al. (1990) for maize under tropical conditions. Not enough data were available for estimation of the coefficients for local soil-crop combinations.

- In reality, sowing date of crops varies among farmers in different villages, because of spatial variation in weather conditions and limited availability of agricultural machinery. In addition, temporal variation in weather conditions causes variations in sowing dates from year-to-year. To take into account the spatial variation, the study area has been sub-divided into three cropping calendar zones, based on average temperature.

- In calculating the water requirements of non-CGMS crops, no differentiation has been made in growth stages and crop coefficients (Kc) for different EMUs, because of lack of information.

- Yield estimates for alfalfa are rough estimates, as the crop could not be ‘equivalenced’ to one of the CGMS crops, and, rather arbitrarily, the yield ratio of barley and silage maize has been used for estimation of alfalfa yield.

4.6.4 Recommendations

In developing countries, there is often a shortage or lack of basic data, which hampers application of basic comprehensive studies. It would be useful for agricultural planning authorities to develop a system for data acquisition and storage in local organizations.

The model system can be used for other crops in different regions. For this purpose, the crop growth simulation model should be calibrated and validated for the relevant crops in these regions. In addition, through aggregation of different regions, crop yield estimates can be generated for higher spatial scales (e.g., province or national), although aggregation methods will have to be tested.

Currently, with the increase in availability of satellite images, more real time spatial data are available for application in different types of quantitative models. For example, in the MARS project, several European countries are cooperating in developing a model system for crop yield forecasting in the European Union. Development of such a system is recommended for Iran as well.

5 Development of a spatial planning model for agricultural policy analysis in Borkhar & Meymeh district, Iran

Abstract

This study aims at developing a model to simulate the reaction of different farm types to various policy instruments to support agricultural planning at regional level. A weighted goal-programming model is developed to integrate the socio-economic and biophysical resources of farm households to assess the immediate effects and the long-term impacts of various policy instruments. This distributed model includes a set of sub-models (farm type-land unit, farm type, village, and subdistrict). Farm types and land units are homogenous in terms of socio-economic and biophysical characteristics, respectively. Maximizing net income and minimizing production cost with different weights are considered objectives of the farm households. Water, land, labour, agricultural machinery, and cropping pattern are introduced as constraints. Biophysical input-output coefficients of the model (yields, fertilizer and water requirements) have been generated spatially via application of a crop growth simulation model and GIS techniques for the crops in the district and modified per farm type. Economic input/output coefficients have been generated by analyzing available data from different on-going projects in the study area. Aggregation of the model from lower to higher scales was performed through identifying constraints relevant at each scale.

Keywords: Farm type classification, Crop simulation, Optimization, Spatial modeling, Production efficiency

5.1 Introduction

Agriculture is one of the most important sectors of the Iranian economy, as it is the major land user and provides employment for the majority of the population. One of the challenges for the agricultural sector is better use of existing resources, e.g., land, water, and labour, for increasing the production and prosperity of farmers.

Agricultural policy instruments (measures) are tools that are used for stimulating farmers to change their behavior for achieving the objectives of policy makers. Agricultural policy instruments not only have impacts on farm structure and income, but also on the environment and society (Topp and Mitchell, 2003).

Ex-ante assessment of the effects and impacts of agricultural policy instruments on the environment, the agricultural sector, and the objectives of different stakeholders is important for decision makers and agricultural planners. The (sets of) objectives of various stakeholders are often different, sometimes they are conflicting and different stakeholders may have different priorities. Some policy instruments may have positive effects on the objectives of some stakeholders, while having negative effects on the objectives of other stakeholders or no effects at all. For example, increasing the farm gate price of products may increase farmers' income and lead to increased use of fertilizers and pesticides, and as a result increase environmental hazards.

Simulation of the behavior of farmers, who are the final decision makers in agricultural land use, in response to different policy instruments, is important. The reaction of farmers to policy instruments can be different, depending on their socio-economic situation, biophysical characteristics of their land, objectives, constraints, and available resources. Farmers are trying to optimize their objective(s), subject to their resources and constraints. Some policy instruments may stimulate a group of farmers to change their behavior, while they do not motivate others. For example, increasing water use efficiency has been among the objectives of Iranian agricultural policy makers during the last two decades. One of the policy instruments that have been implemented was supporting farmers to change their irrigation system (from surface to pressure irrigation) by providing low interest loans. This policy instrument presented an incentive for farmers with medium or large farm sizes to change irrigation systems, but not farmers with small farms, a group to which the majority of farmers in Iran belong, as the costs per ha of this change increase with decreasing farm size.

Agricultural policy models are used for prediction of the reaction of farmers to policy instruments and their impacts on other stakeholders, using a range of indicators at different scale (Happe, 2004). A range of models have been developed for this purpose during the last decade (Kruseman and Bade, 1998; Bouman et al., 1999; Mohamed et al., 2000; Abdelgalil and Cohen, 2001; Arfini et al., 2001; Berger, 2001; Topp and Mitchell, 2003; Happe, 2004; Bazzani, 2005b; Louhichi et al., 2005; Laborte, 2006; Van Ittersum et al., 2008). A list of agricultural policy models developed to support the Common Agricultural Policy (CAP) in the European Union (EU) can be found in the review by Rehman (2006). These models vary in terms of modelling technique (partial or general equilibrium model, econometric model, and mathematical programming model), type of model (static, comparative static or dynamic), spatial scale (regional, national or multinational) and unit of analysis (farm type, land class, river catchment, etc.) (Happe, 2004; Rehman, 2006). The type of modeling approach chosen for quantitative analysis depends on the type of policy to be

analyzed, data availability and the question of interest. Mathematical programming has been used in most farm-based models (Happe, 2004).
Evaluation of the reaction of individual farmers to policies would be ideal, but is impossible because of time and investment limitations. Classification of farm households into homogenous groups (Kruseman and Bade, 1998; Bouman et al., 1999; Mohamed et al., 2000; Berger, 2001; Topp and Mitchell, 2003; Andersen et al., 2006; Laborte, 2006) and evaluation of the reaction of each farm group is a common way, used for solving this problem. The well-known problem of aggregation bias (Day, 1963) is an important issue that should be considered in classifying farmers. Day (1963) has identified three criteria for guaranteeing homogeneity of planning units in linear programming: Technological homogeneity, pecunious proportionality and institutional proportionality.

Most available agricultural planning models in Iran have been developed by economists and were focusing mainly on socio-economic aspects (Torkmani and Khosravi, 2001; Asadpour et al., 2005; Solimanipouri et al., 2005). For biophysical aspects, mostly they use average values over the region of interest. Integration of agro-ecological models with GIS (Geographical Information System) techniques provides an opportunity to simulate crop growth spatially and generate biophysical input/output coefficients for crop production activities per individual piece of land.

The aim of the current study is to develop a model for simulation of the reaction of farmers, operating under different socio-economic and biophysical conditions, to different policy instruments in support of agricultural planning at regional level. A distributed linear programming model for agricultural policy analysis is developed and implemented for one of the districts of Esfahan province in Iran. Biophysical input and output coefficients of the model have been generated spatially, using agro-ecological models and GIS techniques.

Following a general description of the study area, the conceptual framework of land use policy formulation and the role of agricultural policy models in this framework are explained. Description of the model structure, definition and identification of basic planning units, description of model components and generation of input/output coefficients are the main steps in the modelling process which are explained in Sections 5.5 – 5.7 in the process of model development. Validation of the model by comparison of model results with available data from the agricultural census in the year 2003 is described subsequently. The chapter ends with conclusions and a discussion about the developed model.

5.2 The study area

The study area is Borkhar & Meymeh district in Esfahan province, Iran. One of the most important arguments for selection of this area is availability of data and information from earlier studies.

From the total area of 762 500 ha in this district, about 65 000 ha is suitable for agriculture and, on average, about 37 000 ha is cultivated (on average: 22000 ha arable crops, 2000 ha fruit trees and 13000 ha fallow).

Average daily temperature in the study area varies between –2 ^{o}C in winter and 30 ^{o}C in summer. Annual precipitation varies between 100 and 300 mm over the district, concentrated in the winter months from December to April and average annual potential evapotranspiration is around 1400 mm. Water is the most limiting factor for agricultural production. Groundwater used to be the main source of water for the agricultural sector. In addition, a new irrigation network was established in the south-eastern part of the district. Groundwater quality in the region is low. Borkhar & Meymeh district comprises three sub-districts (Bakhsh), six Dehestans, and nine cities (Table 1.1).

5.3 Conceptual framework for land use policy formulation

The general framework for land use policy formulation is presented in Figure 5.1. Policy makers have objectives that may be different from and sometimes, in conflict with, the objectives of farmers. Policy instruments are used for stimulation of farmers to change their behavior in order to achieve objectives of policy makers. By changing the behavior of farmers, changes in land use (systems) could happen. Changes in land use (systems) therefore can be predicted using models that are simulating the behavior of farmers. In this study, a distributed linear programming model has been developed to simulate the behavior of farmers in response to implementation of various policy instruments. Indicators, representing the effect/impact of policy instruments on the different objectives of various stakeholders with respect to economic, social, and environmental impacts of changes in land use systems, are estimated post-model. Overall assessment of policy instruments can then be performed from different perspectives, using multi-criteria evaluation techniques. This information can support assessment of the suitability of various policy instruments.

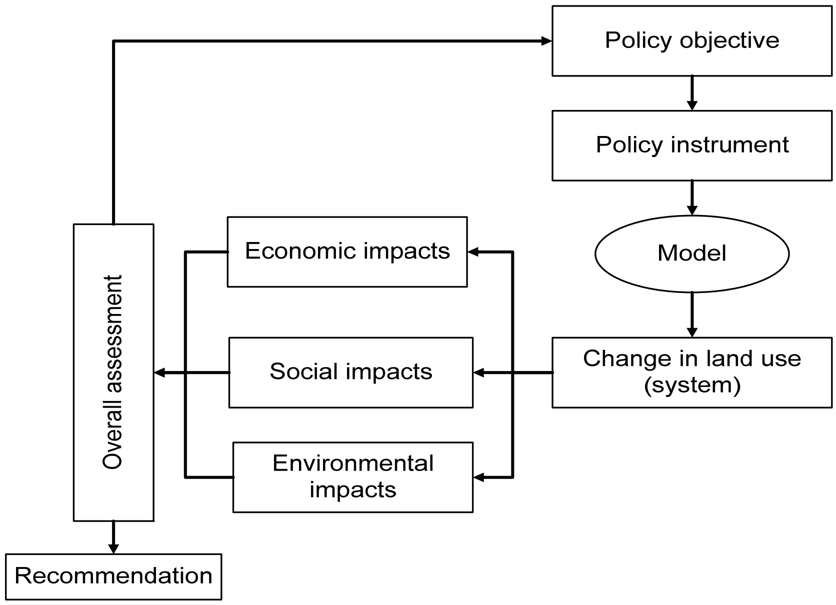


Figure 5.1. Flowchart of land use policy formulation (Sharifi, 2003)

5.4 Model structure

Farmers are classified in various classes, "Farm Types (FT)", based on indicators representing their assets and the management capabilities of the farmer. Land is classified based on its biophysical potentials into "Land Units (LU)". The Farm Types are then combined with land units, forming rather homogenous units in terms of biophysical potential, as well as in resource endowments and management ability of farmers. A linear programming model is developed for each Farm Type-Land Unit (FTLU). As farmers in this region are mostly market-oriented, objectives of net income and production cost have been optimized, considering water, land, labor, machinery and cropping pattern constraints. Twenty-two land use types (10 single crops and 12 double crops in one year), with two irrigation systems (surface and sprinkler), and three levels of irrigation (full irrigation, 20% deficit irrigation and 40 % deficit irrigation) have been defined as decision variables or activities. GAMS (Brooke et al., 1998) has been used for programming and solving the linear programming model.

The overall structure of the model is presented in Figure 5.2. The model integrates various sub-models (farm type-land unit, farm type, village, Dehestan and sub-district model) to form a regional model. In this structure, each of the constraints represents the limitations to the intensity of activities at a specific level. For example, the water constraint is operational at farm type and village level, while the machinery constraint is operational at Dehestan level. In other words, water cannot be transported between villages, while machinery can move freely within the Dehestan. Integration of the agricultural cooperatives and agro-industrial farms with the village models produces the Dehestan model.

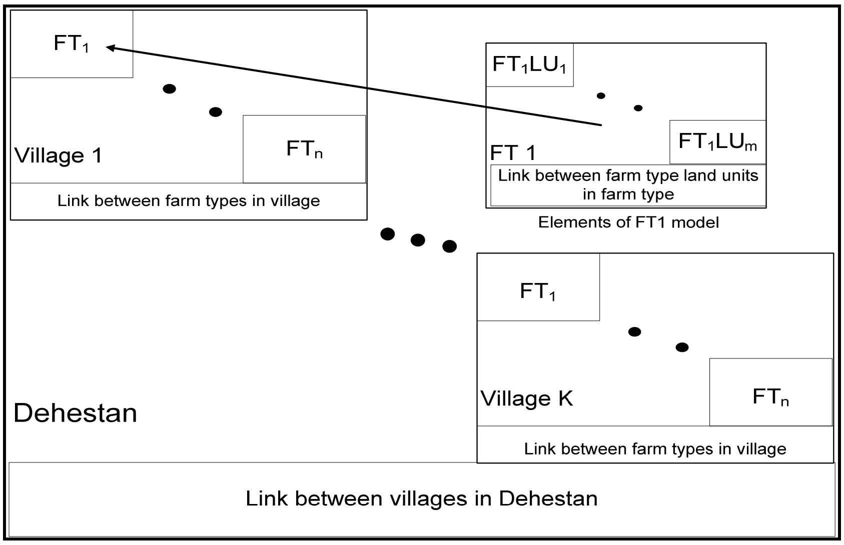


Figure 5.2. Overall structure of the model at Dehestan level (smallest unit is FTLU). Village in this figure can be a real village, an agricultural cooperative or a large agro-industrial unit

5.5 Identification of planning unit (unit of analysis)

As explained earlier, Farm Type-Land Unit (FTLU), formed by combining land units and farm types, has been selected as the basic modeling unit that is assumed homogenous in terms of socio-economic and biophysical characteristics. Hence, first existing agricultural production systems are described. Then these agricultural production systems are classified into homogenous groups, so-called "farm types". The suitable area for agriculture is classified into homogenous units in terms of biophysical characteristics and administrative unit, the so-called "land units". Each land unit is located in one village and each village may have more than one land unit. Finally, farm type-land units are specified by allocating the land of the land units to the different farm types in the village.

5.5.1 Agricultural production systems in the study area

Several types of agricultural production systems exist in the study area (Table 5.1), which are different in terms of ownership, management and objectives (APERI, 2002d).

Table 5.1. Existing agricultural production systems in Borkhar & Meymeh district, Iran (APERI, 2002d)

Main system	Sub-system
Traditional	Sharing system Leasing (Rent) system Hired labour Family type
Cooperative	Rural production cooperatives
Agro-industrial	Agro-industrial units

- ***Traditional agricultural production systems***

Traditional agricultural production systems in the study area were classified into four sub-systems based on the role of the farmer and the agricultural production inputs that should be provided by the farmer (Table 5.2).

Table 5.2. Role(s) of the farmer and inputs that should be provided by the farmer in the sub-systems of traditional agricultural production systems

Sub-system	Role		Agricultural production input				
	Owner	Manager	Land	Water	Labor		Other inputs
					Family	Hired	
Sharing system	-	√	-	-	√	-	√
Leasing (Rent) system	-	√	-	-	√	√	√
Hired-labour system	√	√	√	√	-	√	√
Family system	√	√	√	√	√	-	√

In the sub-systems, in which the farmer and the owner of land and water are different (sharing system and leasing system), total income from agricultural production is shared between the farmer and the owner. In the sharing system, the total production is shared between the farmer and the owner in proportions dependent on their contributions to the production factors and on crop type. For winter crops, the owner receives 1/2 or 1/3 of the production, for summer crops 1/3 (APERI, 2002d). In the leasing system, the farmer pays a fixed amount of money or of crop products as a rent, depending on the land (area and quality) and water rights.

Farmers in these four sub-systems have different objectives and constraints. Farmers in the leasing system and sharing system are less concerned about sustainability of the quality of the land. They are aiming at maximum farm net income in the year (which is one cropping season) that they have the contract. Most of the farmers in these sub-systems are experienced farmers producing efficiently. Labor requirements are more important for farmers in the hired labor system than in the other sub-systems.

Unfortunately, no information was available on the distribution of these agricultural production systems in the study area. Therefore, it was not possible to distinguish among farms of these sub-systems in this study.

- ***Agricultural Cooperatives***

Different types of agricultural production cooperatives (rural production cooperatives, agricultural cooperatives, extension cooperatives and usufruct groups) have been established in Borkhar & Meymeh district during the last five decades (APERI, 2002d), but only three rural production cooperatives still existed at the time of this study.

The rural production cooperatives of Khoosheh and Sonboleh have been established in the study area in the years 1990 and 1998, respectively (Table 5.3). Members of Khoosheh cooperative on average own larger farms than those of Sonboleh (Table 5.4 and Table 5.5). The District agricultural organization used to appoint one of its experts as director (manager) of each of these cooperatives and some technicians as deputy-managers on government salaries. However, since the year 2007, the manager is employed by the cooperative that pays his salary from the cooperative's income. The manager is responsible to the management council, elected by the members of the cooperative. A field survey of Jame Iran consultancy (APERI, 2002d) showed that the performance of these cooperatives was far below the expectations at their establishment. Farmers in these cooperatives are owners of their land and managers of their farms. Farmers are working on their farm individually. Subsidized fertilizers and pesticides are provided by the cooperative. Agricultural machinery is provided by the cooperative at a price 20% below the normal rate in the district.

The third rural cooperative with the name of Shohadai-e-Gorghab cooperative is located in Gorghab village, with membership of all farmers of the village. Management of this cooperative is different from the previous ones. Each farmer belongs to one of the groups that have been established within this cooperative and are represented at cooperative level by a group representative. Each group is responsible for its own well(s). Land preparation is carried out jointly, but other agricultural activities during the growing season are performed individually. Agricultural machinery is provided by the cooperative at a price 20% below the normal rate in the region.

- ***Agro-industrial units***

Integration between cropping and animal husbandry, large farm size, cultivation of fodder crops for animal feeding and use of hired labor are characteristics of this type of agricultural production system. All agro-industrial units are private, except Ghiam that is a parastatal enterprise. Although the number of these units in the district is less than 1% of all farms, they represent 29 and 24% of the total and cultivated agricultural land, respectively (Source: Agricultural census data for the year 2003).

Table 5.3. General information on the rural production cooperatives of Khoosheh and Sonboleh (APERI, 2002d)[*]

	Khoosheh	Sonboleh
Year of establishment	1990	1998
Total area (ha)	2000	3000
Cultivated land (ha/year)	1500	1000
Number of wells	19	43
Number of springs	0	1
Number of qanats	0	6
Number of farmers	90	452

[*] Apparently, these data have been rounded by the consultant. In addition, the number of farmers in Khoosheh cooperative is not equal to the number provided in a personal interview by the former manager of the cooperatives.

Table 5.4. Distribution of farm sizes in Khoosheh cooperative (Source: Interview with Mr Kashfi; former managers of Khoosheh and Sonboleh cooperatives)

Number	Total land (ha)
20	5
25	5-10
15	10-15
25	> 15 ha

Table 5.5. Statistical description of total and cultivated land of the farmers of Sonboleh cooperative before establishment of the cooperative in the year 1997 (Source: Data collected from the cooperative)

	Total land (ha)	Cultivated land (ha)
Mean	5.6	1.9
Median	3.0	0.5
Mode	5.0	0.3
Minimum	0.15	0.0
Maximum	200	75
Sum	3467	1157

5.5.2 Farm type classification

Farm classification is mainly subjective, as farms can be classified in many ways, for instance, based on their objectives, their resource endowments, their technologies, and/or their institutional arrangements. Farmers in different agricultural production systems may engage in different agricultural activities, with different management capability, and have different objectives. Data of the latest agricultural census in the year 2003 were used as a base for farm type classification, as they constitute the most detailed available data on the agricultural sector in the district[1].

From the 7754 agricultural holdings included in the agricultural census 2003 in the district, 404 did not cultivate any land in the cropping season 2002-2003. Therefore, the analysis included 7350 holdings (Table 5.6). All agricultural holdings were classified into one of the three main groups: traditional holdings, agricultural cooperatives, and agro-industrial units. Information and data, obtained during fieldwork through discussions with local experts and managers of cooperatives were used in addition to agricultural census data in the classification process. Farmer-members of two cooperatives (Khoosheh and Gorghab) were extracted easily from the agricultural census database, as they are registered with the name of their villages. Members of the third cooperative (Sonboleh) are living in five different villages and it was not possible to identify these farmers in the agricultural census database. So, holdings of the members of Sonboleh cooperative have been classified as traditional farms in this study. Holdings of farmers that did not belong to cooperatives were classified as traditional or agro-industrial holdings. Holdings, exceeding 50 ha cropped area in the census year were classified as agro-industrial units.

Table 5.6. Number of holdings, total area and cultivated area of agricultural holdings (with and without cultivation in the cropping season 2002-2003) per agricultural production system

	Number of holdings		Total area (ha)		Cultivated area (ha)
	with cultivation	without cultivation	holdings with cultivation	holdings without cultivation	
Traditional holdings	6987	390	18247	885	9182
Agro-industrial units	43	-	9938	-	3716
Khoosheh cooperative	53	-	1145	-	770
Gorghab cooperative	267	14	4462	850	2284
Total	7350	404	33792	1735	15952

Holdings of each group of agricultural production systems were classified individually, taking into account Day's principle (Day, 1963) and the available data. Variables presented in Table 5.7, of which the values have been calculated or derived from the agricultural census 2003, have been used in farm type classification.

[1] Although not directly of influence on the results of this study, it should be noted that some disagreement did exist between the Ministry of Jihad-e-Agriculture and the Statistical Center of Iran (SCI) on the results of this census.

Table 5.7. Variables used in farm type classification

Variable	Day's Condition
Total agricultural land	Institutional and technological similarity
Available water	Institutional similarity
Average production efficiency	Technological similarity
Average income per ha	Pecunious similarity

Although water is the main limiting production factor in the study area, in the agricultural census no information was available on water availability per holding. Available water per holding has been estimated based on the area under cultivation of different crops, potential water requirements of the crops and irrigation efficiency. The cultivated area of different crops for each agricultural holding has been derived from the agricultural census database. Potential crop water requirements (PCWR) per decade have been calculated per village based on 20 years daily weather data (Chapter 4). For each holding, the water required for irrigation of the cultivated crops is calculated per decade by Equation (5.1). Available water is then set equal to the maximum required water per decade. Available water of holdings was converted from mm/decade to l/s.

$$WR_{Holding,Decade} = \frac{\sum_{Crop}(Area_{Crop,Holding} * PCWR_{Crop,Decade})}{IE} \quad (5.1)$$

in which,

$WR_{Holding,\ Decade}$: Water required for cultivation of the crops cultivated in the holding in the cropping season 2002-2003 (mm/decade)
$Area_{Crop,\ Holding}$: Cultivated area of each crop in the holding (ha)
$PCWR_{Crop,\ Decade}$: Potential crop water requirement (mm/decade)
IE: Irrigation efficiency (an average irrigation efficiency of 40% for the entire region has been used (APERI, 2003)).

Production Efficiency (P.E) per crop of each holding is defined as the ratio of crop yield in that holding and potential yield of that crop in the village. Potential yields of the crops for the crop season 2002-2003 have been estimated using a crop growth simulation model and daily weather data for all land units in the district (Chapter 4). Overall Production Efficiency (O.P.E) of each holding has been calculated as the area-weighted average production efficiency of the cultivated crops (Equation (5.2)).

$$O.P.E = \frac{\sum_{Crop}(Area_{Crop} * P.E_{Crop})}{\sum_{Crop} Area_{Crop}} \quad (5.2)$$

in which,

$Area_{crop}$: Area under cultivation of the crop
$P.E_{crop}$: Production efficiency of the crop
Average net income per ha of each crop in the province has been used as benchmark for calculation of the net income of farmers. Average net income of each holding is calculated as the area-weighted average net income per ha of each crop (in analogy to overall production efficiency).

Holdings in each group of agricultural production systems have been classified into different farm types through hierarchical cluster analysis (Cluster method: Ward's method, Measure interval: squared Euclidean distance) based on standardized variables. SPSS software (SPSS Inc., 2007) has been used in cluster analysis. In the process of cluster analysis, variables are standardized with the Z-score method. Farm type classification thus yields the number of farms per farm type in each village (Table 5.9), from which the percentage of each farm type in terms of land use and water availability is calculated.

5.5.3 Land unit determination

Land units[1] are spatially homogenous units in terms of biophysical characteristics and administrative region, which have been identified by overlaying the soil map with weather grids (village polygons in this study) on the agricultural land. This assumes that weather characteristics do not significantly vary over a village.

The lowest administrative level in this study is the village. Identification of the villages and their locations was based on the Agricultural Census 2003, and the Housing and Population Census (HPC) 2006, both performed by SCI (Statistical Center of Iran), in which the smallest geographical units were Abadi and city. Abadi is a unit consisting of one or more parcels or a contiguous area in a sub-district, located outside city borders and registered or commonly regarded as a separate unit. Hence, an Abadi can be a village, a farm, or an establishment. The number of units (Abadies plus cities) identified in Borkhar & Meymeh district was 98 and 92 in the Agricultural Census 2003 and HPC 2006, respectively, among which nine cities and the remainder Abadies. Sixty-four units were surveyed in both censuses, of which 40 consisted of more than three households[2]. The units surveyed in HPC 2006 are geo-referenced.

1 - Land unit was called Elementary Mapping Unit (EMU) in Chapter 4.
2 - Information about Abadies with three households or less is not published, because of the privacy policy applied to the census data.

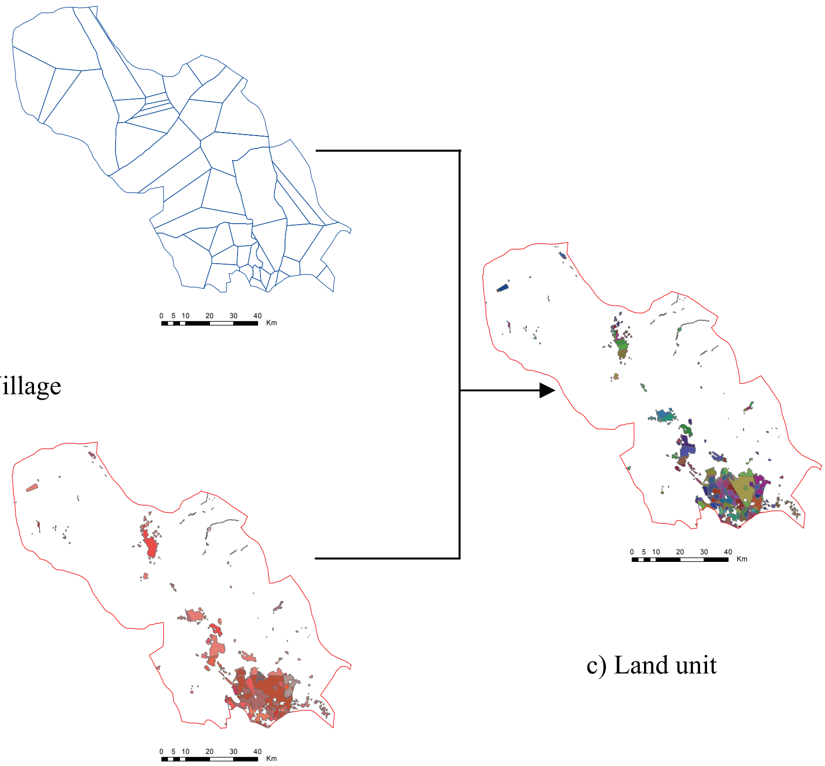
Table 5.8. Total number, average total land area, water availability, net income and overall production efficiency of farm types in Borkhar sub-district for the cropping season 2002-2003

	Farm type	Number	Total land (ha)	Available water (l/s)	Net Income (MRials*/ha)	Overall Production Efficiency
Traditional	FT1	919	0.5	0.4	3.47	0.53
	FT2	360	1.0	0.8	5.42	0.59
	FT3	480	1.1	0.9	1.16	0.19
	FT4	2803	1.2	0.9	2.72	0.40
	FT5	2016	1.7	1.3	2.01	0.30
	FT6	233	11.8	8.6	2.19	0.37
	FT7	118	28.7	17.8	2.27	0.37
	FT8	58	69.9	38.4	2.31	0.37
Agro-industrial	AI1	5	70.0	87.7	4.52	0.60
	AI2	11	88.3	81.8	1.61	0.31
	AI3	18	148.2	55.1	2.60	0.44
	AI4	7	435.7	209.1	2.99	0.50
	AI5	2	1450.0	281.1	2.49	0.43
Gorghab cooperative	G1	6	4.4	4.9	5.65	0.53
	G2	41	4.7	3.4	1.54	0.30
	G3	46	7.6	4.7	2.81	0.49
	G4	153	7.7	4.6	2.21	0.40
	G5	9	76.7	44.3	2.71	0.43
	G6	11	202.7	113.1	2.87	0.46
	G7	1	500.0	300.8	3.81	0.62
Khoosheh cooperative	K1	11	13.2	10.9	2.14	0.38
	K2	31	14.8	10.2	1.67	0.32
	K3	9	43.3	32.5	1.95	0.37
	K4	2	75.0	59.8	2.31	0.42

* 1 MRials = 10^6 Rials ≈ 100 U$ (2008)

In this study, agricultural administrative units have been defined as residential villages and cities exceeding 50 ha in agricultural area and establishments such as large agro-industrial units, and agricultural production cooperatives. By combining the database of the Agricultural Census, the list of Abadies in HPC 2006, the digital map of the study area and knowledge of local agricultural experts, Borkhar & Meymeh district was divided in 47 agricultural administrative units, referred to as 'villages'. The borders for each village were determined based on Thiessen polygons, as these borders were not indicated on available maps (Figure 5.3).

Soil units are homogenous units in terms of soil physical characteristics (soil texture, water holding capacity, saturated hydraulic conductivity, and soil depth). The soil map of the study area has been generated by analyzing and overlaying soil maps from earlier studies, which are different in terms of detail and scale. For the area for which no detailed soil map was available, soil maps from semi-detailed studies or land unit maps from the land evaluation study have been used. In the study area, 19 soil physical classes have been distinguished. By overlaying this soil map with the village map (47 villages) and merging small units (areas less than 50 ha) with larger neighboring polygons, 128 land units have been identified. This process has been explained in detail in Chapter 4.



a) Village

b) Soil unit

c) Land unit

Figure 5.3. Delineation of land units by overlaying the maps of soil units and villages (a) Village map, (b) soil map and (c) land unit map

Table 5.9. Number of farm types (FT), land units (LU) and farm type-land units (FTLU) identified in the villages of Borkhar & Meymeh district

Village	FT	LU	FTLU
Ali Abad	9	5	45
Ali Abadchi	8	2	16
Azan	5	2	10
Bagh miran	4	1	4
Bidashk	3	1	3
Dastgerd	9	3	27
Dawlat Abad	8	4	32
Donbai	3	1	3
Gaz	9	4	36
Ghasem Abad	4	1	4
Gorghab	7	4	28
Habib Abad	9	6	54
Hasan robat paein	6	1	6
Jafar Abad	4	7	28
Jehad abad	7	1	7
Jihad khodkafaei	1	1	1
Kalahrood	3	2	6
Khal sefid	8	2	16
Khorzough	8	5	40
Khosro Abad	7	2	14
Komshecheh	8	4	32
Laibid	4	2	8
Loshab	4	1	4
Maravand	2	1	2
Margh	7	1	7
Mazreh Dastkan	1	2	2
Mazreh Dogholi	2	3	6
Meymeh	7	2	14
Mohsen Abad	7	4	28
Mojtameh karkhaneh ha	1	4	4
Moorcheh khoort	8	3	24
Mooteh	8	1	8
Noor Abad	4	2	8
Padghan Darkhoein	1	2	2
Parvaneh	6	2	12
Robat agha kamal	5	2	10
Robat soltan	2	2	4
Shahpour Abad	11	9	99
Shahin Shahr	5	4	20
Sherkat Iran chai	1	5	5
Shoorcheh	3	1	3
Sin	9	4	36
Soh	6	3	18
Vandadeh	6	1	6
Vazvan	6	2	12
Yaghoot Abad	2	1	2
Ziad Abad	3	5	15

5.5.4 Farm type-Land Unit

Farm Type-Land Units (FTLU) are created by allocating the area of the land units to the farm types identified in the village. In this study, 771 FTLUs were identified in the entire district (Table 5.9).

5.6 Model components

For each planning unit, a linear programming model is developed, and integrated into models at higher levels, e.g., village, Dehestan and sub-district. In this section, model components are briefly explained.

5.6.1 Activities (Decision variables)

Cultivation of two crops in one year is possible in part of the study area (Chapter 4), if water is available. Farmers, that have access to tube wells, could practice double cropping. In that situation, the winter crop should be cultivated earlier than its optimal growing period and the summer crop later. Input and output coefficients of a single crop are different from those of the same crop cultivated in double cropping. Therefore, they are specified as different cropping systems (Table 5.10). As was mentioned earlier, water is the major constraint for agriculture in the study area. Therefore, in this study, special attention was given to water management. In the context of water management, two irrigation systems (surface and sprinkler) and three irrigation regimes (full irrigation, 20% deficit irrigation and 40% deficit irrigation) have been specified for each cropping system. Therefore, activities represent a cropping system irrigated with a specific irrigation system and a specific irrigation regime.

Table 5.10. Cropping systems specified for Borkhar & Meymeh district

Single crop	Double crops
Wheat	Wheat - Sunflower
Barley	Wheat - Silage Maize
Colza	Wheat - Melon
Sugar beet	Wheat - Watermelon
Sunflower	Barley - Sunflower
Potato	Barley - Silage Maize
Silage Maize	Barley - Melon
Alfalfa	Barley - Watermelon
Melon	Colza - Sunflower
Watermelon	Colza - Silage Maize
	Colza - Melon
	Colza - Watermelon

5.6.2 Definition of objectives

Farmers manage their land and water resources. They are the final decision makers on land use in the agricultural sector, in pursuing their objectives, subject to a number of constraints. Objectives may vary among farmers. A list of objectives of different stakeholders, including farmers has been prepared based on the literature (Sumpsi et al., 1996; Mohamed et al., 2000; Gomez-Limon and Riesgo, 2004; APERI, 2005; Laborte, 2006; Bartolini et al., 2007). This list of objectives has been used as a basis for discussion with national, provincial, and regional agricultural planners, managers and experts. As consideration of all objectives makes the model unnecessary complex, only the most important ones have been selected for this study. Net income and production cost were issues that appeared high on the list of farmers' concerns. So, the following objectives have been specified for farmers in this region:

- Maximization of net income
- Minimization of production cost at an acceptable level of net income

The following indicators have been specified for evaluation of the model results, as representative for the objectives of other stakeholders:

- Total net income of farmers in the region
- Environmental hazards
- Employment generated by agricultural activities
- Land, labor and water productivity
- Production of strategic crops such as wheat
- Amount of subsidies paid by the government

These indicators are calculated after optimization at different scales (FTLU, FT, village, Dehestan, Bakhsh (sub-district) and Shahrestan (district)) for further assessment of the policy instrument(s), using a multi criteria evaluation technique.

Goal programming was used for optimization. For this purpose three models have been developed. One model was developed to set the goal of net income. With this model, maximum achievable net income of the farmers in the district from crop production was determined. The second model was used to set the goal of production cost. This model used for minimization of the production cost under the constraint that total net income should not be less than a specific percentage (e.g., 90%) of the maximum achievable net income. The third model is used for combination of the goals, and the objective function of this model is to minimize the weighted deviations from the goals. As the degree of importance of the goals is different, different weights were assigned to each of the goals.

The equations used for calculation of the objective functions of the three models, are as follows[1]:

1 - Indices, variables, and parameters are presented in the Annex.

- ***Objective of model 1: Maximize net income***

Total net income of farmers from agricultural activities is calculated by Equations (5.3)-(5.8):

$$\text{Net Income} = \sum_{\text{Cropsys,Irsys,Irman,FT,LU}} X_{\text{Cropsys,Irsys,Irman,FT,LU}} * \text{Net Income}_{\text{Cropsys,Irsys,Irman,FT,LU}} \quad (5.3)$$

in which,

Net Income: Total net income from crop production of all farm type-land units (Rials)
$X_{\text{cropsys, Irsys, Irman, FT, LU}}$: Area allocated to each activity per FTLU (ha)
Net Income $_{\text{cropsys, Irsys, Irman, FT, LU}}$: Net income per ha of crop production for each activity per FTLU (Rials/ha), calculated by Equation (5.4)

$$\text{Net Income}_{\text{Cropsys, Irsys, Irman, FT, LU}} = \text{Gross Income}_{\text{Cropsys, Irsys, Irman, FT, LU}} - \text{Production Cost}_{\text{Cropsys, Irsys, Irman, FT, LU}} \quad (5.4)$$

in which,

Gross Income $_{\text{cropsys, Irsys, Irman, FT, LU}}$: Gross income of each activity per FTLU (Rials/ha), calculated by Equations (5.5) and (5.6)
Production Cost $_{\text{cropsys, Irsys, Irman, FT, LU}}$: Total production cost of each activity per FTLU (Rials/ha), calculated by Equations (5.7) and (5.8)

$$\text{Gross Income}_{\text{Cropsys, Irsys, Irman, FT, LU}} = \sum_{\text{Crop}} (\text{Gross Income}_{\text{Crop, Irsys, Irman, FT, LU}} * \text{Relation}_{\text{Cropsys, Crop}}) \quad (5.5)$$

$$\text{Gross Income}_{\text{Crop, Irsys, Irman, FT, LU}} = \text{Main Yield}_{\text{Crop, Irsys, Irman, FT, LU}} * \text{Price}_{\text{Crop, Main Yield}} + \text{By Yield}_{\text{Crop, Irsys, Irman, FT, LU}} * \text{Price}_{\text{Crop, By-Product}} \quad (5.6)$$

$$\text{Peoduction Cost}_{\text{Cropsys, Irsys, Irman, FT, LU}} = \sum_{\text{Crop}} (\text{Production Cost}_{\text{Crop, Irsys, Irman, FT, LU}} * \text{Relation}_{\text{Cropsys, Crop}}) \quad (5.7)$$

in which,

Gross Income $_{\text{crop, Irsys, Irman, FT, LU}}$: Gross income of each crop with specific Irsys and Irman per FTLU (Rials/ha)
Production Cost $_{\text{crop, Irsys, Irman, FT, LU}}$: Total production cost of each crop with specific Irsys and Irman per FTLU (Rials/ha)

Relation $_{Cropsys,\ Crop}$: Dummy variable for the relation between cropping system and crop; equals 1 if crop is part of the cropping system, otherwise 0
Main Yield $_{crop,\ Irsys,\ Irman,\ FT,\ LU}$: Yield of main crop product with specific Irsys and Irman per FTLU
By Yield $_{crop,\ Irsys,\ Irman,\ FT,\ LU}$: Yield of crop by-products with specific Irsys and Irman per FTLU
Price $_{crop,\ main\ yield}$: Price of main crop product (Rials/kg)
Price $_{crop,\ by\text{-}products}$: Price of crop by-products (Rials/kg)

$$\begin{aligned} \text{Production Cost}_{Crop,Irsys,Irman,FT,LU} = \; & \text{Seed Cost}_{Crop} + \\ & \text{Pesticide Cost}_{Crop} + \\ & \text{Fertilizer Cost}_{Crop,Irsys,Irman,FT,LU} + \\ & \text{Water Cost}_{Crop,Irsys,Irman,FT,LU} + \\ & \text{Labor Cost}_{Crop,Irsys,Irman,FT,LU} + \\ & \text{Machinery Cost}_{Crop,Irsys,Irman,FT,LU} + \\ & \text{Maintenance \& Operation Cost}_{Irsys,FT} \end{aligned} \qquad (5.8)$$

in which,

Seed Cost$_{Crop}$: Cost of seed of specific crop (Rials/ha)
Pesticide Cost$_{Crop}$: Cost of pesticides for specific crop (Rials/ha)
Fertilizer Cost $_{Crop,\ Irsys,\ Irman,\ FT,\ LU}$: Cost of fertilizers for each crop with specific Irsys and Irman per FTLU (Rials/ha)
Water Cost$_{Crop,\ Irsys,\ Irman,\ FT,\ LU}$: Cost of water for each crop with specific Irsys and Irman per FTLU (Rials/ha)
Labor Cost$_{Crop,\ Irsys,\ Irman,\ FT,\ LU}$: Cost of labor for each crop with specific Irsys and Irman per FTLU (Rials/ha)
Machinery Cost$_{Crop,\ Irsys,\ Irman,\ FT,\ LU}$: Cost of agricultural machinery for each crop with specific Irsys and Irman per FTLU (Rials/ha)
Maintenance & Operation Cost$_{Irsys,\ FT}$: Maintenance and operation cost of irrigation system per irrigation system and farm type (Rials/ha)

Net income of each FT in each village is calculated after model optimization and used in model 3 as a goal of the farm type for this objective.

- ***Objective of model 2: Minimize production cost***

Minimization of production cost is the objective function of model 2. A new constraint has been introduced in this model. Net income of each FT in each village should not be less than a specific percentage (e.g., 90%) of the net income generated with the previous objective function (maximization of net income). Equations (5.7) and (5.8) were used for calculation of the objective function of this model (production cost). Total production cost of each FT in each village was calculated after optimization and used in model 3 as a goal of the farm type for this objective.

- ***Objective of model 3: Minimize weighted deviation from optimum values of two objectives***

Model 3 is a weighted goal-programming model with the objective function of minimizing the deviation from the goals. As the goals have different dimensions and ranges of values, the deviations from the goals have been standardized by dividing by the goal of that farm type for that objective. Equations (5.9)-(5.11) have been used for calculation of the objective function of this model.

$$\sum_{\text{Cropsys, Irsys, Irman, LU}} X_{\text{Cropsys, Irsys, Irman, FT, LU}} * \text{Net Income}_{\text{Cropsys, Irsys, Irman, FT, LU}} + D_{\text{"Income"},FT} - E_{\text{"Income"},FT} = \text{Income goal}_{FT} \tag{5.9}$$

$$\sum_{\text{Cropsys,Irsys,Irman,LU}} X_{\text{Cropsys,Irsys,Irman,FT,LU}} * \text{Total cost}_{\text{Cropsys,Irsys,Irman,FT,LU}} + D_{\text{"production cost"},FT} - E_{\text{"production cost"},FT} = \text{Production cost goal}_{FT} \tag{5.10}$$

$$\text{Weighted deviation} = \sum_{FT} \left(W_{\text{"income"},FT} * \frac{D_{\text{"Income"},FT} + E_{\text{"Income"},FT}}{\text{Income goal}_{FT}} + W_{\text{"production cost"},FT} * \frac{D_{\text{"production cost"},FT} + E_{\text{"production cost"},FT}}{\text{Production cost goal}_{FT}} \right) \tag{5.11}$$

in which,

$D_{\text{objective, FT}}$ and $E_{\text{objective, FT}}$: Auxiliary variables for different objectives and farm types
$W_{\text{objective, FT}}$: Weight of each objective for each farm type
Income goal $_{FT}$ and Production cost goal $_{FT}$ are goals for each farm type for the net income and production cost objectives, respectively.

Weights of the objectives could be determined using the Analytical Hierarchy Process (AHP) technique, based on the relative importance of the objectives for each FT. In this study, as an example, weights of 0.7 and 0.3 were set to the objectives net income and production cost, respectively.

5.6.3 Constraints

- ***Land constraint***

The land constraint is specified at the lowest spatial scale, i.e. the FTLU. The total area under different activities should not exceed the available land in the FTLU (Equation (5.12)).

$$\sum_{\text{Cropsys, Irsys, Irman}} X_{\text{Cropsys, Irsys, Irman, FT, LU}} \leq \text{Available land}_{\text{FT, LU}} \tag{5.12}$$

in which,

X cropsys, Irsys, Irman, FT, LU: Area (ha) under each activity per FTLU
Available land $_{\text{FT, LU}}$: Available land (ha) in each FTLU

Available land in each FTLU was estimated based on the area of the LU and the fraction of the LU in each FT in the village (Equation (5.13)).

$$\text{Available land}_{\text{FT,LU}} = \text{Available land}_{\text{LU}} * \text{Land Fraction}_{\text{FT,V}} \tag{5.13}$$

in which,

Available land $_{\text{LU}}$: Area of LU (ha)
Land Fraction $_{\text{FT, V}}$: Fraction of the LU in each FT per village, calculated by Equation (5.14)

$$\text{Land Fraction}_{\text{FT,V}} = \frac{\text{Available land}_{\text{FT}} * \text{Number of holding}_{\text{FT,V}}}{\sum_{\text{FT}} (\text{Available land}_{\text{FT}} * \text{Number of holding}_{\text{FT,V}})} \tag{5.14}$$

in which,

Available land $_{\text{FT}}$: Total land area (ha) of FT in the district (Table 5.8)
Number of holdings $_{\text{FT, V}}$: Number of holdings in each FT in the village

- ***Water constraint***

Monthly and annual water constraints are specified at FT and village levels. The maximum discharge and the permitted duration of water extraction (6000 hours per year) of each well are prescribed by the regional water organization. Holdings that have access to a well can use water whenever they need. Water is available in the canal only in the period of April – October and distributed between farmers based on their water rights.

- **Monthly and annual water constraints at FT level**

Total water requirement for irrigation of different agricultural activities per farm type in the village should not exceed 1.2 times total available water from different water sources (canal or groundwater) for that farm type per month. This constraint assumes 20% 'water mobility' among farm types. A similar assumption is applied for the annual constraint on water availability.

Monthly water constraint at FT level:

$$10 * \sum_{Cropsys,Irsys,Irman,LU} (X_{cropsys,Irsys,Irman,FT,LU} * \text{Irrigation Requirement}_{Cropsys,Irsys,Irman,FT,LU,Mon} * \text{Relation}_{LU,V}) \leq 1.2 * \text{Available water}_{FT,V,Mon} \quad (5.15)$$

Annual water constraint at FT level:

$$10 * \sum_{Cropsys,Irsys,Irman,LU,Mon} (X_{cropsys,Irsys,Irman,FT,LU} * \text{Irrigation Requirement}_{Cropsys,Irsys,Irman,FT,LU,Mon} * \text{Relation}_{LU,V}) \leq 1.2 * \text{Available water}_{FT,V} \quad (5.16)$$

in which,

The coefficient 10 in Equations (5.15) and (5.16) is a unit conversion factor
Relation $_{LU, V}$: Dummy variable for relation between LU and village; equals 1 if LU is located in the village, otherwise 0
Irrigation Requirement $_{Cropsys, Irsys, Irman, FT, LU, Mon}$: Irrigation requirement (mm) of each activity per FTLU and per month
Available water $_{FT, V, Mon}$: Total available water (m^3) for the FT in the village per month from different water sources (canal, well and qanat), calculated by Equation (5.17)

$$\text{Available water}_{FT,V,Mon} = \text{Available water}_{V,Mon} * \text{Water Fraction}_{FT,V} \quad (5.17)$$

in which,

Available water $_{FT, V, Mon}$: Available water (m^3) for each FT in each village per month
Available water $_{V, Mon}$: Total available water[1] (m^3) per month in each village from different water sources (Section 05.8)
Water Fraction $_{FT, V}$: Fraction water available for the FT per village, calculated by Equation (5.18)

1 - Because of the importance of water in the study area, Section 5.8 is devoted to the description of the methods used for estimation of available water per village.

$$\text{Water Fraction}_{FT,V} = \frac{\text{Available water}_{FT} * \text{Number of holder}_{FT,V}}{\sum_{FT}(\text{Available water}_{FT} * \text{Number of holder}_{FT,V})} \quad (5.18)$$

in which,

Available water $_{FT}$: Total available water (l/s) for each FT, defined in the FT classification
Number of holdings $_{FT,V}$: Number of holdings of each farm type in each village
Available water $_{FT,V}$: Total available water (m^3) for the FT in the village per year from different water sources (canal, well and qanat)

Available water per month from a tube well has been calculated based on the well discharge capacity, 20 working hours per day and number of days in each month. For the canal and the qanat, 24 working hours per day are assumed.

- **Monthly and annual water constraints at village level**

Total water requirements for irrigation of different agricultural activities in the village should not exceed total available water from different water sources (canal, well and qanat) in the village per month and per year.

$$10 * \sum_{Cropsys, Irsys, Irman, FT, LU} (X_{cropsys,Irsys,Irman,FT,LU} * \text{Relation}_{LU,V} * \text{Irrigation Requirement}_{Cropsys, Irsys, Irman, FT, LU, Mon}) \leq \text{Maximum available water}_{V,Mon} \quad (5.19)$$

$$10 * \sum_{Cropsys, Irsys, Irman, FT, LU, Mon} (X_{cropsys,Irsys,Irman,FT,LU} * \text{Relation}_{LU,V} * \text{Irrigation Requirement}_{Cropsys, Irsys, Irman, FT, LU, Mon}) \leq \text{Maximum available water}_{V} \quad (5.20)$$

in which,

Maximum available water $_{V,Mon}$: Maximum available water (m^3) per village, per month
Maximum available water $_{V}$: Maximum available water (m^3) per village, per year

- ***Labor constraint***

Labor constraints have been specified at village level, except for the cities and the agro-industrial units, as enough labor is available in the cities, and agro-industrial units can hire as much labor as needed. Total labor requirements for agricultural activities should not exceed available labor per village, per month.

Available labor per village and per month is calculated by multiplying the number of workers in the village and the number of working days per month.

$$\sum_{\text{Cropsys, Irsys, Irman, FT, LU, Mon}} (X_{\text{cropsys,Irsys,Irman,FT,LU}} * \text{Relation}_{\text{LU,V}} * \text{Labor Requirement}_{\text{Cropsys, Irsys, Irman, FT, LU, Mon}}) \leq \text{Number of workdays}_{\text{Mon}} * \text{Number of workers}_{\text{V}} \quad (5.21)$$

in which,

Labor requirement $_{\text{Cropsys, Irsys, Irman, FT, LU, Mon}}$: Labor requirements of each activity per FTLU and per month
Number of workday $_{\text{Mon}}$: Number of working days per month
Number of worker $_{\text{v}}$: Number of available workers per village

Available labor per village was estimated based on the results of the most recent housing and population census in Iran. The number of households and the population of the villages and cities in Borkhar & Meymeh district in the year 2006 are presented in Table 5.11 (SCI, 2008b). Figure 5.4 shows the population distribution by age and gender in the rural area of Borkhar & Meymeh district. The same distribution exists in urban areas. Analysis of the census data shows that 54 and 51 percent of the males in the rural and urban area were in the age group between 20 and 60. Therefore, in this study 50% of the male population in each village is considered available labor. Although in some villages, females are engaged in farm work, according to local farmers, in general, agricultural activities in this district are carried out by males.

Table 5.11. Number of households and population of the villages and cities in Borkhar & Meymeh district in the year 2006 (SCI, 2008b)

	Village/city	Households	Population			Population per household		
			Total	Male	Female	Total	Male	Female
Ali Abad	Village	676	2702	1405	1297	4.0	2.1	1.9
Ali Abadchi	Village	32	113	65	48	3.5	2.0	1.5
Azan	Village	731	2578	1283	1295	3.5	1.8	1.8
Bagh miran	Village	14	24	9	15	1.7	0.6	1.1
Bidashk	Village	37	102	46	56	2.8	1.2	1.5
Dastgerd	City	4038	15540	7976	7564	3.8	2.0	1.9
Dawlat Abad	City	8661	33941	17661	16280	3.9	2.0	1.9
Donbai	Village	32	114	49	65	3.6	1.5	2.0
Gaz	City	5704	20432	10547	9885	3.6	1.8	1.7
Ghasem Abad	Village	7	15	8	7	2.1	1.1	1.0
Gorghab	Village	1400	5644	3055	2589	4.0	2.2	1.8
Habib Abad	City	2403	9078	4689	4389	3.8	2.0	1.8
Hasan robat paein	Village	362	1762	877	885	4.9	2.4	2.4
Jafar Abad	Village	20	60	60	0	3.0	3.0	0.0
Jehad abad	Village	368	1422	732	690	3.9	2.0	1.9
Kalahrood	Village	128	295	146	149	2.3	1.1	1.2
Khal sefid	Village	5	17	17	0	3.4	3.4	0.0
Khorzough	City	5478	20301	10532	9769	3.7	1.9	1.8
Khosro Abad	Village	115	340	170	170	3.0	1.5	1.5
Komshecheh	City	1072	4395	2276	2119	4.1	2.1	2.0
Laibid	Village	510	1986	982	1004	3.9	1.9	2.0
Loshab	Village	113	342	163	179	3.0	1.4	1.6
Maravand	Village	10	16	10	6	1.6	1.0	0.6
Margh	Village	69	251	128	123	3.6	1.9	1.8
Meymeh	City	1790	5733	2953	2780	3.2	1.6	1.6
Mohsen Abad	Village	781	3074	1599	1475	3.9	2.0	1.9
Mojtameh karkhaneh ha	Village	48	224	224	0	4.7	4.7	0.0
Moorcheh khoort	Village	470	1627	904	723	3.5	1.9	1.5
Mooteh	Village	242	908	463	445	3.8	1.9	1.8
Noor Abad	Village	7	19	12	7	2.7	1.7	1.0
Parvaneh	Village	53	202	114	88	3.8	2.2	1.7
Robat agha kamal	Village	5	10	7	3	2.0	1.4	0.6
Shahin Shahr	City	33515	126070	62868	63202	3.8	1.9	1.9
Shahpour Abad	Village	1312	5172	2693	2479	3.9	2.1	1.9
Shoorcheh	Village	12	32	16	16	2.7	1.3	1.3
Sin	Village	1066	4147	2192	1955	3.9	2.1	1.8
Soh	Village	141	403	193	210	2.9	1.4	1.5
Vandadeh	Village	422	1263	583	680	3.0	1.4	1.6
Vazvan	City	1413	4661	2315	2346	3.3	1.6	1.7
Ziad Abad	Village	442	1487	743	744	3.4	1.7	1.7

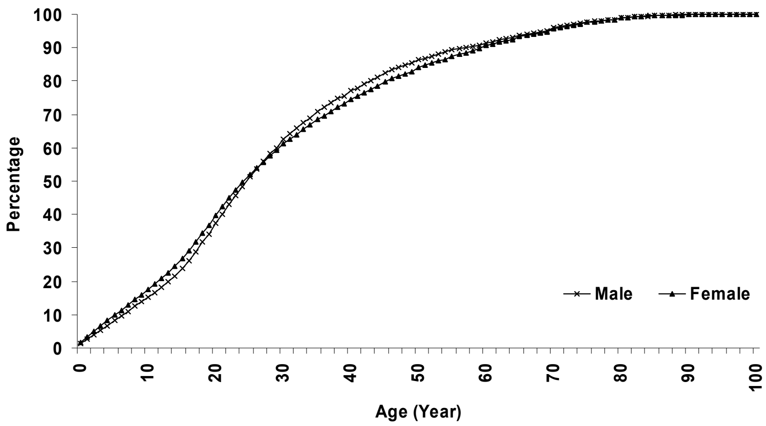


Figure 5.4. Accumulated percentage of the population by age and gender in the rural area of Borkhar & Meymeh district, based on the Housing and Population Census 2006

- ***Tractor constraint***

The tractor constraint has been specified at Dehestan level. The total number of tractor hours required for agricultural activities per month should not exceed tractor availability in the Dehestan.

$$\sum_{\text{Cropsys, Irsys, Irman, FT, LU}} (X_{\text{cropsys,Irsys,Irman,FT,LU}} * \text{Relation}_{\text{LU,Dehestan}} * \text{Tractor Requirement}_{\text{Cropsys, FT, Mon}}) \leq \text{Available Tractor hours}_{\text{Mon}} * \text{Number of tractors}_{\text{Dehestan}} * (1 - \text{lag coefficient}) \quad (5.22)$$

in which,

Tractor requirement $_{\text{Cropsys, FT, Mon}}$: Tractor requirements (hour) of each cropping system per FT and month
Relation $_{\text{LU, Dehestan}}$**:** Dummy variable for location of village; 1 if LU is located in the Dehestan, otherwise 0
Available Tractor hours $_{\text{Mon}}$: Number of available tractor hours in the Dehestan
Number of tractors $_{\text{Dehestan}}$: Number of available tractors in the Dehestan (Table 5.12)
Lag coefficient: Fraction of time the tractor cannot be used because of maintenance requirements. This coefficient is related to age of the tractor, driver experience, and availability of repair shops. Unfortunately, no data were available, and the coefficient was set to 0.3.

Table 5.12. Number of available tractors in the Dehestans of Borkhar & Meymeh district in the year 2003

Dehestan	Total
Eastern Borkhar	72
Central Borkhar	16
Western Borkhar	99
Moorcheh khoort	60
Zarkan	59
Vandadeh	44
Total	350

- ***Wheat production constraint at FT level***

Traditional farmers in the region prefer consumption of bread from homegrown wheat. This constraint has been specified only for farm types 1-5.

$$\sum_{Cropsys,Crop,Irsys,Irman,LU}(X_{Cropsys,Irsys,Irman,FT,LU} * Main\_Yield_{Crop,Irsys,Irman,FT,Lu,"wheat"} * Relation_{LU,V} * Relation_{cropsys,crop}) \geq Wheat\_required_{FT} * Number\_of\_FT_{FT,V} \quad (5.23)$$

in which,

$Wheat\_required_{FT}$: The required wheat for self consuming per FT (kg)

- ***Alfalfa production constraint at FT level***

Animal husbandry for milk and meat production is one of the characteristics of agriculture in this region. Integration of animal husbandry and cropping is also characteristic for the agro-industrial units. Some of the farmers and agro-industrial units prefer feeding homegrown forage. Part of the feed requirements is covered by wheat and barley straw. Homegrown alfalfa and silage maize are additional sources of animal feed. A minimum level of alfalfa production has been specified as a constraint for some of the farm types (agro-industrial units and large farms).

$$\sum_{Irsys,Irman,LU}(X_{"Alfalfa",Irsys,Irman,FT,LU} * Main\_Yield_{"Alfalfa",Irsys,Irman,FT,Lu,"Alfalfa"} * Relation_{LU,V}) \geq Alfalfa\_required_{FT} * Number\_of\_FT_{FT,V} \quad (5.24)$$

in which,

$Alfalfa\_required_{FT}$: The required alfalfa production per FT (kg)

- ***Cropping pattern constraints***

A review of the current cropping pattern in the study area (Table 5.13) shows that cropping patterns did not significantly change during the years 2000-2004. This pattern was selected by the farmers based on their expectations of yields and markets. Markets are not considered in this model, as prices are set as exogenous parameters, while in reality they are based on product supply and demand. Expected crop prices are important factors in cropping pattern selection. To avoid 'overproduction' of commodities that could lead to serious price falls, three additional constraints (Equations (5.25) to (5.27)) were defined to limit the area under cultivation of sugar beet, sunflower and melon (sum of melon and watermelon) to 10% of the total available land, each.

Table 5.13. Percentage of cultivated area of main crops in Borkhar & Meymeh district in the years 2000-2004 (Esfahanian Agricultural Jihad Organization, 2007)

Crop	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	Average
Winter wheat	50.4	51.0	52.6	48.8	47.3	50.0
Winter Barley	11.2	13.5	11.0	10.2	10.3	11.2
Silage maize	6.0	7.8	4.5	16.4	14.6	9.9
Sugar beet	7.7	5.0	7.7	4.7	3.7	5.8
Sunflower	7.7	7.2	5.1	3.2	4.9	5.6
Alfalfa	6.9	6.5	6.6	6.6	6.0	6.5
Melon	3.8	4.1	4.1	3.4	3.7	3.8
Watermelon	0.1	0.1	0.1	0.3	2.5	0.6
Potato	1.4	1.7	1.6	1.4	1.3	1.5

Melon constraint:

$$\begin{aligned}\sum_{Irsys,Irman,FT,LU} (&X_{"Melon",Irsys,Irman,FT,LU} + X_{"Wheat-Melon",Irsys,Irman,FT,LU} + \\ &X_{"Barley-Melon",Irsys,Irman,FT,LU} + X_{"Colza-Melon",Irsys,Irman,FT,LU}) + \\ &X_{"watermelon",Irsys,Irman,FT,LU} + X_{"Wheat-watermelon",Irsys,Irman,FT,LU} + \\ &X_{"Barley-watermelon",Irsys,Irman,FT,LU} + X_{"Colza-watermelon",Irsys,Irman,FT,LU}) \\ &\leq 0.1 * \sum_{Cropsys,Irsys,Irman,FT,LU} (X_{Cropsys,Irsys,Irman,FT,LU}\end{aligned} \quad (5.25)$$

Sunflower constraint:

$$\begin{aligned}\sum_{Irsys,Irman,FT,LU} (&X_{"sunflower",Irsys,Irman,FT,LU} + X_{"Wheat-sunflower",Irsys,Irman,FT,LU} + \\ &X_{"Barley-sunflower",Irsys,Irman,FT,LU} + + X_{"Colza-sunflower",Irsys,Irman,FT,LU}) \\ &\leq 0.1 * \sum_{Cropsys,Irsys,Irman,FT,LU} (X_{Cropsys,Irsys,Irman,FT,LU}\end{aligned} \quad (5.26)$$

Sugar beet constraint:

$$\sum_{Irsys,Irman,FT,LU}(X_{"sugar beet",Irsys,Irman,FT,LU} \leq 0.1* \sum_{Cropsys,Irsys,Irman,FT,LU}(X_{Cropsys,Irsys,Irman,FT,LU} \quad (5.27)$$

5.7 Generation of input/output coefficients (technical coefficients)

Different sets of technical coefficients (I/O coefficients) for the activities included in the planning model have been generated. These coefficients have been generated at the lowest scale possible or required (Table 5.14).

Table 5.14. Scale at which input/output coefficients for the planning model were generated and their relation with irrigation regime and irrigation system

	I/ O factor	Level	Irrigation regime	Irrigation system
Inputs	irrigation	LU	Yes	Yes
	fertilizer	FTLU	Yes	Yes
	Labour	FT	No	Yes
	Machinery	FT	No	No
	Seed	District	No	No
	Pesticide	District	No	No
Outputs	Yield	FTLU	Yes	No
	N-loss	FTLU	Yes	Yes

5.7.1 Generation of biophysical input/output coefficients

Potential biophysical input/output (I/O) coefficients for crops in different cropping systems and irrigation regimes (full irrigation, 20% and 40% deficit irrigation) were generated for each land unit through application of crop growth simulation models (Chapter 4). These I/O coefficients were calculated under the assumption of perfect management and 100% irrigation efficiency, and thus have to be converted to 'expected' biophysical I/O coefficients, required for the developed model.

- **Crop yield**

Expected crop yield per FTLU is calculated by Equation (5.28).

$$Yield_{Crop,FT,LU} = PE_{FT,Crop} * Yield_{Crop,LU} \quad (5.28)$$

in which,

$Yield_{Crop, FT, LU}$: Expected crop yield per FTLU (kg/ha)
$Yield_{Crop, LU}$: Simulated potential crop yield in the LU (kg/ha)
$PE_{FT, Crop}$: Crop production efficiency of FT (Table 5.15)

If crop production efficiency could not be derived from the census data (2002-2003), because the crop was not included, it was replaced by overall production efficiency of the farm type (Table 5.8).

Table 5.15. Crop production efficiencies of different farm types

FT	Wheat	Barley	Sugar beet	Colza	Water melon	Melon	Alfalfa	Silage maize	Potato	Sunflower
FT1	0.51	0.59	0.47	0.59	0.64	0.47	0.59	0.60	0.37	0.43
FT2	0.60	0.70	0.86	-	0.56	0.51	0.60	0.51	0.53	0.53
FT3	0.21	0.22	0.20	-	-	0.10	0.22	0.21	0.18	0.20
FT4	0.41	0.42	0.44	0.47	0.56	0.40	0.36	0.46	0.21	0.35
FT5	0.32	0.33	0.30	0.37	0.72	0.29	0.30	0.36	0.17	0.28
FT6	0.38	0.37	0.40	0.77	-	0.39	0.32	0.54	0.17	0.29
FT7	0.39	0.37	0.39	-	0.37	0.38	0.32	0.42	0.31	0.27
FT8	0.36	0.34	0.39	-	0.57	0.38	0.31	0.63	0.17	0.28
AI1	0.60	0.46	0.69	-	-	0.74	0.44	0.82	-	0.25
AI2	0.34	0.30	0.46	0.46	0.42	0.27	0.30	0.57	-	0.31
AI3	0.45	0.38	0.50	-	0.56	0.61	0.16	0.66	-	0.33
AI4	0.48	0.48	0.58	0.88	0.52	0.55	0.39	0.80	-	0.27
AI5	0.45	0.52	0.52	-	0.89	0.46	0.22	0.09	0.65	0.40
G1	0.49	-	-	-	0.80	0.66	-	0.70	-	0.31
G2	0.39	0.29	-	-	0.69	0.07	0.13	-	-	0.29
G3	0.52	0.36	-	-	0.78	0.43	0.13	0.67	-	0.42
G4	0.47	0.22	-	-	0.47	0.28	0.13	0.35	-	0.35
G5	0.52	0.32	-	-	0.63	0.51	-	-	-	0.31
G6	0.53	0.40	-	-	0.95	0.48	0.20	0.68	0.23	0.30
G7	-	-	-	-	-	-	-	0.78	-	0.30
K1	0.46	0.42	-	-	-	0.39	0.29	-	-	0.30
K2	0.36	0.33	-	-	-	0.30	0.15	-	-	0.28
K3	0.37	0.38	-	-	-	-	0.17	0.60	-	0.35
K4	0.53	0.41	-	-	-	0.16	0.19	0.63	-	0.37

- **Irrigation requirements**

Potential crop water requirements, defined as the difference between potential crop evapotranspiration and effective rainfall, was calculated for the major crops on all land units in the district, based on 20 years daily weather data (Chapter 4). Irrigation requirements exceed crop water requirements, because irrigation efficiency is lower than 100%. In addition, some additional water should be applied for leaching of salts. In this study, irrigation requirements

(IR) have been calculated for crops per decade, land unit and irrigation system, based on potential crop water requirements (CWR), irrigation efficiency (IE), and leaching requirements (LR), as follows:

1- Calculation of potential crop evapotranspiration (ETc) per decade and land unit (Chapter 4)
2- Estimation of effective rainfall (Re) per decade and land unit (Chapter 4)
3- Calculation of potential crop water requirements (CWR) per decade and land unit for three irrigation regimes (full irrigation, 20% and 40% deficit irrigation) (Chapter 4)
4- Estimation of irrigation efficiency (IE) per irrigation system and land unit
5- Estimation of the percolation ratio (PR) per irrigation system
6- Calculation of the leaching fraction (LF) per crop, and water source in each village
7- Comparison of the percolation ratio (PR) and the leaching fraction (LF) to calculate the leaching requirements (LR) per crop, land unit, decade, irrigation system and water source
8- Calculation of the irrigation requirements (IR) per crop, land unit, decade, irrigation system and water source

Irrigation efficiency is defined as the ratio of water stored in the crop root zone and irrigation water applied. Irrigation efficiency varies with irrigation system (design and management) and irrigator experience. Field measurements of irrigation efficiency in Borkhar plain have shown that efficiency of surface irrigation varied between 35 and 52%. Average irrigation efficiencies of 43% and 65% for surface and sprinkler irrigation systems, respectively (APERI, 2003) have been applied to all land units in Borkhar sub-district.

Percolation ratio (PR) which is defined as the ratio of volume of irrigation water lost below the root zone to the total volume of applied water by irrigation varies with type of irrigation system, irrigation regime and soil characteristics. Based on expert knowledge, in this study, DPR was set to 0.3 and 0.2 for surface and sprinkler irrigation, respectively.

The proportion of applied water that is required to pass through the root zone to control salts at a specific level, is called the leaching fraction and is calculated as (Ayers and Westcot, 1985):

$$LF_{Crop,WR} = \frac{EC_{WR}}{5 * EC_{Crop} - EC_{WR}} \tag{5.29}$$

in which,

$LF_{Crop,\,WR}$: Leaching fraction per crop and irrigation water source

EC_{Crop}: Maximum permitted Electrical Conductivity (EC) of the saturation extract of the soil (not causing significant crop yield loss) (dS/m) (Table 5.16)
EC_{WR}: Electrical Conductivity of irrigation water source (dS/m)

Table 5.16. Maximum permitted Electrical Conductivity (ECcrop) of the saturation extract of the soil causing no crop yield reduction (dS/m)

Crop	EC_{crop}
Wheat	6.0
Barley	8.0
Sugar beet	7.0
Silage maize	1.7
Potato	1.7
Alfalfa	2.0
Sunflower	4.8
Melon	2.5
Watermelon	2.5
Colza	8.0

EC of groundwater in the Borkhar plain varied between 1.06 and 6.70 dS/m, based on field measurements in 14 tube wells (Figure 5.5). The quality of canal water is high and maximum salinity was lower than minimum groundwater salinity. Average EC of canal water was 0.5 dS/m (APERI, 2003).

The leaching requirements (LR) for a crop per land unit, irrigation regime, irrigation system, water source, and decade are calculated by Equation (5.30).

$$LR_{crop,LU,Irman,Irsys,WR,Decade} = (LF_{crop,WR} - PR_{Irsys}) * CWR_{crop,LU,Irman,Decade} \geq 0 \qquad (5.30)$$

in which,

$LR_{Crop, LU, Irman, Irsys, WR, Decade}$: Leaching requirements (mm) of the crop per land unit, irrigation regime, irrigation system, water source and decade
$LF_{Crop, WR}$: Leaching fraction per crop and irrigation water source
PR_{Irsys}: Percolation ratio of the irrigation system
$CWR_{Crop, LU, Irman, Decade}$: Crop water requirements (mm) per land unit, irrigation regime, and decade

Irrigation requirements (IR) of a crop per land unit, irrigation regime, irrigation system, water source, and decade are calculated by Equation (5.31).

$$IR_{Crop,LU,Irman,Irsys,WR,Decade} = \frac{CWR_{Crop,LU,Irman,Decade} + LR_{crop,LU,Irman,Irsys,WR,Decade}}{IE_{Irsys,LU}} \qquad (5.31)$$

in which,

IR $_{\text{Crop, LU, Irman, Irsys, WR, Decade}}$: Irrigation requirements (mm) of the crop per land unit, irrigation regime, irrigation system, water source, and decade
IE $_{\text{Irsys, LU}}$: Irrigation efficiency (unit-less) of irrigation system per land unit

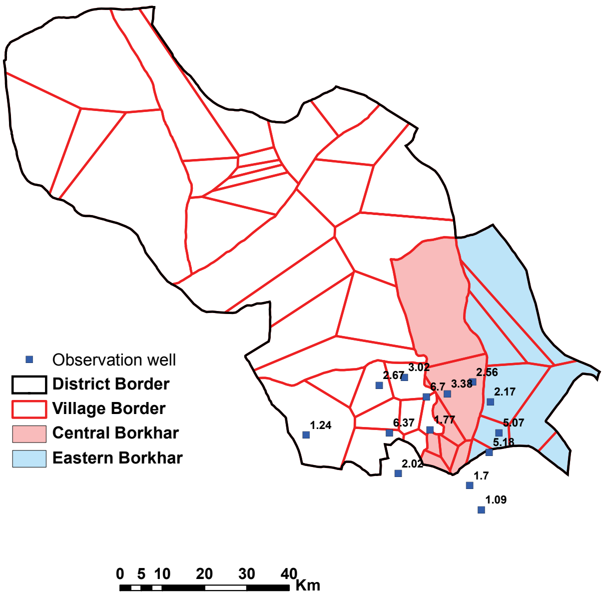


Figure 5.5. EC of groundwater in 14 tube wells in Borkhar plain

- **Fertilizer requirements**

Fertilizer requirements for crop production in each activity have been estimated per FTLU based on expected crop yield and nutrient contents of crop storage organs and residues. The methodology is similar to that applied in Chapter 4.

- **Nitrogen loss (N-loss)**

N-loss is dependent on amount of applied nitrogen, irrigation system and irrigation regime. In this study, N-loss has been set to a fixed proportion of applied nitrogen (10 and 20% percent, respectively for sprinkler and surface irrigation system).

5.7.2 Generation of socio-economic input/output coefficients

Different sources of information and data have been used for estimation of socio-economic input/output coefficients.

- **Labor requirements**

Labor requirements (man-day per ha) for production of each commodity under surface irrigation was estimated based on data from the on-going project of the Iranian Ministry of Jihad-e-Agriculture "*Estimation of production costs of agricultural commodities*", for each agricultural activity (land preparation, crop establishment, irrigation, crop management and harvesting and post–harvest activities) and farm size. Labor use for different activities has been analyzed in relation to farm size, and aggregated to main activity level (Table 5.17). The labor requirements per activity have been converted to monthly labor requirements, taking into account crop calendar and timing of activity in the year. The effect of crop yield on labor requirements for harvesting has not been taken into account. Differences between sprinkler irrigation and surface irrigation are reflected in the labor requirements for irrigation. Labor requirements have not been differentiated for different irrigation regimes.

Table 5.17. Estimated labor requirements (man-day/ha) for different activities of winter wheat cultivation differentiated per farm size (Source: Ministry of Jihad-e-Agriculture)

Main activity	Sub-activity	Average farm size (ha)					
		0.3	1.0	2.3	5.7	25	215
Land preparation	Ploughing	0.8	0.0	0.0	0.0	0.0	0.0
	Discing	0.1	0.0	0.0	0.0	0.0	0.0
	Bordering	2.8	1.6	1.1	1.1	1.3	0.8
	Leveling	0.5	0.1	0.2	0.2	0.2	0.3
	Furrowing	0.0	0.0	0.0	0.0	0.0	0.0
Crop establishmen t	Seeding	0.8	0.6	0.5	0.2	0.1	0.0
	Manure application	0.7	0.3	0.2	0.0	0.1	0.0
	Fertilizer application	0.4	0.3	0.3	0.2	0.1	0.0
Irrigation	Irrigation	8.8	6.7	6.3	7.9	8.4	9.5
Crop management	Cultivator	0.3	0.0	0.0	0.0	0.1	0.0
	Pesticide application	0.3	0.3	0.2	0.1	0.0	0.0
	Weeding	0.0	0.0	0.0	0.0	0.0	0.0
Harvesting & post harvest	Harvest	8.8	4.8	2.8	0.9	0.5	0.0
	Collection & transport of harvested products	2.7	1.3	0.6	0.3	0.2	0.0
	Threshing	2.1	1.0	0.5	0.1	0.1	0.0
	Bagging & loading	0.8	0.5	0.3	0.1	0.1	0.0

- **Agricultural machinery requirements**

Required machine hours for agricultural activities are related to factors such as farm size, soil texture, slope of the plot, crop type, tractor power and efficiency, level of mechanization, etc. In this study, machinery requirements (hours per ha) for agricultural activities have been differentiated only for farm size and crop type. Machinery requirements for different crops and farm sizes have been derived from the project in the Ministry of Jihad-e-Agriculture[1] "*National project for development of agricultural mechanization*". Different levels of mechanization and type of equipments have been considered for different farm types based on their average farm size. Table 5.18 shows machinery requirements for winter wheat as an example.

Table 5.18. Machinery requirements (hours/ha) for different activities of wheat production, differentiated per farm size

Machine (Equipment) Name	< 5 ha	5-10 ha	> 10 ha
Decompactor 2–tooth	4	-	-
Decompactor 3-tooth	-	3	3
Moldboard plow 3-shares	5	-	-
Moldboard plow 4 shares one sided	-	2.8	-
Moldboard plow 4 shares reversible	-	-	2.1
Chisel Plow 7–tooth	-	0.9	-
Chisel Plow 9-tooth	-	-	0.9
Offset Disk	-	0.4	-
Roller harrow 3 m	-	0.9	0.9
Disk harrow (light)	1.5	-	-
Disk harrow (heavy)	-	-	0.6
Leveler	-	1.5	1
Zanbar or Maleh (type of local leveler)	4	-	-
Fertilizer sprayer (centrifuge)	1	0.7	0.5
Grain drill (cereals)	1	1.5	0.5
Sowing combination	-	-	0.5
Turbo-liner sprayer	-	-	0.75
Sprayer 400 Liter	-	6	-
Sprayer 600 Liter	-	-	2.5
Thresher	8	-	-
Baler	-	3	2.5
Wheelbarrow sprayer	12	-	-
Mover	3	-	-
Combine	-	3.5	3

- **Seed requirements**

Seed requirements for each commodity were derived from available reports (APERI, 1999b), questionnaires and data of the production cost project. Seed application rates were not differentiated for farm type, irrigation system or irrigation regime. The value for sugar beet refers to a new cultivar, expected to become a dominant cultivar in the region (Table 5.19).

1 - Data were supplied by the Esfahanian Jihad Agricultural Organization.

Table 5.19. Seed application rate (kg/ha)

Crop	seed application
Wheat	250
Barley	250
Colza	250
Alfalfa	150
Maize	25
Sugar beet	5
Sunflower	20
Melon	14
Watermelon	3
Potato	2000

- **Pesticide requirements**

Pesticide (insecticides, herbicides, and fungicides) requirements, differentiated per crop only (Table 5.20), have been derived from reports of earlier studies in the region (APERI, 1999b). It should be mentioned that these values do not refer to active ingredient.

Table 5.20. Pesticide requirements for different crops (l/ha) in Borkhar & Meymeh district

Crop	Herbicide	Fungicide	Insecticide
Wheat	2	3	1.5
Barley	2	0	0
Colza	3	0	3
Alfalfa	2	0	0
Maize	4	0	3
Sugar beet	5	2	4.5
Sunflower	0	0	3.5
Melon	3	3	12
Watermelon	4	2	8
Potato	1.5	2	4

5.8 Estimation of available water per village

Estimation of available water per village was one of the challenges in this study. Part of the water in the sub-district is provided from the Borkhar irrigation network and the remainder originates from groundwater. Distinguishing groundwater from canal water is important because of their differences in:

- Duration of water availability: farmers can pump 6000 hours per year from tube wells any time they need, but in the canal, water is available only in the period April-October.
- Water discharge: Discharge from the wells is almost constant throughout the year, but water availability in the canal varies in time. In addition, water availability in the canal depends on precipitation in the current year and varies from year–to-year.

- Water quality: the quality of groundwater is lower than that of canal water and consequently has higher leaching requirements and as a result higher irrigation requirements.
- Water cost: the price of groundwater depends on well depth (groundwater table depth) and the price of energy. It varies within the sub-district and differs from the price of canal water.

Three methods were used to estimate water availability in the year 2003 per village:

- Method 1: Estimation based on available maps and data from the Esfahanian regional water company;
- Method 2: Estimation based on the cropped area (Agricultural Census 2003) in each village;
- Method 3: Combination of methods 1 and 2.

5.8.1 Method 1: Estimation based on available maps and data from the Esfahanian regional water company

- ***Estimation of available water in the canal per village***

Borkhar irrigation network is a modern irrigation network, in operation since 1997. It has a conveyance canal, two main canals (Bel and Haji Abad) and 20 secondary canals (Figure 5.6). The water in the system originates from the Chadegan reservoir. Distribution of water in the canals is based on the water rights of farmers. In years with insufficient storage in the reservoir to meet all water rights, allocation to farmers is reduced proportionally. Water is available in the canal in the period April-October. Monthly water deliveries to the irrigation network are increasing from April until July and then remain almost constant in the months July, August and September.

Monthly water availability in each secondary canal for the year 2003 was estimated from:

- Daily water data in the secondary canals in the year 2006
- Average monthly water supply at the inlet of the irrigation network in the years 2003 and 2006 (Table 5.21)

Total available water in the secondary canals is partitioned among the villages in proportion to the canal length in the village (Table 5.22). Monthly water supply in the year 2003 (Table 5.24) was estimated per canal and village by multiplying the quantity distributed in the year 2006 (Table 5.22) with the ratio of available water in the years 2003 and 2006 (Table 5.21).

Table 5.21. Total monthly water supply at the inlet of Borkhar irrigation network in the years 2003 and 2006 (Mm^3) and the ratio of available water in the years 2003 and 2006

Year	2003	2006	Ratio 2003/2006
Jan	0	0	
Feb	0	0	
Mar	0	0	
Apr	1.3	5.3	0.25
May	8.8	12.1	0.73
Jun	9.3	13.0	0.72
Jul	9.6	14.0	0.69
Aug	10.7	14.0	0.76
Sep	10.5	13.9	0.76
Oct	0	4.5	
Nov	0	0	
Dec	0	0.3	
Total	50.1	77.1	0.65

Table 5.22. Estimated available water distributed to the secondary canals and villages of Borkhar sub-district in July 2006 (l/s)

Canal name	Ali Abad	Dastgerd	Dawlat Abad	Habib Abad	Khorzough	Komshecheh	Mohsen Abad	Shahpour Abad	Sherkat Iran chai
CN5							380		
CN6							15	135	
CN7								41	
CN8						14		257	
CN9						7		63	
CN10						20			
CN11						60			
CN12				20		80			
CS5					82				
CS6									
CS7		50							
CS8		61			41				
CS9			30				30		60
CS10			16				64		
CS11	182						52	52	104
CS12	43			65				108	
CS13				70				30	
Total	225	111	46	155	123	181	541	685	164

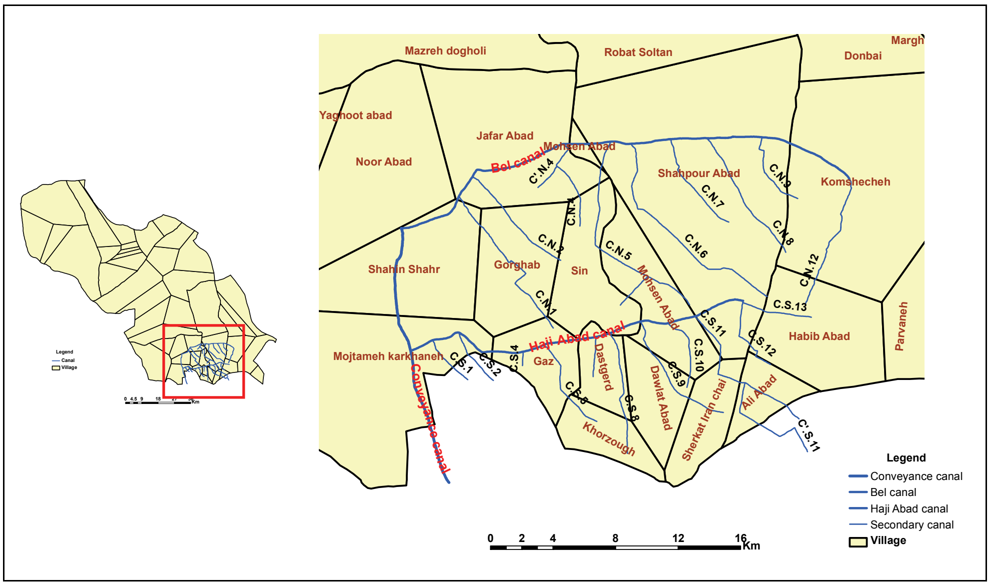


Figure 5.6. Location of Borkhar irrigation network in Borkhar & Meymeh district

- ***Estimation of groundwater availability per village***

Groundwater used to be the main source of agricultural water in Borkhar sub-district that was extracted through qanats and tube wells. The number of agricultural wells per village was determined by overlaying well and village maps (Figure 5.7). Agricultural wells in Borkhar sub-district are deep wells with an average depth of 164 m. Average discharge per well in the villages of Parvaneh, Ali Abadchi and Komshecheh is low compared to that in other villages (Table 5.23).

Qanats also form a source of agricultural water in the villages of Donbai, Margh and Shoorcheh, with total discharges of 15, 28 and 6 l/s, respectively. Estimated total available water from different water sources in the year 2003 is presented in Table 5.24.

Table 5.23. Number, average well depth and discharge of agricultural wells in the villages of Borkhar sub-district in the year 2006

Village	Number of wells	Average well depth (m)	Total discharge of wells (l/s)	Average discharge per well (l/s)
Ali Abad	16	187	266	16.6
Ali Abadchi	23	128	173	7.5
Donbai	1	105	24	24.0
Habib Abad	27	211	646	23.9
Komshecheh	23	156	207	9.0
Parvaneh	34	103	297	8.7
Dastgerd	9	173	152	16.9
Dawlat Abad	8	186	157	19.6
Khorzough	11	174	146	13.3
Mohsen Abad	28	197	581	20.8
Robat Soltan	4	136	98	24.5
Shahpour Abad	55	189	982	17.9
Sherkat Iran chai	19	193	317	16.7
Total	258	164	4046	15.7

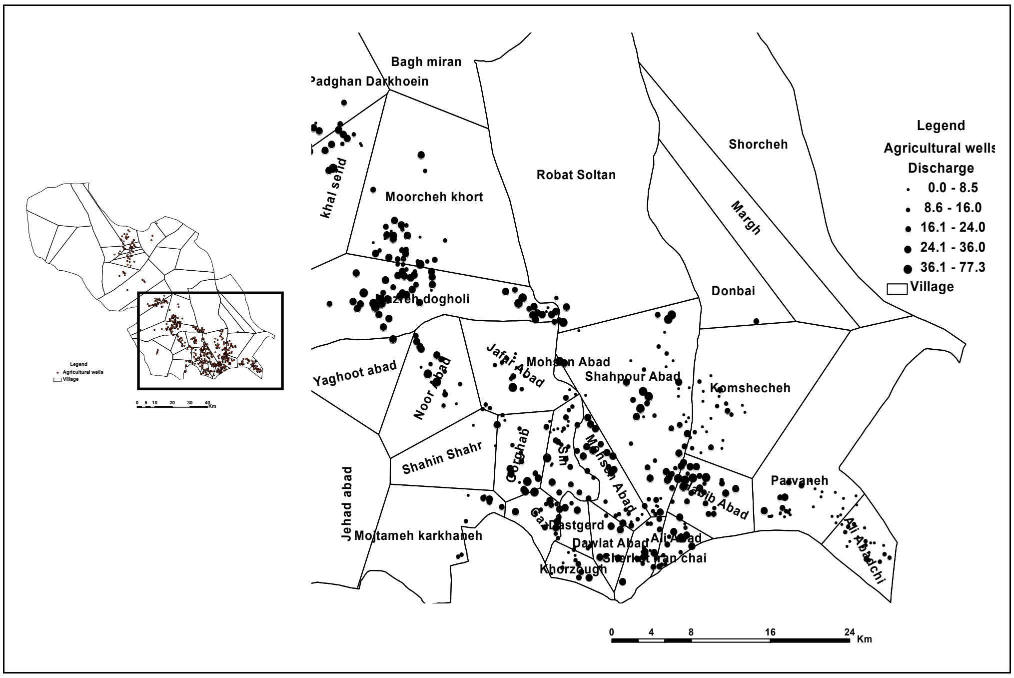


Figure 5.7. Location of agricultural wells in Borkhar & Meymeh district

Table 5.24. Total and available water in the villages of Borkhar sub-district and contribution from different sources in the year 2003 estimated by method 1 (see text for explanation)

	Available water (l/s)			Source of available water (%)	
Village	Canal	Groundwater	Total	Canal	Groundwater
Ali Abad	164	266	430	38	62
Ali Abadchi	0	173	173	0	100
Donbai	0	39	39	0	100
Habib Abad	113	646	759	15	85
Komshecheh	131	207	338	39	61
Margh	0	28	28	0	100
Parvaneh	0	297	297	0	100
Shoorcheh	0	6	6	0	100
Dastgerd	80	152	232	34	66
Dawlat Abad	33	157	190	17	83
Khorzough	90	146	236	38	62
Mohsen Abad	394	581	975	40	60
Robat Soltan	0	106	106	0	100
Shahpour Abad	500	982	1482	34	66
Sherkat Iran chai	120	317	437	27	73
Total	1626	4103	5729	28	72

5.8.2 Method 2: Estimation based on the cropped area (agricultural census 2003) in each village

Total water requirement for full irrigation of crops cultivated in each village per decade was calculated by summation of the water requirements of the holdings in the village (Equation (5.1)). The maximum water requirements for irrigation of the crops are considered as maximum available water in the village. Assuming the same distribution between groundwater and canal water in the village as in the previous method, allows calculation of available water per village and water source (Table 5.25).

5.8.3 Method 3: Combination of methods 1 and 2 (correction of results of method 2 by comparison with method 1)

Comparison of the results of methods 1 and 2 shows:

1- Total available water in the sub-district estimated by method 1 is 85% of that estimated by method 2, which could be an indicator of application of deficit irrigation in the sub-district.
2- Available water estimates for the villages based on methods 1 and 2 are different (Figure 5.8). These differences could be due to:
   - Inaccurate borders of villages: Borders for the villages were identified based on Thiessen polygons. Incorrect borders for the villages would

lead to inaccurate allocation of water resources between villages in method 1.

- Inaccurate report of census data: Some of the farmers, that have land in the villages in Borkhar sub-district, are living in nearby cities. These farmers, at the time of the agricultural census, were in the cities and it seems that their agricultural activities have been allocated to the cities instead of to their villages. This also can be seen from Figure 5.8, which shows that total available water in the cities estimated with method 2 exceeds that estimated with method 1, while in some of the villages such as Shahpour Abad and Mohsen Abad it is the reverse.

As farm type classification was based on the agricultural census data and the benchmark data, which are also used for comparison of the model outputs, originate from the agricultural census, estimates of available water based on method 2 seem more appropriate. In method 3, total available water estimates based on method 2 have been modified by multiplying by 0.85 (the ratio of estimated total available water in method 1 and method 2) (Table 5.26).

Table 5.25. Total available water in the villages of Borkhar sub-district in the year 2003 estimated by method 2 (see text for explanation)

Village	Available water (l/s)		
	Total	Canal	Groundwater
Ali Abad	732	279	453
Ali Abadchi	254	0	254
Donbai	7	0	7
Habib Abad	1111	165	946
Komshecheh	466	181	285
Margh	191	0	191
Parvaneh	439	0	439
Shoorcheh	16	0	16
Dastgerd	439	151	288
Dawlat Abad	1063	185	878
Khorzough	618	236	382
Mohsen Abad	210	85	125
Robat Soltan	54	0	54
Shahpour Abad	904	305	599
Sherkat Iran chai	203	56	147
Total	6709	1904	4805

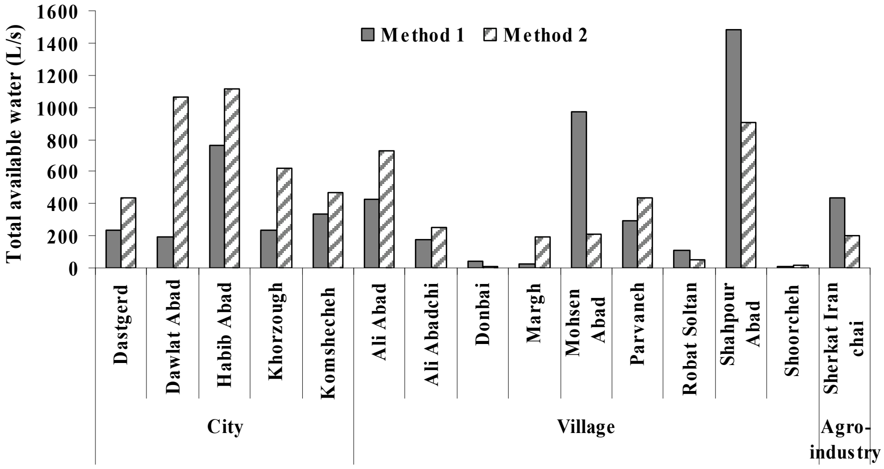


Figure 5.8. Total available water estimated in the villages and cities of Borkhar sub-district by methods 1 and 2 (see text for explanation)

Table 5.26. Total available water in the villages of Borkhar sub-district in the year 2003 estimated by method 3 (see text for explanation)

Village	Available water (l/s)		
	Total	Canal	Groundwater
Ali Abad	625	238	387
Ali Abadchi	217	0	217
Donbai	6	0	6
Habib Abad	949	141	808
Komshecheh	398	155	243
Margh	163	0	163
Parvaneh	375	0	375
Shoorcheh	14	0	14
Dastgerd	375	129	246
Dawlat Abad	908	158	750
Khorzough	528	202	326
Mohsen Abad	179	73	107
Robat Soltan	46	0	46
Shahpour Abad	772	260	512
Sherkat Iran chai	173	48	126
Total	5728	1403	4325

5.9 Model experimentation

Calibration and validation of a model are required to build up confidence in model performance. The model has to be calibrated based on local data, and should subsequently be validated based on an independent set of data. In this study, calibration and validation of the model were performed simultaneously, using the same set of data, because of time and data limitations. For this purpose, the model was implemented and tested for Borkhar sub-district[1], located in the southeastern part of the district. This sub-district comprises 15 units (9 villages, 5 cities, and one large agro-industrial unit) in two Dehestans (eastern Borkhar and central Borkhar). Calibration and validation was performed manually by changing the coefficients and comparing model outputs (cropped area and crop production) at the village and sub-district levels.

The model was run three times, i.e. for each of the water availability estimates (Section 0). The model results were compared with census data for the year 2003 at village and sub-district level considering different single and multi objectives. Figure 5.9 shows the model outputs (allocated land to crops and crop production) in comparison to the agricultural census data at sub-district level. Model results indicate that the deviations from the census data are smallest when net income and production costs are optimized simultaneously.

1 - Borkhar & Meymeh district comprises three sub-districts, i.e. Borkhar, Central and Meymeh. Validation has been performed only for Borkhar sub-district.

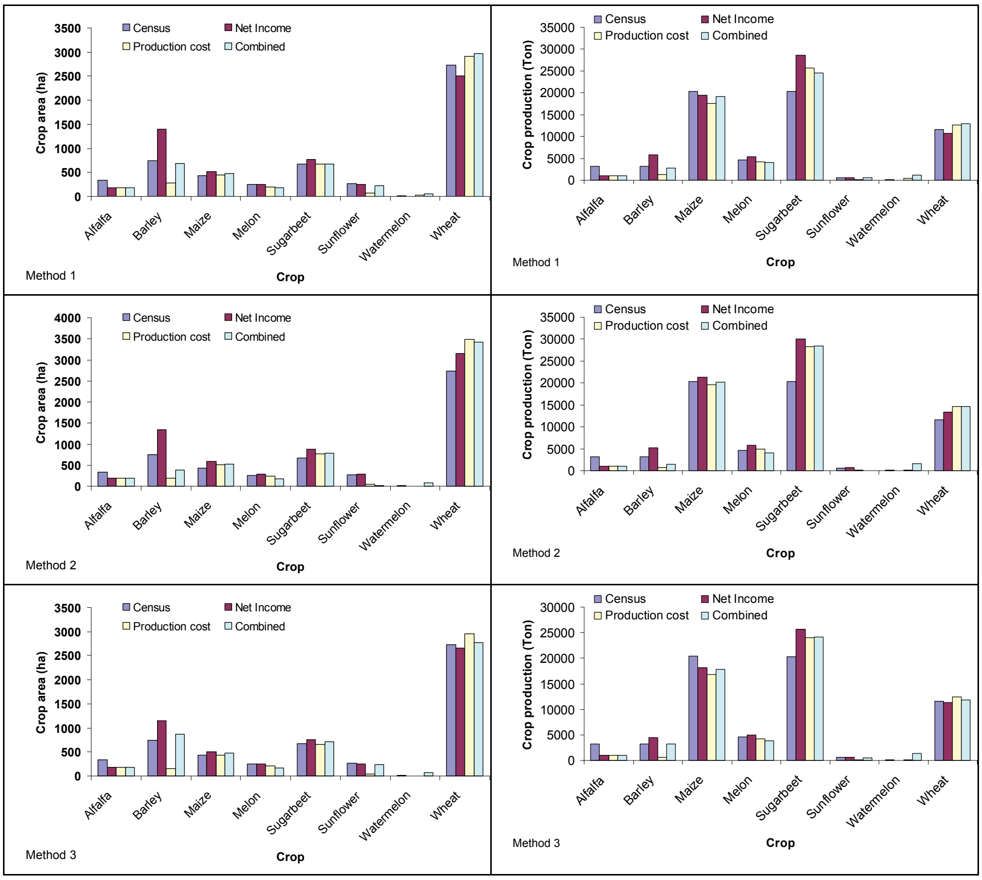


Figure 5.9. Comparison of the cropped areas and the corresponding production simulated by the model for single (net income and production cost) and combined objectives and three methods of estimation of available water in the village, with the census data 2003

Figures 5-10 and 5-11 compare the model results (multi-objective) for three methods of available water estimation in the villages to the census data. As total available water from methods 1 and 3 are the same at sub-district scale, results of the model in these cases are comparable (Figure 5.10 and Figure 5.11). Different distributions of available water between the villages in methods 1 and 3 lead to differences in model results. Model results based on method 3 show higher correlation with the census data at village scale (Table 5.27), because water was distributed between villages based on census data. Hence, water availability based on method 3 was selected as the most appropriate method and used for further analysis.

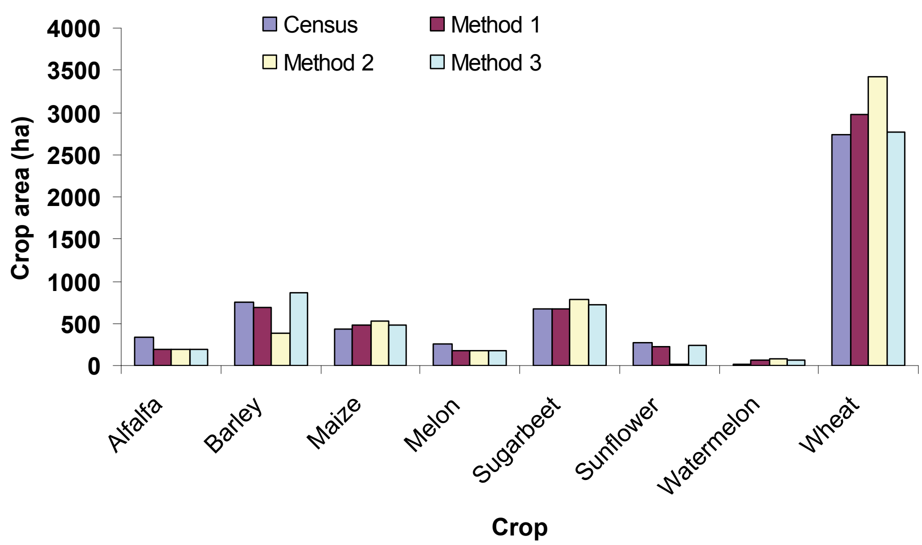


Figure 5.10. Comparison of model-allocated land to different crops (for three methods of available water estimation) with census data at sub-district scale

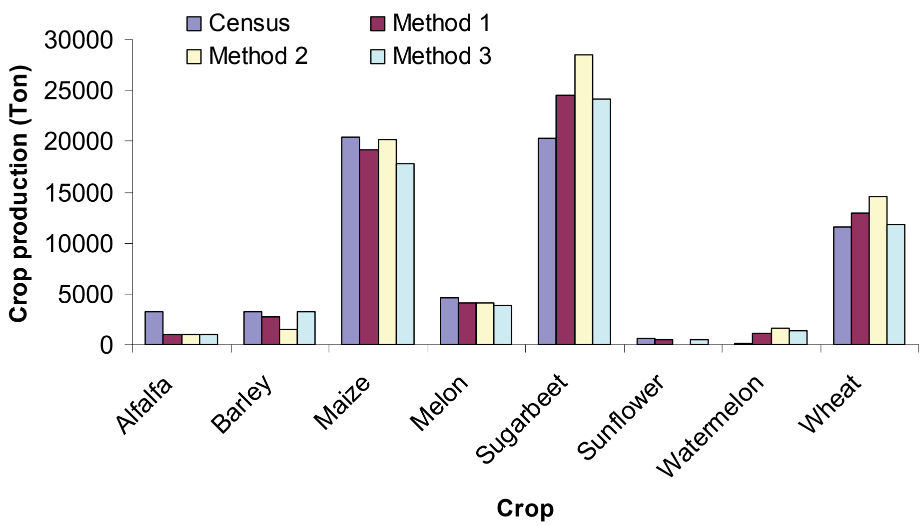


Figure 5.11. Comparison of model-calculated production of different crops (for three methods of available water estimation) with census data at sub-district scale

Table 5.27. Correlation coefficients between model outputs for three methods of water availability estimation and census data for crop area, crop production and their combination

	Crop area (n= 120)	Crop production (n= 120)	Crop area & production (n= 240)
Method 1	0.56	0.67	0.59
Method 2	0.60	0.89	0.63
Method 3	0.70	0.87	0.73

Major binding constraints in method 3 of water estimation are determined by review of the outputs (solution) of the linear programming model as follows:

Monthly water availabilities at village and FT level are binding constraints in the months April-July in all villages and farm types, but the shadow prices of these constraints in June are much higher than in the other months. This is the time that both winter and summer crops are in the field and need irrigation. The area constraints for alfalfa and melon are binding. Alfalfa is a crop, that is economically not attractive to farmers, therefore, it can not compete with other crops. This is illustrated by the negative shadow price of the alfalfa constraint in model 1 (maximize net income). Only farm types that need alfalfa for feeding their animals cultivate this crop. On the other hand, melon is a crop yielding a high net income, making it an attractive option for all farmers. As production of melon increases, the price decreases dramatically, as it cannot be stored by farmers, so it should be sold at harvest time and apparently the demand elasticity of the crop is very low. It has happened in the past that farmers did not even harvest their products because of the low price. Tractor and labor constraints are not binding.

Indicators representing the objectives of other stakeholders were calculated after model optimization to evaluate the current situation (Table 5.28). Prices in the year 2005 have been used for calculation of production cost and income.

Table 5.28. Indicators calculated after optimization of model 3 with three methods of water availability estimation (see text for explanation)

	Unit	Method 1	Method 2	Method 3
Total cropped area	ha	5448	5589	5483
Total cropped area with full irrigation	ha	1112	1215	1222
Total cropped area with 20% deficit irrigation	ha	4336	4373	4261
Area of wheat	ha	2971	3432	2766
Area of barley	ha	682	392	863
Area of sunflower	ha	222	13	238
Area of sugar beet	ha	673	780	715
Area of silage maize	ha	476	523	477
Production of wheat	kg	12930.4	14619.9	11799.4
Production of barley	kg	2765.4	1518.5	3288.1
Total net income	MRials *	30188.3	31071.9	27862.2
Total production cost	MRials	27104.3	28476.0	27125.9
Total employment	Man-day	110290	118782	112054
Total water use	m^3	57574.4	61090.0	58202.7
Total required fertilizer (N)	kg	1114.8	1117.2	993.8
Total required fertilizer (P)	kg	932.8	1077.7	945.9
Total required fertilizer (K)	kg	112.8	144.6	90.9
Water productivity	Rials/ m^3	524	509	479
Labour productivity	Rials/Man-day	273719	261586	248650
Total nitrogen loss	kg	102.6	102.8	91.4
Total pesticide use	kg	36.9	40.5	36.5
Total subsidy on fertilizers	Rials	851.7	912.4	823.2

* 1 MRials = 10^6 Rials ≈ 100 U$ (in 2008)

5.10 Discussion

A distributed multi-scale model to estimate the impacts of various policy instruments on agricultural development is developed and applied. The model is based on identification of homogenous units (farm type-land unit) in terms of biophysical and socio-economic characteristics. The farm type-land units are then aggregated to form farm types, which are aggregated to form villages, sub-districts and finally districts. An innovative feature of this model is its distribution over space that allows for specification of spatially variable input/output relations. In addition, different sets of input/output coefficients were used for different groups of farm types according to their crop production efficiency. So, input/output coefficients are determined per planning unit. Moreover, constraints were specified at the lowest spatial scale that was relevant. As a result, it can be expected that this model reduces the aggregation errors that are inherent in most optimization models.

The use of crop growth simulation models for determination of the biophysical input/output coefficients of the model is one of the strong points of the method. Crop yields and water and nutrient (fertilizer) requirements that are very important in agricultural planning have been estimated spatially. As crop simulation models can reflect variation in yield-determining and yield-limiting factors in time and space and hence the temporal and spatial variation in input requirements to realize targeted output levels, the technical coefficients more closely resemble reality and provide an option for scenario and risk analysis. Biophysical input/outputs of the model (crop yield, water and fertilizer requirement) were determined for each soil type, based on 20 years daily weather data in Chapter 4. In this analysis, averages of 20-year biophysical input/outputs were used. As these parameters are available for all 20 years, analysis of policy instruments could be done for different scenarios (for example, dry and wet years (periods)).

In the model, three irrigation regimes were specified which may not cover all irrigation regimes currently used in the study area. More irrigation regimes could also be implemented.

In the developed model, both crops in the double cropping system have one specific irrigation system and irrigation regime (management). For the irrigation system that might be logical, but not for irrigation regime (management) in all cases. A farmer may be applying deficit irrigation in the winter crop and full irrigation in the summer crop or vice versa. This option should be considered in the future update of the model.

Each basic planning unit represents a combination of two different entities, that can be improved or modified separately. Farm types, which reflect socio-economic characteristics, are more amenable to change than land units that reflect biophysical characteristics. This is useful when planners/decision makers want to update the model.

Different farm types can be specified by applying different methods of clustering and even with one method, but by different measures of distance and standardization methods. Although in this study results of different clustering methods on farm type classification have been analyzed and Ward's method with squared Euclidean measure distance was selected and applied for model development, some others could be applied.

The planning model assumes that farmers are trying to optimize their objectives (in this case, net income and production costs), which may not be true in all cases. In reality, some farmers are satisfiers; some others are conservative and want to avoid risk. In this study, the issue of risk that is inherent in agricultural systems, was not considered in the model development. The model could be expanded to consider other objectives.

Normally, farmers are having more than one objective therefore, goal programming was applied to consider different objectives to support policy formulation and simulate the reaction of farmers to policy instruments (Chapter 6). The priority and importance of objectives could be different among farm types. The relative importance of the objectives for the different farm types should be determined in discussions with local farmers and experts. Structured pair-wise comparison techniques (Sharifi et al., 2004), in the context of an Analytical Hierarchy Process can be applied to elucidate the priority of various objectives.

Results of the model showed a reasonable match with the order of historical data. As the available information from different organizations was far from consistent, and the quality of the different data sets is impossible to assess, it was difficult to accurately assess the quality of the model results. For example, the total area under cultivation in Borkhar & Meymeh district in 2003 was 15967 ha, based on the Agricultural Census, while based on data of the Ministry of Jihad-e-Agriculture in the same year, it was 19555 ha. Crop area can be determined using satellite images, although that was not done in this study.

Although the price of agricultural products is dependent on supply and demand, in this study they were assumed exogenous, as the area is small and its production is unlikely to influence agricultural prices. Prices, however, should be considered as endogenous if this model is going to be used at higher spatial scale, e.g. provincial or national. In that case, some of the constraints such as cropping pattern and melon should be released, because these constraints were specified to reduce the effects of exogenous price setting.

These types of models are very data and knowledge demanding. For example, it requires knowledge of crop growth simulation and its detailed data requirements. This includes daily weather data, soil physical and chemical properties and management information on crop husbandry for each relevant elementary mapping unit. Fortunately, knowledge is increasing, and availability of detailed data is improving. Many detailed data, required for crop growth simulation models, are collected by satellites at very high temporal (from hours to few weeks) and spatial (from few centimeters to kilometers) resolution. Therefore, applicability of this type of models in the management of natural resources is increasing. It is important to realize that planners and decision makers should make use of all the relevant available data and information in the process of planning and decision-making, even though this information may vary widely in type, format and quality, and may have been collected for different purposes. This is the analyst's job to cope with inconsistency, different quality and format of the data and make them useful in the planning process. In the present study, this concept was operationalized, in that an attempt was made to make use of all relevant data with different quality and format.

In the current model, only arable farming activities are included. Farmers may have income from other activities such as animal husbandry, cultivation of fruit trees and from off-farm activities. These activities were not considered in this study because of lack of expertise and time constraints. However, for a complete analysis of farmers' response to policy measures, these activities should be included, as farmers optimize their objectives considering both on-farm and off-farm activities.

6 Policy formulation for agricultural development: A case study in Borkhar sub-district, Esfahan province, Iran

Abstract

A methodology is developed for policy formulation in the arable farming sector. First, policy objectives and their relevant policy instruments are determined. Then a distributed simulation model is used to assess the impacts of policy instruments by simulating the reaction of various groups of farmers, considering their socio-economic and biophysical situations. Different social, economic and environmental indicators are selected to assess the impacts of policy instruments on the various policy objectives. A multi-criteria evaluation technique is used to assess, compare and rank the effectiveness of policy instruments. Robustness of the ranking is assessed through uncertainty analysis. The methodology is applied to three policy instruments aiming at increasing agricultural water productivity in Borkhar sub-district, Esfahan province, Iran.

Keywords: Indicator, Policy instrument, Multi-criteria evaluation, Water policy

6.1 Introduction

A policy is typically described as a deliberate plan of action to guide decisions and achieve rational outcome(s) (objectives). The policy formulation process consists of selecting policy objectives, identification of policy instruments and assessment and analysis of their impacts. Policy instruments are the tools that can be used to achieve the policy objectives. Therefore, policy objectives are ends and policy instruments are means to achieve ends. Agricultural policy instruments are used to stimulate farmers to change their behavior in order to better achieve policy objectives. Farmers respond to policies based on *their* objectives, and on available resources and constraints. Therefore, farmers can respond differentially to policy instruments because of differences in terms of objectives, resources, constraints and technologies. Changes in the behavior of farmers will have impacts on the environment and on realization of the objectives of other stakeholders in agricultural development.

Various policy instruments are available to achieve (a) specific policy objective(s), but these instruments may have different impacts on the degree of realization of objectives of other stakeholders and of other objectives of policy makers. Ex-ante impact assessment of policy instruments is an essential step in the development of new policies and helps policy makers to select the most appropriate instrument(s). It should be noted in this context that impact assessment is an aid in decision-making, not a substitute for it (European Commission, 2005). Ex-ante assessment of agricultural policy instruments is not an easy task, because of the involvement of many stakeholders, each with its own behavior and different value systems related to the importance of social, economic and environmental indicators. Indicators are used to assess the impacts of policy instruments (European Commission, 2005; Ewert et al., 2005; Rossing et al., 2007) as a basis for negotiations among various stakeholders and communication among experts from different scientific fields. Appropriate indicators for policy impact assessment should be selected in discussions with different stakeholders, considering their objectives. The overall impact, in terms of environmental, economic, and social indicators can be evaluated through multi-criteria evaluation techniques (Sharifi, 2005).

In this chapter, the policy formulation process using the model developed in Chapter 5 is demonstrated. In this process, the impacts of current and proposed agricultural policies in the Iranian Fourth Five-Year Development Plan (FFYDP) in Borkhar sub-district, Esfahan province, Iran are assessed. The flow chart of the policy formulation process, applied in this chapter, is presented in Figure 6.1 and explained in Chapter 5. This framework is coherent with the key steps in impact assessment proposed by the European Commission (2005).

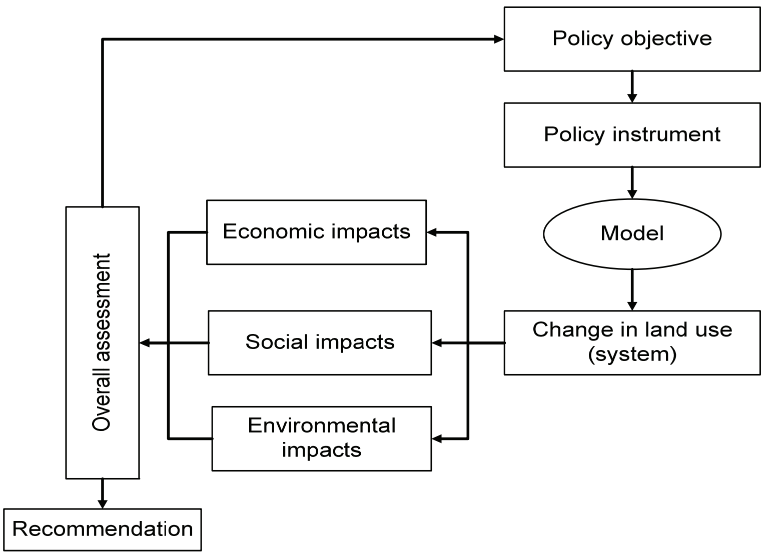


Figure 6.1. Flowchart of land use policy formulation (Sharifi, 2003)

The chapter starts with a review of agricultural policy objectives in Iran. Current agricultural policy objectives and the associated policy instruments in the arable farming sector, proposed in the FFYDP, are explained. Subsequently, relevant social, economic, and environmental indicators are selected to assess the impacts of policy instruments. In the subsequent section, impacts of the policy instruments on the behavior of farmers are assessed, using the planning model that has been developed in Section 5.5. In this study, as an example, the impacts of various policy instruments designed to increase water productivity are assessed, and their performance compared, using a multi-criteria evaluation technique. The chapter ends with a discussion and conclusions.

6.2 Review of agricultural policy objectives in Iran

Agricultural development objectives are different among countries and evolve in association with the various stages of development in one country. A review of agricultural policies in Iran over the last 60 years shows the variation in importance attached to the agricultural sector and in the agricultural policies/objectives in the consecutive national development plans. Some of the objectives of policy makers in the various national development plans (of which five were formulated before the Islamic revolution in 1979) were (Kazem Nejad et al., 2005):

- Increasing crop production,
- Land reform,
- Supporting consumers and providing cheap inputs for the industry by reducing the production cost of agricultural products (subsidizing agricultural production inputs and machinery),
- Creating (new) employment in the agricultural sector,
- Increasing farmers' income to reduce the income gap between the rural and urban sectors,
- Creating a balance between income in the agricultural sector and that in other sectors,
- Increasing the self-sufficiency index of strategic crops,
- Improving the nutritional status of the population,
- Promoting sustainable agriculture.

National agricultural development documents produced in the preparations for the FFYDP have been investigated to identify current agricultural policy objectives and policy instruments in Iran. Objectives formulated for the agricultural and natural resources sectors in the FFYDP, summarized by APERI (2005), are:

- Protection, rehabilitation, improvement, and expansion of natural resources; sustainable use of these resources, taking into account the ecological balance and environmental sustainability,
- Increasing quantity and quality of agricultural production to improve the nutritional status of the society through increased production and productivities of agricultural inputs,
- Providing food security based on national production and emphasis on self-sufficiency in strategic crop products,

- Reorganization of the agricultural market and increasing export of agricultural products,
- Improvement and expansion of agricultural infrastructures, with emphasis on land and water.

Objectives for each of the main sub-sectors are defined in the national agricultural development document. As the focus of this study is on the arable farming sub-sector, only objectives related to this sub-sector are considered in the further analysis. These objectives are (APERI, 2005):
- Increasing the self-sufficiency index of strategic crops,
- Increasing the production of forage crops to increase the supply of animal protein from 23 to 29 gram per capita per day (34 grams in the 5th plan[1]),
- Increasing productivity of agricultural inputs,
- Objective-oriented agricultural subsidies.

6.3 Identification of policy objectives and instruments in the arable farming sub-sector

Policy-making starts with identification of the policy objectives. Policy makers can then select different (types of) policy instruments to achieve their objectives. In this study, some of the policy instruments relevant for the arable farming sub-sector, and applicable in Iran are selected and assessed. First, some of the policy objectives for the arable farming sub-sector, formulated in FFYDP and their corresponding policy instruments are explained.

- **Increasing the self-sufficiency index of strategic crops**

Increasing the self-sufficiency index of strategic crops has been the objective of Iranian policy makers in the consecutive national plans after the Islamic revolution. Wheat, rice, sugar beet, sugar cane, oil-seeds, (grain) maize and potato were classified as strategic crops in the fourth and fifth Iranian national development plans.

Identification of *all* these crops as strategic already indicates conflicts between policy objectives. Policy instruments aimed at increasing production of one crop may have impacts on the production of the others. For example, increasing the guarantee price of wheat and providing technical support to wheat producers were among the policy measures implemented for increasing wheat production. In response to these policy measures, the area under cultivation of wheat increased, however with negative impacts on barley cultivation (e.g., Table 2.1). Therefore, self-sufficiency in wheat was celebrated in Iran in the year 2004, but

1 - Preparations for the fifth national development document were started at the latest stage of this study. Information is available from the APERI website (http://www.agri-peri.ir/).

in subsequent years, Iran again became a wheat importer. This unstable situation with respect to wheat self-sufficiency is associated with conflicts between policy objectives and competition between different strategic crops. As a consequence of the decrease in barley production, its price rose above that of wheat. In that situation, some of the farmers used wheat, and even bread, which is highly subsidized, instead of barley for animal feed. Support for winter colza, an oilseed crop, recently introduced by agricultural policy makers for most of Iran, will increase this competition for scarce resources.

Table 6.1. Total production[1] of strategic crops (10^6 kg) at the beginning of the planning period, target production at the end and required annual rate of production increase (%) in the 4th and 5th Iranian five-year development plans (APERI, 2005)

	4th plan			5th plan[2]		
	Base year	Target	Increase rate	Base year*	Target	Increase rate
Wheat	13406	15880	2.9	14953	17335	3.0
Sugar beet	5933	7000	2.8	5257	6035	2.8
Oilseed crops	393	700	10.1	598	2350	31.5
Potato				4358	5053	3.0

*Production in the base year is set to the average production over the years 2005-2007

It seems unlikely that with the currently available resources and technologies, full self-sufficiency in all strategic crops can be achieved in Iran. Policy makers should therefore set priorities in the list of strategic crops, and define realistic targets for the degree of self-sufficiency in these crops. Table 6.1 shows the predicted national production and the targeted production increase for the strategic crops in the fourth and fifth national development plans.

Increasing the guarantee prices and providing technical support to wheat and colza producers are currently applied as policy instruments to increase production of these crops.

- **Increasing the production of forage crops**

Although part of the population of Iran is suffering from malnutrition, because of improper distribution of the food (APERI, 2005), average energy and protein intake per capita is sufficient (Table 6.2). The proportion of carbohydrate, fat and protein in total energy intake is an indicator of the quality of the diet. In Iran, the average proportions over the years 1989-2001 of carbohydrate, fat and protein in total energy intake were 0.78, 0.1 and 0.12, respectively (Askari, 2004). Adequate ranges for these components are 0.45-0.65 for carbohydrates,

1 - Production of all crops in this Chapter is expressed in marketable product and fresh matter.
2 - These are preliminary data (http://www.agri-peri.ir/dabirkhane/baste/25_87b.pdf).

0.20-0.35 for fat and 0.10-0.35 for proteins[1]. This would indicate that in Iran the proportion of energy derived from fat is at the low side. Around 90 and 75% of the total consumed energy and protein in the period 1989-2001 originated from plant sources (Table 6.2). Therefore, increasing the proportion of animal protein in the diet was one of the objectives of Iranian policy makers in the FFYDP. For achieving this objective, animal production should be stimulated, for which the production of forage crops should be increased. Table 6.3 shows the targeted production of forage crops at the end of the fourth and fifth development plans.

Table 6.2. Average daily intake of energy and protein per capita in Iran in the period 1989-2001 (Askari, 2004)

	Energy (cal)			Protein (g)		
	Plant	Animal	Total	Plant	Animal	Total
1989	2737	324	3061	62.2	17.5	79.7
1990	2773	303	3076	61.7	16.9	78.6
1991	2732	320	3052	63.0	18.5	81.5
1992	3029	344	3373	69.4	18.7	88.1
1993	2952	354	3306	66.4	20.1	86.5
1994	2789	346	3135	62.0	19.8	81.8
1995	3170	350	3520	71.8	20.0	91.8
1996	3234	363	3597	72.7	20.1	92.8
1997	3163	357	3520	70.1	20.3	90.4
1998	3454	367	3821	77.1	20.6	97.7
1999	3267	363	3630	69.0	20.8	89.8
2000	2946	376	3322	62.0	20.9	82.9
2001	3168	366	3534	68.9	21.0	89.9

Table 6.3. Total production (10^6 kg) of forage crops at the beginning of the planning period, target production at the end and required annual rate of production increase (%) in the 4th and 5th Iranian five-year development plans (APERI, 2005)

	4th plan			5th plan[2]		
	Base year	Target	Increase rate	Base year*	Target	Increase rate
Barley				2972	4208	7.2
Alfalfa				5070	7111	7.0
Other forage crops				9772	15737	10.0
All forage crops	13342	18500	5.6	17814	27056	8.7

*Production in the base year is set to average production in the years 2005-2007

Increasing the guarantee price and providing technical support are currently applied as policy instruments to increase production of these crops.

1 - http://www.sparkpeople.com/resource/nutrition_articles.asp?id=372
2 - These are preliminary data (http://www.agri-peri.ir/dabirkhane/baste/25_87b.pdf)

▪ **Increasing productivity of agricultural inputs**

Different definitions of agricultural productivity are available in the literature (Tahamipour, 2006). Agricultural productivity has been defined as agricultural output (in terms of economic return, biomass, fresh or dry yield, nutritional value (e.g., energy or protein)) per unit value of agricultural inputs. Productivity can also be expressed on the basis of one of the production factors, which is referred to as partial (factor) productivity. The most common partial indicators are land, labour, capital and, more recently, water productivity. In this study, productivity is defined in monetary terms.

Increasing total factor productivity by 1.6% per year was set as one of the targets of the arable farming sub-sector in the FFYDP. For achieving this target, partial productivity of individual production factors (water, land, labour and capital) should be increased. For example, increasing the agricultural water productivity by 5% per year was set as one of the sub-goals in this plan.

Various policy instruments have been designed to increase water productivity:

- Supporting farmers to change irrigation systems by providing low-interest loans,
- Lining of traditional canals,
- Appropriate water pricing for each watershed,
- Promoting production of crops with high water use efficiency,
- Improved management of water resources.

▪ **Objective-oriented agricultural subsidies**

Supporting agriculture by subsidizing agricultural inputs, agricultural mechanization, and agricultural insurance has been part of the Iranian agricultural policies during the last decades. The specific items supported and the level of the subsidies varied in the course of time, because of changes in policy objectives in the various national development plans (Table 6.4). In the period 1991-2000, most of the subsidies were paid on fertilizers, pesticides, seeds and agricultural insurance. Highly subsidized fertilizers and pesticides may lead to their over-use, with serious risks for pollution of soil and water. In 2008, the subsidy on pesticides was withdrawn and plans are discussed to reduce the subsidy on fertilizers. Energy (fuel and electricity) is a highly subsidized commodity in Iran (Table 6.5), not presented in Table 6.4, as this subsidy is paid by the Ministry of Energy and not by the Ministry of Jihad-e-Agriculture. Total subsidies for energy in the agricultural sector are almost 10 times those paid for all other items combined (Table 6.4 and Table 6.5). Again, these high subsidies form a dis-incentive for judicious use of energy in agriculture.

Table 6.4. Agricultural subsidies (10^9 Rials*) paid for different items during the years 1991-2000 in Iran (APERI, 2005)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Fertilizers	78.6	76.1	238.5	522	557.9	492	521.3	453.1	470.7	543.1
Mechanization of sugar beet cultivation	1.3	1.3	1.3	0	0	0	0	0	0	0
Animal medicines	0	0	37.5	0	0	0	0	9.3	13.5	12.5
Direct price support for crops	1.2	0	39.4	0	0	0	0	0	0	0
Expansion project of sugar cane and related industries	18	45	27.6	0	0	0	0	0	0	0
Seeds and pesticides	5.1	10	8	16.1	54.9	70	66.5	42.8	58.9	58
Indirect support for cotton production	5.4	4	0	0	0	0	0	0	0	0
Increase sugar content in sugar beet	2.3	4.6	4.7	1.2	7.6	7.1	0	0	0	0
Agricultural insurance	0	9.9	5.2	5.2	8.7	10.5	11.5	11.5	62	75
Compensation of damages to livestock caused by hazards	1.5	6	7.5	0	9.4	13	0	0	0	0
Compensation of crop damages caused by hazards	0	0	0	8.7	16.5	12	2.5	0	0	0
Tooba project **	0	0	0	0	0	0	0	0	0	211.4
Total	113.4	156.9	369.7	553.2	655	604.6	601.8	516.7	605.1	900

*1 US$ ≈ 10 000 Rials (2008)
** Objective of this project is soil protection and generation of employment through cultivation of (fruit) trees on steep sloping lands.

Table 6.5. Subsidies (10^9 Rials*) paid for energy (fuel and electricity) in the Iranian agricultural sector during the years 1999-2001 (Iranian Ministry of Energy, 2000; 2001; 2002)

Year	Fuel	Electricity	Sum
1999	4232.7	2419.6	6652.3
2000	5738.7	4202.7	9941.4
2001	4466.7	4880.6	9347.3

*1 US$ ≈ 10 000 Rials (2008)

6.4 Indicators

Indicators are used as a means to assess alternative policy scenarios to support the policy debate. Selection of appropriate indicators is crucial for appropriate assessment of policy instruments. The set of indicators should represent all aspects of the problem without redundancies. Indicators should be relevant to the policy objectives (Lehtonen et al., 2005), measurable and applicable at different spatial scales. Social, economic, and environmental indicators (Table 6.6) were selected, based on the objectives of farmers, agricultural policy makers, sustainability in agriculture, and literature (Mohamed, 1999; OECD, 2001; Bazzani et al., 2005). Classification of indicators into social, economic and environmental indicators is to some extent arbitrary, as some of the indicators could be associated with more than one objective. For example, employment both has social and economic aspects, total fertilizer use has both economic and environmental aspects.

6.4.1 Economic indicators

The three policy objectives of agricultural policy makers for the arable farming sub-sector in FFYDP have been classified as economic objectives. Total production of strategic crops and forage crops in this sub-district have been identified as indicators for policy objectives 1 and 2, respectively. However, sunflower, an oil-seed crop, has not been classified as a strategic crop in this study, because most sunflower produced in this sub-district is confection sunflower, used for production of snacks. Water, labour and land productivity have been selected as indicators for policy objective 3. Productivity can be expressed in terms of net income or of food production (grain, energy, protein) per unit of input (water, labour or land, each in its own physical unit). In this analysis, productivity is defined as net income per unit of input. Total net income and production costs have also been selected as economic indicators, both being important for policy makers and farmers. Total expenditure on government subsidies has been selected as the last economic indicator.

6.4.2 Social indicators

Employment rate is a socio-economic indicator, in this study classified as a social indicator. Employment rate is defined as the ratio of the agricultural labour force and the total work force. The total work force consists of a well-defined segment of the total population and is therefore constant. Therefore, the employment rate is an indicator of total generated agricultural employment. Self-sufficiency in food production has also been selected as a social indicator. Food production can be expressed in dry weight, energy or protein. Overall food self-sufficiency at the sub-district and individual household scale are used as indicators. Overall self-sufficiency is expressed in the ratio of total food production (in terms of energy and protein) and total food requirements at sub-district scale. Daily energy and protein requirements were set to 12 560 Joules (3000 calories) and 70 grams per capita, respectively, approximately equal to the values defined as targets in FFYDP (APERI, 2005). The proportion of farm households producing the required food (in terms of energy and protein) for a family (4 persons) is defined as indicator for individual household self-sufficiency. The Gini coefficient (Gini, 1921) with a value between 0 and 1, is used as indicator for income distribution. Higher values indicate larger inequality in income distribution.

6.4.3 Environmental indicators

Total pesticide use, fertilizer use and leaching of nitrogen have been selected as environmental indicators. Total nitrogen leaching is directly related to total N fertilizer, but is also affected by type of irrigation system used. Therefore, both indicators have been selected.

Agriculture is not the only sector with a claim on land and water resources. In terms of environmental objectives, maintenance of ecological goods and services is also an important objective. Hence, part of the land and water resources should be allocated for nature development. This is much more important in regions with a dry climate such as Borkhar sub-district, as realization of the development of a green area, a high priority for the region, because of its contribution to the welfare of the population and the protection of the environment, requires more efforts. Therefore, in this study, the total cropped area and total water use for agriculture have been selected as environmental indicators.

Table 6.6. Selected social, economic, and environmental indicators for assessment of agricultural policies

Objective	Sub-objective	Indicator	Unit
Economic	Production of strategic crops (Policy objective 1)	Wheat production	kg
		Sugar beet production	kg
		Colza production	kg
	Production of forage crops (Policy objective 2)	Barley production	kg
		Silage maize production	kg
		Alfalfa production	kg
	Productivity (Policy objective 3)	Water productivity	Rials/m^3
		Labour productivity	Rials/man-day
		Land productivity	Rials/ha
	Income	Net income	Rials
	Production cost	Production cost	Rials
	Government costs (Subsidies)	Fertilizer subsidy	Rials
		Irrigation system subsidy	Rials
Social	Employment	Total employment	Man-day
			-
	Overall self-sufficiency	Self-sufficiency in energy	%
		Self-sufficiency in protein	%
	Household self-sufficiency	Household self-sufficiency in energy	%
		Household self-sufficiency in protein	%
	Equity (income distribution)	Gini coefficient	-
Environmental	Nitrogen emission	N-leaching	kg
	Pesticide use	Pesticide use	kg
	Fertilizer use	Fertilizer-N	kg
		Fertilizer-P	kg
		Fertilizer-K	kg
	Agricultural land use	Cropped area	ha
	Agricultural water use	Irrigation water used	m^3

6.5 Policy impact assessment

In order to decide on the relevance of policy instruments, their efficiency and effectiveness should be assessed. Impacts can be estimated in different ways, i.e. through expert judgment, analogy or simulation (Sharifi, 2004). In this study, simulation modelling is used to assess impacts. The impacts of many of the policy instruments proposed in FFYDP for the arable farming sub-sector can be assessed with the developed simulation model (Chapter 5), but for illustrative purposes, only a limited number of the policy measures have indeed been analyzed. Three policy instruments, aimed at realizing the policy objective of “increasing water productivity” were implemented and their impacts were simulated using a goal programming model that minimizes the weighted deviations from the maximum possible value for each of the farmers’ objectives, i.e. maximize net income and minimize production cost (Chapter 5).

6.5.1 Base run

The base scenario refers to the situation in the year 2006, which was different from the year 2003 that was used for model calibration and validation. The differences are:

- Total available water in the canals in the year 2006 was 1.18 times that in the year 2003,
- Water was available during 7 months (April-October), instead of during 6 months (April-September) as in the year 2003,
- Sprinkler irrigation systems covered 480 ha land,
- All three irrigation regimes can be applied,
- Colza has been added to the list of crops that can be cultivated in the region.

Results of the base run were used as a benchmark for comparison of the impacts of policy instruments.

6.5.2 Policy instrument 1: Re-distribution of canal water

In this run, total available water in the canal is the same as in the base run, but it can be used as required, in any month of the year (12 months).

6.5.3 Policy instrument 2: Increasing water price

The water price is different for groundwater and canal water. Currently, 1-3% of the gross income of crop production is paid as costs for canal water to local water authorities. The lowest value refers to traditional irrigation networks with unlined canals and the highest to modern irrigation networks such as Borkhar irrigation system. The average water price per m^3 of canal water can be calculated from crop price, average crop yield and average seasonal water use for irrigation of that crop. The price of groundwater can be calculated based on the annual installments of the establishment costs (costs of drilling the well and purchase of the pumping system) and the annual costs for water extraction and maintenance of well and pumping system. It varies with well depth, groundwater table depth and water discharge of the well. In general, the price of groundwater is much higher than that of canal water. In this study, the average price for canal water and groundwater was set to 30 and 100 Rials per m^3, respectively.

The price of (canal) water is currently low in Iran. Some policy makers are of the opinion that this leads to less efficient use of water in the agricultural sector. Setting an appropriate water price per watershed is one of the policy instruments considered for improving water productivity. Doubling of the water price has been selected as policy instrument 2. In policy run[1] P2-1, the price of canal water has been doubled, and in policy run P2-2, the price of both canal water and groundwater.

6.5.4 Policy instrument 3: Promoting replacement of surface irrigation systems by sprinkler irrigation systems

Supporting farmers to change irrigation systems from surface to pressure irrigation by providing low-interest loans is one of the agricultural policy instruments in Iran. Irrigation efficiency at farm scale of pressurized irrigation systems is usually higher, resulting in higher water productivity. However, introduction of this system has some socio-economic limitations such as high initial cost, the need for skilled labour, and the need for protection of the system, of which the cost is the most important. Farmers are offered subsidized loans for the total installation costs of the pressurized irrigation system, with a pay-back period of 15-20 years. The difference between the interest paid by the farmer (5%) and the normal bank rate (14%) is subsidized by the government. This policy measure has been effective for farmers with medium and large farms, but has not stimulated smallholders, as the initial costs per unit area increase with decreasing farm size. The area served by pressurized irrigation systems is thus constrained by financial and technical (e.g., installation, use, maintenance) problems. In policy run P3, the maximum area under pressurized irrigation systems is limited to 2000 ha.

6.5.5 Policy instrument 4: Implementation of all three policy instruments combined

Usually, policy makers are using more than one policy instrument at the same time. However, different policy measures may affect each other. In policy

1 - Policy runs are different versions of policy instruments.

instrument 4, the three previous policy measures are combined. The various policy measures and the base run are summarized in Table 6.7.

Table 6.7. Characteristics of the various policy runs

Policy description	Policy run	Water availability in canal (months)	Water price (Rials*/m³)		Area served by sprinkler irrigation systems (ha)
			Canal	Groundwater	
Situation in the year 2006	Base	7	30	100	480
Increasing duration of water availability in the canal	P1	12	30	100	480
Increasing water price	P2-1	7	60	100	480
	P2-2	7	60	200	480
Increasing area of sprinkler irrigation system	P3	7	30	100	2000
All	P4-1	12	30	100	2000
	P4-2	12	60	100	2000
	P4-3	12	60	200	2000

* 1 US$ ≈ 10 000 Rials

6.5.6 Policy impacts

The responses of various farm types to the selected policy measures were simulated using the model developed in Chapter 5. The model was adapted for each policy run and then used for prediction of the cropping patterns (see Chapter 5 for a list of cropping activities) selected by each farm type. The total area under cultivation of different crops (Table 6.8) and their production (Table 6.9) are calculated by aggregation of the model outputs to sub-district scale.

The selected social, economic and environmental indicators have been calculated (Table 6.10) for each of the policy runs, based on the area of the selected agricultural activities and their inputs and outputs. The impacts of the policy instruments on the various policy objectives and on the social, economic and environmental indicators are compared with the base run in Table 6.11. The relative impacts of policy instruments on different indicators are presented in Figure 6.2, showing the largest relative deviation from the base run in the production of colza. This is because the production of this crop in the base run (454 Mg) is small compared to that of other crops (e.g., 15452 Mg for wheat). Figure 6.2 also illustrates that one policy measure may lead to better performance of one indicator and more unfavorable performance of another indicator for the same policy objective.

Table 6.8. Estimated total area (ha) under cultivation of different crops in Borkhar sub-district in the various policy runs

Crop	Base	P1	P2-1	P2-2	P3	P4-1	P4-2	P4-3
Wheat	3950	3748	4004	4143	4185	4215	4244	4297
Colza	194	125	154	60	363	185	167	107
Barley	827	658	923	507	831	933	997	921
Sunflower	324	305	330	57	358	351	354	355
Sugar beet	971	916	991	942	1074	1054	1062	1065
Maize	647	611	660	628	716	703	708	710
Melon	224	207	249	247	273	255	261	293
Watermelon	100	99	81	67	85	96	93	62
Alfalfa	205	187	202	181	350	192	199	223

Table 6.9. Estimated total production (10^6 kg) of different crops in Borkhar sub-district in the various policy runs

Crop	Base	P1	P2-1	P2-2	P3	P4-1	P4-2	P4-3
Wheat	15452	15129	15557	16173	16649	16739	16610	17215
Barley	2801	2295	3051	1784	2774	3372	3386	3026
Colza	454	294	363	139	852	430	395	250
Sunflower	683	670	745	117	791	824	841	680
Sugar beet	36268	34543	37397	35661	39353	38100	39900	36976
Maize	22766	21329	22096	22183	23833	24806	24293	26696
Melon	4934	4628	5281	5233	5904	5632	5566	6100
Watermelon	2025	2008	1650	1354	1741	1955	1887	1261
Alfalfa	1145	1101	1100	960	1895	1103	1139	1076

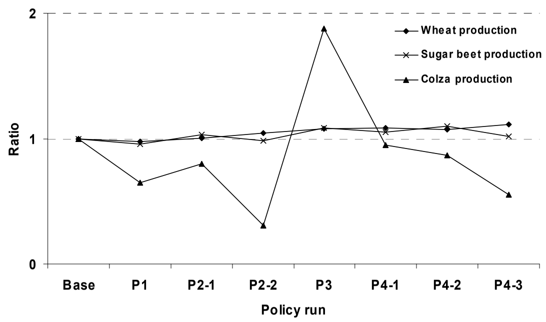
Comparison of the indicators related to policy objective 1 (increasing production of strategic crops) shows that the best performance in terms of colza production is attained in policy run P3, combined with satisfactory performance for the production of wheat and sugar beet (Figure 6.2-a). Maximum production of wheat is attained in policy run P4-3, however combined with lower production of sugar beet and colza than in policy runs P3, P4-1 and P4-2. Production of sugar beet is highest in policy runs P3 and P4-2, 8 and 9% higher, respectively than in the base run. Overall, policy run P3 shows the best performance in terms of the indicators for policy objective 1.

Table 6.10. Estimated social, economic and environmental indicators in Borkhar sub-district, Esfahan province, Iran, in the current situation (base run) and in the various policy runs

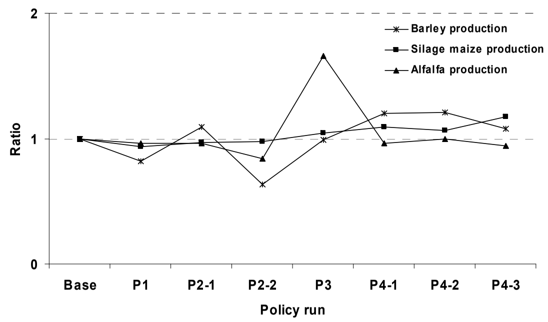
Objective	Sub-objective	Indicator	Unit	Policy run							
				Base	P1	P2-1	P2-2	P3	P4-1	P4-2	P4-3
Economic	Production of strategic crops (Policy objective 1)	Wheat	Mg	15452	15129	15557	16173	16649	16739	16610	17215
		Sugar beet	Mg	36268	34543	37397	35661	39353	38100	39901	36976
		Colza	Mg	454	294	363	139	852	430	395	250
	Production of forage crops (Policy objective 2)	Barley	Mg	2801	2295	3051	1784	2774	3372	3386	3026
		Silage maize	Mg	22766	21330	22096	22183	23833	24806	24293	26696
		Alfalfa	Mg	1145	1101	1100	960	1895	1103	1139	1076
	Productivity (Policy objective 3)	Water	Rials/m^3	665.5	670.1	660.4	620.8	696.6	716.9	697.8	627.7
		Labour	Rials/man-day	296886	305046	291792	273983	328918	336620	327837	288316
		Land	MRials/ha	5.7	5.94	5.57	5.29	5.57	5.67	5.54	4.92
	Net income	Income	MRials	42447.9	40694.1	42270.8	36135.1	45878.2	45265.1	44756.4	39507.8
	Production cost	Production cost	MRials	30596.7	28495.8	31775.1	33133.5	35185.2	33957.3	34786.1	39245.5
	Subsidy	Fertilizer	MRials	1081.6	1047.9	1110.2	1042.1	1211.9	1194.6	1191.9	1176.9
		Irrigation system	MRials	722.6	756.3	756.8	726.3	2901.1	2867.7	2895.9	2870.5
Social	Overall self-sufficiency	Energy	%	170.8	160.5	169.7	162.6	186	185.2	184.1	189.3
		Protein	%	218.9	207.6	218.5	209.7	240.8	237.5	236.4	243.9
	Household self-sufficiency	Energy	%	75.8	60	75.8	74.1	71.8	73.7	73.1	74.5
		Protein	%	75.8	77.6	76.4	79.8	75.4	73.7	73.1	83.9
	Employment	Total employment	Man-day	142977	133404	144866	131888	139482	134469	136520	137030
	Income distribution (equity)	Gini coefficient	-	0.52	0.52	0.53	0.56	0.56	0.56	0.57	0.58
Environmental	Nitrogen leaching	N Loss	Mg	107.5	103	105.6	100.6	100.8	97.7	101	94.3
	Pesticide use	Pesticide use	Mg	51.2	47.8	52	49.5	56.5	55	55.4	55.5
	Fertilizer use	Fertilizer (N)	Mg	1304.8	1259.4	1298.7	1235.2	1434.4	1396.3	1408.5	1377.8
		Fertilizer (P)	Mg	1225.1	1169.6	1266.2	1175.6	1347.2	1340.6	1338.1	1324.9
		Fertilizer (K)	Mg	176.6	154.3	157.3	188.7	158.3	136.1	171.7	140.3
	Agricultural land use	Cropped area	ha	7441	6856.6	7594.4	6830.2	8234.4	7986	8083.8	8033.4
	Agricultural water use	Irrigation water used	Mm^3	63.8	60.7	64	58.2	65.9	63.1	64.1	62.9

Table 6.11. Ratio of the indicator values in the various policy runs and in the base run

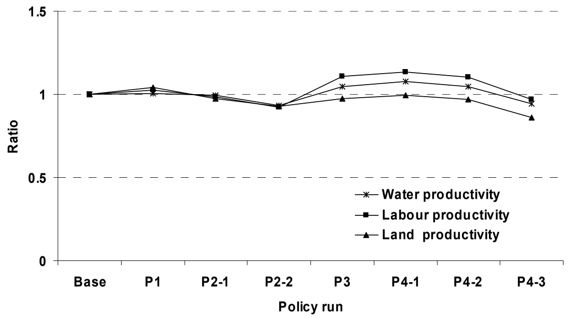
Objective	Sub-objective	Indicator	Policy run						
			P1	P2-1	P2-2	P3	P4-1	P4-2	P4-3
Economic	Production of strategic crops (Policy objective 1)	Wheat	0.98	1.01	1.05	1.08	1.08	1.07	1.11
		Sugar beet	0.95	1.03	0.98	1.09	1.05	1.10	1.02
		Colza	0.65	0.80	0.31	1.88	0.95	0.87	0.55
	Production of forage crops (Policy objective 2)	Barley	0.82	1.09	0.64	0.99	1.20	1.21	1.08
		Silage maize	0.94	0.97	0.97	1.05	1.09	1.07	1.17
		Alfalfa	0.96	0.96	0.84	1.66	0.96	0.99	0.94
	Productivity (Policy objective 3)	Water	1.01	0.99	0.93	1.05	1.08	1.05	0.94
		Labour	1.03	0.98	0.92	1.11	1.13	1.10	0.97
		Land	1.04	0.98	0.93	0.98	0.99	0.97	0.86
	Net income	Income	0.96	1.00	0.85	1.08	1.07	1.05	0.93
	Production cost	Production cost	0.93	1.04	1.08	1.15	1.11	1.14	1.28
	Subsidy	Fertilizer	0.97	1.03	0.96	1.12	1.10	1.10	1.09
		Irrigation system	1.05	1.05	1.01	4.01	3.97	4.01	3.97
Social	Overall self-sufficiency	Energy	0.94	0.99	0.95	1.09	1.08	1.08	1.11
		Protein	0.95	1.00	0.96	1.10	1.08	1.08	1.11
	Household self-sufficiency	Energy	0.79	1.00	0.98	0.95	0.97	0.96	0.98
		Protein	1.02	1.01	1.05	0.99	0.97	0.96	1.11
	Employment	Total employment	0.93	1.01	0.92	0.98	0.94	0.95	0.96
	Income distribution (equity)	Gini coefficient	1.00	1.02	1.08	1.08	1.08	1.10	1.12
Environmental	Nitrogen leaching	N Loss	0.96	0.98	0.94	0.94	0.91	0.94	0.88
	Pesticide use	Pesticide use	0.93	1.02	0.97	1.10	1.07	1.08	1.08
	Fertilizer use	Fertilizer (N)	0.97	1.00	0.95	1.10	1.07	1.08	1.06
		Fertilizer (P)	0.95	1.03	0.96	1.10	1.09	1.09	1.08
		Fertilizer (K)	0.87	0.89	1.07	0.90	0.77	0.97	0.79
	Agricultural land use	Cropped area	0.92	1.02	0.92	1.11	1.07	1.09	1.08
	Agricultural water use	Irrigation water use	0.95	1.00	0.91	1.03	0.99	1.00	0.99



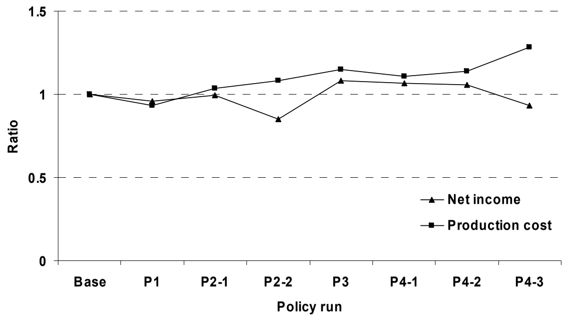
a) Policy objective 1: increasing production of strategic crops



b) Policy objective 2: increasing production of forage crops



c) Policy objective 3: increasing productivity of agricultural inputs



d) Farmers' objectives

Figure 6.2. Ratio of the indicator values in the various policy runs and those in the base run related to policy objective 1 (a), policy objective 2 (b), policy objective 3 (c) and farmers' objectives (d)

With respect to the indicators for policy objective 2 (increasing production of forage crops), the production of alfalfa and barley shows more variation than that of silage maize in the various policy runs (Figure 6.2-b). Maximum production of alfalfa is attained in policy run P3 (1895 Mg), i.e. 1.66 times that in the base run, while production of silage maize and barley is higher in policy runs P4-1, P4-2 and P4-3. Maximum production of silage maize and barley is attained in policy runs P4-3 and P4-2. In neither of the policy runs are the most favourable values for all three indicators of policy objective 2 combined. Hence, selection of the most appropriate policy instrument for this policy objective is not unequivocal.

Examination of the indicators related to policy objective 3 (increasing productivity of agricultural inputs) shows that only in policy run P1 the values of all indicators are higher than in the base run (Figure 6.2-c). Maximum values of water and labour productivity are attained in policy run P4-1, i.e. 8 and 13% higher, respectively than in the base run. In addition, the relative increase in labour productivity is larger than that in water and land productivity in policy runs P3, P4-1, P4-2 and P4-3 (Figure 6.2). The productivity of inputs expressed in different terms (net income, energy and protein) shows different trends. Water and labour productivity in terms of energy and protein are higher in policy run P4-3 than in the other policy runs (Table 6.12).

Table 6.12. Ratio of productivity of agricultural inputs based on net income, energy and protein in different policy runs and that in the base run

Productivity	Term	P1	P2-1	P2-2	P3	P4-1	P4-2	P4-3
Water	Income	1.01	0.99	0.93	1.05	1.08	1.05	0.94
	Energy	0.99	0.99	1.04	1.05	1.10	1.07	1.12
	Protein	1.00	0.99	1.05	1.06	1.10	1.07	1.13
Land	Income	1.04	0.98	0.93	0.98	0.99	0.97	0.86
	Energy	1.02	0.97	1.04	0.98	1.01	0.99	1.03
	Protein	1.03	0.98	1.04	0.99	1.01	0.99	1.03
Labour	Income	1.03	0.98	0.92	1.11	1.13	1.10	0.97
	Energy	1.01	0.98	1.03	1.12	1.15	1.13	1.16
	Protein	1.02	0.98	1.04	1.13	1.15	1.13	1.16

Net income of farm households is higher in policy runs P3, P4-1 and P4-2 than in the base run. In policy run P1, both indicators of farm household objectives (net income and production cost) are lower than in the base run. Net income is highest in policy run P3, i.e. 8% higher than in the base run, combined with 15% higher production cost, while in policy run P4-1, income is 7% higher with an 11% increase in production cost.

Total food production and overall self-sufficiency are highest in policy run P4-3. In all policy runs, except P2-1, total employment is lower than in the base run, with the lowest value in policy run P2-2. In all policy runs, the inequality in income distribution, as expressed in the Gini coefficient, exceeds that in the base run. The most unfavorable value for this indicator is attained in policy run P4-3. As the installation cost of sprinkler irrigation systems per unit area increases with decreasing farm size, the system is adopted on large farms, resulting in increased income, while income of the small farms, where the system is not adopted, is not affected. Labour requirements of sprinkler irrigation systems are lower than those of surface systems, so that total labour requirements decrease with increasing area of sprinkler irrigation systems.

From an environmental point of view, more favorable values than in the base run for *all* indicators are attained only in policy run P1. In terms of the individual indicators, policy runs P4-3, P2-2 and P4-1 show better performance than P1 and the base run for the indicators N Loss, N-fertilizer use and K-fertilizer use, respectively.

6.6 Evaluation of policy instruments

As indicated in the introduction, selection and assessment of indicators is an important step in the policy formulation process. The overall value of a policy (instrument) depends on its overall impact, taking into account all indicators. As illustrated for the different indicators in Section 6.5, it is difficult to select the most appropriate policy instrument, even for one policy objective, as no single instrument leads to improvements in all indicators. Therefore, a multi-criteria evaluation technique is used for analysis and aggregation of the indicators. Such a multi-criteria evaluation of the impacts of policy instruments evaluates the performance of each policy instrument with respect to the various indicators. DEFINITE software (Janssen et al., 2001) was used for the analysis that includes the following steps:

6.6.1 Standardization of indicators

Indicators should be standardized before further analysis, as they are expressed in different units and display different ranges of values (Table 6.10). All indicators were converted into utility with a value between 0 and 1, using the maximum standardization method (Table 6.13). In this method, scores are standardized with a linear function between 0 and the highest absolute score. For a benefit effect the absolute highest score is indicated with 1, for a cost effect the lowest score becomes 1 (Sharifi, 2005). It would be better to decide about the standardization method for each indicator individually.

Table 6.13. Standardized values of indicators in the base run and in the various policy runs

Objective	Sub-objective	Indicator	Benefit / Cost	Policy run							
				Base	P1	P2-1	P2-2	P3	P4-1	P4-2	P4-3
Economic	Production of strategic crops (Policy objective 1)	Wheat	B	0.9	0.88	0.9	0.94	0.97	0.97	0.96	1
		Sugar beet	B	0.91	0.87	0.94	0.89	0.99	0.95	1	0.93
		Colza	B	0.53	0.35	0.43	0.16	1	0.51	0.46	0.29
	Production of forage crops (Policy objective 2)	Barley	B	0.83	0.68	0.9	0.53	0.82	1	1	0.89
		Silage maize	B	0.85	0.8	0.83	0.83	0.89	0.93	0.91	1
		Alfalfa	B	0.6	0.58	0.58	0.51	1	0.58	0.6	0.57
	Productivity (Policy objective 3)	Water	B	0.93	0.93	0.92	0.87	0.97	1	0.97	0.88
		Labour	B	0.88	0.91	0.87	0.81	0.98	1	0.97	0.86
		Land	B	0.96	1	0.94	0.89	0.94	0.95	0.93	0.83
	Net income	Income	B	0.93	0.89	0.92	0.79	1	0.99	0.98	0.86
	Production cost	Production cost	C	0.22	0.27	0.19	0.16	0.1	0.13	0.11	0
	Subsidy	Fertilizer	C	0.11	0.14	0.08	0.14	0	0.01	0.02	0.03
		Irrigation system	C	0.75	0.74	0.74	0.75	0	0.01	0	0.01
Social	Overall self-sufficiency	Energy	B	0.9	0.85	0.9	0.86	0.98	0.98	0.97	1
		Protein	B	0.9	0.85	0.9	0.86	0.99	0.97	0.97	1
	Household self-sufficiency	Energy	B	1	0.79	1	0.98	0.95	0.97	0.96	0.98
		Protein	B	0.9	0.92	0.91	0.95	0.9	0.88	0.87	1
	Employment	Total employment	B	0.99	0.92	1	0.91	0.96	0.93	0.94	0.95
	Income distribution (equity)	Gini coefficient	C	0.09	0.1	0.08	0.02	0.03	0.03	0.01	0
Environmental	Nitrogen leaching	N Loss	C	0	0.04	0.02	0.06	0.06	0.09	0.06	0.12
	Pesticide use	Pesticide use	C	0.09	0.15	0.08	0.12	0	0.03	0.02	0.02
	Fertilizer use	Fertilizer (N)	C	0.09	0.12	0.09	0.14	0	0.03	0.02	0.04
		Fertilizer (P)	C	0.09	0.13	0.06	0.13	0	0	0.01	0.02
		Fertilizer (K)	C	0.06	0.18	0.17	0	0.16	0.28	0.09	0.26
	Agricultural land use	Cropped area	C	0.03	0.08	0.03	0.12	0	0.04	0.03	0.05
	Agricultural water use	Irrigation water use	C	0.1	0.17	0.08	0.17	0	0.03	0.02	0.02

6.6.2 Assigning priorities to objectives, sub-objectives and indicators

The relative importance of the objectives, sub-objectives and indicators for each sub-objective was defined through assignment of a weight factor. A structured pair-wise comparison method (Sharifi et al., 2004) was applied to determine the weights. In this method, objectives, sub-objectives and indicators are first sorted based on their importance from most to least important. The relative importance of each indicator is then derived through comparison with its neighbour. Since the indicators are in rank order, an indicator in comparison with the adjacent one can be equally, weakly more or strongly more important. In this method, the most important indicator is not compared to the least important one and only the two adjacent ones are compared with each other (Taleai et al., 2007). In this process, equally important indicators attain identical values. Weakly and strongly more important indicators will receive 1 and 2 extra points in value judgment, respectively. Ideally, this process should be carried out in collaboration with the relevant stakeholders. As time constraints prevented stakeholder consultations, weights were assigned based on subjective judgment of the author: Economic objectives were assumed more important than social and environmental objectives. Weight settings within the economic objective are presented in Table 6.14 as an example. Table 6.15 shows weights derived for each objective, sub-objective and all indicators.

Table 6.14. Weight settings within the economic objective (Method: Structured pair-wise comparison)

	Production of strategic crops	Production of forage crops	Productivity	Net Income	Production cost	Subsidies	Weight
Production of strategic crops	1	2	2	2	3	4	0.315
Production of forage crops		1	1	1	2	3	0.176
Productivity			1	1	2	3	0.176
Net Income				1	2	3	0.176
Production cost					1	2	0.097
Subsidies						1	0.060

Table 6.15. Weights of main objectives, sub-objectives and indicators at each level and overall weight of the indicators determined by structured pair-wise comparison

Level 1		Level 2		Level 3		Overall
Objective	weight	sub-objective	weight	Indicator	Level 3	
Economic	0.60	Production of strategic crops (Policy objective 1)	0.315	Wheat	0.50	0.095
				Sugar beet	0.25	0.047
				Colza	0.25	0.047
		Production of forage crops (Policy objective 2)	0.176	Barley	0.33	0.035
				Silage maize	0.33	0.035
				Alfalfa	0.33	0.035
		Productivity (Policy objective 3)	0.176	Water	0.50	0.053
				Labour	0.25	0.026
				Land	0.25	0.026
		Net income	0.176	Net income		0.105
		Production cost	0.097	Production cost		0.058
		Subsidy	0.060	Fertilizer	0.50	0.018
				Irrigation system	0.50	0.018
Social	0.20	Overall self-sufficiency	0.424	Energy	0.50	0.042
				Protein	0.50	0.042
		Household self-sufficiency	0.227	Energy	0.50	0.023
				Protein	0.50	0.023
		Employment	0.227	Total Employment	1	0.045
		Income distribution (equity)	0.122	Gini coefficient	1	0.024
Environmental	0.20	Nitrogen Leaching	0.250	N Loss	1	0.050
		Pesticide use	0.250	Pesticide use	1	0.050
		Fertilizer use	0.250	Fertilizer (N)	0.33	0.017
				Fertilizer (P)	0.33	0.017
				Fertilizer (K)	0.33	0.017
		Agricultural water use	0.125	Irrigation water use	1	0.025
		Agricultural land use	0.125	Cropped area	1	0.025

6.6.3 Ranking of the policy runs

The policy runs were ranked based on the scores of the indicators and their relative importance for the various objectives using a weighted additive linear function (weighted sum). Results of the multi-criteria analysis (Table 6.16) show that policy run P3 ranks first. This policy run yields the highest score for the economic objective, but the lowest score for the environmental objective. The first rank thus derives from the high weight assigned to the economic policy objective and the smaller variation in scores of the best and worst policy runs with respect to the environmental objective. Obviously, if other priorities would have been assigned to the indicators and their corresponding sub-objectives and objectives, the ranking would have been different. In the practice of policy formulation, the priorities should be based on the views of the decision makers. In fact, the multi-criteria evaluation should be used as a forum for discussion, negotiation and decision-making involving all stakeholders.

Table 6.16. Overall score and scores of the economic, social and environmental objectives in the multi-criteria evaluation of the various policy runs

Policy run	Economic	Social	Environmental	Overall
Base	0.76	0.83	0.06	0.64
P1	0.73	0.78	0.12	0.62
P2-1	0.75	0.83	0.06	0.63
P2-2	0.67	0.79	0.11	0.58
P3	0.82	0.85	0.03	0.67
P4-1	0.78	0.84	0.06	0.65
P4-2	0.77	0.84	0.04	0.63
P4-3	0.7	0.86	0.07	0.61

6.6.4 Uncertainty analysis

To evaluate the robustness of the ranking, an uncertainty analysis on the weights and scores has been carried out. Errors in the scores (assuming 10% error in the scores of all indicators) would result in some changes in the middle part of the rankings, but the same policy runs would be selected as the most and the least favorable (Table 6.17). Even 20% error in the weights of all indicators would not affect the ranking of the policy runs (Table 6.18).

6.6.5 Sensitivity analysis

The difference between the overall scores of the two most effective policy runs (P3 and P4-1) is small (Table 6.16). An analysis was carried out to determine the weights of the main objectives that would lead to reverse ranking of these two policy runs.

To reverse the order in the ranking of the two top policy runs, the weight of the economic objective should be reduced by 50% in favor of the environmental objective (Table 6.19), meaning that the decision makers would have to strongly change their minds to arrive at an alternative ranking. In other words, only stakeholders with widely diverging views would select different policy instruments, so it can be concluded that the ranking is robust.

Table 6.17. Probability of different policy runs obtaining different ranks due to uncertainty in the scores (10% error in the scores of all indicators)

Policy run	Rank								Overall score (out of 8)
	1	2	3	4	5	6	7	8	
P3	0.64	0.24	0.06	0.04	0.01	0.00	0.00	0.00	7.40
P4-1	0.11	0.33	0.29	0.16	0.08	0.02	0.00	0.00	6.11
Base	0.18	0.19	0.11	0.11	0.12	0.10	0.11	0.08	5.06
P4-2	0.01	0.09	0.25	0.32	0.24	0.08	0.01	0.00	5.03
P2-1	0.02	0.07	0.18	0.26	0.27	0.15	0.05	0.01	4.67
P1	0.04	0.07	0.10	0.10	0.16	0.19	0.20	0.16	3.68
P4-3	0.00	0.00	0.00	0.01	0.10	0.39	0.45	0.06	2.58
P2-2	0.00	0.00	0.00	0.01	0.03	0.07	0.19	0.70	1.46

Table 6.18. Probability of different policy runs obtaining different ranks due to errors in their weights (20% error in the weights of all indicators, sub-objectives and objectives)

Policy run	Rank								Overall score (out of 8)
	1	2	3	4	5	6	7	8	
P3	1	0	0	0	0	0	0	0	8
P4-1	0	1	0	0	0	0	0	0	7
Base	0	0	0.67	0.34	0	0	0	0	5.72
P4-2	0	0	0.34	0.63	0.03	0	0	0	5.31
P2-1	0	0	0	0.03	0.97	0	0	0	4.03
P1	0	0	0	0	0	0.98	0.02	0	2.98
P4-3	0	0	0	0	0	0.02	0.98	0	2.02
P2-2	0	0	0	0	0	0	0	1	1

Table 6.19. Weights of the main objectives used in the overall multi-criteria assessment and at the reversal point of runs P3 and P4-1

Objective	Original weight	Weight at reversal point
Economic	0.60	0.31
Social	0.20	0.22
Environmental	0.20	0.47

6.6.6 Analysis of results

The integrated impact assessment of the policy instruments shows that policy run P3 is the most attractive, followed by P4-1. Implementation of the policy instruments specified in these runs results in expansion of the area under sprinkler irrigation systems to 2000 ha. The difference between the two policy runs is in the duration of water availability in the canal: In P4-1, 12 months, compared to 7 months in P3. This difference results in a 1 and 4% lower total net income and total production cost, respectively in P4-1, as a consequence of the different cropping activities that are selected. Consequently, different impacts are expected on the different indicators. The impacts in policy run P3 are superior to those in P4-1 in terms of the social and economic objectives, but are less favorable in terms of the environmental objective. Examination of the overall scores of the impacts of all policy runs shows that policy run P3 is the most favorable in terms of the economic, second in terms of the social and most unfavorable in terms of the environmental objective. The most unfavorable policy run is P2-2 in which the price of both, canal and groundwater is increased. The most unfavorable but one is run P4-3, which is the same as P2-2, with the addition of an expanded area under sprinkler irrigation systems.

Increasing the price of canal water hardly affects the behavior of farmers, as illustrated by the small differences in the overall scores for the various objectives (economic, social and environmental) of runs that only differ in the price of canal water (P1 *vs*. base run and P4-1 *vs*. P4-2) (Table 6.16). This is the consequence of the low price of canal water, and thus its small share in the total production costs.

On the other hand, the price of groundwater has a larger influence on the behavior of farmers and consequently on the scores of the various objectives, as the cost of groundwater constitutes a much larger proportion of the total production costs. Impacts are most unfavorable in policy runs P2-2 and P4-3, in both of which the price of groundwater is increased. That results in the lowest values of net income, at 85 and 93%, respectively of that in the base run. Increasing the price of groundwater leads to increased (land, labour and water) productivity in terms of produced energy and protein, but reduced productivity in monetary terms (Table 6.12). As the productivity indicators have been defined as economic indicators, increasing the groundwater price results in more unfavorable values for the economic indicators, but in improved values for almost all environmental indicators (comparison of the impacts in policy runs P2-2 *vs*. P2-1 and P4-3 *vs*. P4-2).

As the irrigation efficiency of sprinkler irrigation systems is higher than that of surface irrigation, and water availability is the major constraint for agriculture in the region, the total cropped area and as a result total fertilizer and pesticide use are higher in these systems. Hence, increasing the area of pressurized irrigation systems (compare impacts in P3 with the base run) leads to more favorable overall scores for the economic and social objectives, but more unfavorable scores for the environmental objective.

Increasing the period of water availability in the canal from 7 to 12 months (P1 *vs*. the base run and P4-3 *vs*. P3) results in lower net income and production cost, with a greater reduction in production cost. This is due to the differential weights assigned to net income (0.7) and production cost (0.3) in the model. The assumption is that farmers are taking into account both net income and production cost to select their cropping activities. Overall assessment of the indicators shows that this policy measure results in more unfavorable scores for the economic and social objectives and more favorable scores for the environmental objective.

Results of this analysis show that different policy instruments show interactions and that implementation of a combination of different policy instruments would not be the best policy. In this study, in policy run P4-3, representing implementation of the combination of *all* policy instruments, water productivity in terms of energy and protein is highest, but the overall score is lowest. Thus, the question arises whether higher water productivity should be pursued at all costs.

6.7 Discussion and conclusions

6.7.1 Methodology

Policy formulation starts with definition of policy objectives, followed by identification of potentially available policy instruments and assessment and analysis of policy impacts. Usually, policy makers want to attain a multitude of policy objectives with varying priorities, as was illustrated for agricultural policy makers in Iran. Various policy instruments are available to policy makers to influence the behavior of farmers in order to achieve their objectives. For selection of the most appropriate policy instrument, ex-ante analysis is required to identify the response of farm households to their implementation, as a basis for establishing the effectivity and efficiency of the instruments.

The response of farm households to various policy instruments has been determined using a distributed simulation model that integrates their biophysical and socio-economic situation at local level (farm type - land unit). This model simulates the selection of a mix of cropping activities for different types of farm households for different land units within each village (spatially), taking into account the possible effects of various policy instruments. These activities are aggregated to higher spatial scales (farm type, village and sub-district). Social, economic and environmental indicators, required to assess the policy instruments, are aggregated for each policy instrument at these different scales. This provides a basis for policy impact analysis at different scales, based on site-specific information. Development and application of this distributed model is one of the strengths of this study.

The multi-criteria evaluation technique which has been applied for overall assessment of the policy instruments allows evaluation of their impacts on policy objectives from different perspectives.

Results of this type of analysis can be used as a basis for negotiation among various stakeholders with different objectives. Policy makers can also use this approach to learn more about the acceptability of various policy instruments and their expected effectivity and efficiency.

This type of analysis can support policy makers in selecting the most appropriate policy instrument(s) before implementation, and thus save time and money and reduce frustration. If the situation would change, the model could be updated and the analysis repeated to examine whether action is required.

In practice, the best results are to be expected when the priority of the relevant indicators is determined in collaboration and discussion with the various stakeholders. In the current study, a (subjective) bias has been introduced towards economic indicators. A bias in the list of indicators is one of the weaknesses of many developed impact assessment tools (Van Ittersum et al., 2008). On the other hand, the results of the uncertainty and sensitivity analyses show that the ranking of the policy instruments is not very sensitive to deviations in the scores and weights of the indicators. However, further analysis is necessary to establish the range in scores and weights among different stakeholders.

The method of standardization of the indicators is also important in determining their score. In principle, one should try to develop proper value function for each indicator. In this study, all indicators were converted to utility, applying the maximum standardization method.

6.7.2 Expansion of the methodology

In this study, only a few policy instruments were analyzed, although many others could have been studied. For this purpose, the simulation model (Chapter 5) should be adapted for examination of alternative policy instruments. Depending on the selected policy instrument, input/output tables or model parameters should be adapted or it may be necessary to add (an)other set(s) of constraints. Easy updating of the model has been a consideration in the process of model development. For this purpose, all parameters and calculations have been defined at the lowest spatial scale possible.

Subsidies on energy and agricultural inputs were part of the policy instruments in the various national development plans in Iran. However, in the latest development plan, reducing the subsidies was identified as a new policy objective. By reducing the subsidies, production cost will increase as will crop farm gate prices, the magnitudes depending on the contribution of subsidies to the production cost. The higher crop prices may result in lower demand, which could lead to a reduction in crop prices. In this study, prices were defined as exogenous variables; therefore, this tool may not be very suitable for subsidy analysis. For more realistic results in subsidy analyses, it might be better to determine prices exogenously, using macro-economic models (Khaledi, 2007) or expert knowledge, and introduce the new set of prices in the optimization model. So, connecting micro and macro level analyses is essential for analysis of this type of policy instruments (Sissoko, 1998; Van Ittersum et al., 2008).

Providing technical support to farmers is a new policy instrument, recently introduced in Iran. Agricultural engineers are giving technical support to farmers with low production efficiency. This policy instrument can also be analyzed with the current model, as crop production efficiency is one of the characteristics of the farm types identified.

7 General discussion

Agriculture is one of the most important sectors in the Iranian economy, providing a substantial proportion of the food to the country's 70 million inhabitants, in addition to raw materials for some of its industries. The contribution of the agricultural sector to the value of non-oil exports (year 2005) and total employment (year 2006) was around 22 and 18%, respectively (SCI, 2006; IRICA, 2007). The sector is the major user of land and water in the country. More than 17 million hectares of land are cultivated and about 94% of all available water in Iran is used in agricultural production (Alizadeh and Keshavarz, 2005).

Agricultural planning and policy formulation in Iran is carried out as part of national development planning. After formulation of nine national development plans, ample experience in planning has been built up, which is mainly based on general information about existing resources, vague goals, and expert judgment. Although extensive detailed information related to bio-physical and socio-economic conditions has been and is being collected, that is rarely used in the planning process. One of the reasons for this situation is the lack of an appropriate discussion and decision support tool that allows integration of biophysical and socio-economic information in the planning and policy formulation process. Therefore, there is a need for a support system that can integrate and aggregate (detailed) biophysical and socio-economic information at various spatial scales to facilitate agricultural planning.

The number of issues and the associated problems involved in agricultural policy formulation are immense. On the one hand because the agricultural sector is expected to contribute to a wide range of objectives, such as food security and food safety, production of raw materials for industries, generation of employment, generation of export income, provision of ecological goods and services, to mention the most important ones, and on the other hand, because the agricultural sector is heterogeneous, comprising a relatively large number of producers, each with its own resources, constraints and aspirations. Moreover, increasingly, consumers and special interest groups, such as nature conservationists and animal protection groups claim a stake in the agricultural production process and its impacts on quality of the food and the natural resources. Consequently, contributions from a wide range of disciplines are required to assess and analyze the impacts of agricultural policies. Tensions between aggregation levels, between stakeholders and between disciplines which frequently occur (Rabbinge and Van Ittersum, 1994), make agricultural system analysis complex, tedious and thus very difficult. Under these conditions, formulating policies and selecting policy instruments to achieve agricultural policy objectives that may be in conflict with other objectives of policy makers and with those of other stakeholders, is challenging. Therefore, ex-ante assessment of the effects of agrarian policies on objectives of different stakeholders, including policy makers and on agricultural sustainability is an absolute necessity for agricultural planners and policy makers.

Iran, like many other countries in the world, has launched many different programs and projects to evaluate the capacity of its various resources. In the framework of these projects and programs, large amounts of detailed data and additional information on different themes have been and are being collected, e.g., social, economic, biophysical, that constitute rich data sources, some of which are directly and some indirectly related to the agricultural sector. On the other hand, in the scientific community, many natural and socio-economic processes are studied, and the insights gained in these studies have been formalized in the form of various agro-ecological and bio-economic models that can potentially be used in support of the agricultural planning and policy formulation processes (Van Keulen, 2007). In the social and decision sciences, knowledge about planning and decision support systems has increased. Integration of these models, data and knowledge in a system to support agricultural planning and policy formulation is an important issue that receives extensive attention in the research community (e.g., (Bazzani, 2005a; López-Ridaura et al., 2005; Roetter et al., 2005; Nidumolu et al., 2006; Hengsdijk et al., 2007; Van Ittersum et al., 2008; Sterk et al., 2009) and was the subject of this research.

This study aimed at development and evaluation of an appropriate spatial planning support system to formulate agricultural policies and assess the impact and effectiveness of possible policy instruments. The system follows the framework for planning and decision making as developed by Sharifi and Zucca (2009). It will make use of the relevant and available socio-economic and biophysical information, and data collected for research and development projects by various organizations.

The specific research objectives were:
1. To develop a model for land resource analysis
2. To develop a planning model that integrates biophysical and socio-economic information to support agricultural policy formulation
3. To develop a model to support policy impact analysis

The system should provide a base for analysis at different spatial scales and negotiations among various stakeholders, including agricultural planners at different positions. As planning is a dynamic process and the “planning process” is becoming more important than the “plan” itself (Sharifi, 2003), the planning process requires proper support.

The philosophy behind this study was that a concept should be developed that can be implemented for agricultural policy formulation within the framework of national development planning. Therefore, the study has focused on methodology development, using one of the districts of Esfahan province as a case study. Following extensive discussions with policy makers on the usefulness and effectivity of the methodology, it may be extended to other regions in the country.

7.1 Strengths of the methodology

The planning support system developed in this study integrates detailed data from different sources and organizations (e.g., Ministry of Jihad-e-Agriculture, Ministry of Energy, meteorological stations, agricultural research institutes, disciplinary specialists, farmers) in different formats (reports, databases, maps, …) to support agricultural policy formulation and analysis.

In this section, some of the strong points of the methodology are discussed.

7.1.1 Spatial estimation of biophysical input-outputs

Spatial and temporal variability in biophysical resources and their impacts on crop yields and input requirements for crop production have been taken into account. Use of agro-ecological models to estimate crop production and its input requirements (water and fertilizer) per land unit for single and double cropping systems is one of the strengths of the method. Results of the biophysical resource analysis show significant spatial and temporal variation in yields, water and fertilizer requirements. These characteristics also vary significantly for different irrigation regimes and cropping systems.

The results of spatial analyses of biophysical resources can be used for different purposes (Chapter 5) by agricultural planners; in this study, they were used for generation of biophysical input-output coefficients in the planning model. Traditionally, agricultural planners in Iran have been using average crop yields, production targets and input requirements over the district in their plans, estimated on the basis of trend analyses of crop yields and production inputs, neglecting spatial variation in resource qualities. Use of location-specific input-output coefficients and spatial estimation of production resources (e.g., land and water) improves the quality of the analyses by reducing the aggregation bias due to spatially fixed input-outputs and ignoring inter-farm type variability in resource endowments (Jansen and Stoorvogel, 1998).

Spatial analysis of biophysical resources can be used to identify and assess (spatial) policy instruments. The policy instrument(s) that might be effective in achieving the policy objectives can be related, among other factors, to the gap between current and potential levels of crop production. This issue was not pursued in the current study, as the policy objectives and policy instruments that were analyzed were extracted from current agricultural policy documents in Iran.

7.1.2 Integration of biophysical and socio-economic data

Identification of an integrated unit of analysis was one of the crucial points for integration of biophysical and socio-economic data (Mohamed et al., 2000), as these data are reported for different spatial units (e.g., socio-economic data at the village scale, i.e. an administrative unit and biophysical data at the land unit scale, i.e. a natural resource unit), and its effects on the magnitude of aggregation bias (Day, 1963; Jansen and Stoorvogel, 1998). The integrated unit of analysis (farm type-land unit, FTLU) in this study is a combination of farm type (FT, identified based on data from agricultural holdings in the agricultural census of 2003) and land unit (LU, identified based on soil and administrative data), homogenous units in terms of socio-economic and biophysical characteristics, respectively. In each FTLU, resource endowments (e.g., land and water), potential production level and production efficiency are relatively similar. Therefore, based on Day's principle (Day, 1963), this should lead to restricted aggregation bias (Mohamed, 1999).

Separation of land unit and farm type is useful for possible updating of these units in the course of development. The properties of farm types that are assumed homogenous in terms of socio-economic characteristics, may change substantially in a relatively short time in the course of agricultural development, through for instance specialization or expansion, contrary to those of land units that only change over much longer time horizons.

In policy assessment, the integrated biophysical and socio-economic information is applied to simulate the reaction of farm households to policy instruments. Biophysical data at land unit scale were used for simulation of crop production in the potential and water-limited production situations. As the crop growth simulation model does not consider crop management, the concept of production efficiency was introduced in the farm classification to convert potential biophysical input-output coefficients at land unit scale to expected input-output coefficients at farm type-land unit scale. Socio-economic data were introduced into the system at farm type, village and sub-district scales.

7.1.3 Stakeholder involvement

Unfortunately, in this study stakeholders were insufficiently involved, as time constraints prevented extensive stakeholder consultations, but their possible involvement is considered in the design of the system, specifically in the sub-systems of policy impact assessment and policy analysis. Objectives of farmers used in this study (net income and production cost) were derived from interviews and discussions with farmers in different groups of agricultural production systems, managers of agricultural cooperatives, local officials and experts of the Jihad-e-Agriculture organization, provincial and national agricultural planners. As the (relative) importance of objectives is not the same for all farm types, in the model a provision is included to assign weights to different objectives for different farm types. The relative importance of different objectives for each farm type should be determined in consultations with and analysis of different groups of farmers.

Policy makers constitute the most important group of stakeholders involved in the process of policy impact assessment and analysis. Policy formulation starts with identification of policy objectives and relevant policy instruments. To assess the impact of different policy instruments, which aim at interventions in different components of the system, the planning model should be adapted. Policy impact analyses can be carried out from the perspective of policy makers at different spatial scales (e.g., local, provincial or national) or from that of different interest groups (e.g., agricultural, environmental, economic, consumer, etc.).

Transparent discussions, with participation of all relevant stakeholders can be based on explicit results of the model, provided there is agreement on the indicators. Discussions in which national and provincial policy makers participate might reduce the conflicts and disagreements about proposed plans between national and provincial planners.

7.1.4 Integrated assessment of policy impacts

A multi-criteria evaluation technique was used for integrated assessment of the policy impacts on the various social, economic and environmental objectives from the various perspectives of stakeholders. The most challenging issues in this analysis are the selection of the indicators and the assignment of their weights (preferences). It is not realistic to expect policy makers and stakeholders to be able to quantify the weights for the various objectives in advance (Sharifi et al., 2002). The structured pair-wise comparison method (Sharifi et al., 2004) is a simple method suggested to guide weight assignment. This method is carried out in two steps, which makes it easier for stakeholders: First a ranking is proposed of all indicators, after which each indicator is compared to its neighbor in verbal form (equally, weakly more or strongly more important) (Taleai et al., 2007). Although the weight assignment is challenging, analyses can be repeated easily by changing the weights and comparing the individual scores of the indicators, as well as the overall score. Such multiple analyses allow illustration of the consequences of priority setting in the objectives on the degree of goal attainment and the exchange values between different objectives. The DEFINITE software (Janssen et al., 2001) which was used in this study for multi-criteria analysis, supports sensitivity and uncertainty analysis on the weights and the scores of the indicators, which is useful for testing the robustness of the ranking, as a basis for selection of the most favorable policy instrument(s).

7.1.5 Multi-scale analysis

The developed model for agricultural policy formulation is a distributed model that simulates the behavior of farm households in response to policy measures, taking into account their socio-economic situation, the biophysical characteristics of their land and various production constraints at different spatial scales. Aggregation bias which is inherent in linear programming models, can be considerably reduced in the developed model for policy formulation, by selecting an appropriate basic planning (modelling) unit and the linkage between the planning models at different spatial scales. The regional model is constructed through aggregation of the farm type-land unit models and in linking, constraints were specified at different levels.

The decision on the relevant agricultural policy is mainly based on the overall assessment of the impacts of policy instruments at higher spatial scales such as the district, but impacts of policy instruments at lower scales such as farm (type), village, Dehestan and sub-district are also important for policy and decision makers, especially since the ‘ultimate’ decisions on land use (change) are made at farm (household) scale. In this study, impacts of policy instruments on the selected indicators are determined at the scale of the basic planning unit (FTLU) and then aggregated to higher scales. Therefore, the impacts of the policy instruments can be assessed at different spatial scales.

In addition, the aggregated outputs of the model can be used by agricultural planners to estimate the requirements for agricultural inputs such as fertilizers and pesticides.

7.2 Limitations/weaknesses of the methodology

In this section, some of the weaknesses/limitations of the planning support system are discussed, per sub-system.

7.2.1 Biophysical resource analysis

Homogeneity of the EMUs The Elementary Mapping Units (EMU) were assumed homogenous in terms of soil, weather and administrative unit. However, they might show different degrees of homogeneity, because:

a) The most detailed available soil maps were used that were of different scales in different parts of the district.

b) As no information was available on the borders of the villages, borders were created on the basis of Thiessen polygons. As a result, village polygons might not be accurate.
c) Weather was assumed homogenous over the agricultural area in each village. Weather characteristics were generated by interpolation of weather data from the weather stations for the centre of each village. In large villages (with the synthetic borders), the weather could be different in the centre of the EMUs and at its borders, although this difference is unlikely to be significant in terms of crop yields and input requirements.

Validity of crop parameters Several cultivars for each crop are cultivated in the study area, but only one set of characteristics for a specific cultivar for each crop was used for growth simulation in the entire district. Moreover, crop characteristics of silage maize, sugar beet, sunflower and potato were calibrated only marginally, because of lack of field data.

Different accuracy in the spatial estimates of crop yield and water requirements WOFOST could not be applied for some of the crops in the study area, either because of model limitations or lack of available data for model calibration. The alternative approach that was used for estimation of the water requirements of alfalfa, melon, water melon and colza could not properly take into account the spatial variation in crop water requirements. The crop coefficients used for calculation of the water requirements vary spatially, because of the spatial variation in weather characteristics, but in this study an average value for the entire district was used. Although WOFOST is a generic crop growth simulation model and use of a generic model is preferable, its application for indeterminate crops such as melon and watermelon is difficult. Incorporation of a routine for such crops could be an option in its further development.

Limitations of the crop growth simulation model in the water-limited production situation WOFOST, the model applied for crop growth simulations has some shortcomings in the water-limited production situation:

- The root zone is assumed homogenous in vertical direction
- Interactions of water and nutrients are not taken into account

7.2.2 Policy impact assessment

Homogeneity of farm types Farm type classification was based on agricultural census data from the district, using statistical analysis, using available land, available water, production efficiency and net income per ha as criteria. In estimating these variables, assumptions had to be made that may not be valid for all farm households. For example, total available water for the farms was calculated assuming full irrigation of the crops (applying the potential water requirements) and fixed irrigation efficiency for all farms. In addition, in estimating the production efficiency, actual yields were divided by calculated potential yields per crop for each village. Potential water requirements and crop yields were estimated in the biophysical resource analysis based on daily weather data of the census year. These values were thus derived from the models, that may have errors. As a result, the homogeneity of the farm types distinguished cannot be unequivocally established.

Distribution of land and water resources among farm type-land units In the absence of (spatial) information on the ownership of the land and water resources, several assumptions were made to distribute available land and water among the villages and farm types. Although the applied methodology for this distribution can be considered one of the strong points of this study, improvements may be possible.

- Digital maps of land and water resources were available, but it was not clear to which village and which farm type they belonged. Allocation of land and water resources among villages was thus based on the village borders, created using the Thiessen polygons.

- The area of each land unit has been partitioned among the farm types in the village, based on the number of farm types and the available land per farm type. This assumption may not be valid for smallholders.

- Total available water in each village has been distributed among the farm types in the village based on the number of farm types and the available water per farm type, calculated in the farm type classification. This assumes that water is freely available to all users within the village.

Modelling issues Despite the qualities of the developed bio-economic model in simulating the response of farm households to implementation of policy instruments, there are possibilities to improve.

- *Crop rotation* Crop rotations were considered in earlier versions of the model (Farhadi Bansouleh et al., 2008), but have subsequently been removed, because of lack of local data to quantify sequence effects of crops as a basis for generation of input-output coefficients for crop rotations.

- *Animal and horticultural activities* More than 30% of the agricultural holdings in Borkhar & Meymeh district owned at least 2 animals in the year 2003. Animal husbandry, fruit tree cultivation and greenhouse activities should be included in the bio-economic model, as they are using part of the agricultural resources (e.g., land, water, and labor) and are thus in competition with arable cropping activities. These activities may also influence the farmers' objectives and constraints. In this study, these activities and their effects on the behavior of farmers were not taken into account. In the current model, only one constraint (alfalfa production constraint) related to animal husbandry activities was specified for some of the farm types. Although alfalfa is cultivated in the district and used for animal feeding, it was not selected by the model, as it can not compete financially with other crops and income from animal husbandry activities was not included in the model. To force the model to select alfalfa which is needed to feed animals, the constraint on alfalfa production was specified for large holdings and agro-industrial units, which practice animal husbandry as an economic activity.

- *Irrigation regimes for each crop in double cropping activities* In the current model, both winter and summer crops in double cropping activities are assumed to apply the same irrigation regime, which, in practice is not always the case.

- *Risk* Risk is an important issue in agricultural planning, for instance with respect to both, crop production and prices (Laborte, 2006). It was not investigated in this study and should be considered in subsequent versions of the model.

- *Other objectives of farmers and the weights of the objectives in the discussion with farmers* Some of the farm types may have other objectives than considered in this study. The objectives of farmers and their relative importance should be determined in discussions and consultations with farmers' representatives. In an earlier version of the model, maximization of water productivity was also considered one of the objectives of farmers (Farhadi Bansouleh et al., 2008), but it was omitted in the final version of the model, as it is an objective of policy makers not farmers.

Data issues: All data that were used in this study were available from earlier studies and projects. Collection and management of these data was a major task, as they were stored in different organizations in different formats. This made data collection, saving data in databases, and quality control of data a time-consuming and tedious task. Some data were not made available at all for this study or only after a prolonged period and complex negotiations. Inconsistencies appeared in the data and maps provided, sometimes even within one organization. One of the strengths of this study was development of a planning support system based on accessible data.

7.2.3 Policy analysis

- **Vague list of policy objectives** Careful examination of agricultural development documents yielded a long list of objectives for agricultural planning that, however were vague and too general. Identification, quantification and prioritization of relevant indicators for all these objectives needs further study and discussions with planners and policy makers involved in the actual practice of national and/or regional development planning. However, by increasing the number of indicators, assessment of policy instruments will become more difficult.

- **Limited involvement of stakeholders** Although the importance of stakeholder involvement in the development of a collaborative spatial planning support system was understood, insufficient attention was paid to stakeholder consultation in this study.

- **Bias in the water and irrigation issues** A bias toward water and irrigation management is apparent in the list of activities and policy instruments in the current study. This bias has two reasons: 1) *Importance of water and irrigation in Iran* Water is the major constraint for agricultural development in most of Iran, especially in the study area which has a dry climate. Therefore, irrigation methods and regimes leading to high water use efficiencies are promoted by agricultural policy makers and used by farmers. 2) *Interest and position of the author as one of the stakeholders*: The author is an irrigation engineer who is working in the Water Engineering Department of Razi University, Iran, involved in teaching and research in the field of irrigation and water management.

7.3 Operational issues for application of the system

The methodology developed in this study can be applied to other regions (districts) of the country, as it was developed on the basis of data availability in Iran. No primary data collection was carried out, as one of the starting points for this study was that all required data for this system would have to be extracted from earlier and on-going projects, programs and studies. Implementation of this system in other regions requires data for and knowledge of the models developed for biophysical resource analysis, policy impact assessment and policy analysis. Almost all required data for implementation of the system are available for different administrative units in Iran. Scarcity of data, such as for solar radiation does not limit application of crop growth simulation models, as this characteristic can be derived from other weather characteristics, e.g., sunshine-hours and temperature with acceptable accuracy. Calibration and validation of crop characteristics needs at least two years of detailed field experimentation, which should be planned.

Understanding of the basic principles of the three types of models used in this study is required for implementation and possible modification of the system in other regions. The following issues should be considered for operationalization of this system.

Complexity of the system Complexity in the spatial planning support system for agricultural policy formulation is unavoidable, because agricultural planning is complex and influenced by a wide variety of factors and processes such as policy objectives of policy makers, biophysical characteristics of the land, availability and quality of other resources, available technologies for agricultural production, markets, type of policy instruments, aims and aspirations of farmers, etc. Moreover, some of these elements vary in time and/or space or among (groups of) agricultural production systems. The complexities in the developed system reside mainly in the biophysical resource analysis and policy impact assessment parts that should be executed by analysts. The multi-criteria evaluation technique, which was applied in the overall assessment of policy impacts, looks easy, but it is not. It needs stakeholder analysis, consultation with the stakeholders, and translation of the verbal preferences of stakeholders into weights of objectives from different perspectives.

Knowledge requirements Knowledge from different disciplines (e.g., soil science, meteorology, agronomy, economics, environmental sciences, social sciences, planning, simulation, etc.) is used in the developed system. For implementation of this system in other districts, elements of the models (e.g., list of activities, input-output coefficients of the activities, priority of objectives, available resources, etc.) should be modified, based on the situation in that district. Therefore, for implementation of the system in other districts, basic knowledge about these models is required.

User-friendly interface for interaction between different models The developed system comprises different models, in which part of the outputs of one model were used as input in another model. As the focus of this study was on system development rather than system automation, interactions between the models are carried out manually. Development of a user-friendly interface to integrate all these models and data would be a useful addition to the system.

Investment requirements Crop characteristics included in the crop growth simulation model are variety-specific. These characteristics should be calibrated and validated based on at least two years field data. Considering the different varieties cultivated in different parts of the country, a major investment should be made in a national research project to collect the necessary information.

It is recommended to design a national research project to calibrate and validate crop characteristics for major crops/varieties in different climates of Iran. Use of available data from historical and on-going research would be an option for calibration of crop characteristics. In some agricultural studies, especially in agronomy departments, daily field observations are recorded. This wealth of data could be used to initiate calibration of crop characteristics, as crop varieties cultivated in Iran are generally location-specific.

Up-scaling of the methodology The original objective of this study was to develop a planning support system for national level; however, the question is whether the applied methodology can be applied at provincial and national level. A multi-disciplinary research project is required for up-scaling of the developed planning support system to provincial and national level. In the aggregation, the link between micro and macro levels should be considered, and prices of crop products should become endogenous. Involvement of agricultural planners, especially experts of APERI, the Agricultural Planning and Economic Research Institute, involved in supporting agricultural policy formulation in the Iranian Ministry of Jihad-e-Agriculture, would increase the chances of development of an appropriate planning support system for agricultural policy formulation at national level.

7.4 Concluding remarks

The system developed in this study represents a relevant further step in the development of computer-aided decision support systems for land use analysis that have received ample attention in the research community, in response to the perceived needs of policy makers (Sterk et al., 2009). As these authors extensively document, however, impact of these modeling tools in what has been called the ‘unruly practice of land use planning’ (Van Keulen, 2007) is extremely difficult to assess. It thus appears that still a long way has to be gone to bridge the gap between ‘the policy makers that are asking questions that land use modelers cannot answer and the land use modelers that are generating answers to questions that policy makers are not asking’, to paraphrase an assessment by prof. C.T. De Wit of Wageningen Agricultural University, one of the ‘fathers’ of land use modeling (De Wit et al., 1988).

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Summary

In this study, a system was developed to support agricultural planners and policy makers in land resource analysis, policy formulation, identification of possible policy measures and policy impact analysis. The research is part of a larger programme, aiming at development of a model system to support agricultural policy formulation at national level. The current study focused on methodology development and its implementation in Borkhar & Meymeh district in Esfahan province, Iran.

The system comprises three main components, i.e. resource analysis, policy impact assessment and policy evaluation. The biophysical resource analysis was carried out using CGMS, the Crop Growth Monitoring System which includes WOFOST, a generic crop growth simulation model. This model simulates growth of annual crops in the potential and water-limited production situations, based on daily weather data, crop characteristics and soil physical characteristics. For this purpose, crop characteristics of winter wheat and winter barley were calibrated based on research data from the agro-meteorological research center of Kaboutar Abad, Esfahan, Iran. Crop characteristics of silage maize, sugar beet, sunflower and potato were calibrated based on yields of the best agricultural producers in the region.

For the weather stations in which solar radiation was not measured, it was estimated from sunshine-hours or temperature, using empirical relations. A sensitivity analysis on method of solar radiation estimation was carried out to test model performance in terms of simulated crop yield and water requirements for winter barley and sugar beet as representatives of winter and summer crops, respectively. Results of this analysis showed that the maximum difference in simulated crop yield based on estimated and measured solar radiation is less than 10%.

CGMS was used for land resource analysis at the regional (district) scale. The potentially suitable area for agriculture in the district was identified and classified into 128 homogenous units (referred to in this study as Elementary Mapping Units, EMU) in terms of soil, weather and administrative unit. For each EMU, soil physical characteristics were derived from available soil maps and soil analyses reports. Daily weather characteristics (maximum and minimum temperature, vapor pressure, wind speed, rainfall, and solar radiation) were generated for the centre of each EMU by interpolation of daily weather data of 33 weather stations, located in and around the district. CGMS was then modified to allow calculation of irrigated crop yields. Yields of major crops and water requirements per decade were simulated using CGMS for three irrigation regimes (full irrigation, 20% and 40% deficit irrigation). Fertilizer requirements

for the three macro-nutrients, nitrogen, phosphorus and potassium, for each level of crop production were estimated based on soil chemical characteristics, crop yields and nutrient content in economic crop products and crop residues. An alternative methodology was developed for spatial estimation of crop yields, water and fertilizer requirements of crops (alfalfa, melon, watermelon, and colza) that could not be simulated by CGMS, either because of model limitations or lack of data for model calibration. The ratio of current and potential crop yields, referred to as production efficiency, was used as an indicator of management ability of farmers and was used in farm classification.

The policy formulation process consists of three steps: i) selection of policy objectives, ii) identification of policy instruments and iii) assessment and analysis of their impacts. In this study, policy objectives and relevant policy instruments were derived from the latest agricultural development documents. A model was developed to assess the impacts of policy instruments and another model for analysis of these impacts from different perspectives. As reactions of farmers to policy instruments may be different, depending on their socio-economic situation and the biophysical characteristics of their land, a planning (modelling) unit was defined, homogenous in terms of biophysical and socio-economic characteristics. For this purpose, farms belonging to each of the agricultural production systems (e.g., traditional, cooperative and agro-industrial) were classified into farm types, based on land and water availability, overall production efficiency and average net income per ha. These farm types were combined with land units to form the basic units of analysis, i.e. farm type-land units (FTLU), homogenous in terms of biophysical potential, as well as in resource endowments and management ability of farmers.

A distributed linear programming model was developed to assess policy impacts by simulating the response of the various farm types to specific policy instruments. This model is optimizing a utility function, composed of a combination of net income and production cost, subject to various constraints at different spatial scales (e.g., farm type-land unit, farm type, village, and sub-district). The model was validated based on the conditions of the year 2002-03 by comparing simulated crop yields and total crop production in Borkhar sub-district with detailed agricultural census data. Indicators, representing the effect/impact of policy instruments on economic, social, and environmental objectives of various stakeholders were selected and quantified in a post-model analysis.

In a model experiment, the reactions of the different farm types to three policy instruments, aiming at increasing agricultural water productivity in Borkhar sub-district were simulated. A multi-criteria evaluation technique was used for policy analysis through overall assessment of the various economic, social and

environmental indicators to evaluate the effectiveness of various policy instruments.

The developed system represents a further step in the development of computer-aided decision support systems for land use analysis that have received ample attention in the research community, in response to the perceived needs of policy makers. The consultations with planners in the course of the study, leads to the conclusion, however, that still a long way has to be gone to bridge the gap between the policy makers that are asking questions that land use modelers can not answer and the land use modelers that are generating answers to questions that policy makers are not (willing to) ask(ing).

Samenvatting

In deze studie is een systeem ontwikkeld ter ondersteuning van landbouwkundige planners en beleidsmakers bij de analyse van natuurlijke hulpbronnen, formulering van beleid, identificatie van mogelijke beleidsmaatregelen en analyse van de effecten van invoering van dergelijke maatregelen. Deze studie maakt deel uit van een groter onderzoeksprogramma, gericht op de ontwikkeling van een model ter ondersteuning van het formuleren van landbouwbeleid op nationale schaal. De huidige studie richtte zich op de ontwikkeling van methodologie en toepassing van di methode in Borkhar & Meymeh district in de provincie Esfahan, in Iran.

Het systeem bestaat uit drie grote onderdelen, namelijk analyse van natuurlijke hulpbronnen, beleidsontwikkeling en beleidsevaluatie. De biofysische analyse van de natuurlijke hulpbronnen is uitgevoerd met behulp van CGMS, het Crop Growth Monitoring System, waarvan WOFOST, een generiek simulatiemodel.voor de groei van éénjarige gewassen, deel uitmaakt. Dit model simuleert de groei van éénjarige gewassen in de potentiële en de water-beperkte productiesituaties, op basis van dagelijkse weersgegevens, gewaskarakteristieken en fysische bodemkarakteristieken. Daartoe zijn de eigenschappen van wintertarwe en wintergerst gekalibreerd, gebaseerd op gegevens uit onderzoek in het agrometeorologische onderzoekscentrum van Kaboutar Abad, Esfahan, Iran. Gewaskenmerken van snijmaïs, suikerbiet, zonnebloem en aardappelen zijn geijkt op basis van de opbrengsten van de beste agrarische producenten in de regio.

Voor de weerstations waar zonnestraling niet was gemeten, is die straling geschat op basis van gemeten zonne-uren of van temperatuur, met behulp van empirische relaties. Een gevoeligheidsanalyse is uitgevoerd om de gevoeligheid van modeluitkomsten, in termen van gesimuleerde opbrengsten en benodigde hoeveelheden water, te toetsen voor wintergerst en suikerbiet als vertegenwoordigers van de winter- en de zomergewassen. De resultaten laten zien dat het maximale verschil in gesimuleerde opbrengst gebaseerd op geschatte en gemeten zonnestraling minder is dan 10%.

CGMS is gebruikt voor de analyse van de natuurlijke hulpbronnen op regionale schaal. Het potentieel voor landbouw geschikte areaal in het district werd vastgesteld en verdeeld in 128 eenheden, homogeen in termen van bodemkarakteristieken, weersgesteldheid en administratieve eenheid (in deze studie worden die eenheden aangeduid als Elementary Mapping Units, EMU). Voor iedere EMU zijn de bodemfysische karakteristieken afgeleid uit beschikbare bodemkaarten en bodemanalyses. Dagelijkse weersgegevens (maximum en minimum temperatuur, luchtvochtigheid, windsnelheid, neerslag en zonnestraling) zijn gegenereerd voor het centrum van elke EMU door

interpolatie van de dagelijkse weersgegevens van 33 weerstations, gelegen in en rondom het district. CGMS is daarna aangepast om berekening van de opbrengst van geïrrigeerde gewassen mogelijk te maken. De opbrengsten van de belangrijkste gewassen en de waterbehoeften per tiendaagse periode zijn gesimuleerd met behulp van CGMS voor drie irrigatieregimes (volledige irrigatie, 20% en 40% deficit irrigatie). De kunstmestbehoeften voor de drie macronutriënten, stikstof, fosfor en kalium, voor ieder van de productieniveaus zijn berekend op basis van bodemchemische kenmerken, gewasopbrengsten en nutriëntengehalten in de hoofdproducten en de gewasresten.
Een alternatieve methode is ontwikkeld voor de ruimtelijke schatting van gewasopbrengsten en water- en kunstmestbehoeften voor de gewassen (luzerne, meloen, watermeloen, en koolzaad) die niet konden worden gesimuleerd door CGMS, hetzij als gevolg van beperkingen van het model of vanwege het ontbreken van gegevens voor calibratie van het model.
De verhouding van actuele en potentiële opbrengsten, gedefinieerd als productie-efficiëntie, is gebruikt als indicator voor de kwaliteit van het beheer van de bedrijven en is gebruikt in de bedrijfsclassificatie.

Het proces van beleidsformulering bestaat uit drie stappen: i) selectie van de beleidsdoelstellingen, ii) identificatie van relevante beleidsinstrumenten en iii) beoordeling en analyse van hun effecten. Beleidsdoelstellingen zijn afgeleid uit recente beleidsdocumenten. Vervolgens is een model ontwikkeld om de effecten van de verschillende beleidsmaatregelen vast te stellen, en een model om de effecten te beoordelen vanuit verschillende perspectieven. De reacties van boeren op beleidsmaatregelen kunnen verschillen, in afhankelijkheid van hun sociaal-economische omstandigheden en de kwaliteit van hun land. Daarom zijn planningeenheden gedefinieerd die homogeen zijn in zowel sociaal-economisch als biofysisch opzicht.
Bedrijven uit elk van de verschillende productiesystemen (traditionele, coöperatieve en agro-industriële) zijn geclassificeerd in bedrijfstypen, gebaseerd op de beschikbaarheid van land en water, hun productie-efficiëntie en het gemiddelde netto inkomen per ha. Deze bedrijfstypen zijn gecombineerd met landeenheden om te komen tot de basiseenheden van de analyse, de bedrijfstype-landeenheden (FTLU), homogeen in termen van biofysisch potentieel, beschikbaarheid van hulpbronnen en de beheerscapaciteit van de boeren.

Een gedistribueerd lineair programmeringsmodel is ontwikkeld om de respons van de verschillende bedrijfstypen op het invoeren van de beleidsmaatregelen te simuleren. In het model wordt een ‘utilityfunctie’ geoptimaliseerd, die bestaat uit een combinatie van het netto inkomen en de productiekosten, met verschillende beperkingen gedefinieerd op verschillende ruimtelijke schalen (bijv. bedrijfstype-landeenheid, bedrijfstype, dorp, en sub-district). Het model is gevalideerd op basis van de situatie in het jaar 2002-03 door vergelijking van gesimuleerde opbrengsten en totale productievolumes van verschillende gewassen in Borkhar sub-district, met gedetailleerde gegevens uit de landbouwtelling. Indicatoren, die de effecten weergeven van beleidsmaatregelen op de economische-, sociale- en milieudoelstellingen van de verschillende belanghebbenden zijn geïdentificeerd en gekwantificeerd in een post-model analyse.

In een experiment met het model zijn de reacties van de verschillende bedrijfstypen gesimuleerd op drie beleidsmaatregelen, gericht op het verhogen van de waterproductiviteit in de landbouw in Borkhar sub-district. Een multi-criteria evaluatietechniek is gebruikt voor een overall analyse van de verschillende indicatoren om de effectiviteit van de verschillende beleidsmaatregelen vast te stellen.

Het ontwikkelde systeem vormt een belangrijke verdere stap in de ontwikkeling van computer-aided beslissingsondersteunende systemen voor landgebruiksanalyse, zoals die ruime aandacht hebben gekregen in de onderzoekswereld, in response op de aanwezig geachte behoeften van beleidsmakers. De interactie met planners in de loop van de studie hebben geleid tot de conclusie dat er nog een lange weg te gaan is om de afstand te overbruggen die bestaat tussen de beleidsmakers die vragen stellen die de ontwikkelaars van landgebruiksmodellen niet kunnen beantwoorden en de ontwikkelaars van landgebruiksmodellen die antwoorden genereren op vragen die beleidsmakers niet (willen) stellen.

(Summary in Persian) خلاصه

در این مطالعه یک سیستم جهت پشتیبانی برنامه ریزان و سیاست گزاران کشاورزی در ارزیابی منابع اراضی و تدوین و آنالیز سیاستهای کشاورزی تهیه گردید. این تحقیق بخشی از یک برنامه وسیعتر می باشد که هدف آن ارایه یک سیستم پشتیبانی برای تدوین سیاستهای کشاورزی در سطح ملی می باشد. در مطالعه کنونی تمرکزروی تدوین متدو لوژی و بکار بردن آن در یک شهرستان (شهرستان برخوارو میمه واقع در استان اصفهان) بوده است.

سیستم تدوین شده دارای سه زیر سیستم به نامهای 1) ارزیابی منابع اراضی، 2) تعیین و برآورد آثار سیاستها و 3) ارزیابی آثار سیاستها می باشد. ارزیابی منابع بیو فیزیکی با استفاده از سیستم نظارتي رشد محصول (CGMS[1]) که شامل مدل شبیه سازی رشد گیاه WOFOST می باشد، انجام گرفت. WOFOST یک مدل عمومی (Generic) شبیه سازی رشد محصولات کشاورزی می باشد که قادر است رشد گیاهان زراعی یک ساله را درشرایط پتانسیل و آبیاری محدود (کم آبیاری) براساس خصوصیات گیاهی، اطلاعات روزانه هواشناسی و خصوصیات فیزیکی خاک شبیه سازی کند. پارامترهای گیاهی مدل WOFOST باید برای گیاهان مختلف بر اساس شرایط محلی کالیبره شود. در این مطالعه پارامترهای گیاهی این مدل برای گندم و جو براساس اطلاعات موجود ازمشاهدات و تحقیقات انجام گرفته در مرکز تحقیقات هواشناسی کشاورزی کبوتر آباد اصفهان کالیبره گردید. پارامترهای گیاهی برای ذرت علوفه ای، چغندرقند، آفتابگردان (آجیلی) و سیب زمینی براساس اطلاعات موجود و حداکثر عملکردهای ثبت شده در منطقه به طور تقریبی کالیبره گردید.

تشعشع خورشیدی یکی از پارامترهای اساسی در رشد گیاه می باشد که در تعداد کمی از ایستگاههای هواشناسی اندازه گیری می شود. این پارامترهواشناسی در ایستگاههایی که اندازه گیری نشده است از طریق روابط تجربی براساس سایرپارامترهای هواشناسی (ساعات آفتابی یا درجه حرارت) محاسبه گردید. آنالیز حساسیت روی نتایج مدل شبیه سازی رشد گیاه نسبت به روشهای مختلف برآورد تشعشع انجام گردید. برای این منظور عملکرد و آب مورد نیاز گندم و ذرت علوفه ای (به عنوان نمایندگان محصولات زمستانه و تابستانه) براساس تشعشع خورشیدی محاسبه شده با روشهای مختلف، با استفاده از مدل WOFOST برآورد و مورد آنالیزقرار گرفت. نتایج آنالیزنشان داد که بیشترین میزان اختلاف در عملکرد برآورد شده براساس تشعشع محاسباتی با روشهای مختلف با عملکرد برآورد شده براساس تشعشع اندازه گیری شده کمتر از 10 درصد می باشد.

در این مطالعه ازCGMS جهت ارزیابی منابع اراضی درسطح منطقه (شهرستان) استفاده گردید. در این راستا ابتدا اراضی مناسب برای کشاورزی مشخص وسپس به تعدادی واحد همگن (128 واحد در شهرستان برخوارو میمه) از نظر خاک، اقلیم و اداری تقسیم، و واحد اراضی (Land Unit; LU) نامیده شدند. خصوصیات فیزیکی خاک هر کدام از این واحدهای همگن از روی نقشه ها و گزارشهای خاکشناسی موجود استخراج گردید. پارامتر های روزانه هواشناسی (درجه حرارت حداقل و حداکثر، سرعت باد، فشاربخار(رطوبت نسبی)، بارندگی و تشعشع خورشیدی) در مرکز ثقل هر کدام از واحدهای همگن با میانیابی داده های روزانه 33 ایستگاه هواشناسی (درون شهرستان و یا مجاور آن) تولید گردید. عملکرد و آب موردنیاز(برای هر دهه) محصولات عمده منطقه درحالت پتانسیل برای هرکدام ازواحدهای همگن محاسبه شد. از آنجا که CGMS قادر به درنظر گرفتن آبیاری بطورمستقیم نیست، برنامه جداگانه ای برای محاسبات زمان و عمق آبیاری تهیه گردید. از طریق این برنامه مقدارآب خالص جهت آبیاری در رژیمهای 20 و 40 درصد کم آبیاری محاسبه ودر زمانی که باید

[1] Crop Growth Monitoring System

آبیاری انجام گیرد به بارندگی اضافه گردید. نتایج CGMS در حالت آبیاری محدود بیانگروضعیت رویشی گیاه با رژیم آبیاری اعمال شده می باشد. تعدادی از گیاهان موجود در منطقه (یونجه، خربزه، هندوانه و کلزا) به دلایل محدودیت مدل و یا کمبود اطلاعات جهت کالیبراسیون پارامترهای گیاهی ، قابل شبیه سازی با این مدل نبودند. برای محاسبه عملکرد و آب موردنیازاین گیاهان در واحدهای همگن یک روش ترکیبی ارائه گردید. میزان کود مورد نیاز برای سه عنصراصلی (نیتروژن، فسفر و پتاسیم) درسطوح مختلف تولید (آبیاری کامل، 20 و 40 درصد کم آبیاری) برای تمامی محصولات و واحدهای همگن براساس خصوصیات شیمیایی خاک، میزان عملکرد و درصد این عناصر در محصول اصلی و بقایای گیاهی برآورد گردید. نسبت عملکرد جاری به عملکرد پتانسیل که کارایی تولید (Production efficiency) نامیده شده است، شاخصی از وضعیت مدیریت مزرعه می باشد که در گروه بندی مزارع بکار رفته است.

فرآیند تدوین سیاست شامل سه مرحله می باشد: 1) انتخاب اهداف سیاستی 2) تعیین سیاستها و 3) ارزیابی آثار سیاستها و تعیین سیاست مطلوب. در این مطالعه، اهداف و ابزارهای سیاستی از سندهای مربوط به توسعه بخش کشاورزی ایران استخراج گردیده است. عمده تمرکزاین مطالعه روی مرحله 3 این فرآیند می باشد. یک مدل برای تعیین (برآورد) آثارابزارهای سیاستی و مدلی دیگر برای آنالیز این آثار از دیدگاههای مختلف تهیه گردید. از آنجا که واکنش کشاورزان به ابزارهای سیاستی با توجه به خصوصیات اقتصادی-اجتماعی آنها و همچنین خصوصیات بیوفیزیکی اراضی آنها ممکن است متفاوت باشد، واحد برنامه ریزی همگنی از نظرشرایط اقتصادی-اجتماعی و بیوفیزیکی تعریف گردید. برای این منظور بهره برداران هر یک از سیستمهای تولید (سنتی، شرکتهای تعاونی تولید و واحدهای کشت ودام) براساس میزان آب، زمین، راندمان تولید و میانگین درآمد در هکتار به کلاس های مختلف بهره برداری (Farm Type; FT) گروه بندی شدند. با تقسیم کردن اراضی واحدهای ارضی (Land Unit) بین Farm Type های موجود در آن واحد، واحدهایی همگن از نظر منابع بیوفیزیکی و شرایط اقتصادی- اجتمایی تولید گردید که در این مطالعه Farm type-Land unit (اختصاراً FTLU) نامیده شده و به عنوان کوچکترین واحد برنامه ریزی انتخاب گردید.

به منضورتعیین آثارسیاستها برای هر یک از واحدهای برنامه ریزی یک مدل برنامه ریزی خطی تدوین گردید که از اجتماع و به هم پیوستن مدل واحدهای برنامه ریزی، مدل واحدهای بزرگتر از قبیل ده، دهستان و بخش به دست آمد. این مدل واکنش گروههای مختلف کشاورزان به سیاستها را شبیه سازی می کند. این مدل اهداف کشاورزان را که ترکیبی از درآمد خالص و هزینه تولید میباشد با توجه به محدودیتهای مختلف در سطوح مختلف (FTLU، FT، روستا، دهستان و بخش) بهینه می سازد. جهت بررسی اعتبار مدل تهیه شده، مدل براساس شرایط سال 2003 – 2002 در بخش برخوار شهرستان برخوارو میمه اجرا و نتایج مدل (سطح زیر کشت و تولید محصولات مختلف) با آمار استخراج شده از سرشماری کشاورزی در همان سال مقایسه گردید.

با اسفاده ازمدل تدوین شده واکنش کشاورزان بخش برخوار به سه ابزارسیاستی پیشنهاد شده جهت افزایش بهره وری آب در بخش کشاورزی مورد بررسی قرار گرفت. آثارسیاستها روی اهداف اقتصادی، اجتماعی و زیست محیطی توسط شاخص هایی که به این منظور تعریف گردیده ، محاسبه شد. این شاخصها با استفاده از روش ارزیابی چند معیاره (Multi Criteria Evaluation) از دیدگاههای مختلف قابل بررسی و آنالیز می باشند که در مطالعه کنونی به عنوان نمونه از یک دیدگاه این آنالیز انجام گرفت.

سیستم ارایه شده دراین مطالعه قدم دیگری است در زمینه توسعه سیستمهای کامپیوتری پشتیبان تصمیم گیری برای تجزیه وتحلیل کاربری اراضی که با توجه به نیاز سیاستگزاران، به طور قابل ملاحظه ای در جامعه تحقیقاتی به آن پرداخته شده است. از مشورتهای انجام شده در طول این تحقیق با برنامه

ریزان میتوان نتیجه گرفت که هنوز راه طولانی در پیش می باشد تا فاصله بین سیاستگزاران و تهیه کنندگان مدلهای کاربری اراضی برداشته شود. سیاستگزاران سوالاتی را می پرسند که تهیه کنندگان مدلهای کاربری اراضی نمیتوانند به آنها جواب بدهند و تهیه کنندگان مدلهای کاربری اراضی جوابهایی را آماده می کنند که مورد سوال سیاستگزاران نیست.

Annex 1: Calibrated crop file of barley

CRPNAM='Barley , Iran, Kabutarabad'

```
** emergence
TBASEM   =  0.0    ! lower threshold temp. for emergence [cel]
TEFFMX   =  30.0    ! max. eff. temp. for emergence [cel]
TSUMEM   =  210.0     ! temperature sum from sowing to emergence [cel d]

** phenology
IDSL    =   0      ! indicates whether pre-anthesis development depends
                   ! on temp. (=0), daylength (=1) , or both (=2)
DLO     = -99.0    ! optimum daylength for development [hr]
DLC     = -99.0    ! critical daylength (lower threshold) [hr]
TSUM1    = 1147.0     ! temperature sum from emergence to anthesis [cel d]
TSUM2    = 693.0     ! temperature sum from anthesis to maturity [cel d]
DTSMTB   =   0.00,   0.00,     ! daily increase in temp. sum
             2.00,   2.00,     ! as function of av. temp. [cel; cel d]
            35.00,   35.00,
            45.00,   35.00
DVSI = 0.          ! initial DVS
DVSEND   =   2.00   ! development stage at harvest (= 2.0 at maturity [-])

** initial
TDWI     = 200.00   ! initial total crop dry weight [kg ha-1]
LAIEM    =   0.274 ! leaf area index at emergence [ha ha-1]
RGRLAI   =   0.0075 ! maximum relative increase in LAI [ha ha-1 d-1]

** green area
SLATB    =   0.00,    0.0020,   ! specific leaf area
             0.45,    0.0020,   ! as a function of DVS [-; ha kg-1]
             1.05,    0.0020,
             2.00,    0.0020
SPA      =   0.000  ! specific pod area [ha kg-1]
SSATB =  0.0, 0.0,  ! specific stem area [ha kg-1]
         2.0, 0.0   ! as function of DVS
SPAN     =  40.0  ! life span of leaves growing at 35 Celsius [d]
TBASE    =   0.0    ! lower threshold temp. for ageing of leaves [cel]

** assimilation
KDIFTB = 0.0, 0.55, ! extinction coefficient for diffuse visible light [-]
         2.0, 0.55  ! as function of DVS
EFFTB  = 0.0, 0.45, ! light-use effic. single leaf [kg ha-1 hr-1 j-1 m2 s]
```

```
     40.0, 0.45  ! as function of daily mean temp.
AMAXTB  =  0.00,  35.00,
           1.00,  35.00,
           1.70,  35.00,
           2.00,   5.00
TMPFTB  =  0.00,   0.00,    ! reduction factor of AMAX
          10.00,   1.00,    ! as function of av. temp. [cel; -]
          15.00,   1.00,
          30.00,   1.00,
          35.00,   0.00
TMNFTB  =  0.00,   0.00,    ! red. factor of gross assim. rate
           3.00,   1.00     ! as function of low min. temp. [cel; -]

** conversion of assimilates into biomass
CVL    =  0.72  ! efficiency of conversion into leaves [kg kg-1]
CVO    =  0.74  ! efficiency of conversion into storage org. [kg kg-1]
CVR    =  0.72  ! efficiency of conversion into roots [kg kg-1]
CVS    =  0.69 ! efficiency of conversion into stems [kg kg-1]

** maintenance respiration
Q10    =  2.0    ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]
RML    =  0.0300 ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]
RMO    =  0.0070 ! rel. maint. resp. rate stor.org. [kg CH2O kg-1 d-1]
RMR    =  0.0100 ! rel. maint. resp. rate roots [kg CH2O kg-1 d-1]
RMS    =  0.0150 ! rel. maint. resp. rate stems [kg CH2O kg-1 d-1]
RFSETB  =  0.00,   1.00,    ! red. factor for senescence
       2.00,   1.00     ! as function of DVS [-; -]

** partitioning
FRTB   =  0.00,   0.60,    ! fraction of total dry matter to roots
          0.40,   0.45,    ! as a function of DVS [-; kg kg-1]
          0.76,   0.04,
          1.00,   0.00,
          2.00,   0.00
FLTB   =  0.00,   0.80,    ! fraction of above-gr. DM to leaves
          0.33,   0.80,    ! as a function of DVS [-; kg kg-1]
          0.80,   0.40,
          1.00,   0.10,
          1.01,   0.00,
          2.00,   0.00
FSTB   =  0.00,   0.20,    ! fraction of above-gr. DM to stems
          0.33,   0.20,    ! as a function of DVS [-; kg kg-1]
          0.80,   0.60,
          1.00,   0.90,
```

```
              1.01,   0.15,
              2.00,   0.00
FOTB    =   0.00,   0.00,    ! fraction of above-gr. DM to stor. org.
              0.80,   0.00,    ! as a function of DVS [-; kg kg-1]
              1.00,   0.00,
              1.01,   0.85,
              2.00,   1.00

** death rates
PERDL    =   0.040  ! max. rel. death rate of leaves due to water stress
RDRRTB  =   0.00,    0.000,    ! rel. death rate of stems
                 1.50,    0.000,    ! as a function of DVS [-; kg kg-1 d-1]
                1.5001,  0.020,
                 2.00,    0.020
RDRSTB  =   0.00,    0.000,    ! rel. death rate of roots
                 1.50,    0.000,    ! as a function of DVS [-; kg kg-1 d-1]
                 1.5001,  0.000,
                 2.00,    0.000

** water use
CFET     =   1.00   ! correction factor transpiration rate [-]
DEPNR    =   4.5    ! crop group number for soil water depletion [-]
IAIRDU   =   0      ! air ducts in roots present (=1) or not (=0)

** rooting
RDI      =  10.    ! initial rooting depth [cm]
RRI      =   1.2   ! maximum daily increase in rooting depth [cm d-1]
RDMCR    = 90.     ! maximum rooting depth [cm]

** nutrients
** maximum and minimum concentrations of N, P, and K
** in storage organs        in vegetative organs [kg kg-1]
NMINSO   =   0.0110 ;      NMINVE   =   0.0030
NMAXSO   =   0.0310 ;      NMAXVE   =   0.0105
PMINSO   =   0.0016 ;      PMINVE   =   0.0004
PMAXSO   =   0.0060 ;      PMAXVE   =   0.0020
KMINSO   =   0.0030 ;      KMINVE   =   0.0070
KMAXSO   =   0.0080 ;      KMAXVE   =   0.0280
YZERO    = 200.    ! max. amount veg. organs at zero yield [kg ha-1]
NFIX     =   0.00   ! fraction of N-uptake from biol. fixation [kg kg-1]
```

Annex 2: Average of soil characteristics of top soil in the villages of Borkhar & Meymeh district

Village ID	Village name	pH	Organic carbon (mg/kg)	P_OLSEN (mg/kg)	$K_{exchang}$ (mmol/kg)	NBASE	PBASE	KBASE
1101	Ali Abad	7.4	6	12.8	10.6	44.9	6.4	157.6
1102	Ali Abadchi	7.4	4.8	9.7	8.4	35.9	4.9	146.2
1103	Donbai	7.5	2.8	21.5	6.6	21.4	10.6	146.0
1104	Habib Abad	7.4	6	12.8	10.6	44.9	6.4	157.6
1105	Komshecheh	7.3	3.8	15.4	7.8	27.8	7.9	172.7
1106	Margh	7.5	2.8	21.5	6.6	21.4	10.6	146.0
1107	Parvaneh	7.4	4.3	6.4	8.5	32.2	3.2	159.3
1108	Shoorcheh	7.5	2.8	21.5	6.6	21.4	10.6	146.0
1201	Dastgerd	7.4	4.5	11.1	10.8	33.7	5.6	196.4
1202	Dawlat Abad	7.4	7	5.4	7	52.4	2.7	92.8
1203	Khorzough	7.4	7	5.4	7	52.4	2.7	92.8
1204	Mohsen Abad	7.2	3.7	8.7	6.6	26.4	4.7	161.0
1205	Robat Soltan	7.8	4.5	8.1	7.1	36.7	3.1	82.1
1206	Shahpour Abad	7.3	6.2	25.3	11.6	45.3	13.0	183.6
1207	sherkat Iran chai	7.4	7.5	9	7.7	56.1	4.6	96.8
2101	Hasan robat paein	7.6	8.5	42.9	7.1	66.5	20.6	66.2
2102	laibid	7.6	8.5	42.9	7.1	66.5	20.6	66.2
2103	Loshab	7.6	8.5	42.9	7.1	66.5	20.6	66.2
2104	Mooteh	7.6	8.5	42.9	7.1	66.5	20.6	66.2
2201	Azan	7.6	8.5	42.9	7.1	66.5	20.6	66.2
2202	Ghasem abad	7.6	5.4	16.6	12.9	42.2	7.8	169.2
2203	Jihad Khodkafaei	7.4	4.7	11.7	5.2	35.2	5.9	91.8
2204	Khosro abad	8.1	4	14.8	8.4	34.7	5.7	60.0
2205	Maravand	7.9	7	14.7	19.3	58.3	5.4	139.5
2206	Meimeh	7.5	6	9.8	5.7	45.9	4.6	77.0
2207	Robat agha kamal	7.9	7	14.7	19.3	58.3	5.4	139.5
2208	Vandadeh	7.6	5.4	16.6	12.9	42.2	7.8	169.2

Annex 2 (continued): Average of soil characteristics of top soil in the villages of Borkhar & Meymeh district

Village ID	Village name	pH	Organic carbon (mg/kg)	P_OLSEN (mg/kg)	$K_{exchang}$ (mmol/kg)	NBASE	PBASE	KBASE
2209	Vazvan	7.6	13	43.8	32.7	101.7	20.6	214.8
2210	Ziad abad	7.6	8.5	42.9	7.1	66.5	20.6	66.2
3101	Gaz	7.5	5.1	12.7	8.4	39.0	6.1	127.5
3102	Gorghab	7.3	4.6	8.6	10.2	33.6	4.5	199.3
3103	Jafar Abad	7.4	4.4	11.5	5.8	32.9	5.8	107.0
3104	Jehad abad	7.7	2	6.1	3.8	16.0	2.7	80.0
3105	mojtameh karkhaneh haee sanati va sangbori	7.5	5.1	12.7	8.4	39.0	6.1	127.5
3106	Noorabad	7.4	5.9	8.6	7.4	44.1	4.3	111.4
3107	Shahin Shahr	7.3	4.6	8.6	10.2	33.6	4.5	199.3
3108	Sin	7.3	3.8	9.5	13.2	27.8	5.0	292.3
3109	yaghoot abad	7.8	4.5	8.1	7.1	36.7	3.1	82.1
3201	Bagh miran	7.9	7	14.7	19.3	58.3	5.4	139.5
3202	Bidashk	7.9	7	14.7	19.3	58.3	5.4	139.5
3203	Kalahrood	7.9	7	14.7	19.3	58.3	5.4	139.5
3204	khal sefid	7.4	2.9	7.1	7.3	21.7	3.6	174.2
3205	Mazreh dastkan	7.4	4.7	11.7	5.2	35.2	5.9	91.8
3206	Mazreh dogholi	7.8	4.5	8.1	7.1	36.7	3.1	82.1
3207	Moorcheh khort	7.4	3.9	12.8	6.1	29.2	6.4	121.8
3208	Padghan Darkhoein	7.3	4.5	5.7	5.4	32.9	3.1	107.1
3209	Soh	7.9	7	14.7	19.3	58.3	5.4	139.5

Annex 3: Code of villages

Village name	Village ID	Bakhsh code	Dehestan code	Village code
Ali Abad	1101	1 (Borkhar)	1 (Eastern Borkhar)	01
Ali Abadchi	1102			02
Donbai	1103			03
Habib Abad	1104			04
Komshecheh	1105			05
Margh	1106			06
Parvaneh	1107			07
Shoorcheh	1108			08
Dastgerd	1201		2 (Central Borkhar)	01
Dawlat Abad	1202			02
Khorzough	1203			03
Mohsen Abad	1204			04
Robat soltan	1205			05
Shahpour Abad	1206			06
Sherkat Iran chai	1207			07
Hassan Robat paein	2101	2 (Meymeh)	1 (Zarkan)	01
Laibid	2102			02
Loshab	2103			03
Mooteh	2104			04
Azan	2201		2 (Vandadeh)	01
Ghasem Abad	2202			02
Jihad khodkafaei	2203			03
Khosro abad	2204			04
Maravand	2205			05
Meymeh	2206			06
Robat agha kamal	2207			07
Vandadeh	2208			08
Vazvan	2209			09
Ziad Abad	2210			10
Gaz	3101	3 (Central)	1 (Western Borkhar)	01
Gorghab	3102			02
Jafar Abad	3103			03
Jehad Abad	3104			04
Mojtameh karkhaneh haee sanati	3105			05
Noorabad	3106			06
Shahin shahr	3107			07
Sin	3108			08
Yaghoot abad	3109			09
Bagh miran	3201		2 (Moorcheh khoort)	01
Bidashk	3202			02
Kalahrood	3203			03
Khal sefid	3204			04
Mazreh dastkan	3205			05
Mazreh dogholi	3206			06
Moorcheh khoort	3207			07
Padghan darkhoein	3208			08
Soh	3209			09

Annex 4: List of indices

Index	Description	Members
Crop	Crops	Wheat, Barley, Sugar beet, Sunflower, Potato, Maize, Alfalfa, Melon, Watermelon, Colza
Cropsys	Cropping systems	Wheat, Barley, Maize, Sugar beet, Sunflower, Melon, Watermelon, Potato, Colza, Alfalfa, Wheat-Maize, Wheat-Melon, Wheat-Sunflower, Wheat-Watermelon, Barley-Maize, Barley-Melon, Barley-Sunflower, Barley-Watermelon, Colza-Maize, Colza-Melon, Colza-Sunflower, Colza-Watermelon
Irsys	Irrigation systems	Surface, Sprinkler
Irman	Irrigation managements	Fully irrigation, 20 % Deficit irrigation, 40 % Deficit irrigation
WR	Water Resource	Canal, qanat, well
FT	Farm types	FT1*FT8, AI1*AI5, G1*G7, K1*K4
LU	Land units	128 land units in the district
V	Villages	47 villages in the district
Dehestan	Dehestans	Eastern Borkhar, Central Borkhar, Western Borkhar, Moorcheh khoort, Zarkan, Vandadeh
Mon	Months	January, February, March, April, May, June, July, August, September, October, November, December
Decade	Decade	DEC1 – DEC 36
Product	Type of products	Main-product, By-Product
Objective	Objectives of farmers	Net Income, Production cost

Annex 5: List of variables and parameters in the model

Variable / Parameter	Explanation	Unit
$Alfalfa\_required_{FT}$	The required alfalfa production per FT	kg
Available land $_{FT}$	Total land of each FT	ha
Available land $_{FT, LU}$	Available land of each FTLU	ha
Available land $_{LU}$	Suitable area for agriculture in the LU	ha
Available Tractor hours $_{Mon}$	Number of available hours of tractors in Dehestan	hour
Available water $_{FT}$	Total available water of each FT	L/s
Available water $_{FT, V}$	Total available water of the FT in the village per year	m^3
Available water $_{FT, V, Mon}$	Available water of each FT in each village per month	m^3
Available water $_{V, Mon}$	Total available water of each village from different water sources per month	m^3
By Yield $_{crop, Irsys, Irman, FT, LU}$	Yield of crop by-products with specific Irsys and Irman per FTLU	kg
CWR $_{Crop, LU, Irman, Decade}$	Crop water requirements per land unit, irrigation regime, and decade	mm
D $_{objective, FT}$	Auxiliary variable per objective and farm type	-
E $_{objective, FT}$	Auxiliary variable per objective and farm type	-
EC $_{Crop}$	Maximum permitted Electrical Conductivity (EC) of the saturation extract of the soil	dS/m
EC $_{WR}$	Electrical Conductivity of irrigation water source	dS/m
Fertilizer Cost $_{Crop, Irsys, Irman, FT, LU}$	Cost of fertilizers per crop, Irsys and Irman	Rials/ha
Gross Income $_{crop, Irsys, Irman, FT, LU}$	Gross income of each crop with specific Irsys and Irman per FTLU	Rials/ha
Gross Income $_{cropsys, Irsys, Irman, FT, LU}$	Gross income of each activity per FTLU	Rials/ha
IE $_{Irsys, LU}$	Irrigation efficiency of irrigation system per land unit	-
Income goal $_{FT}$	Goal of farm type for objective of net income	Rials
IR $_{Crop, LU, Irman, Irsys, WR, Decade}$	Irrigation requirements of the crop per land unit, irrigation regime, irrigation system, water source, and decade	mm
Irrigation Requirement $_{Cropsys, Irsys, Irman, FT, LU, Mon}$	Irrigation requirement of each activity per FTLU and month	mm
Labor requirement $_{Cropsys, Irsys, Irman, FT, LU, Mon}$	Labor requirements of each activity per FTLU and per month	man-day/ha
Labour Cost $_{Crop, Irsys, Irman, FT, LU}$	Labour cost for production of each crop with specific Irsys and Irman per FTLU	Rials/ha
Lag coefficient	Fraction which tractor can not be used in the case of maintenance	-
Land Fraction $_{FT, V}$	Land fraction of FT per village	-
LF $_{Crop, WR}$	Leaching fraction per crop and irrigation water source	-
LR $_{Crop, LU, Irman, Irsys, WR, Decade}$	Leaching requirements of the crop per land unit, irrigation regime, irrigation system, water source and decade	mm

Machinery Cost $_{Crop, Irsys, Irman, FT, LU}$	Cost of agricultural machinery for each crop with specific Irsys and Irman per FTLU	Rials/ha
Main Yield $_{crop, Irsys, Irman, FT, LU}$	Yield of main crop product with specific Irsys and Irman per FTLU	kg
Maintenance & Operation Cost $_{Irsys, FT}$	Cost of maintenance and operation of irrigation system per irrigation system and farm type	Rials/ha
Maximum available water $_{V}$	Maximum available water per village in the year	m^3
Maximum available water $_{V, Mon}$	Maximum available water per village and month	m^3
Net Income	Total net income	Rials
Net Income $_{cropsys, Irsys, Irman, FT, LU}$	Net income of the production of each activity per FTLU	Rials/ha
Number of holder $_{FT, V}$	Number of holders of each FT in each village	-
Number of tractors $_{Dehestan}$	Number of available tractors in Dehestan	-
Number of workday $_{Mon}$	Number of work days per month	day
Number of worker $_{v}$	Number of available workers per village	Man
PE $_{FT, Crop}$	Crop production efficiency of FT	-
Pesticide Cost $_{Crop}$	Cost of pesticides for production of each crop	Rials/ha
PR $_{Irsys}$	Percolation ratio of the irrigation system	-
Price $_{crop, by-products}$	Price of crop by-products	Rials/kg
Price $_{crop, main yield}$	Price of main crop product	Rials/kg
Production Cost $_{crop, Irsys, Irman, FT, LU}$	Total production cost of each crop with specific Irsys and Irman per FTLU	Rials/ha
Production Cost $_{cropsys, Irsys, Irman, FT, LU}$:	Production cost of each activity per FTLU	Rials/ha
Production cost goal $_{FT}$	Goal of farm type for objective of production cost	Rials
Relation $_{Cropsys, Crop}$	Dummy variable for the relation between cropping system and crop; equals 1 if crop is part of the cropping system, otherwise 0	-
Relation $_{LU, Dehestan}$	Dummy variable for location of village; 1 if LU is located in the Dehestan, otherwise 0	-
Relation $_{LU, V}$	Dummy variable for relation between LU and village; equals 1 if LU is located in the village, otherwise 0	-
Seed Cost $_{crop}$	Cost of seed for production of each crop	Rials/ha
Tractor requirement $_{Cropsys, FT, Mon}$	Tractor requirement of each cropping system per FT and month	hour
W $_{objective, FT}$	Weight of the objective for each farm type	-
Water Cost $_{Crop, Irsys, Irman, FT, LU}$	water cost for production of each crop with specific Irsys and Irman per FTLU	Rials/ha
Water Fraction $_{FT, V}$	Water fraction of FT per village	-
Wheat_required $_{FT}$	The required wheat for self consuming per FT	kg
X $_{cropsys, Irsys, Irman, FT, LU}$	Area allocated to each activity per FTLU	ha
Yield $_{Crop, FT, LU}$	Expected crop yield per FTLU	kg/ha
Yield $_{Crop, LU}$	Simulated potential crop yield in the LU	kg/ha

Annex 6: List of Acronyms

Symbol	Description
APERI	Agricultural Planning and Economic Research Institute
asl	above sea level
CAP	Common Agricultural Policy
CGMS	Crop Growth Monitoring System
CSPSS	Collaborative Spatial Planning Support System
CV	Coefficient of Variation
DEM	Digital Elevation Model
DM	Dry Matter
EC	Electrical Conductivity
EMU	Elementary Mapping Unit
FAO	Food and Agriculture Organization
FFYDP	Fourth Five-Year Development Plan
GAMS	General Algebraic Modeling System
HI	Harvest Index
HPC	Housing and Population Census
I/O	Input/Output
IRIMO	Islamic Republic of Iran Meteorological Organization
ISWRI	Iranian Soil and Water Research Institute
ITC	International Institute for Geo-information Science and Earth Observation
JRC	Joint Research Center
LAI	Leaf Area Index
LAIM	Maximum Leaf Area Index
LINGRA	LINtul GRAssland
MARS	Monitoring of Agriculture by Remote Sensing
N.A.	Not available
OECD	Organization for Economic Co-operation and Development
PSS	Planning Support System
SCI	Statistical Center of Iran
SMU	Soil Mapping Unit
SRTM	Shuttle Radar Topography Mission
SWAP	Soil Water Atmosphere Plant
TAGP	Total Above Ground dry matter Production
TWSO	Total dry Weight of Storage Organs
WOFOST	WOrld FOod STudies

Curriculum Vitae

Bahman Farhadi Bansouleh was born on 23rd of September 1974 in Islam Abad, Kermanshah, Iran. He completed his secondary school in physics and mathematics in 1992. In the same year he was accepted at Shiraz University, Shiraz, Iran. In 1996, he obtained a B.Sc degree in Agricultural Engineering- with specialization in Irrigation. He was honored by the 2nd rank in the national entrance exam for M.Sc. in Irrigation and Drainage in 1996. He obtained his M.Sc. degree from Tehran University in November 1998, ranking first among his classmates.

In the period April 1998- January 1999, he worked with the National Water and Soil Engineering Company, Karaj, Iran. In this period, he contributed to the project on "Identification of criteria for design and installation of pressurized irrigation systems in Iran". In February 1999, he joined the Irrigation Department in the Faculty of Agriculture in Razi University, Kermanshah, Iran, as lecturer in drainage engineering, principles of irrigation, design of irrigation systems, engineering economics, and introduction to computer sciences. In the summer of 2000, he obtained the professional license for design and installation of pressurized irrigation systems from the Iranian Centre for Pressurized Irrigation Systems, which gave him the opportunity to design sprinkler and drip irrigation systems in Kermanshah province, Iran.

During his M.Sc-studies he was a student member of the Iranian Committee of Irrigation and Drainage. In 2002, after establishment of the local branch of the Iranian Committee of Irrigation and Drainage in West Iran, he became a member of the committee.

In 2002, he was awarded a full-time Ph.D. scholarship by the Iranian Ministry of Science, Research and Technology, following his acceptance in the national exam. He started his Ph.D. in the International Institute for Geo-information Science and Earth Observation (ITC) and Wageningen University in the Netherlands in September 2004. After his Ph.D. he will resume his position in Razi University, as assistant professor.

ITC Dissertation list

A list of ITC dissertation can be found in:
http://www.itc.nl/research/phd/phd_graduates.aspx

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC
PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review of Literature (5.6 ECTS)
- Review of agricultural policy formulation in Iran (2005)

Writing of Project Proposal (7 ECTS)
- Development of a collaborative spatial planning support system for agricultural policy formulation related to land and water resources in Borkhar district, Iran (2005)

Laboratory Training and Working Visits (3.6 ECTS)
- Practical CGE modelling with GAMS; Ecomod course; University of Brussels (2005)
- Five-year planning process in Iran; visiting several national and provincial organizations in Iran (2005 and 2006)

Post-Graduate Courses (7 ECTS)
- Spatial decision support systems and multi-criteria evaluation techniques; ITC (2005)
- Planning support systems: scenario development and analysis; ITC (2005)
- Conflict management & collaborative decision support systems; ITC (2005)

Deficiency, Refresh, Brush-up Courses (2.8 ECTS)
- Principles and applications of GIS and remote sensing for water resources and environmental management; ITC (2004)
- Quantitative analysis of land use systems (QUALUS); PPS (2005)

Competence Strengthening / Skills Courses (2.8 ECTS)
- Scientific writing for non-native English speakers; ITC (2006)
- E-learning components: multimedia; ITC (2006)

Discussion Groups / Local Seminars and Other Scientific Meetings (6.7 ECTS)

- Presentation and discussion of the research project in Collaborative Spatial Planning and Support System (CSPSS) workshop, Tehran, Iran (2005)
- More than 100 hours discussion with experts in different departments of: Agricultural Planning and Economic Research Institute (APERI) in Teheran, Iran; Iranian Management and Planning Organization (IMPO) in Teheran, Iran; Jihad Agricultural Organization, Esfahan, Iran; Agricultural Research Centre, Esfahan, Iran; Agricultural Management Office, Shahin Shahr, Iran; Jihad Agricultural Organization, Kermanshah, Iran; Agricultural Research Centre, Kermanshah, Iran (2005, 2006 and 2007)
- Two department research days in the department of Urban and Regional Planning and Geo-information Management (PGM), International Institute for Geo-Information Science and Earth Observation (ITC) (2005 and 2007)
- Presentation and discussion of research progress in APERI (2007)
- Presentation and discussion of research progress in Agricultural Organization Office, Esfahan, Iran (2007)
- Past and future of land evaluation, 139th themadag; ITC, Enschede (2007)
- Presentation of PhD research in the ITC PhD day (2008)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.5 ECTS)

- PhD Master class with ESRI (Environmental Systems Research Institute) (2005)
- PE&RC Weekend (2008)
- PhD Master class with INPE (National Institute for Space Research of Brazil) (2008)

International Symposia, Workshops and Conferences (3.9 ECTS)

- IIICGMS Expert meeting and GEOLAND training workshop; Arlon, Belgium (2006)
- ISPRS Commission VII mid-term symposium: " *Remote Sensing: From Pixels to Processes*"; Enschede, the Netherlands (2006)
- The XXI ISPRS Congress; Beijing, China (2008)

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