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Development of a land suitability assessment approach for fish pond site selection within the landscape of Khorezm, Uzbekistan, combining Geographic Information Systems and Multi-Criteria Evaluation

by

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Garching, 24.04.2005

Olaf Kranz

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Summary

The integration of aquaculture, in particular fish ponds into the agricultural landscape is one possible strategy for an economically and ecologically more sustainable use of marginal land in the Khorezm region in Uzbekistan.

The aim of this study is to develop a land suitability assessment approach for fish pond site selection in this region. Based on the review of relevant literature the most crucial factors and constraints for fish pond sites were identified. Additionally, expert knowledge as well as in situ observations in the region were incorporated to ensure that results are adjusted to the local condition and are user-targeted. GIS methods (e.g. spatial interpolation, reclassification, calculation of distance and cost-distance surfaces, spatial overlay and buffering) and MCE techniques were combined for the land suitability evaluation in a transparent and understandable modelling approach with respect to local decision makers' preferences.

The different factors were categorised into suitability classes and standardised using fuzzy set membership functions to ensure comparability. The model was applied at a regional scale for use by policy makers and regional planners. At a local scale the model was carried out as a case study on the P. Mahmud farm, Khiva rayon, to support detailed land use planning. At regional as well as at local scale two different scenarios considering both ecological and economical preferences of potential decision makers were generated using varying factor weights. The spatial patterns of suitable and unsuitable areas in the final suitability maps reflected these different factor weights. The area of suitable and very suitable sites amounted to approximately 60 % of the whole area of Khorezm. In contrast, highest suitability at local scale was only reached by less than 40 % and 15 % of the farm area, concerning an ecological and an economical perspective, respectively.

This study showed that the integrated use of GIS and MCE was an effective and innovative method to produce reliable and understandable results for supporting site planning in aquaculture.

Zusammenfassung

Eine nachhaltige Strategie für eine effektivere ökonomische und ökologische Nutzung marginaler Böden in der usbekischen Provinz Khorezm ist die Umwandlung dieser Flächen für den Betrieb von Aquakulturen, speziell von Fischteichen. Das Ziel der vorliegenden Studie ist die Entwicklung eines methodischen Ansatzes zur Selektierung geeigneter Flächen für die Anlage von Fischteichen.

Aufbauend auf Literaturrecherchen, Befragung von usbekischen Aquakultur-Experten und Geländekampagnen in Khorezm wurden die Standortfaktoren, welche für die Anlage von Fischteichen in der Zielregion relevant sind, identifiziert und nutzerorientiert implementiert. Komplexe GIS-Modellierungen (z.B. räumliche Interpolation, Reklassifizierung, Distanz- und Kostenoberflächen-Berechnung, räumliche Verschneidung und Pufferung) und Methoden der MCE wurden in dieser Studie kombiniert, um eine räumliche Standortevaluierung durchzuführen, welche auf rational nachvollziehbaren, strukturierten und die Präferenzen der Entscheidungsträger berücksichtigenden Grundlagen beruht.

Die unterschiedlichen Faktoren wurden in Eignungsklassen kategorisiert und mit Fuzzy-Methoden standardisiert, um eine Vergleichbarkeit zu erreichen. Für jeden dieser Faktoren wurde durch GIS-Modellierung jeweils eine Faktorenkarte im regionalen (Khorezm) und lokalen Maßstab (P. Mahmud Farm) generiert, um sowohl usbekischen Regionalplanern als auch Landwirten und Landschaftsplanern eine Entscheidungshilfe zu geben. Für beide Maßstabsebenen wurden zwei Szenarien simuliert, die aufgrund der variierenden Gewichtungen der Eingangsfaktoren ökonomische und ökologische Präferenzen der Entscheidungsträger repräsentieren. Diese unterschiedliche Gewichtung drückt sich deutlich im räumlichen Verteilungsmuster der finalen Standorteignungskarten aus. Der Anteil hoher und sehr hoher Standorteignung an der Gesamtfläche der Provinz Khorezm beträgt ca. 60 %. Im Gegensatz dazu liegt dieser Anteil auf lokaler Ebene lediglich bei unter 40 % (ökologische Präferenz) bzw. ca. 15 % (ökonomische Präferenz).

Die vorliegende Arbeit hat gezeigt, dass die Kombination von GIS und MCE zur Evaluierung potenziell geeigneter Standorte für Aquakulturen eine effiziente und innovative Methode darstellt, um rational nachvollziehbare Planungsgrundlagen zu erstellen.

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1 Introduction

After the break-up of the Union of Soviet Socialist Republics (USSR) aquaculture production in the newly independent Central Asian states has been dramatically declined. However, since the second half of the 1990s some recovery in aquaculture can be observed (VARADI ET AL. 2000). In Uzbekistan aquaculture development could be strengthened by revitalising the existing, formerly prosperous inland aquaculture sector. This sector consists of mainly medium to large fish pond farm complexes, former fish sovkhozes which have now been privatised. The integration of aquaculture into other sectors, in particular agriculture could be considered as another promising strategy in developing the region's aquaculture to reach sustainable economical and ecological development (VLEK ET AL. 2003).

In the north-western part of Uzbekistan the Khorezm oblast is one of the 12 provinces (oblasts or viloyats) of the Republic. Agriculture is the key sector of the economy where most important cultivated crops are wheat, rice and cotton. Due to the climatic conditions most of the agricultural land in Khorezm requires irrigation. This leads to the common problem of salinisation of water and soils in irrigated landscapes of arid and semiarid regions. In general, increasing salt concentrations in water and soils result in decreasing productivity. Sites with low productivity are less profitable for agriculture. The production of heavily irrigated, mono-cropped cotton over many decades combined with poor irrigation and drainage management has degraded the agricultural landscape. Nowadays, degraded areas are abandoned from cropping because of shallow, saline groundwater tables and high soil salinity. Although scattered throughout the irrigated region, the size of the degraded areas amounts to about 20 % of the total territory. These areas represent suitable sites to restructure the present land use into use by fish ponds as investigated by the German-Uzbek Khorezm project (VLEK ET AL. 2003), funded by the German Ministry for Education and Research (BMBF; project number 0339970C).

Although fresh water fish species are sensitive to high salinity they can tolerate significantly higher levels of salt in water than crops. Thus, the widespread irrigation system in Khorezm with its dams, reservoirs, irrigation and drainage canals offers a great diversity of water bodies for fish production and ensures the availability of water in many areas. The demand for fish in Khorezm is growing due to an increasing population (PETR ET AL. 2002). Together with an optimal density of population and good access to markets, this creates favourable social and economic conditions for development of a private fish production (PETR ET AL. 2002).

The revenue from the fish production caught from ponds on marginal land can provide substantial additional income for farmers, especially for those farmers who cultivate crops on land with decreasing productivity. Furthermore, these integrated farming systems ensure the use of irrigation or drainage water and agricultural by-products, such as cow dung as locally available fish feed to substitute expensive imported fish feed. Thus, the combination of fish pond culture with the traditional farm crop production might be a profitable strategy to reach both a sustainable aquaculture and agricultural production (VLEK ET AL. 2003).

However, clear decisions where to allocate land for fish ponds within the landscape are difficult to make, because the areas in Khorezm have different suitability for different uses. The primary challenge is to identify the most important ecological factors and constraints that determine suitable fish pond sites in Khorezm. The set of criteria should also take into account where the economic conditions promise a productive integration of aquaculture.

The different factors and constraints for suitable fish pond sites may have a specific areal extent and value and can thus be compared against each other by spatial modelling according to their relative importance in order to find the optimum fish pond sites. The described process requires evaluation methods based on rational reasoning based on ecological and economical principles. Geographic Information Systems (GIS) with their unique capabilities for automatisation and analysing a variety of spatial data have become an increasingly integral component of spatial decision support in natural resource management over the past few years (NATH ET AL. 1999). Complementary, Multi-Criteria-Evaluation (MCE) offers a collection of procedures and techniques to reveal decision makers' preferences and to incorporate them into spatial decision making. Thus, the integrated use of GIS and MCE can be useful for spatial multi-criteria decision analysis to investigate suitable locations for fish pond construction within the agricultural landscape of Khorezm.

The objective of this study is to develop a land suitability assessment approach for fish pond site selection in Khorezm, Uzbekistan. The specific objectives are 1) to develop a locally adjusted modelling framework for fish pond site selection in Khorezm based on ecologic versus economic preferences of potential decision makers; 2) to apply and to validate the robustness of the model for mapping suitable fish pond locations. The models will be applied at a regional scale for use by policy makers and at a local scale based on a case study on the P. Mahmud farm, Khiva rayon to support land use planning.

The present thesis is structured into six chapters that are summarised in the following. After a short summary about the state of research concerning aquaculture in Uzbekistan, land suitability assessment methods and spatial multi-criteria evaluation in aquaculture are outlined in chapter 2. The main characteristics of the study area will be described briefly in chapter 3. Chapter 4 presents the methodologies and data used to reach the objectives of the study. Chapter 5 illustrates and discusses the results of this thesis followed by a conclusion and a brief recommendation in chapter 6.

2 State of research

2.1 Aquaculture in Uzbekistan

Uzbekistan is one of the four main producing countries of fish in the former Union of Soviet Socialist Republics (USSR). Until the 1960s fishing in Uzbekistan concentrated on the freshwater of the Aral Sea and the deltas of the inflowing rivers. Only one hatchery and one small fish farm existed near Tashkent (PETR ET AL. 2002). Due to the continuous desiccation and increased salinity in the Aral Sea linked with the application of water in the monocultivation of cotton, fish harvest decreased tremendously during the 1960s and 1970s and since 1983 there has been no fishing in the Aral Sea any more. New fish sources had to be found so that during the 1970s fishing increased sharply in Lake Sarykamysh and the Aydar-Arnasai lake system located in the northwest and east of Uzbekistan, respectively. Again the increasing salinity might be the reason why the lake Sarykamysh lost its fishery value. From that it was realised that fishing under conditions of continuous irrigation of agricultural fields could not replace the quantity of fish lost from the Aral Sea. In the following a large-scale program of fish production for all types of inland water bodies was developed by the Ministry of Fisheries of the former USSR in cooperation with the Uzbekistan government (PETR ET AL. 2002). After the break-up of the USSR fish production has been dramatically declined in the region. Today, no national program and even no specific fishery development project supported by the government are existent in Uzbekistan (PETR ET AL. 2002). The result is a largely unexploited fishery potential of water bodies of the irrigation system (see figure 1).

Figure 1 Subsistence fishing in Khorezm (photographed by G. RÜCKER 2004)

A similar trend as for the capture fisheries can be observed for the aquacultural production. From 1985 to 1995 a significant decrease of 9.5 % in aquacultural production was observed. The main limitation has been the absence of formulated fish feed (BARG 1997). As shown in table 1 some recovery in aquaculture can be observed since the second half of the 1990s in both fresh water fish farming and drainage water fish farming (VARADI ET AL. 2000, PETR ET AL. 2002).

Table 1 Capture fisheries and aquaculture in Uzbekistan

Year	Capture fisheries			Aquaculture			Total
	Lakes	Reservoirs	Rivers	Fish farms with fresh water	Fish farms with water saline	Total	
	1000 t						
1980s*	5.5	1.0	0.5	No data	No data	23.0	30.0
1994	2.0	0.8	0.3	No data	No data	14.6	17.7
1996	1.2	0.3	0	3.8	1.2	5.0	6.5
1999	3.1	0.4	0	4.1	1.5	5.6	9.1
2000	2.7	0.3	0	No data	No data	6.2	9.2
* average for the decade							

Source: KAMILOV 2002, after PETR ET AL. 2002

In Uzbekistan the major aquaculture production is from fresh water aquaculture (PETR ET AL. 2002). The two dominant fish species are common carp (*Cyprinus carpio*) and silver carp (*Hypophthalmichthys molitrix*). Together with the drop in total fish production a decrease in the availability of fish for human consumption can be noticed (PETR ET AL. 2002). This results in raised prices and steadily increasing imports of fish and fishery products. In a nutrient perspective, this is a critical tendency considering that fish as a human food commodity provides about 10 % of total dietary protein supply (BARG 1997).

Because of the increasing demand of a growing population for fish as well as the rising prices for fish products, fish production became a profitable business since the year 2000 in Uzbekistan (QURAMBAEVA 2004). After PETR ET AL. 2002 there is a good development potential for capture fisheries as well as aquaculture in the country. The widespread irrigation system with its dams, reservoirs, irrigation and drainage canals offers a diversity of water bodies for fish production and ensures the availability of water almost in all regions. However, water pollution with pesticides as well as the common problem of salinity are major restrictions to the development of aquaculture.

An important task to replace the loss of the Aral Sea fish in a sustainable manner will be a better use of the existing water bodies (see figure 2).

Figure 2 Existing water bodies in the agricultural landscape of Khorezm (photographed by G. RÜCKER 2004)

It has been recognised that major effort and a close collaboration among the countries of the region are required to reach this goal (PETR ET AL. 2002). Hence it appears that not only the quantity of fish capture will be the main target in developing the aquaculture in Khorezm but also the integration of aquaculture into the landscape. This implies a better integration of agriculture and aquaculture, for example by using lucerne as locally available fish feed (KARIMOV 2005).

2.2 Land suitability assessment methods

The term land suitability assessment describes the process of evaluating land for one or more purposes by systematic comparison of the requirements of a certain land use with the qualities of land (DALAL-CLAYTON & SADLER 2005). The early land evaluation approaches focused on the collection of basic land data and land use data. This has mainly been done by each competent authority individually with the result that more complex and difficult questions faced by policy-makers and land use planners could not be answered. Depending on whether land suitability decisions are requested at regional or at local level different questions may arise for different users. To answer these questions multiple data sets about both land resources and socioeconomic information need to be collected, analysed and integrated for a synthesised land suitability assessment. Within this evaluation expert knowledge can be used for interpretation of the different input data. There are generally four approaches of land suitability assessments which focus on the decision support by using expert knowledge: Land Capability Classification (KLINGEBIEL & MONTGOMERY 1961, after DALAL-CLAYTON ET AL. 2000), the FAO Framework for Land Evaluation (FAO 1976, after DALAL-CLAYTON ET AL. 2000), the USBR (United States Bureau of Reclamation) land classification system for irrigation schemes (USBR 1953, after DALAL-CLAYTON ET AL. 2000), and various parametric indices. Recently, decision trees became established as a more transparent way of using expert knowledge (DALAL-CLAYTON ET AL. 2000).

The Land Capability Classification is the most widely used land evaluation method. It was first developed by the United States Soil Conservation Service for interpretation of soil maps for farm planning. This method uses three levels of classification. At the first level land is classified taking the degree of its limitations for sustained use into account. At subclass level the limitations which can not be influenced by the farmer have to be identified. Within the subclass the capability unit combines soils that are suitable for similar crops and that require similar management. The most obvious disadvantage of this method is that land can not be graded from best to worst without taking the proposed land use into account. Except from identifying totally unsuitable areas this assessment can not help to choose between alternative uses (DALAL-CLAYTON ET AL. 2000).

For planning irrigation projects the USBR system has been developed. This approach integrates physical and financial criteria of land suitability in the same evaluation procedure. Within this system land is classified in terms of its payment capacity. In other words, land classification is carried out concerning the money remaining for the farmer after all costs except water charges are paid.

FAO published the first principles of land evaluation in 1976 within “A framework for land evaluation”. These principles specified that land should be evaluated concerning its suitability for a range of alternate land use. The latter should be based on several criteria, in particular the requirements of specific land uses and an inter-disciplinary analysis of inputs and benefits. Furthermore, the physical, economical and social context should be taken into account as well as environmental impacts and sustainability (GEORGE 2003).

The fourth main group of land suitability assessment methods consists of various parametric indices. These parametric techniques assume that land suitability is determined only by a few major factors. The best known parametric method is the Storie Index Rating (STORIE 1978, after DALAL-CLAYTON & SADLER 2005).

Within the framework of land evaluation GIS are one of the most significant developments. The use of GIS provides extensive potentials for analysing alternate scenarios. The graphic capabilities of these systems allow producing results which can be useful for guiding decision making at various administrative and technical levels (GEORGE 2003). On the other hand Multi-Criteria Evaluation has more recently been used as a powerful technique to deal with several partly conflicting goals within the land suitability assessment.

2.3 Spatial multi-criteria decision support analysis for site selection in aquaculture

Spatial (GIS-based) multi-criteria decision making (MCDM) can be described as a collection of techniques for analysing geographic events where the results of the decisions depend on the spatial arrangements of the events. Although most spatial decision problems are multi-criteria the process and appropriate algorithms of multi-criteria decision analysis are not well established into common GISs (MALCZEWSKI 1999). Nevertheless these two research technologies can strongly benefit from each other. The decision making process can be made more effective by combining the powerful capabilities of GISs for managing and analysing spatial data and the wide range of methodologies of MCDM.

Differences in biophysical and socioeconomical characteristics at different locations result in the fact that planning activities to promote and monitor the development of aquaculture in individual regions have inherently a spatial component. Besides the spatial component the mentioned planning activities always deal within the framework of a multi-criteria decision making process. Several applications of spatial multi-criteria decision support analysis have been made from which the most important for aquaculture will be summarised in the following. The most interesting evaluations concerning the objectives of the present thesis are the ones which deal with the subject of site selection (see table 2). Among this the case studies demonstrate a large extent of GIS applications using numerous analytical methods and different GIS software packages at a wide range of geographic scales. A good overview of case studies in aquaculture is given by NATH ET AL. 2000.

For the state of Sinaloa, Mexico, a study was carried out by AGUILAR-MANJARREZ and ROSS (1995) to develop a detailed GIS to provide planners and managers with a tool to assess land suitability for aquaculture and agriculture. The system should provide guidance for exploring the impact of potential land use restructuring options. First, models from the input data were designed to integrate their output to finally assess site suitability by the use of Multi-Criteria Evaluation (MCE) and Multi-Objective Land Allocation (MOLA) techniques. Altogether 14 criteria, represented as factors or constraints (see chapter 4.3) were included in the evaluation.

Table 2 GIS applications in aquaculture

Purpose	Geographical region	Used GIS software	Author(s)
Inland fisheries and aquaculture	General	IDRISI, ArcInfo, GIMMS, MundoCart/CD	MEADEN AND KAPETSKY 1991
Freshwater fish farming	Latin America	ArcInfo	KAPETSKY AND NATH 1997
Tilapia and *Clarias* culture in ponds	Ghana	ArcInfo, ERDAS Imagine	KAPETSKY ET AL. 1991
Freshwater fish farming	Caribbean island states	ArcInfo	KAPETSKY AND CHAKALAL 1998
Shrimp farming in ponds and fish culture in cages	Johor (State) Malaysia	ERDAS Imagine	KAPETSKY 1989
Warm water aquaculture	Continental Africa and Madagascar	ERDAS Imagine, ArcInfo	KAPETSKY 1994
Inland aquaculture	Continental Africa	ArcInfo	AGUILAR-MANJARREZ AND NATH 1998
Use of watershed ponds and reservoirs for aquaculture	Thai Nguyen, Vietnam	ArcView, ENVI	YI ET AL. 2003
Crap and shrimp aquaculture	South-western Bangladesh	IDRISI	SALAM ET AL. 2003
Land aquaculture	Sinaloa (State), Mexico	IDRISI	AGUILAR-MANJARREZ and ROSS 1995

Source: Adapted and updated from NATH ET AL. 2000

Two main categories of factors were identified: physical/environmental characteristics (e.g. water resources, climate, soils, and topography) and land use type and infrastructure (e.g. agriculture, livestock rearing). Polluted areas, protected areas and urban development were defined as constraints. Variable standardisation with Boolean (constraints) and fuzzy methods were applied to ensure the comparability of the various criteria. Factors were then weighted by using the pairwise comparison developed by SAATY (1977) within the context of a decision making process known as the Analytical Hierarchy Process (AHP, see chapter 4.4). The following generation of factor maps as well as the steps before were done using the automated MCE procedure in IDRISI. In order to maximise the land allocation area for aquaculture and agriculture the MOLA technique was applied in the final step.

The procedure demonstrates the powerful opportunities of the combination of GIS and MCE concerning the analysis of a diverse range of data to generate useful information for decision makers involved in policy development and technical assessment (NATH ET AL. 2000, AGUILAR-MANJARREZ & ROSS 1995). However, the evaluation outputs can be further improved by the integration of economic analysis and marketing tools. This would allow a more comprehensive examination of potential costs and benefits of the planned measure (NATH ET AL. 2000).

The underlying concept of the studies worked out by KAPETSKY (1994), AGUILAR-MANJARREZ & NATH (1998), KAPETSKY & NATH (1997), KAPETSKY ET AL. (1991), KAPETSKY & CHAKALAL (1998) and KAPETSKY (1989) are similar. The analytical procedures involved three main phases:

a) Identification, classification and standardisation of essential criteria for development
b) Integration of primary criteria and
c) Model development for manipulation of selected criteria

The most important categories of essential factors were the following: economics (e.g. farm gate sales, urban market potential), water availability (e.g. precipitation, rivers, and evaporation), fish growth and overwintering (e.g. water temperature), engineering capabilities (e.g. soil properties, slope) and agricultural by-products such as fish feed. Additionally, major cities, water bodies and protected areas have been defined as constraints within the Multi-Criteria Evaluation. After standardisation of the criteria they were grouped into a series of models and submodels which were used to investigate the opportunities for small-scale and commercial fish farming in ponds. The main model for assessing the land suitability for aquaculture involved the MCE method to integrate the submodels developed in the previous phase. The most critical step in these studies was the weighting procedure of criteria considering their relative importance to both small-scale fish farming as well as commercial farming systems. The verification of the results was done by comparing the resulting suitability maps with fish farm locations derived from GPS measurements.

In general, the major disadvantage of these studies was the data inaccuracy and restriction of their spatial and temporal availability. Due to the small scale of some case studies (e.g. whole Africa) it is not quite clear if the results have been used by local decision makers. Further restrictions for local use of the results as guideline for the suitability of land for aquaculture are a lack of appreciation of the methods used as well as of outcomes generated. Furthermore, the low priority of aquacultural development as well as constraints imposed by the poor state of most African governmental agencies involved in aquacultural development restrict the local use of the results (NATH ET AL. 2000).

3 Study area

The study area consists of two sites located in Uzbekistan. The province of Khorezm was selected as target area to develop and apply a locally adjusted modelling framework for fish pond site selection at regional scale. Within the Khorezm oblast the P. Mahmud farm in the Khiva rayon was chosen to apply this model for mapping suitable fish pond locations at a local scale for land use planners (see figure 3).

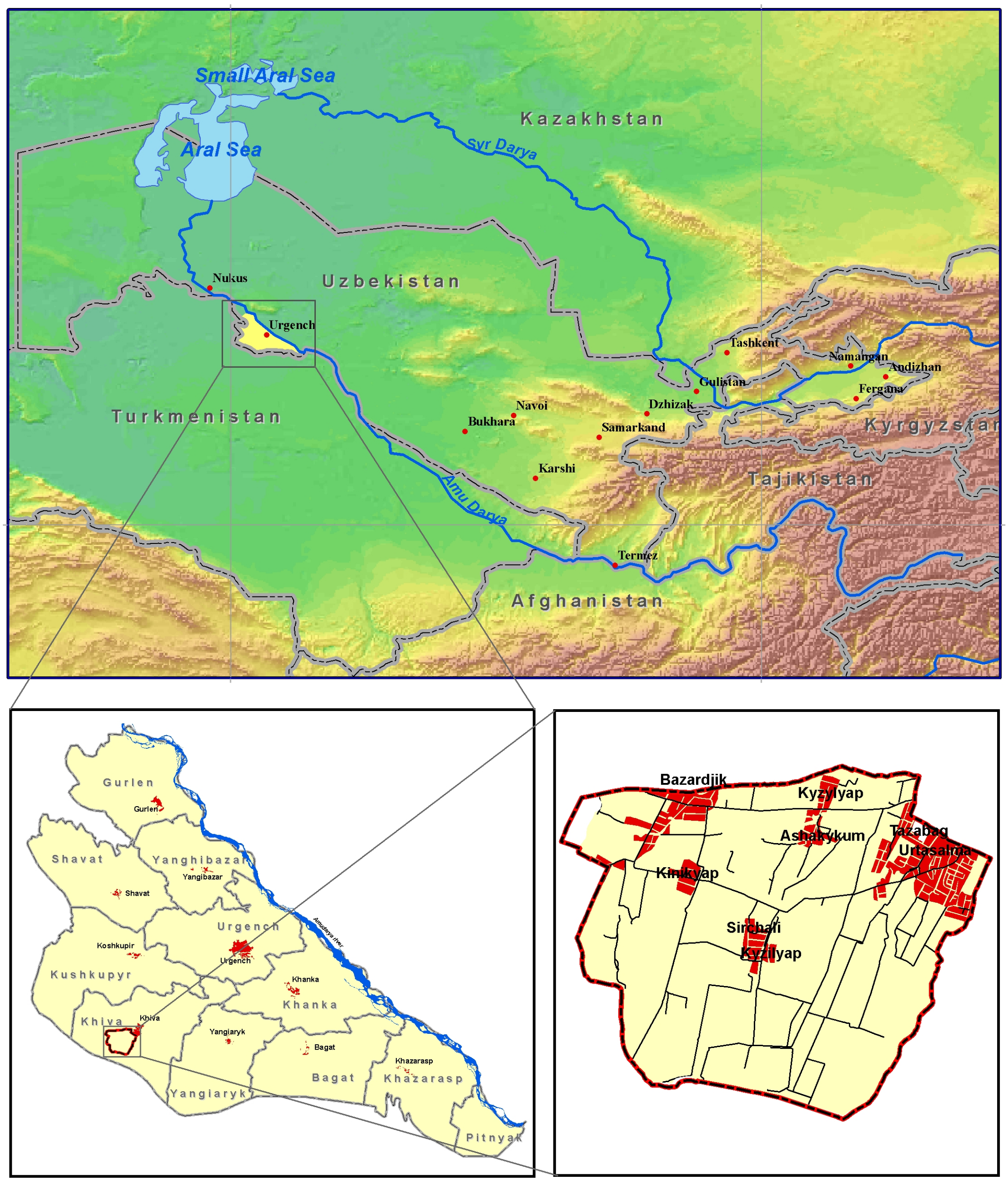


Figure 3 The study area; lower left: Khorezm with districts, lower right: P. Mahmud farm with villages

A short summary about the conditions of Uzbekistan in general and the study area in particular is outlined in this chapter.

The Republic of Uzbekistan is located in Central Asia. In the north Uzbekistan is delimited by the Ust-Urt plateau, in the northeast by the sandy desert Kyzylkum, and in the southeast by snow-capped mountain ranges (see figure 3). Uzbekistan can be characterised by an extremely continental climate, with large daily and seasonal differences in air temperature. Due to approximately 100 mm rainfall per year this area has a high aridity. Most of the water in Uzbekistan is provided by the rain- and snowfall in the mountains. Approximately 98 % of the water is used for irrigated agriculture, 0.5 % for domestic supply, and 1.5 % for industrial needs (KAMILOV & URCHINOV 1995). Uzbekistan is rich in natural and artificial water bodies, rivers, lakes, reservoirs, canals and ponds and only some rivers in the mountains are not affected by irrigation.

Figure 4 Example for competing water use; left: rice cultivation, right: pond (photographed by G. RÜCKER 2004)

In the north-western part of Uzbekistan at the border to Turkmenistan, the Khorezm oblast is one of the 12 provinces (oblasts or viloyats) of the Republic. The continental climate results in hot summers with temperatures of 26 to 28° C on average in July. In contrast the winter is dominated by frost and temperatures of -4° C on average in

January. Agriculture is the key sector of the economy where most important cultivated crops are wheat, rice and cotton. Due to the climatic conditions most of the agricultural land in Khorezm requires irrigation. The huge amount of water needed in agriculture, especially in rice cultivation sometimes lead to competing water use (see figure 4). Due to open canals and often overirrigation, salinisation of water and soils in irrigated landscapes of arid and semiarid regions is a common problem.

4 Data and methodology

In theory, every GIS study can be subdivided into seven phases: identifying project requirements, formulating specifications, developing the conceptual framework, locating data sources, organising and manipulating data for input, analysing data and verifying outputs (NATH ET AL. 2000). The development of options for establishing fish ponds as an alternative land use is the main requirement of the present study.

4.1 Conceptual framework

A sustainable land use restructuring strategy requires accurate decisions on how to allocate natural resources effectively to specific land uses. Generally, two main categories of criteria are necessary for evaluating the most suitable sites for fish pond construction: Socio-economic characteristics such as market conditions and infra-structure on the one hand and biophysical characteristics including water availability, terrain suitability and climatic conditions on the other hand. Clear choices are few and the fact that sites in a large region as in Khorezm may have different suitability for a specific purpose, faces the decision maker with a broad range of uncertainties, from a predictable (deterministic) situation to an uncertain situation (HUSDAL 2002).

The integrated use of Geographical Information Systems (GIS) and Multi-Criteria Analysis (MCA) can be a promising approach to resolve this complexity due to the complementarities of the two tools. While GIS are powerful tools for managing, preprocessing and presenting spatial data, MCA is an efficient technique for modelling the complex spatial land suitability evaluations (CHAKHAR & MARTEL 2003). There are several MCA models which could be used for spatial land evaluation modelling. They differ from each other according to the aggregation procedure, e.g. the way how they evaluate different alternatives. The easiest would be a simple overlay of all information layers that have to be taken into account. Through the definition of thresholds, areas can be evaluated in terms of suitability for certain purposes. Suitability in one criterion will not compensate for non-suitability in any other criterion. Such a procedure is called *Boolean Overlay*. However, this method requires crisp entities (e.g. constraints) such as criteria and is best applied when it can be assumed that all factors have equal importance or weight in the whole study area (HUSDAL 2002). In the present study, area constraints or restrictions for establishing fish ponds are for example given by forest patches or urban development areas. Furthermore, each criterion to evaluate the suitability of soils for fish pond construction, e.g. by soil texture, physical clay content, skeleton, soil type and soil salinity was given equal importance to build one combined soil suitability factor as input into the main suitability analysis.

In contrast, the Weighted Linear Combination (WLC) allows weighting the different factors. These weights define the relative importance of the factors and determine how individual factors will aggregate (EASTMAN 2003A, HUSDAL 2002). In this study WLC (see chapter 4.3.6.1) will be used for the analysis of factors with different importance concerning the condition for suitable fish pond sites.

The general methodological procedure as represented in figure 5 shows that the selected data used in the study were first preprocessed by GIS modelling techniques in order to provide the relevant factors and constraints. Based on literature review and local expert opinion, the main factors for fish pond locations in Khorezm were identified as economics, water availability, engineering and terrain suitability. The main constraints are infrastructure, settlements, forest patches, rice cultivation and minimum area size. The factors have a different data range and scale, thus were standardised for comparison. The factors were then weighted and entered together with the constraints into the MCE. Using data at a different scale and weighting, suitability maps were generated for regional and local scale planning. Finally, the suitability map outputs were validated, using the location of existing lakes.

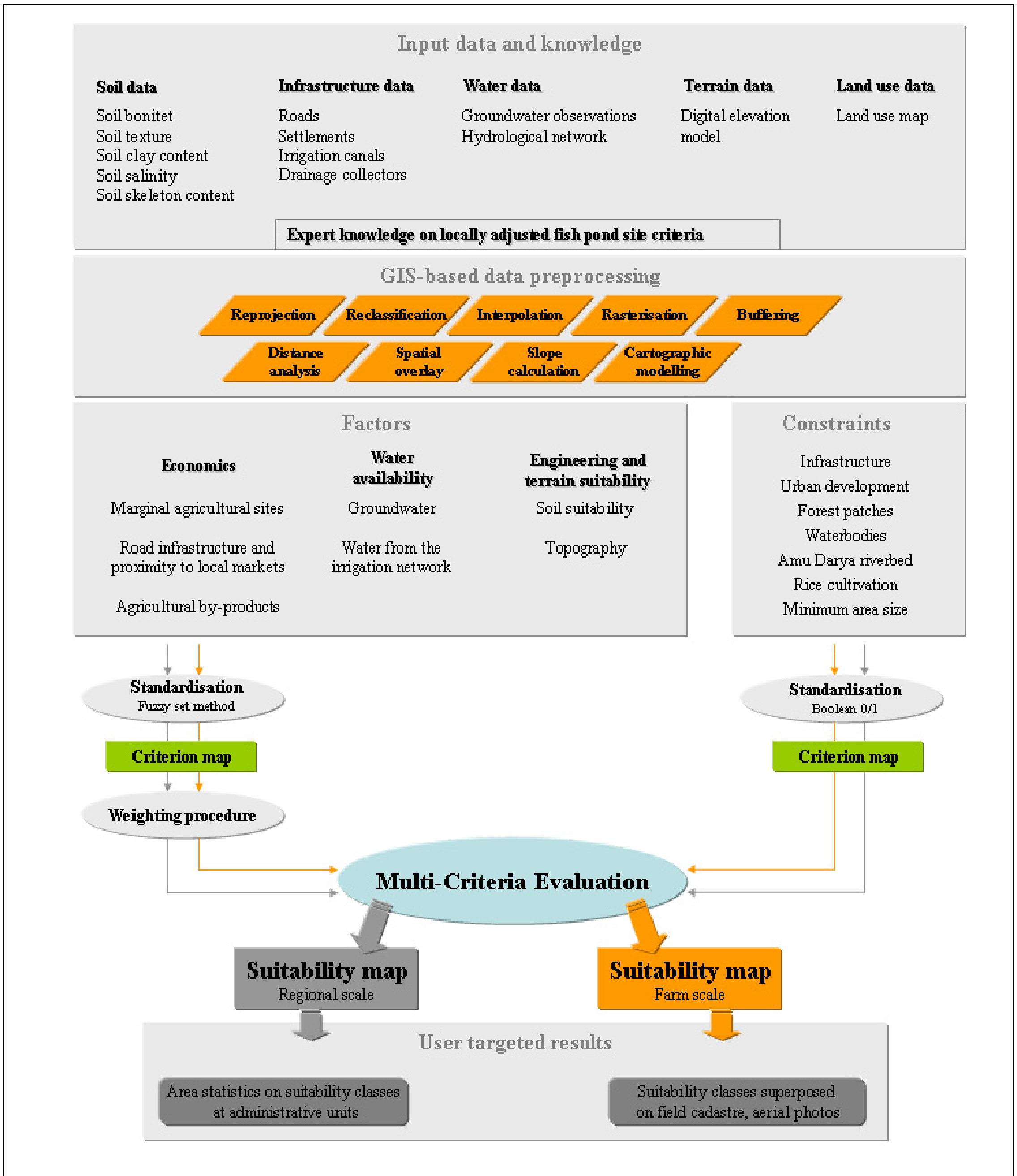


Figure 5 Conceptual framework of the present study

4.2 Geographic Information Systems

Within the last years many definitions of GIS came to existence. However, due to the fact that today the label GIS is widely attached none of these definitions is entirely satisfactory (LONGLEY ET AL. 2001). Two aspects of GIS are important to focus on: technology and problem solving. Concerning the technology GIS can be defined as a set of tools for the input, storage, manipulation, analysis and output of spatial information on the atmosphere, the landscape and the lithosphere (BARTELME 1995). Furthermore, a GIS displays all information in one standardised projection system (WORBOYS 1997, ANTENUCCI ET AL. 1991, LONGLEY ET AL. 2001), which makes it superior for spatial analysis compared to other graphical information systems (BILL 1996).

Within the present thesis the evaluation criteria were projected in the following coordinate system to ensure that the same geographical reference system is used within the whole project:

Coordinate System:	Pulkovo_1942_GK_Zone_11
Central Meridian:	63
Central_Parallel:	0
Scale Factor:	1
False Easting:	11500000
False Northing:	0
Datum:	Krasowsky
Units:	metre

Additionally, it was necessary to use exactly the same spatial extend for all raster files because the used GIS IDRISI Kilimanjaro is not able to handle raster data of different spatial extend (regional maps: upper left corner: X = 11254500, Y = 4656000, columns = 3850, rows = 3700; local maps: upper left corner: X = 11268000, Y = 4592000, columns = 1400, rows = 1300). Within the framework of this study an extensive geodatabase was developed including both data at regional as well as data at local scale. The following GIS were used for data processing and analysing: IDRISI Kilimanjaro, ArcGIS 8.3/9.0, ENVI 4.1.

4.2.1 Data management

"Data are at the heart of a GIS and any system is only as good as its population of data" (WORBOYS 1997, p. 12). From this quotation it is obvious how important data collection and processing are to ensure sound results within the evaluation procedure. Furthermore, all spatial data need to be projected in one standardised system. Spatial data as the basis of a GIS represents both a geometric and a thematic component. The former defines the spatial objects while the latter consists of a set of additional attributes that describe the objects. An independent data base should be used for data storage and to provide meta-data information. This ensures that the attribute tables are restricted to a minimum within the GIS which is important to keep track of the most important parameters. Within the present thesis data from the Khorezm central GIS data base (RUECKER ET AL. 2004) were used as input data for this study. This database provides the geometric object information in shapefile format while the attributes are additionally stored within an MS Access data base. The same is true for meta-data information such as the origin of data or underlying classification systems.

4.2.2 Vector-to-raster conversion

In general, two types of data models are distinguished for managing spatial data: vector and raster. Data sets in vector format are entities represented by multiple pairs of coordinates while one coordinate represents one point. By connecting points, lines can be generated, thus a line in vector format is represented by a number of coordinates along its length. Examples for such vector lines are the irrigation network consisting of canals and collectors and the roads network. Polygons can be generated by connecting the line back at the starting point. A set of coordinates at the corners of the polygon defines its spatial component. Each of the objects of a vector layer has an identifier which points to its attributes stored in an attached database. The various geographical objects stored in vector format have a definite spatial relation called topology (point, line and polygon). The topology defines the spatial relationship within and between objects and accordingly allows spatial analysis on geographical data.

Data sets in raster format are stored in a two-dimensional matrix of uniform grid cells. These so-called pixels are usually square or at least rectangular. In the raster data structure the only topology is cell adjacency. The value of each pixel represents the thematic information at a given location. Due to the fact that each pixel represents only one value, the resolution of the provided information depends on the cell size of the raster image. The digital elevation model for example has a resolution of 90 m. This implies that every pixel represents an average height value for an area of 810 m². For spatially overlaying raster layers in IDRISI Kilimanjaro (EASTMAN 2003 A/B) a homogenous cell size as well as the same extend of all images is imperative. Depending on the spatial scale in which the data from the Khorezm central GIS data base were provided regional scale maps were processed at a resolution of 30 m while for maps at local scale a cell size of 10 m was defined.

An important advantage of the raster model is the possibility to represent continuously distributed data, such as soil information as one data layer. In this study all vector data sets (e.g. soil data, irrigation network, settlements) were converted into raster layers to provide final suitability maps with continuous data distribution. In this rasterisation or vector-to-raster conversion (MACZEWSKI 1999) each pixel in the raster gets a value which represents a value from one attribute of the vector table. This means that each of the thematic information stored in the database will be represented by one raster layer.

Point objects are represented by a single cell in the raster layer. Polygons are converted to continuous pixels with the same value while lines are made by connecting pixels into a one-pixel-thick line.

4.2.3 Interpolation

In spatial analysis it is common to combine the information of several layers in order to analyse for example the relationship among the variables. Such analysis would be impossible if only the values of a selection of points are known and these points do not coincide between the layers. Although the sample points do coincide, it could be helpful to evaluate a given subject for the whole study area instead of just for selected points. In case of continuous data, with the value at one location being dependent upon neighbouring values it is necessary to generate a continuous surface. Usually it is impossible to measure the value of an attribute for every pixel in an image. The technique of creating a full surface is called interpolation. Interpolation is defined as the process of inserting, estimating or finding a value intermediate to the values of two or more known points in space. Estimation of an elevation value at an unsampled point is based on the known elevation values of surrounding points (EASTMAN 2003A). There is one principle that underlies all spatial interpolation methods. It is the first law of geography defined by TOBLER: "Everything is related to everything else, but near things are more related than those far apart." (TOBLER 1970, after UNIGIS module 8, unit 5; LONGLEY ET AL. 2001).

The different interpolation methods can be divided into global and local techniques. Those who consider all data points at once are called global interpolators. They produce accurate results concerning a small scale for the entire study area but may fit very poorly for a particular location. Instead, a local interpolator calculates new values for unknown pixels by using values of known cells close to them. The distance to or the number of the neighbouring pixels can usually be defined by the user.

Another possibility of classifying interpolation techniques is how they handle original data values. An exact interpolation technique always obtains the original values of the sample data points in the resulting surface, while an inexact interpolator may assign new values to known data points (EASTMAN 2003A).

What kind of technique should be used depends on the purpose of the analysis and the data availability. In general, it can be said that the result will be more realistic the more measured data points are provided. Within the present thesis interpolation was used to calculate a surface for groundwater data. For whole Khorezm 2215 measured points were used for interpolation. From these, 76 points were used to create a groundwater surface at local scale. Earlier studies which interpolated groundwater point data for Khorezm used the kriging method (IBRAKHIMOV 2005). To ensure the comparison of groundwater maps generated within these studies with results derived from the present evaluation, Kriging was used as interpolation technique as well.

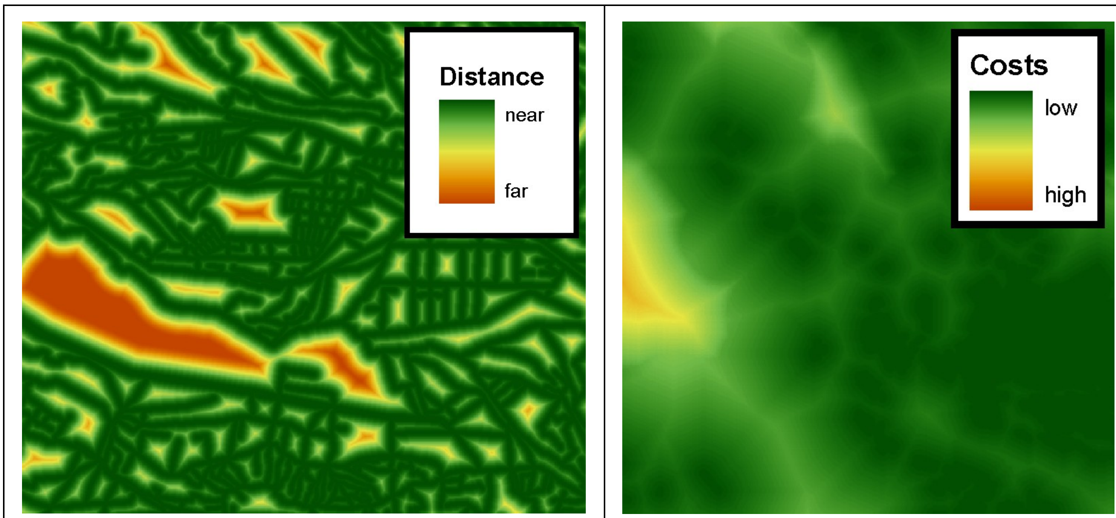
Kriging is a geostatistical method to create continuous surfaces from point data. It was named after KRIGE, a South-african Engineer and Statistician who developed fundamental geostatistical algorithms. Kriging is an exact interpolation technique and can be used either as global or local interpolator. Comparing Kriging with the simple distance-weighted average method Kriging techniques allow a great flexibility in defining the model to be used in the interpolation procedure. It is a well known fact that points that are closer together have more similar values than points that are further apart. Within the geostatistical Kriging procedure this is not restricted to an Euclidean distance. Instead, a weighted mean is calculated which takes the spatial pattern of the data points into consideration. In addition, the Kriging procedure creates an image of variance. This image provides information about the quality of the interpolated values for each pixel. It can be used as a diagnostic tool to refine the model which was defined before starting the Kriging procedure. The best model results in an image where the distribution of variance is as close to zero as possible. However, this is not a measure of the accuracy of the generated surface (EASTMAN 2003A).

4.2.4 Reclassification

Reclassification of data is the procedure of creating a new map image by assigning new values to an input image. The reclassification was used to perform database queries on single attributes and to produce Boolean images. Original values were specified as individual values or as ranges of values while output values were specified as individual values. Any value left out of the specified reclassification ranges will remain unchanged. For example, reclassification was applied for generating the factor road infrastructure and proximity to local markets to ensure the differentiation of well- and less-developed areas within the calculation of a cost distance surface (see chapter 5.1.1.2). Another example is the data processing concerning the factor soil suitability where reclassification was used to combine different classes of soil texture to classes of suitability.

4.2.5 Distance mapping functions

Distance mapping functions are techniques where distance plays a key role in the spatial analysis. Distance operations are common in Geographic Information Science (GISc) and are based on the First Law of Geography formulated by WALDO TOBLER (see chapter 4.2.3). Distance mapping functions are global functions which means that the output value at each location of the computed output raster dataset is potentially a function of all cells in the input image. In the resulting image every pixel is assigned a value representing its distance from the nearest feature (EASTMAN 2003B). Several distance mapping functions have been developed for measuring both straight line distance and distance measured in terms of other factors, such as travel costs or proximity. The straight line distance function calculates the Euclidean distance from each cell to the closest source (see figure 6A). Usually, the distances are measured in projection units such as metres and are calculated from cell centre to cell centre (McCoy & Johnston 2002). Within the present thesis a straight line distance surface was generated for the canals and collectors layer (see chapter 5.3.2.2). In this case the distance from each cell to the closest canals or collectors segment was calculated as a measure of water availability.



A) Straight distance | B) Cost weighted distance

Figure 6 Distance mapping functions

The cost weighted distance functions modify the above described straight line distance by some other factors. These factors can be described as costs to travel through any existing cell. Accordingly, cost weighted distance mapping finds the least accumulative cost from each cell to the nearest/cheapest source. This kind of calculation takes into account that the shortest distance is not necessarily the fastest or cheapest. Cost can be money, time or preference (McCoy & Johnston 2002). While straight distance is measured in units such as metres, cost weighted distance calculates values in terms of some measure of cost. The resulting values are called cost distances, the output raster image cost distance surface (Eastman 2003b). As input for calculating the cost weighted distance two raster datasets are necessary, the source image and a cost raster (or friction surface) which identifies the costs of travelling through every cell. These cost raster values are always calculated relative to some fixed base amount which is given a value of 1. The cost distance image incorporates both the actual distance travelled as well as the frictional effects encountered along the way. Even if the cost raster is a single raster dataset, it can be derived by combining several criteria. In IDRISI Kilimanjaro a module called COST was used to generate a cost distance surface. This module allows applying barriers in distance calculations by assigning a value of -1 in the cost raster (EASTMAN 2003).

Within this study the cost weighted distance was calculated for a layer combining the road network of Khorezm with settlements as the friction surface as additional input for the measure of proximity.

4.2.6 Buffering

Generating buffer zones is one of the most important transformations and they are among the most popular functions available in a GIS. In this study, buffering was applied to the roads network of Khorezm to define a corridor of proximity to the nearest road segment. Buffer operation builds a buffer zone as area within a specified distance of designated target features (point, line or polygon). In this context generating buffer zones can be described as one kind of distance operator as described in chapter 4.3.5 (see figure 7).

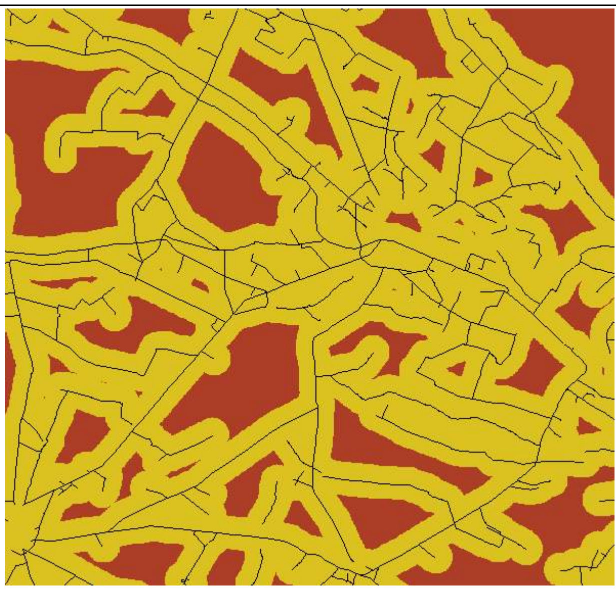


Figure 7 Buffer zones for road network, black = roads, yellow = buffer zone

The width of the buffer can be defined individually or by an object's attribute value. Buffering is possible in vector format as well as in raster images. In raster images calculating buffer zones can be described as the classification of cells according whether they lie outside or inside the specified distance. In vector format the buffer zone is a new set of objects. The resulting layer contains circular-, corridor- or polygon-shaped objects for the input layer representing points, lines or polygons, respectively (MALCZEWSKI 1999, LONGLEY ET AL. 2001).

4.2.7 Spatial overlay

The spatial overlay procedure creates a new output layer as the result of combining two or more input layers. In this study, e.g. this technique was applied to combine the different constraint maps into one single dataset and to integrate the water mask into the soil bonitet layer.

Spatial overlay is generally possible in vector format as well as in raster format. If the input layers are in raster format the resulting image contains a value for each pixel that results from arithmetic or logical combination of the values of the input datasets. Even if a spatial overlay in raster format is simpler, the result can be totally different from the results using vector overlay. An important difference between raster and vector overlay is that there is no set of rules for combination in vector format. Instead the result contains all the input information as a new rearranged and combined dataset. Moreover, two forms of overlay exist in vector format, depending on whether a discrete or field object perspective is taken. Dealing with discrete objects the task is to determine whether two objects overlap and to evaluate the area of overlap. Afterwards the new area formed by the overlap has to be defined and created as one or more new objects. From the field perspective the task is to interrogate the input datasets simultaneously. In this case the overlay first creates a new dataset in which the input regions are partitioned into smaller areas with uniform characteristics on both field variables. There will be two sets of attributes for each area in the new dataset, one for each of the input datasets. All the boundaries will be retained but they will be broken into smaller segments at intersections of boundaries of the input datasets. The result is a single dataset that combines both inputs. Having this single dataset it is much simpler to query the data through simple interrogation. The complexity of the described process of a spatial overlay in vector format was one of the greatest barriers to the development of vector GIS (LONGLEY ET AL. 2001). A great problem of the spatial overlay in vector format is the occurrence of sliver polygons where lines in each dataset represent the same feature on the ground. This happens for example due to different generalisation of the input datasets or because of digitising from different maps.

4.2.8 Digital elevation model and slope calculation

The most often used representation of the topography in a GIS is the digital elevation model (DEM). Within this study a DEM was used to calculate slopes. The elevation of the earth's surface is represented by an elevation value for each grid cell in a raster image. There are two different ways how the elevation value can be calculated. Either it is the elevation of the cell's central point or it is the mean elevation of the cell. Through transformation of the values of a DEM it is possible to generate derivative measures, such as slope and aspect.

Before calculating slopes it is recommended to examine the quality of the DEM to estimate the quality of the final product. Within this study elevation data from the Shuttle Radar Topography Mission (SRTM) with a resolution of 90 m which is available on the internet for free was used to generate a digital elevation model (ftp://e0mss21u.ecs.nasa.gov/srtm/). Most tiles of this product have some errors, such as no data values or values that have extreme values. To correct these false or missing values different filter algorithms provided by the software ENVI 4.1 were used. In a first step a bit error filter was applied to remove bit-error noise, which is usually the result of spikes in the data caused of isolated pixels that have extreme values unrelated to the image scene. In ENVI the bit-error removal uses an adaptive algorithm to replace spike pixels with the average of neighbouring pixels. The local statistics (mean and standard deviation) are used to set a threshold for valid pixels. Additionally, a median filter was applied to remove further defects. Median filtering smoothes an image, while preserving edges larger than the kernel dimensions. This is suitable for removing salt and pepper noise or speckle. The median filter in ENVI 4.1 replaces each centre pixel with the median value within the neighbourhood specified by the filter size. Within the present study a 3 x 3 kernel filter size was used. The median filter was used because of the flat terrain in Khorezm; otherwise the effect of smoothing the terrain would be too strong. In this case the centre elevation values were smoothed by 1 to 3 m on average.

After these adjustments the slope values were calculated using the SLOPE module of the IDRISI Kilimanjaro GIS software. This calculation was made by comparing the elevation of cells to the neighbouring pixels followed by the determination of the gradient of the slope (EASTMAN 2003A). The number of surrounding pixels used for calculating slope varied. The same is true for the weights given to each of the surrounding points in the calculation. Due to the fact that slope is a function of resolution, the spatial resolution used to calculate slope should always be specified (LONGLEY ET AL. 2001).

4.2.9 Cartographic modelling

Cartographic models divide the whole data processing from raw data to the final product into elementary components (BILL & ZEHNER 2001). The set of procedures that define the final product is called a model. The development of cartographic models was used to describe the data processing procedure in a logical and repeatable manner. This should support to structure the involved procedures and to identify the necessary data. Furthermore cartographic models serve as a source of documentation of the data processing (EASTMAN 2003B). Modelling plays one of the most fundamental roles for GIS. GIS provide two main possibilities to develop models. On the one hand models can be created graphically and on the other hand they can be designed by using a script language. Although these are different ways to generate models they are essentially the same. In both cases input layers have to be specified, functions and/or operators have to be defined and outputs have to be specified. The final result of a model is a new dataset. For simple equation-based modelling image calculators can be used to combine several layers. Within the present thesis the IDRISI Macro Modeller was used to develop cartographic models.

4.3 Spatial Multi-Criteria Evaluation

One strategy of the ZEF/UNESCO project in which the present thesis is embedded is to replace marginal agricultural land by introduction and management of fish ponds (ZEF 2002). This task of land use restructuring is very difficult as, due to the multitude of natural resource and socio-economic factors involved, the decision process deals with a broad range of uncertainties. There are two kinds of decisions which need to be distinguished, policy decisions and resource allocation decisions. While policy decisions are commonly used to inform the decision makers, the resource allocation decisions are intended to involve decisions of planners and implementers (e.g. farmers or farm managers) that directly affect the practical utilisation of resources. Such decisions can be supported by Multi-Criteria Evaluation (MCE).

4.3.1 Definitions and characteristics of spatial Multi-Criteria Evaluation

Various definitions of Multi-Criteria Evaluation (MCE) can be found in the literature. ROY 1996 (after CHAKHAR & MARTEL 2003, p. 49) defines MCE as "a decision-aid and a mathematical tool to compare different alternatives or scenarios according to many criteria, often contradictory, in order to guide the decision makers towards a judicious choice." Furthermore, MCE is primarily concerned with combining the information from several criteria to form a single, synthesised index of evaluation (NIHAR ET AL. 2001).

Conventional multi-criteria decision making (MCDM) techniques assume a spatial homogeneity of variables within the study area. This is unrealistic in many natural resource applications where usually a high spatial variability occurs. For example, soil types together with their characteristic soil parameters (such as salinity and texture) depend on various ecofactors and accordingly vary strongly over Khorezm.

In contrast spatial multi-criteria analyses have an explicit geographic component so that they require both data on criterion values and their geographical locations (MALCZEWSKI 1999). Thus, spatial multi-criteria decision making is the process to combining geographically defined input data into a resultant decision including decision rules that define a relationship between the input maps and the output map. A critical aspect of these analyses is that the result does not only depend on the spatial pattern of the attributes but also on the judgement of the weight of the attributes value involved in the decision making process. When MCDM are combined with GIS, the GIS must have appropriate capabilities concerning data acquisition, storage, retrieval, manipulation and analysis. On the other hand the MCDM must be robust and rationally understandable for aggregating the geographical data and the decision makers' preferences into one-dimensional values of alternative decisions (MALCZEWSKI 1999).

Two types of spatial multi-criteria decision making can be distinguished according to MALCZEWSKI 1999: spatial multi-attribute decision making (MADM) and spatial multi-objective decision making (MODM). In this context criteria are descriptive variables such as road infrastructure, soil texture or groundwater which need to be taken into consideration to reach an objective. An objective is the ultimate goal that has to be achieved, e.g. finding suitable land for fish pond construction and which is functionally related to, or derived from a set of attributes. Thus, MADM deals with single objective decision problems, whereas the same criteria are used to model several objectives within the MODM (EASTMAN 2003A, CHAKHAR & MARTEL 2003). In this study, MADM was generally applied to support the objective of identifying suitable fish ponds. Furthermore, MADM was extended to MODM, because two scenarios or objectives, including ecological and economical preferences for suitable fish pond sites were analysed.

These two MCDM types can be further subdivided into the categories single-decision-maker and group decisions. Each category may again consist of deterministic, probabilistic and fuzzy decisions. The deterministic decisions assume that the required information and data are known with certainty. Furthermore, there is a well-known deterministic relationship between every variable and the corresponding decision result. For example, identifying settlements as constraints for fish pond site selection it is evident that all settlement areas will be classified as unsuitable within the MCE. Decision analysis under uncertainty on the state of each variable and the relationships between the variable and the decision can be carried out by probabilistic or fuzzy set analysis. The difference between these two approaches is the way how they deal with uncertainty. While probabilistic analysis treats uncertainty as randomness or likelihood, fuzzy set analysis deals with the type of uncertainty associated with imprecise information (MALCZEWSKI 1999).

4.3.2 The decision making process

Due to the fact that decision making in natural resource management can become a complex process the sequence of activities needs to be well organised. The most widely accepted generalisation of the decision making process is the one introduced by SIMON, 1960 (after MALCZEWSKI 1999) after which the decision making process can be structured into three major phases as shown in figure 8.

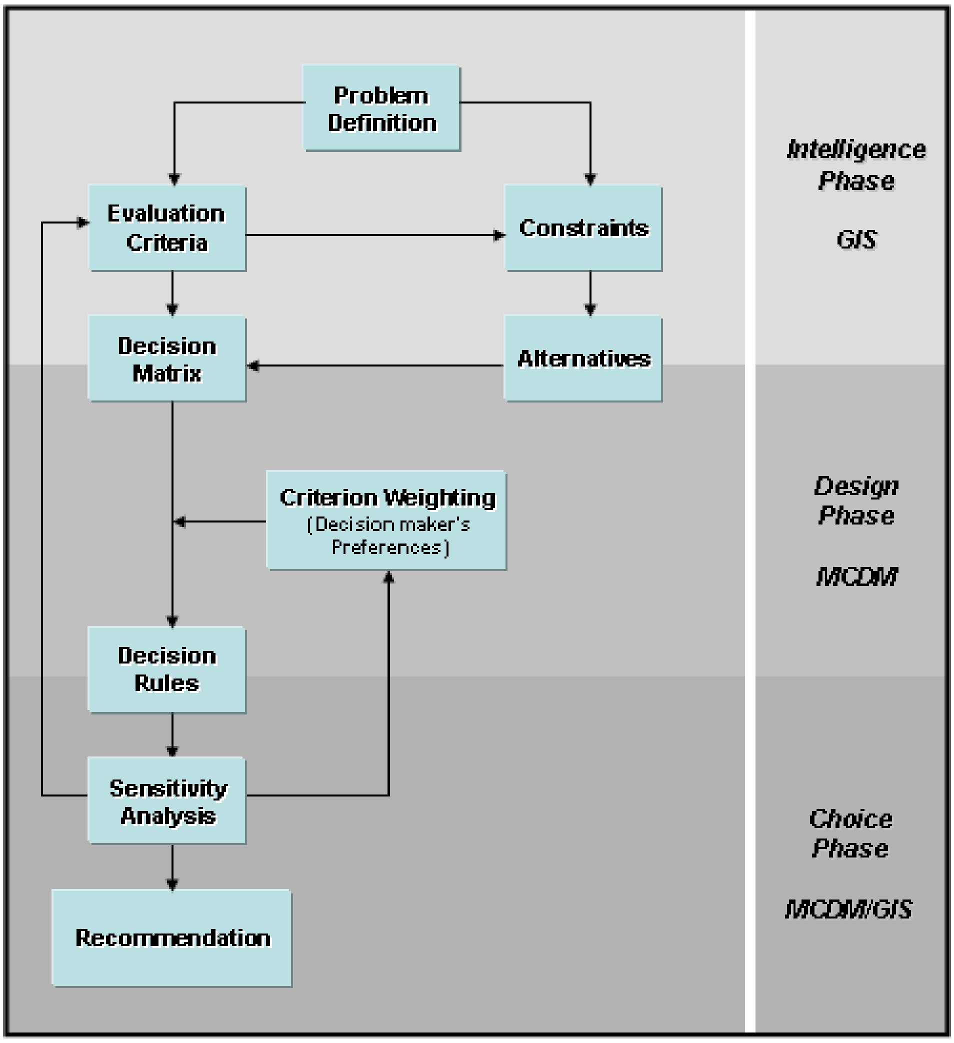


Figure 8 The decision making process **(Source: Malczewski 1999)**

The three phases of the decision making process are:

a) Intelligence: This phase includes the scanning of the decision environment for conditions calling for decisions.

b) Design: This phase involves inventing, developing and analysing a set of possible solutions to the problem identified during the intelligence phase.

c) Choice: Within the choice phase the generated alternative decisions are evaluated and one of them is selected for action.

The mentioned stages of decision making do not necessarily follow a linear pathway. Instead it may be necessary to loop back to an earlier phase at any point.

In the intelligence phase, any decision making process begins with the recognition of the *decision problem* and the definition of the objective of the evaluation. In this study the decision problem is to identify suitable sites for fish pond construction.

Afterwards a comprehensive set of attributes is specified to solve the problem. Within this step called *evaluation criteria* a measurement scale is established for each attribute and all criteria are arranged in one decision matrix. Examples for evaluation criteria used in the present study are marginal land and the irrigation network. Evaluation criteria can be represented in the form of maps, so called criterion maps or data layers in GIS terminology. In this phase the capabilities of GIS concerning data handling and analysing are used to generate the input information for the MCE.

After the evaluation criteria are elaborated *constraints* are defined to determine the scope of feasible alternatives. Constraints in this study are for example settlements, irrigation canals and forest patches. Linked to that *alternatives* may be generated to resolve constraints. For example, a possible alternative to resolve irrigation canals as a constraint might be the integration of fish ponds directly into the canal.

The next step in decision making is to determine which criterion is more important than others by specifying weights. This step of *criterion weighting* ensures that the decision makers' preferences are taken into account. The defined weight for each factor also determines how it will tradeoff relative to other factors within the evaluation procedure. For example, a relatively high weight of groundwater can compensate for poor scores on the factor slope, even if the unweighted suitability score for groundwater is not particularly good. In contrast, slopes with a high suitability score but a small weight can only weakly compensate for poor scores of groundwater. Following the weighting of factors within one evaluation, weighting was also applied here to model the differences between ecologic and economic decision preferences.

At the transition of the design phase to the choice phase the *decision rules* are defined. The decision rules define how to rank alternatives and which alternative should be preferred to another. Within the present thesis two techniques for the aggregation of the defined criteria were applied: Boolean intersection, Weighted Linear Combination (WLC). A third approach called Order Weighted Average (OWA) was only discussed and evaluated for application. Boolean intersection is the simplest type of aggregation which multiplies all single factor layers. Boolean constraints are crisp set membership functions which can be classified exactly into suitable and unsuitable images with values 1 and 0, respectively. This was only used for spatial modelling of constraints in this study. The WLC method first multiplies each standardised factor map by its factor weight and afterwards sums the results. In addition to the factor weights a second set of weights is defined within the OWA aggregation method. These order weights control the way in which the weighted factors are aggregated (EASTMAN 2003B). A detailed methodological description of these decision rules is outlined in chapter 4.3.6. The robustness of the multi-criteria decision making is determined by a *sensitivity analysis* to identify the effects of changes in the input data (input maps and weights) on the outputs. Various different factor weights for the identified criteria as well as several different data preprocessing techniques were applied. The aim was to identify how the various decision elements interact and influence the final result.

The results of the multi-criteria decision analysis are a recommendation as guideline for the decision making. The recommendation includes a set of alternatives which are ranked based on the sensitivity analysis. The results are various suitability maps for fish ponds on two different scales: regional (Khorezm) and local (local scale, P. Mahmud farm). In addition, area statistics und spatial variability descriptions for input factors, constraints and the final suitability maps were generated to provide both cartographic as well as quantitative information to the decision makers. Furthermore, the processed datasets and the results will be integrated into the existing GIS-database to expand the information to be used in Uzbekistan.

4.3.3 Selecting evaluation criteria

Within the decision making process a set of criteria or variables is selected. This set of criteria is called the *decision set* (EASTMAN 2003A). A criterion is some basis for making a decision that can be measured and evaluated, e.g. water availability or proximity to local markets. Criteria are of two types: factors and constraints.

A factor is a criterion that enhances or detracts from the suitability of a specific alternative for the activity under consideration. Groundwater table for instance is a typical factor for fish pond site selection. Factors are most commonly measured on a continuous scale without sharp boundaries which implies a form of uncertainty. Thus they are fuzzy set membership functions. In contrast to the classic crisp set with distinct

thresholds fuzzy sets are characterised by a fuzzy membership grade that ranges from 0 to 255 (or 0.0 to 1.0). For example, in evaluating whether water from an irrigation canal is within reach, a fuzzy membership function was defined so that a distance of 1 km from any location to the next canal has a membership of 0, and a distance of 0 km has a membership of 255. Between 1 km and 0 km the fuzzy membership of the distance to the next canal gradually increases on the scale from 0 to 255 (see chapter 4.3.4.2).
A constraint serves to limit the alternatives or variables under consideration. Constraints are expressed in the form of Boolean (logical) maps. Boolean constraints are crisp set membership functions which can be classified exactly into suitable/unsuitable images with values 1 and 0, respectively. Areas be considered are represented by the value 1 and excluded areas were expressed by the value. In this study areas of urban development compose for example a Boolean constraint.

4.3.3.1 Principle guidelines for selecting evaluation criteria

A well-balanced approach for selecting evaluation criteria is generally recommended to avoid both oversimplification of the evaluation by selecting only a few relevant criteria, and by defining not too many evaluation criteria that may try to capture every specific condition within the decision making process, This approach should survey all possible criteria and in addition should provide a reasonable mechanism for selecting the set of criteria. The following basic conditions were considered.

a) The set of evaluation criteria is complete, which means that the selected criteria cover all aspects of the decision problem.
b) The decision set is operational and decomposable.
c) The number of attributes is as small as necessary to avoid redundancy (MALCZEWSKI 1999).

In this study the set of evaluation criteria needs to be unambiguous, comprehensible and transparent for decision makers, because the research results should be applicable for regional and local planning of land use restructuring.

There is no universal technique available for determining the relevant set of evaluation criteria. Thus, specifying the set of evaluation criteria is specific to the problem, the study site and the spatial scale. Irrespective from the decision problem the procedure of identifying and defining the set of evaluation criteria is iterative to eliminate and summarise redundant criteria or subdivide them into further attributes (MALCZEWSKI 1999). Based on literature review on fish pond suitability analysis and fish pond planning suitable evaluation criteria for evaluating areas were identified. Complementary, knowledge from Uzbekistan experts working in this field as well as results from field work were incorporated to ensure that the criteria are relevant and adopted to the local conditions.

As a next step the ranges of values that pertain to a desired level of suitability for each criterion was specified (EASTMAN 2003B). The MCE was carried out at both regional scale and local scale, to result in coarser and more detailed fish pond target areas, respectively. This hierarchical approach will do justice to the fact that at different levels (region, farm) ecological functions are controlled in a different way by scale dependent factors (VIGLIZZO ET AL. 2003). Therefore, some criteria were applicable at regional scale but not at farm scale and vice versa.

4.3.3.2 Criteria of suitable fish pond sites in Khorezm

Three main factor categories were identified to be most important for suitable fish pond sites in Khorezm. These factor categories were further divided into nine specific factors and for both regional and local spatial scale as shown in table 3.

Table 3 Factors for small, decentralised fish farms in Khorezm

Factor Category	Specific Factor	Regional scale	Local scale
Economics	Marginal agricultural site indicated by soil bonitet	1:25,000	1:10,000
	Good road infrastructure and proximity to markets	1:50,000	1:25,000/1:10,000
	Inputs from agricultural by-products	***For discussion only***	***For discussion only***
	Water temperature	***For discussion only***	***For discussion only***
Water availability	Water from groundwater	1:100,000	1:100,000
	Water from irrigation network (canals and collectors)	1:50,000	1:25,000/1:10,000
	Water loss due to evaporation and seepage	***For discussion only***	***For discussion only***
Engineering and terrain suitability	Soil suitability	1:100,000	1:25,000/1:10,000
	Topography	1:100,000	not available

Note: The factors that were labelled "For discussion only" were not implemented in the MCE, but only explained because data were not available.

Economic factors, such as marginal areas with poor yield, but good infrastructure and local market demand, need to be spatially identified as potential fish pond target areas to ensure the profitability of fish ponds. Water availability is an important factor to achieve efficient and continuous water supply for fish in the ponds. Engineering and terrain suitability factors, such as soil suitability and local topography for constructing fish ponds are taken into account. However, these factors are less important due to less pronounced terrain and low cost technical option to change topography in Khorezm. Due to the lack of Khorezm-wide data on water loss as well as on agricultural by-products, these specific factors could not be considered although they were important to some extent. Concerning the factor water temperature a correlation between measured water temperatures with air temperature was carried out for selected ponds. These results were used to support decision makers with additional information for calculating fish growth and to select or exclude certain species for fish production.

For fish pond site selection four constraint categories were identified which were divided into ten specific constraints and preprocessed according to the scale at which they were evaluated (see table 4).

Table 4 Constraints and constraint characteristics for small, decentralised fish farms in Khorezm

Constraint category	Specific constraint	Regional scale	Local scale
Ecological constraints	Water bodies and rivers	1:25,000	1:10,000
	Forest patches	For discussion only	1:10´000
	Protected areas	For discussion only	For discussion only
Urban development and settlements	Oblast centre	1:50,000	1:10,000
	Rayon centre		
	Settlements		
Infrastructure	Roads	1:50,000	1:25,000/1:10,000
	Irrigation network		
General conditions	Minimum area size	1:50,000	1:10,000

Note: The constraints that were labelled "For discussion only" were not implemented in the MCE, but only explained because data were not available.

Ecological constraints such as forest patches and protected areas were identified as important criteria in the MCE to exclude sites where fish ponds should not be integrated into the landscape in order to protect the natural site. In order to ensure this protection fish ponds may be implemented within the landscape at a certain distance to these natural areas. Furthermore, a certain distance to settlements was specified to protect settlements from increasing moisture by raised groundwater level caused by nearby fish ponds. The importance of a settlement was used to determine the distance to fish ponds to account for the future expansion of different settlements, with cities expanding generally more extensive than villages.

4.3.4 Generating criterion maps

After identifying the set of evaluation criteria the representative spatial data were selected from the Khorezm central GIS data base (RUECKER ET AL. 2004). According to the classification of criteria into factors and constraints the corresponding factor and constraint maps were spatially modelled over Khorezm and the P. M. Farm as map layers (criterion maps) within a GIS-database (EASTMAN 2003A, MALCZEWSKI 1999).
The selected data which were available as ESRI shapefile format (ESRI Inc.) were converted to IDRISI vector format for further analysis in the IDRISI Kilimanjaro GIS-software. The IDRISI GIS-software was mainly used for its flexible MCE tool. In the subsequent rasterisation procedure the evaluation criteria were projected to a Gauss-Krueger coordinate system (see chapter 4.2).

For further processing of the data in the MCE analysis it was necessary to set exactly the same spatial extent for the files use for regional and local scale analysis. In IDRISI Kilimanjaro this was done by specifying both a regional and a local scale reference raster file with defined spatial extent and “empty data content” using the module INITIAL. These “empty” raster images were then used for the rasterisation procedure within the modelling. After further steps of data processing for specific criteria, the criterion maps were standardised. For standardisation of constraints Boolean functions were applied, whereas factors were standardised by transforming them into values which represent a positive correlation with suitability.

4.3.4.1 Boolean maps

Boolean constraints are crisp set membership functions which can be classified exactly into suitable and unsuitable images with values 1 and 0, respectively. Thus, areas excluded from consideration in the MCE were expressed by the value 0, whereas those to be considered were represented by the value 1. Forest patches, for instance, are areas that have to be protected from any effect that originates from the maintenance of fish ponds. For the standardisation procedure this means, that a value of 0 was defined within a certain distance from the constraint, whereas all other areas at the same forest patch data layer were classified as 1.

4.3.4.2 Fuzzy set membership

The simplest approach of standardisation of continuous data is a linear scaling as shown in the following equation (EASTMAN 2003A):

$$X_i = (R_i - R_{min})/(R_{max} - R_{min}) * standardised\_range \qquad \text{[Eq. 1]}$$

where X_i is the standardised value at a certain location

R = raw score

Rmin = minimum score

Rmax = maximum score

Standardised_range = range used for standardisation

However, the application of linear scaling between minimum and maximum should only be applied after careful consideration of the inherent data distribution. This is important to avoid that possible outliers are used in the standardisation.

Within the GIS software IDRISI Kilimanjaro a more advanced standardisation of continuous factors is provided by a whole range of fuzzy set membership functions and accordingly possibilities for a wise definition of the minimum and maximum values concerning their inherent meaning. Fuzzy sets are characterised by a fuzzy membership classification that ranges from 0 to 255 (or 0.0 to 1.0) indicating a continuous increase from non-membership to membership. For example, in evaluating water availability parameterised as the distance of a location to an irrigation canal, a fuzzy membership function was defined such that a distance of 1 km to the next canal represents a membership of 0, and a distance of 0 km has a membership of 255 (see figure 9).

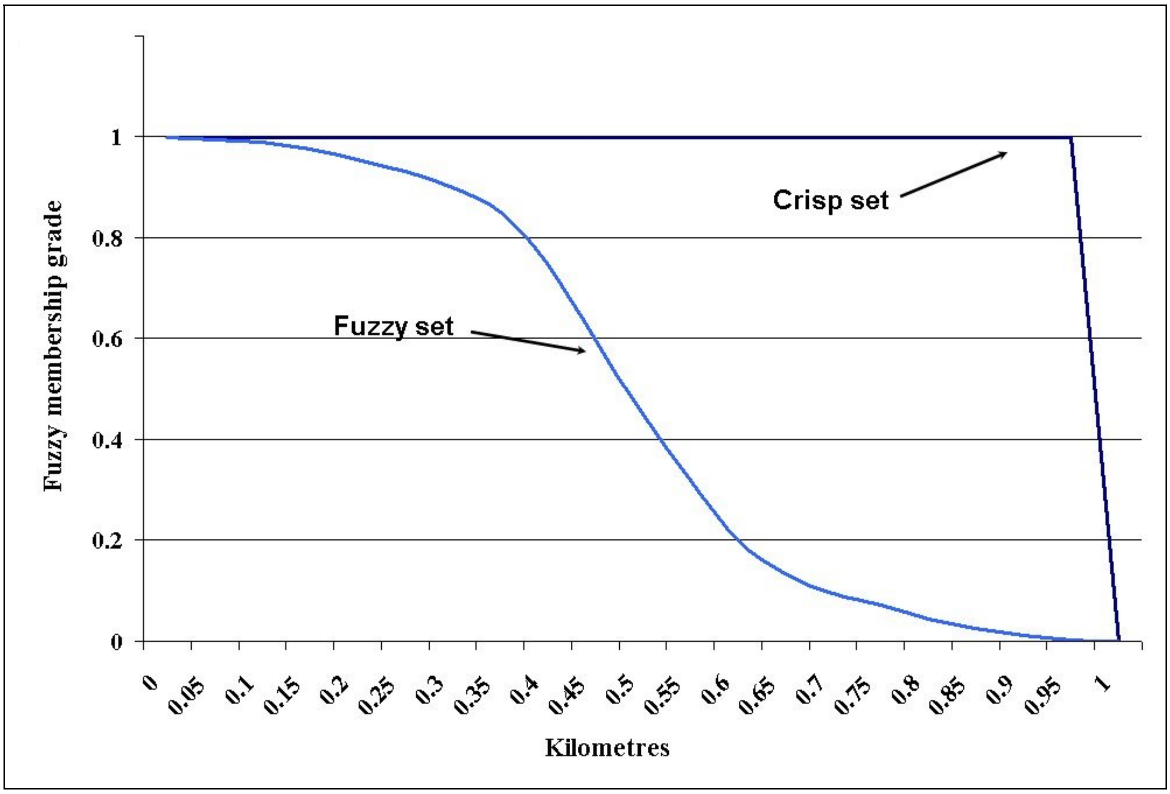


Figure 9 Fuzzy set versus crisp set membership function

Between 1 km and 0 km the fuzzy membership of the distance to the next canal gradually increases on the scale from 0 to 255 (see figure 9). As a comparison, the resulting criterion map would be totally different if the underlying standardisation function would be Boolean, because all areas between 0 and 1 km would be of equal suitability, irrespective of their individual distance to the next canal.

The IDRISI Kilimanjaro module FUZZY was used to standardise the various factors which were considered in the MCE. The following three types of fuzzy membership functions are provided by the module. The listed functions are controlled by four points sorted from low to high on the measurement scale. The first point marks the location where the membership function begins to rise above 0. The second point indicates where it reaches 255. The third point indicates the location where the membership grade begins to drop again below 1, while the fourth point marks where it returns to 0. Points may be duplicated to create monotonic or symmetric functions. For all factors the output was scaled from 0-255.

a) Sigmoidal membership function

The most commonly used function in fuzzy theory is the sigmoidal membership function. It is generated using the following cosine function (EASTMAN 2003B):

For monotonically decreasing functions:

$\mu = \cos^2 \alpha$ [Eq. 2]

where $\alpha = (x - \text{point c})/(\text{point d} - \text{point c}) * \pi / 2$

when $x <$ point c, $\mu = 1$

For monotonically increasing functions:

$\mu = \cos^2 \alpha$ [Eq. 3]

where $\alpha = (1 - (x - \text{point a})/(\text{point b} - \text{point a})) * \pi / 2$

when $x >$ point b, $\mu = 1$

The sigmoidal function can take different forms (see figure 10).

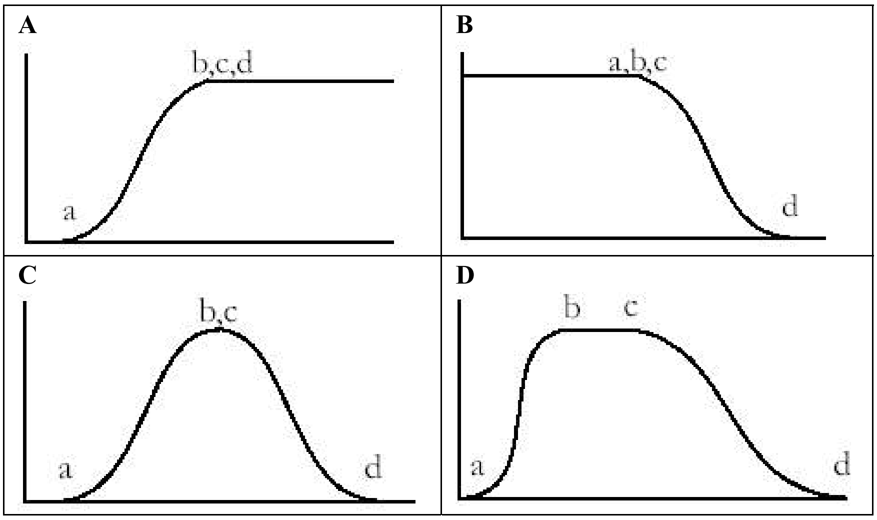


Figure 10 Curves of the sigmoidal membership function (Source: EASTMAN 2003A)

As shown in figure 10 there are four possible types of curves. The curve of a monotonically increasing function raises from 0 to 1 and afterwards stays constant (see figure 10A). In the reverse case the function is called a monotonically decreasing function (see figure 10B). The proximity to canals and collectors might be a good example for these curve types. Starting at a value of 0 which represents the distance to a certain canal the curve decreases continuously to a value of 1000 for a 1 km distance to a certain canal. The resulting criterion map shows values of 255 (most suitable) to 0 (least suitable) within a range of 1 km distance to the next canal or collector. Thus, water availability continuously decreases with increasing distance to canals and collectors.

Two symmetric membership curves for the sigmoidal membership function are shown in figure 10C and 10D. Even if they are symmetric functions there is no requirement of geometric symmetry, except for the fact that the curve rises and falls again. Accordingly, it is quite likely that the shape of the curve differs between control point a and b and the control points c and d. A geometrically asymmetric function was used for standardising the groundwater table (GWT) information. Starting from 0 cm the curve rises to a value 1 at a GWT of 30 cm, stays at this level until the GWT reaches 150 cm and falls again. Water will not be available at GWT 200 cm, so that the curve reaches the value 0 again. This approach ensures that both too high as well as too low GWT are classified as less suitable while the optimum ranges from 30 cm to 150 cm.

b) J-shaped membership function

Even if the sigmoidal membership functions seem to be advantageous for many cases the J-shaped function is also quite common. Figure 11 illustrates the different variants of the J-shaped membership function.

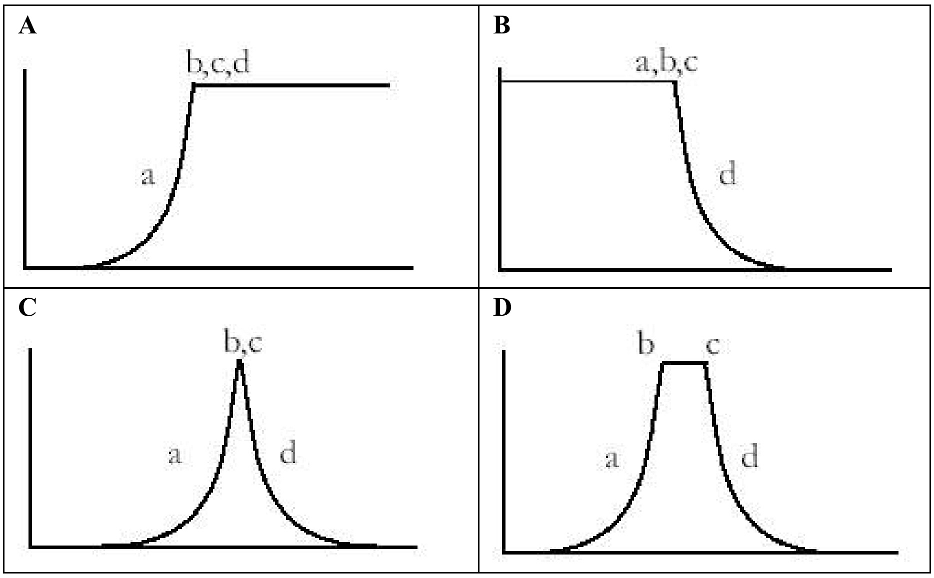


Figure 11 J-shaped membership function (Source: EASTMAN 2003A)

The formula of the J-shaped function is defined as follows (BURROUGH 1989, after EASTMAN 2003B):

$\mu = 1/(1 + ((x - p2)/(p2 - p1))^2)$ [Eq. 4]

where p1 = point 1 and p2 = point 2

when $x > p2$ then $\mu = 1$

In contrast to the sigmoidal function the value 0 is only reached at infinity. Thus, the inflection points a and d indicate the points at which the curve reaches 0.5 rather than 0. The J-shaped function is asymptotic to 0 and therefore would never produce areas with a complete membership of unsuitability. Accordingly, the J-shaped membership function is not suitable if the criterion maps need to be unambiguous and comprehensible for decision makers.

c) Linear membership function

The linear membership function is the simplest one and often used in electronic devices. Figure 12 illustrates the linear function and its variants as well as the position of the inflection points.

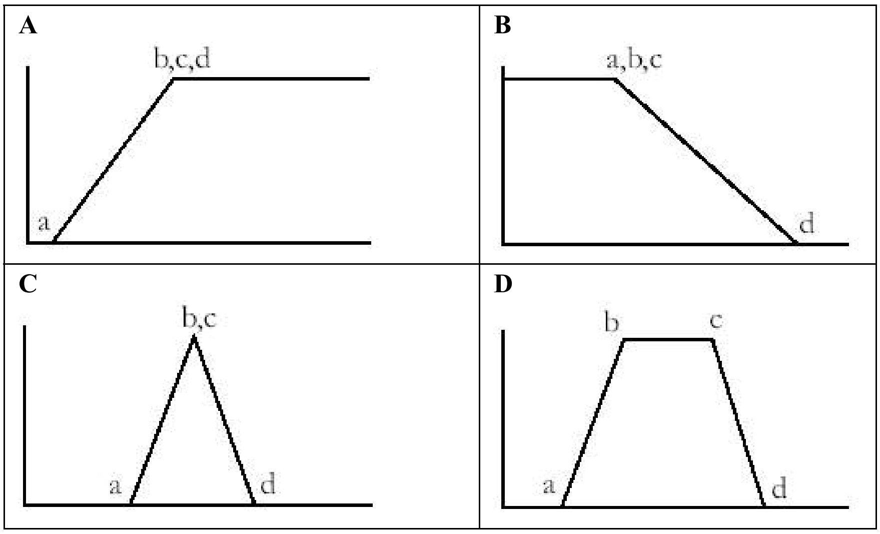


Figure 12 Linear membership function (Source: EASTMAN 2003A)

The linear function was used to standardise the slope factor. Slopes up to 5 % can be defined as suitable for fish pond construction while slopes of more than 8 % involves difficulties in locating and developing. Between 5 % and 8 % suitability decreases linear from 255 to 0.

4.3.5 Criterion weighting

Following the definition of the comprehensive evaluation factors and constraints the procedure in the decision making process requires to rank the criteria according to their relative importance. This step of *criterion weighting* ensures that the decision makers' preferences are taken into account. The defined weight for each factor also determines how it will tradeoff relative to other factors within the evaluation procedure. For example, a relatively high weight of groundwater can compensate for poor scores on the factor slope, even if the unweighted suitability score for groundwater is not particularly good. In contrast, slopes with a high suitability score but a small weight can only weakly compensate for poor scores of groundwater (MALCZEWSKI 1999). The weight usually is an additional value which is assigned to an evaluation criterion. The larger this value, the more important is the criterion within the evaluation process. To ensure compatibility the weights are normalised to sum up to 1 (see equation 5).

$$W = (w_1, w_2, ..., w_n),\ \Sigma\, w_j = 1 \qquad \text{[Eq. 5]}$$

where W is the normalised weight

$w_1, w_2, ..., w_n$ is the set of weights

Many different techniques and algorithms have been developed for the assessment of weights during the multi-criteria evaluation. They do not only differ in their theoretical foundation but also in terms of their accuracy and their degree how easy they can be applied within the decision process.

In the simplest case, criteria weights may be accomplished by rank order. This means that every criterion under consideration is ranked in order to the decision makers' preferences (1 = most important, 2 = second important, etc; or vice versa). After the ranking process there are several procedures available to generate numerical weights such as rank sum, rank reciprocal and rank exponent method.

Another set of methods for assessing the importance of weights is the category of rating methods. The basis for estimating the weight of the set of evaluation criteria is a predetermined scale (e.g. 0 to 100). In the case of a scale from 0 to 100, a weight of 0 indicates that the concerned criterion can be ignored while a weight of 100 means that only this criterion should be taken into consideration. This method is called *point allocation* approach. A modification of this approach is the *ratio estimation procedure* (EASTON 1973; after MALCZEWSKI 1999). Starting with assigning a value of 100 to the most important criterion, proportionately smaller weights are given to less important criteria. The score for the least important criterion is taken for calculating the ratios (w_j/w^*, where w* = lowest score, w_j = score for the jth criterion) which are finally normalised by dividing each weight by the total.

A comfortable approach is to arrange the multitude of information to be weighted into *pairwise comparison* to consider only two criteria at a time. The technique was developed by Saaty, 1977 (after EASTMAN, 2003A; MACZEWSKI, 1999, WEERAKOON 1996) and is implemented in IDRISI Kilimanjaro. The approach was applied within the context of a decision making process known as Analytical Hierarchy Process (AHP).

In Saaty's approach these weights were generated based on the principal eigenvector of a square reciprocal matrix of pairwise comparison between the criteria. This procedure ensures the consideration of the relative importance of the compared criteria with regard to the stated objective. Ratings are provided on a 9-point continuous scale to rate the relative importance of two criteria as shown in table 5. For developing the weights all possible pairs of the factors have to be entered into a pairwise comparison matrix (see table 5). As this matrix is symmetrical, only the lower half has to be filled in while the remaining cells are the reciprocals of the lower triangle.

Table 5 Continuous rating scale

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
Less important					More important			

Source: EASTMAN 2003A

Additional comparisons can be added, such as 1/4 between 1/3 and 1/5, where the contrast between adjacent values is too high. The result is a comparison matrix (row versus column) which reflects the relative importance of the factors. Table 6 shows an example for a pairwise comparison matrix used in this study.

Table 6 An example for a pairwise comparison matrix

	Irrigation network	Groundwater	Road infrastructure, proximity to markets	Slope	Marginal land	Soil suitability
Irrigation network	1	1	2	6	1/2	2
Groundwater table	1	1	2	6	1/2	2
Road infrastructure, proximity to markets	1/2	1/2	1	4	1/2	2
Slope	1/6	1/6	1/4	1	1/6	1/3
Marginal land	2	2	2	6	1	2
Soil suitability	1/2	1/2	1/2	3	1/2	1

A set of weights is calculated by dividing each value of the first column by the sum of this column. This needs to be repeated for each column to derive the so called normalised pairwise comparison matrix (see table 7).

Table 7 Normalised pairwise comparison matrix

	Irrigation network	Groundwater	Road infrastructure, proximity to markets	Slope	Marginal land	Soil suitability
Irrigation network	0.19	0.19	0.26	0.23	0.16	0.21
Groundwater table	0.19	0.19	0.26	0.23	0.16	0.21
Road infrastructure, proximity to markets	0.1	0.096	0.13	0.15	0.16	0.21
Slope	0.03	0.03	0.03	0.04	0.05	0.035
Marginal land	0.39	0.39	0.26	0.23	0.32	0.21
Soil suitability	0.1	0.096	0.06	0.12	0.16	0.11

Afterwards the values of this normalised pairwise comparison matrix are averaged (EASTMAN 2003A), dividing the sum of normalised scores for each row by the number of criteria (see table 8).

Table 8 Weights derived by pairwise comparison

Factor	Weight
Irrigation network	0.2085
Groundwater table	0.2085
Road infrastructure, proximity to markets	0.1397
Slope	0.0369
Marginal land	0.3011
Soil suitability	0.1052
SUM	*0.9999*

The sum of the weights must always be one as required by the weighted linear combination procedure. The principal eigenvectors was easily calculated with the module WEIGHT of the IDRISI Kilimanjaro GIS-software. Concerning the decision makers' economic or ecologic preferences the different criteria were weighted accordingly for small and decentralised fish farms where the fish production costs and profit do not exceed those of agriculture. These farms are comparable to subsistence farms with farm-gate and short distance sales.

Simultaneously with the relative importance of criteria a consistency ratio (CR) as an index of inconsistency were generated. For further information on how to calculate CR please refer to MALCZEWSKI 1999 (p. 184). For consistency ratios higher than 0.1 it is indicated to re-evaluate the weights (EASTMAN 2003A). A consistency ratio of more than 0.2 was rated as unsatisfactory by KAPETSKY & NATH (1997). Besides it is possible to determine where the inconsistencies arise.

The factor weights were defined examining the relevant literature on site selection in aquaculture, e.g. the extensive and profound references of the FAO (AGUILAR-MANJARREZ & NATH 1998, KAPETSKY ET AL. 1991, KAPETSKY 1994, KAPETSKY 1997, KAPETSKY 1998, KAPETSKY & CHAKALALL 1998, MEADEN & KAPETSKY 1995, VARADI ET AL. 2000).

4.3.6 *Decision rules*

Following the procedure in the decision making process (see figure 8), a decision rule can be described as the step by which the selected criteria are ranked and combined within a particular evaluation and by which evaluations are compared and acted upon. In this context the decision rule is the procedure to combine criteria into a single composite map. By doing this it integrates the data and information on the criteria and the decision makers' preferences into an overall assessment of the alternatives.

With an increasing number of criteria (layers) the logic of evaluating them will become confusing which lead to the use of special routines to assist with this process. Using MCE the information of numerous criteria is combined to a single index of evaluation. In GIS, two techniques are commonly used for MCE: the Boolean overlay and the index overlay procedure. In the Boolean overlay criteria are assessed by thresholds of suitability to generate Boolean maps. Afterwards, these maps are combined by logical operators such as union (logical OR) or intersection (logical AND) (SAHOO ET AL. 2001). However, in most decision making processes the different attributes under consideration do not have the same level of importance, as relevant for this study. Thus, the index overlay method allows weighting the factors while combining them. There are two well-known index overlay techniques: Weighted Linear Combination (WLC) and Order Weighted Average (OWA) (MALCZEWSKI 1999). In the present study the decision support module provided by the GIS-Software IDRISI Kilimanjaro was used which provides both WLC as well as OWA (EASTMAN 2003A).

Finally, the MCE was carried out at both regional scale and local scale, to result in coarser and more detailed fish pond target areas, respectively.

4.3.6.1 Weighted Linear Combination (WLC)

Weighted Linear Combination (WLC) methods are the most commonly used techniques for assessing spatial multi-attribute decision making processes. These methods are also known as Simple Additive Weighting (SAW). The WLC combines continuous criteria while taking their relative importance into account. The latter can be defined by assigning weights to the criteria as described in chapter 4.3.5. Formally, the WLC is performed by the following formula (EASTMAN 2003A; MALCZEWSKI 1999):

$S = \sum w_i x_i$ [Eq.6]

where S is the suitability

w_i is the weight of factor

i and x_i is the criterion score of factor i.

The most preferred alternative is selected by identifying the maximum value of the suitability. Within the MCE it is necessary to also take Boolean constraints into account. In this case, the procedure can be modified as follows:

$S = \sum w_i x_i * \prod c_j$ [Eq. 7]

where S = suitability

c_j = criterion score of constraint j

$\prod$ = product

The suitability calculated from the factors ($\sum w_i x_i$) is multiplied by the product of the contraints ($\prod c_j$). If a given pixel determined by a constraint the product $\prod$ will be 0 just as the whole result of the equation. Therefore, this site is classified as unsuitable for fish pond construction. However, if the product $\prod$ is unequal to 0 all c_j as well as $\prod$ will be 1. The result is that the suitability index is calculated by the sum of the weighted factors (RESSL 1999). When applying WLC on fuzzy variables the technique can be directly applied, because the values are comparable (HUSDAL 2002), otherwise the factors must be standardised due to the different scales in which the criteria are measured (see chapter 4.3.4).

4.3.6.2 Order Weighted Average (OWA)

Order Weighted Average (OWA) offers an extraordinarily flexible tool for MCE. OWA is similar to the above described WLC method except that a second set of weights is used, which are called order weights. Like traditional WLC techniques, it allows to combine factors with variable factor weights. However, using order weights it also allows control over the degree of tradeoff between factors as well as the level of risk one wants to assume. In cases where sets of factors clearly do not have the same level of tradeoff, OWA allows to temporarily treat them as separate suitability analyses, and then to recombine them. The order weights control the way in which the weighted criteria are aggregated using the following formula:

$S = \sum w_{ij} x_i wo_i$ [Eq. 8]

where S is the suitability

w_{ij} is the weight of class j from map

i, x_i is the criterion scale of map i

wo_i is the order weight of map i

As shown by the equation, OWA also uses criterion weights similar to the WLC method but in addition a set of order weights. Order weights are a set of weights assigned not to factors themselves but to the rank order position of factor values for a given location (pixel). This reordering step is a fundamental aspect of the OWA aggregation rule (MALCZEWSKI 1999). After factor weights are applied, the factor with the lowest suitability score is given the first order weight. Adjacent, the second order weight is assigned to the next higher-ranked factor, and so forth. This procedure will be repeated until all factors are ranked at the given pixel. Thus, it is possible that a single order weight can be applied to pixels from any of the various criteria depending on their relative rank order at the particular location. The relative skew toward either minimum or maximum of the order weights controls the level of risk (EASTMAN 2003A). The degree of overall tradeoff is the degree to which the criterion weights are applied in the aggregation procedure. EASTMAN 2003A described OWA as still somewhat experimental but potentially revolutionary as GIS technique for non-Boolean suitability analysis and decision making. However, using a second set of weights which are not assigned to factors themselves but to the rank order position of factor values for a given location makes the resulting suitability map less understandable for decision makers. Due to this the OWA approach was taken into consideration but has not been applied in order to produce transparent and comprehensible results.

5 Results and discussion

The first result of the present study was the identification of a set of criteria including both factors, their weights and constraints for suitable fish pond site selection in Khorezm. The criteria data were rasterised, analysed and standardised to derive sound criterion maps as input into the MCE. Finally, WLC was carried out at both regional and local scale using two different sets of factor weights representing a more ecological and a more economical perspective of the decision maker, respectively.

5.1 Factor analyses for fish pond site selection in Khorezm

Three main categories of factors were identified to be most important for suitable fish pond sites in Khorezm. These factor categories were further divided into six specific factors with specific thresholds and weights for regional and local scale analysis (see table 9).

Due to the fact that comprehensive data about water loss as well as about agricultural by-products were not available, these specific factors could not be considered as factors for fish pond site selection even if they were identified as important to some extent. The same is true for water temperature.

Favourable economic conditions, such as marginal areas with poor yield or high groundwater level and salinity, but good infrastructure and local market demand, were identified as important criteria for potential fish pond target areas. From an economical perspective this is the most important factor category. Thus, the factor weights of the two specific factors within this category were defined particularly high. Water availability is an important factor to achieve efficient and continuous water supply for ponds. In contrast to favourable economic conditions, water availability was weighted high for a more ecological orientated MCE. Engineering and terrain suitability factors, such as soil suitability and local topography were taken into account, but are much less important due to less pronounced terrain and low cost technical options to change topography.

Table 9 Factors and factor characteristics for small, decentralised fish farm sites in Khorezm

Factor category	Specific factor	Factor threshold for suitability	Regional scale	Local scale
Favourable economic conditions	Good road infrastructure and good proximity to markets	< 12 km to next settlement centre, 1 km to next road	1:50,000	1:25,000/ 1:10,000
	Marginal agricultural sites indicated by soil bonitet and water mask	Lakes < 0.5 ha = very suitable; Soil bonitet class 4 (low to extremely low) = suitable;	1:25,000	1:10,000
Adequate water availability	Water availability from the irrigation canals network	1 km buffer around irrigation canals	1:50,000	1:25,000/ 1:10,000
	Water availability from groundwater table	Groundwater table > 30 cm and < 200 cm	1:100,000	1:100,000
Engineering and terrain suitability	Soil suitability: Texture (30, 100, 200 cm) Salinity Clay content Skeleton	 Light to heavy loamy, not sandy None saline to moderate: Na+ cation < 6dS/m, salt capacity < 200 > 45 % Skeleton content not big or very big, fractions < 20 %	1:100,000	1:25,000/ 1:10,000
	Topography: Slope	< 8 %	1:100,000	not applicable

5.1.1 *Economics*

5.1.1.1 Marginal agricultural sites

Marginal areas could be used for establishing aquaculture ponds as an alternative land use option to create additional income for farmers. The strategy behind is to use land where site conditions are very poor and yields are low. For Khorezm as a whole this information can be derived from a soil bonitet map at a scale of 1:25,000. The evaluation on local scale is based on a more detailed soil bonitet map at a scale of 1:10,000.

Soil bonitet is a comparative measure of soil quality under the conditions of average farming activities. Originally defined as a 100-point scale related to cotton as a reference crop it was used to evaluate irrigated soils for all other crops. The value of bonitet defined the effectiveness of land resources use. Accordingly, soil bonitet defines the potential soil fertility using average farm activities. For example, under maximum fertility which equals to a soil bonitet value of 100 points 40 ct/ha of cotton can be harvested (0.4 ct/ha per bonitet point). The soil bonitet value is calculated by a combination of those soil characteristics that have highest influence on crop growth, such as soil texture, humus content and salinity.

To define marginal agricultural areas low to extremely low fertility characteristics were defined as suitable for fish pond construction. Figure 13 shows the spatial distribution of soil bonitet as well as existing water bodies at regional and local scale.

For Khorezm nine groups of soil bonitet are theoretically possible. The relevant area shares for the study sites are listed in table 10.

Table 10 Soil bonitet classes in Khorezm

<table>
<tr><th>Soil bonitet class</th><th>Soil bonitet points</th><th>Fertility characteristics</th><th>Area of Khorezm [km²]</th><th>Area of Khorezm [%]</th><th>Area of P.Mahmud farm [km²]</th><th>Area of P.Mahmud farm [%]</th></tr>
<tr><td>1</td><td>91 to 100</td><td>Very high</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>2</td><td>81 to 90</td><td>High</td><td>20.91</td><td>0.5</td><td>--</td><td>--</td></tr>
<tr><td>3</td><td>71 to 80</td><td>Increased</td><td>305.35</td><td>6.6</td><td>--</td><td>--</td></tr>
<tr><td>4</td><td>61 to 70</td><td>Good</td><td>1001.03</td><td>21.8</td><td>14.8</td><td>56.3</td></tr>
<tr><td>5</td><td>51 to 60</td><td>Average</td><td>750.76</td><td>16.3</td><td>3.6</td><td>13.8</td></tr>
<tr><td>6</td><td>41 to 50</td><td>Reduced</td><td>687.23</td><td>15.0</td><td>7.1</td><td>27.2</td></tr>
<tr><td>7</td><td>31 to 40</td><td>Low</td><td>631.50</td><td>13.7</td><td>0.2</td><td>0.9</td></tr>
<tr><td>8</td><td>21 to 30</td><td>Very low</td><td>238.10</td><td>5.2</td><td rowspan="2">0.5</td><td rowspan="2">1.8</td></tr>
<tr><td>9</td><td>Less than 20</td><td>Extremely low</td><td>959.90</td><td>20.9</td></tr>
</table>

Figure 13 shows a large belt of extremely low bonitet in the south of Khorezm where desert areas are predominant. The same is true for areas along the Amu Darya riverbed.

About 20 % of the whole area of Khorezm is characterised by soils with very low bonitet, whereas low soil bonitet areas cover approx. 14 % of Khorezm. This means that low to extremely low soil bonitet areas comprise 39.8 % of the total area of Khorezm. In contrast, areas with very high bonitet do not exist in Khorezm and high soil bonitet areas are limited to some isolated areas in the north and south of the oblast (0.5 %).

Good soil bonity areas comprise the largest bonitet class which occurs particular in the northwest and in the centre.

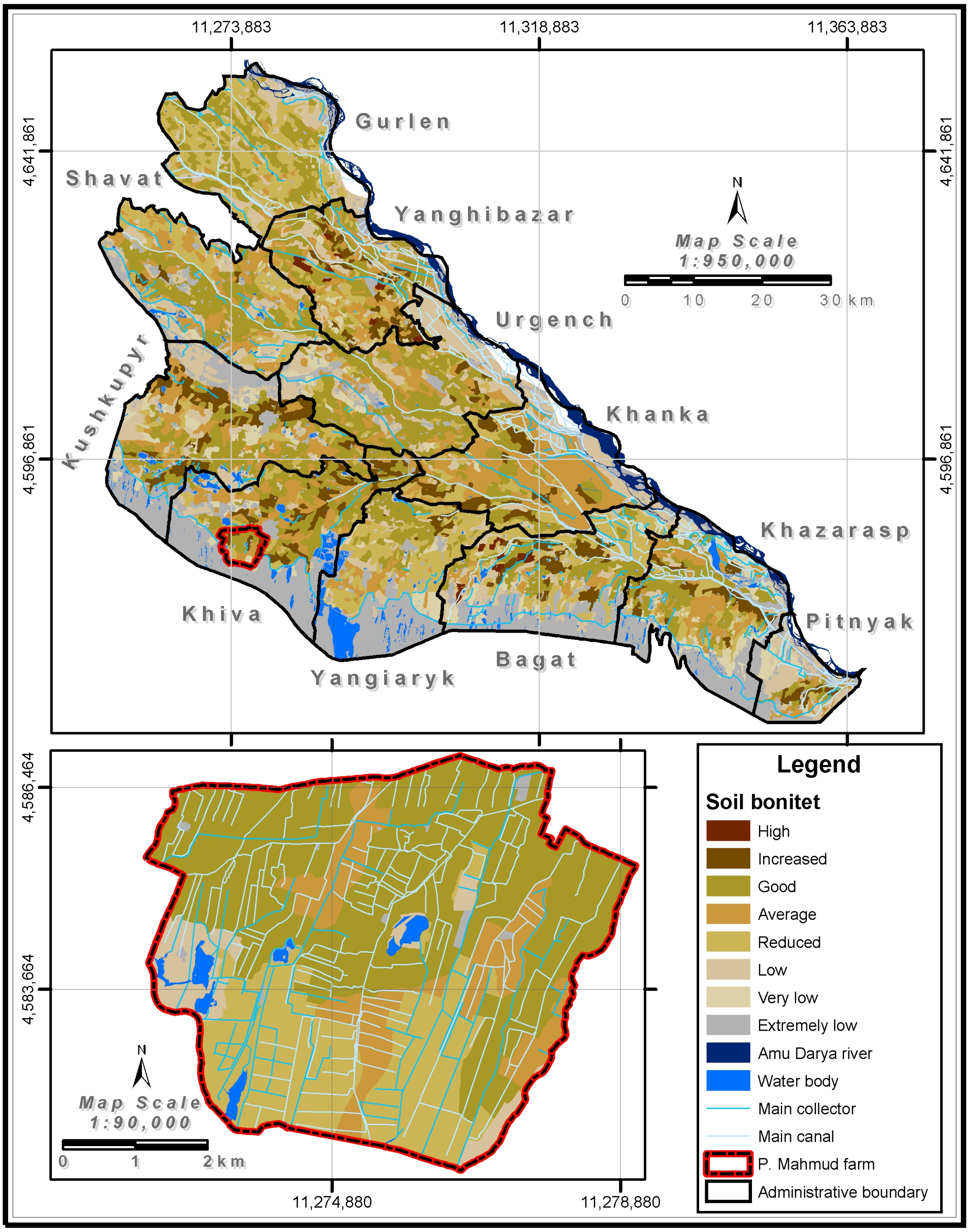


Figure 13 Soil bonitet as indicator for marginal agricultural land

The soil bonitet of the P. Mahmud farm is characterised by smaller and isolated areas of extremely low and very low (1.8 %) as well as low soil bonitet (0.8 %). In contrast, very high, high and increased soil bonitet does not exist on the farm. But most of the area (56 %) has a good soil bonitet. Overall, the northern part of the P. Mahmud farm is characterised by predominantly good soil bonitet while mainly soils with reduced and low bonitet occur in the south.

In addition to the soil bonitet information, a detailed water mask was used to identify water bodies of a certain size on local scale. The idea behind was that small-sized water bodies can be categorised as additional marginal agricultural sites, thus also suitable fish pond sites. Furthermore, small lakes are most favourable for restructuring land use into fish ponds due to the fact that implementation cost for excavations can be reduced to a minimum. After the FAO guidelines (1995), subsistence and small-scale commercial ponds under semi-intensive management (incl. fertilisation and some feeding) in Africa have a size of 100 to 1000 m^2. For Khorezm the suggested minimum area size maybe even larger of approx. 1 ha to be economically profitable when integrated with agricultural activities (personal communication with Dr. John Lamers).

However, the result of the selection of existing water bodies on the P. Mahmud farm demonstrates that there is no pond of less than 1 ha area size. Consequently, lakes of equal or less than 1 ha could only be demarcated at regional scale and were defined as very suitable for fish pond construction. Due to the uncertainty concerning the minimum size of fish ponds the final decision about whether a lake is too large for aquacultural use or not can only be made on-site. Consequently, at the present stage all existing lakes were defined as very suitable for fish pond construction. An adjustment is designated when profound information will be available.

The soil bonitet classes 9 (extremely low) to 3 (increased) were reclassified for fish pond sites from suitable to less suitable. In contrast, soils with bonitet classes 1 and 2 were classified as unsuitable for the objectives of the present study due to their favourable soil characteristics concerning agricultural use. Figure 14 shows the cartographic model that was used to process the soil bonitet data.

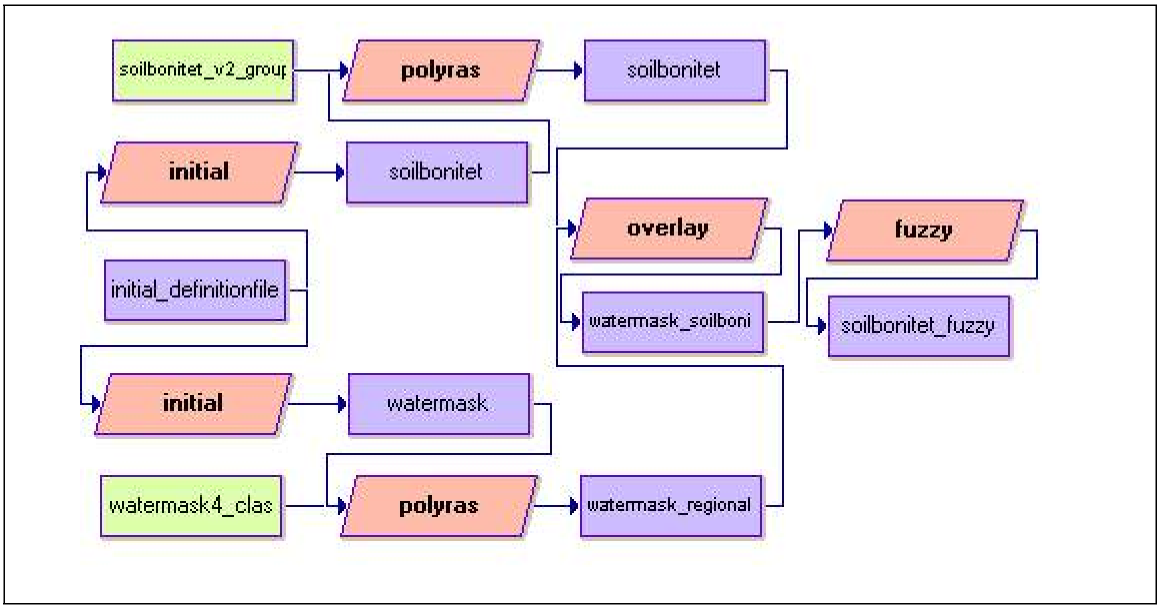


Figure 14 Cartographic model for soil bonitet

The values for the bonitet groups were deduced from the vector files which were then converted into raster format. These values were used within the rasterisation procedure as new pixel values of the empty initialisation file. Considering the lakes, the watermask was generated from Landsat satellite images of 2002 (KAISER, B. 2004). Simultaneously the vector watermask including all water bodies of the Khorezm oblast was converted to raster format setting a value of 10 (highest suitability) for the lakes larger than 1 ha that was used in the following standardisation. In the overlay function, the maximum option was defined to derive the maximum value in corresponding positions on the first (soil bonitet) and second (water mask) image. The resulting image consisted of values between 0 and 10 representing unsuitable to very suitable, respectively. For standardising this dataset, a linear fuzzy set membership function (see chapter 4.3.4.2) was applied. The final result was a criterion map of marginal land represented by a combination of soil bonitet and small-sized water bodies (see figure 12).

The spatial pattern of suitable and unsuitable areas reflects the spatial distribution of soil bonitet classes as well as existing water bodies at regional and local scale very well. The desert areas in the south with their low fertility are the most suitable areas except for the larger or smaller existing lakes. Soil with good fertility which are particularly spreaded in the northwest and in the centre are moderately to less suitable for the implementation of fish ponds. At local scale the sharp boundary between high and low fertility soils can be observed in the final criterion map as well with targeting areas for fish ponds being especially in the south. Due to the fact that more than half of the whole area of the P. Mahmud farm has a good fertility and should thus remain under agricultural use this area is less suitable for fish pond construction.

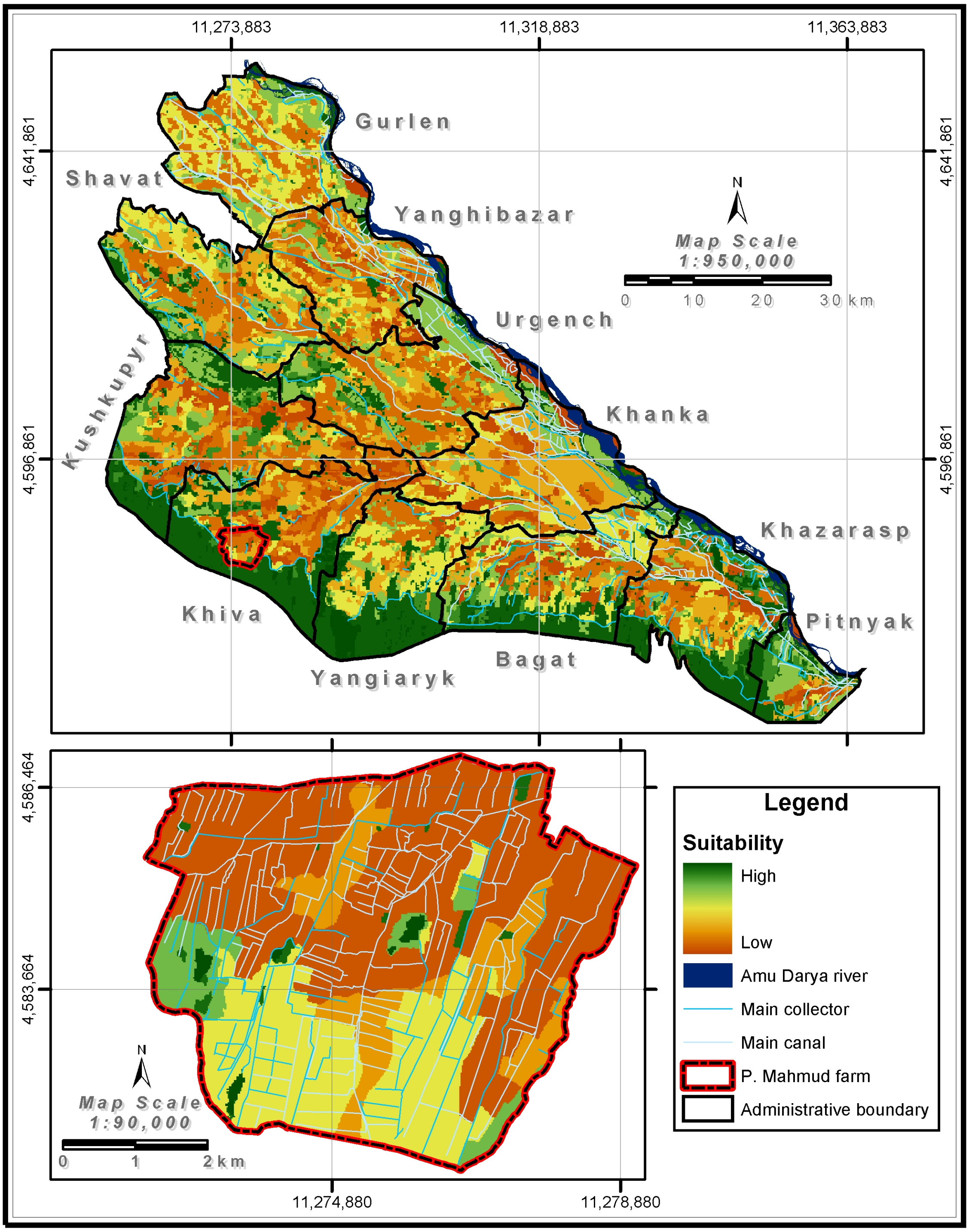


Figure 15 Criterion maps for marginal agricultural sites

5.1.1.2 Road infrastructure and proximity to local markets

Road infrastructure is another important criterion related to economics to ensure the successful development of fish farming. On the one hand paved roads are the basis for delivering fish products to local markets. Accordingly, the road infrastructure can be parameterised as travel time proximity. On the other hand the probability of electricity and communication lines is enhanced where all-weather roads exist (KAPETSKY 1994).

Furthermore, the potential of local markets should be high enough to establish fish farming as a profitable alternative to agriculture. Thus, fish farms must be located in the relative vicinity of settlements to avoid high transportation costs. Furthermore, it can be assumed that the larger the distance between the fish farm and the local market, the lower the profit for small and decentralised fish farms. This relationship is based on a tendency of an increasing density of fish ponds per district with increasing population density as observed in Africa (KAPETSKY 1994).

Although suitable sites for small-scale fish farming with moderate fish production is targeted in this study, some factors and outputs may be relevant to commercialise farms in addition. Highest returns from aquaculture can for example be achieved by selling products directly to the public via the "farmgate". Farmgate sales are usually confined to a short walking distance between 2 and 4 km (KAPETSKY 1994). For commercial fish farms in Khorezm local markets can be assumed most important for selling. If the fish farm is located close to a rayon centre or to the oblast centre Urgench it may be possible to establish a fish delivery service or to sell to local hotels, restaurants and supermarkets (MEADEN & KAPETSKY 1991). Thus, farmgate sales together with the local market potential result in a distance of 10 km along the road network to settlements as indicator for proximity. Additionally, it was assumed that the proximity of a certain road is 1 km. This assumption is based on the fact that very small roads and country lanes were not included in the available dataset. Accordingly, this is a good possibility to deal with the uncertainty of the data. To improve the results it might be helpful to include the importance of a certain settlement (rayon centre, oblast centre) into the evaluation and to distinguish a different proximity between them. Due to the fact that this can only be done when more reliable experience concerning economical information may become available the evaluation was carried out without using this additional input.

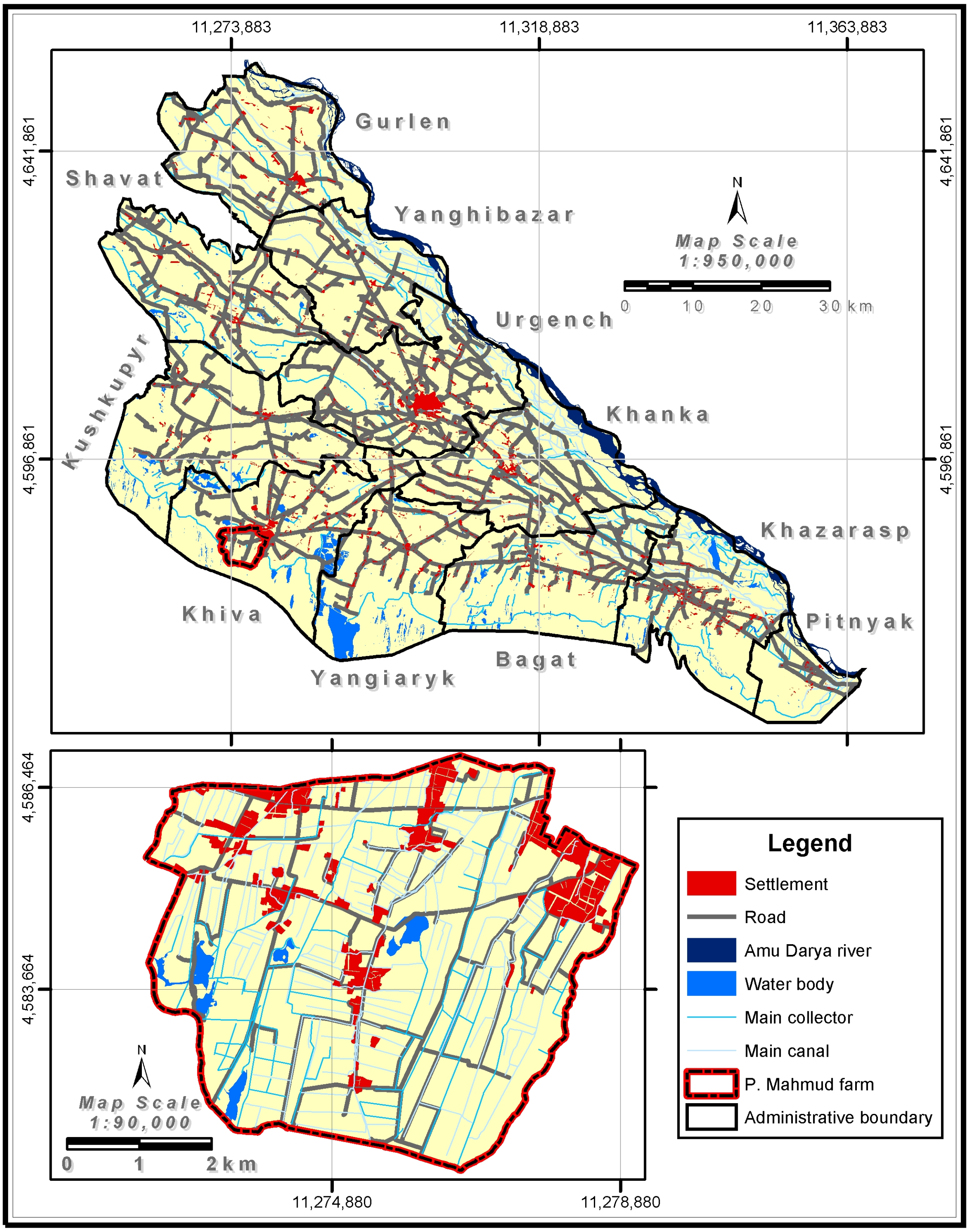


Figure 16 Road infrastructure and settlements at regional and local scale

As shown in figure 16, Khorezm has a wide-spread road network except from the desert in the south and some smaller areas along the Amu Darya river in the east. The distribution of settlements follows a similar pattern. Although the rural districts are sparsely populated there are numerous settlements in the province which can be considered as a good demand for fish products (see figure 16), especially because fish is a very well accepted and popular dish in Khorezm. At the farm scale the northern area is characterised by many settlements compared to just a few settlements in the south. In both areas the road infrastructure can be described as fairly well-distributed. The road infrastructure and proximity to local markets were parameterised in the GIS as shown in figure 17.

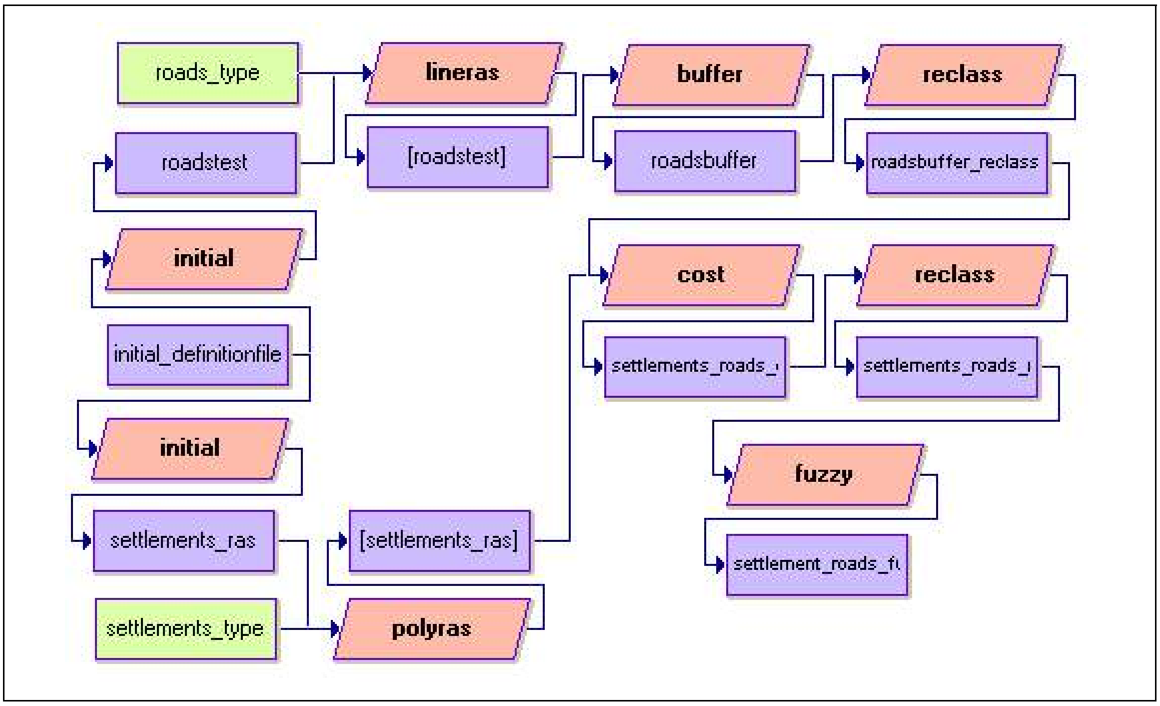


Figure 17 Cartographic model for road infrastructure and proximity to local markets

As the cartographic model shows, the vector maps of both settlements and roads were converted into raster format. Afterwards the road network was buffered with an area of 1 km Euclidean distance. Areas outside the buffer zone were reclassified with a value of 3, whereas inside a value of 1 was defined. This procedure ensured the differentiation of well- and less-distributed road and settlement areas within the generation of the cost distance surface. Thus, movement within well-distributed road and infrastructure areas is three times easier than in sparse distributed areas. The result of the cost distance calculation is an image with values ranging from -1 for areas around the calculated surface and 350 which was the defined maximum growth distance. Further reclassification was used to convert the value -1 into 351. This ensures that all these areas were classified as unsuitable within the following fuzzy set membership calculation. Figure 18 shows the resulting criterion map for road infrastructure and proximity to local markets.

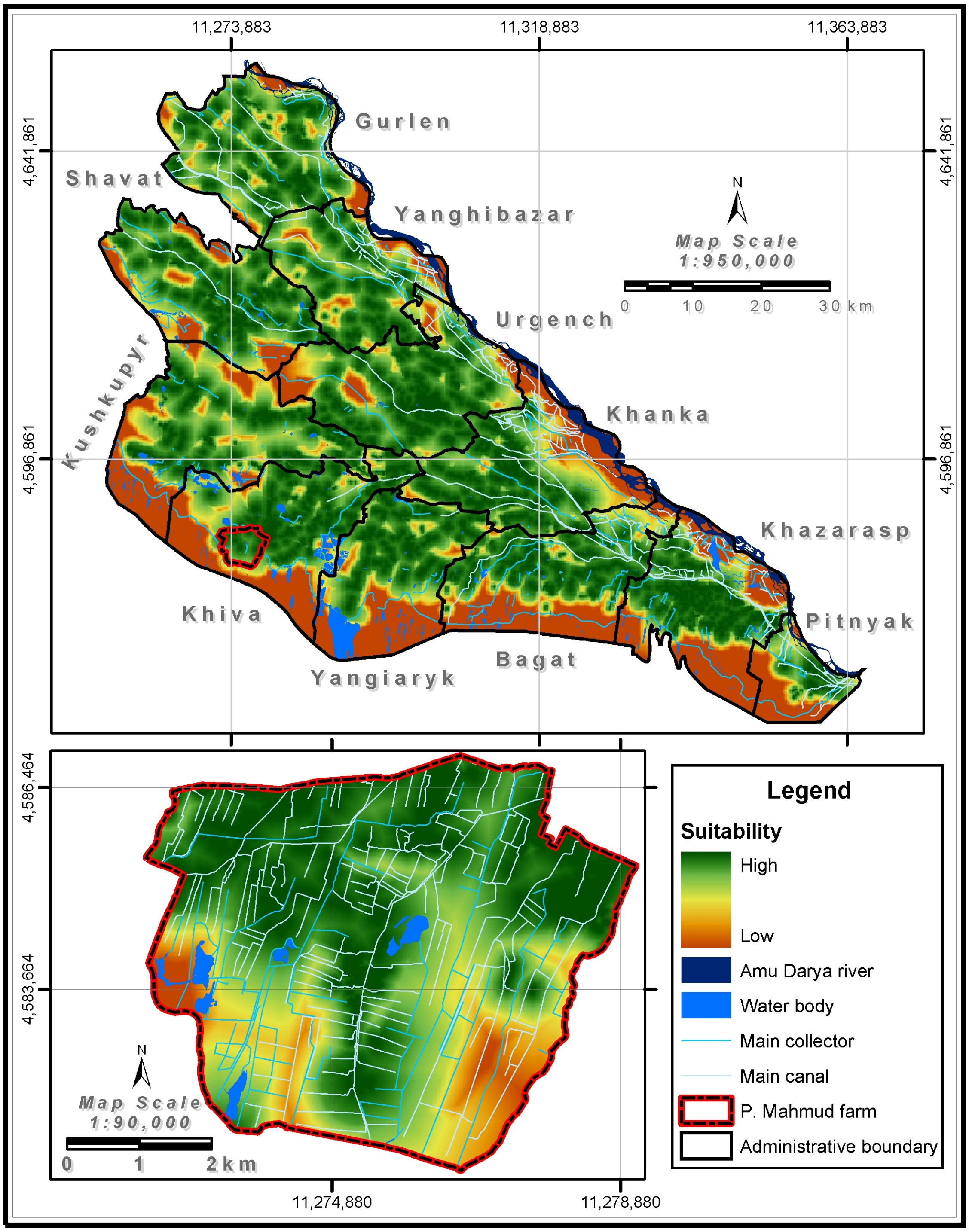


Figure 18 Criterion maps for road infrastructure and proximity to local markets

In all areas close to settlements and roads a high suitability for fish ponds is indicated. The greater the distance to a certain road or settlement the smaller the fuzzy set membership value and accordingly the suitability index. Areas with low suitability are mainly in the desert and along the Amu Darya river. Another large area of unsuitability is at the border of the Urgench and the Shavat province and the south-eastern and south-western parts of the P. Mahmud farm where there are no settlements. The relatively high suitability in the south-western corner results from a small village south of P. Mahmud farm. Although this settlement was included into the evaluation it can not be recognised on the maps which show only the farm area.

5.1.1.3 Agricultural by-products as fish farm inputs

Agricultural activities were identified as an important indicator of aquaculture potential in two ways. On the one hand, it was assumed that agriculture implies at least a minimum amount of infrastructure for development and that agricultural activity is related to the existence of local markets in villages or towns. This was mainly modelled by road and settlement distribution. On the other hand, agricultural activities may provide a source of by-products that can be used as locally available fish feed or fertilizer (KAPETSKY & NATH 1997).

Agricultural by-products for direct feeding are essential for a successful integration of fish farming into the existing agricultural economy. Using agricultural by-products for small-scale fish farming, yields will be higher than it would be possible from the natural production of the pond only. In addition, the use of by-products allows the partial replacement of artificial feeds which implies a reduction of feed costs (KAPETSKY & NATH 1997). Accordingly, agricultural by-products could contribute to the establishment of integrated agriculture-aquaculture farming as targeted in the land use restructuring in Khorezm.

The objective is to identify the varieties of agricultural by-products that could be used as inputs for fish farming, their availability and locations. After KAPETSKY (1994) the needed information can be related to agroclimatic suitability as measured by the length of growing period (LGP). This relation gives a good overview on the potential availability of certain crops at national or continental scale. However, for an assessment on regional and local scale the derived information was considered to be too coarse. Furthermore, the LGP as an indicator for the availability of agricultural by-products was considered as being insufficient due to the fact that the region is characterised by extremely continental climate with arid conditions all over the year.

A promising source of locally available fish feed might be cow dung. TACON found out that from 18 fish farms visited in Kenya, 83 % used fresh cow manure for pond fertilisation (AGUILAR-MANJARREZ & NATH 1998). This factor is not as dynamic as the land use pattern and can be modelled by the distribution of farm households with cattle. The idea was to derive the needed information from high resolution ASTER and Landsat 7 ETM+ data. However, the analysis of several satellite data led to the conclusion that it was impossible within the time framework of this study to generate reliable information on cow dung availability, parameterised by the size of cow sheds, because the roof of cow sheds could spectrally as well as spatially not clearly be discriminated from the roofs of other buildings. Thus, the availability of agricultural by-products was identified as an important factor for fish pond site selection but could not be included into the final MCE.

5.1.2 Water availability

5.1.2.1 Groundwater

Although Khorezm is characterised by an extremely continental climate with only about 100 mm annual rainfall, groundwater tables are relatively high due to input via irrigation. Thus, groundwater was identified as a major source for water in Khorezm besides water from the irrigation network. When considering water availability from groundwater it is important to take not only the quantity into account, but also the variability of the groundwater table. In Khorezm the groundwater table fluctuated strongly over the past decades. Accordingly, the use of a one year average was assessed as to be less representative and uncertain. Instead, a ten-years average was used to take the temporal variability of groundwater tables over Khorezm into consideration. Due to the fact that the causes for water quantity variations at any location depend on the hydrological cycle and the management at this particular site and neighbouring sites a detailed hydrological assessment might improve the results. On the other hand such analyses are complex and time consuming. Within the present study it was assumed that the assessment of a ten-years average provides fairly reliable results.

Altogether 2215 measured points for the whole area of Khorezm and 76 points covering the farm scale were used to calculate a potential mean surface for groundwater table data. Earlier studies which interpolated groundwater point data for Khorezm used the kriging method (MIRZAKHAYOT 2005). To ensure the comparison of groundwater maps generated within these studies with results derived from the present evaluation kriging was used as interpolation technique as well. As kriging method ordinary kriging with a spherical semivariogram model and a search radius of 10 points was applied in ArcGIS 9.0. In general, groundwater tables in the whole area of Khorezm ranged from 1.30 m to 2.40 m and 1.47 m to 1.93 m, at regional and local scale, respectively.

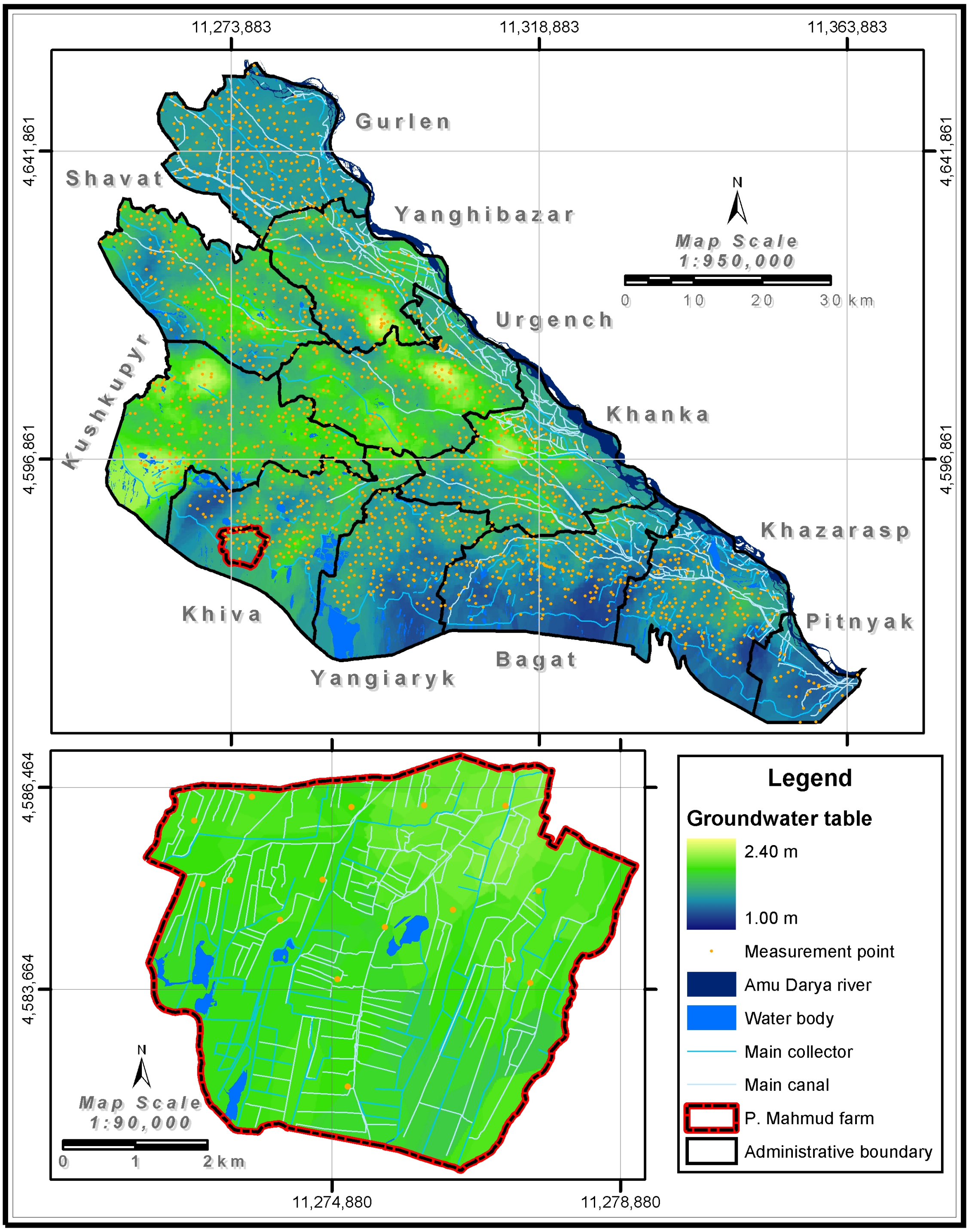


Figure 19 Groundwater table at regional and local scale

Concerning the spatial distribution it can be observed that the south-eastern part of Khorezm is characterised by high groundwater table (see figure 19). However, KAPETSKY ET AL. (1991) and AGUILAR-MANJARREZ & NATH (1998) point to the fact that groundwater as a source for ponds is not recommended if through its use the ponds cannot be drained. In Khorezm several lakes used for fishing are fed by ground water and are drained by drainage channels. Therefore it can be concluded that groundwater is an effective source for fish ponds if groundwater levels are not too high. According to AGUILAR-MANJARREZ & NATH (1998) a minimum groundwater depth of 30 cm was defined within this study to allow drainage. A groundwater table of 30 cm to 150 cm was assumed as the optimum while a water level of more than 200 cm was identified to deep for fish pond construction. The spatial distribution of mean groundwater table is shown in figure 19.

With regard to the above mentioned spatial distribution it can be summarised that most parts of Khorezm have optimum conditions concerning groundwater supply. However, the groundwater level in the provinces Urgench, Yanghibazar and Kushkupyr is clearly below-average.

After the interpolated raster images were saved to GeoTIFF format they were imported to IDRISI Kilimanjaro to serve as input for the fuzzy set membership function (see figure 20). Within the fuzzy module a symmetric sigmoidal membership function (see chapter 4.3.4.2) with the inflection values 0, 30, 150 und 200 were applied. Due to the fact that the imported raster images lost their projection information during the import, this information was defined again. The resulting images are shown in figure 20.

Figure 20 Cartographic model for water availability from groundwater

The maps in figure 21 describe the different spatial distribution suitability based on groundwater levels. At regional scale areas of low suitability can be observed where groundwater tables are deeper than 2 m which is true for large areas in the provinces Urgench and Kushkupyr as well as in the south of Yanghibazar and in the northern

Khanka. At local scale the spatial differences are only minor with generally higher suitability in the south and gradually lower suitability in the north.

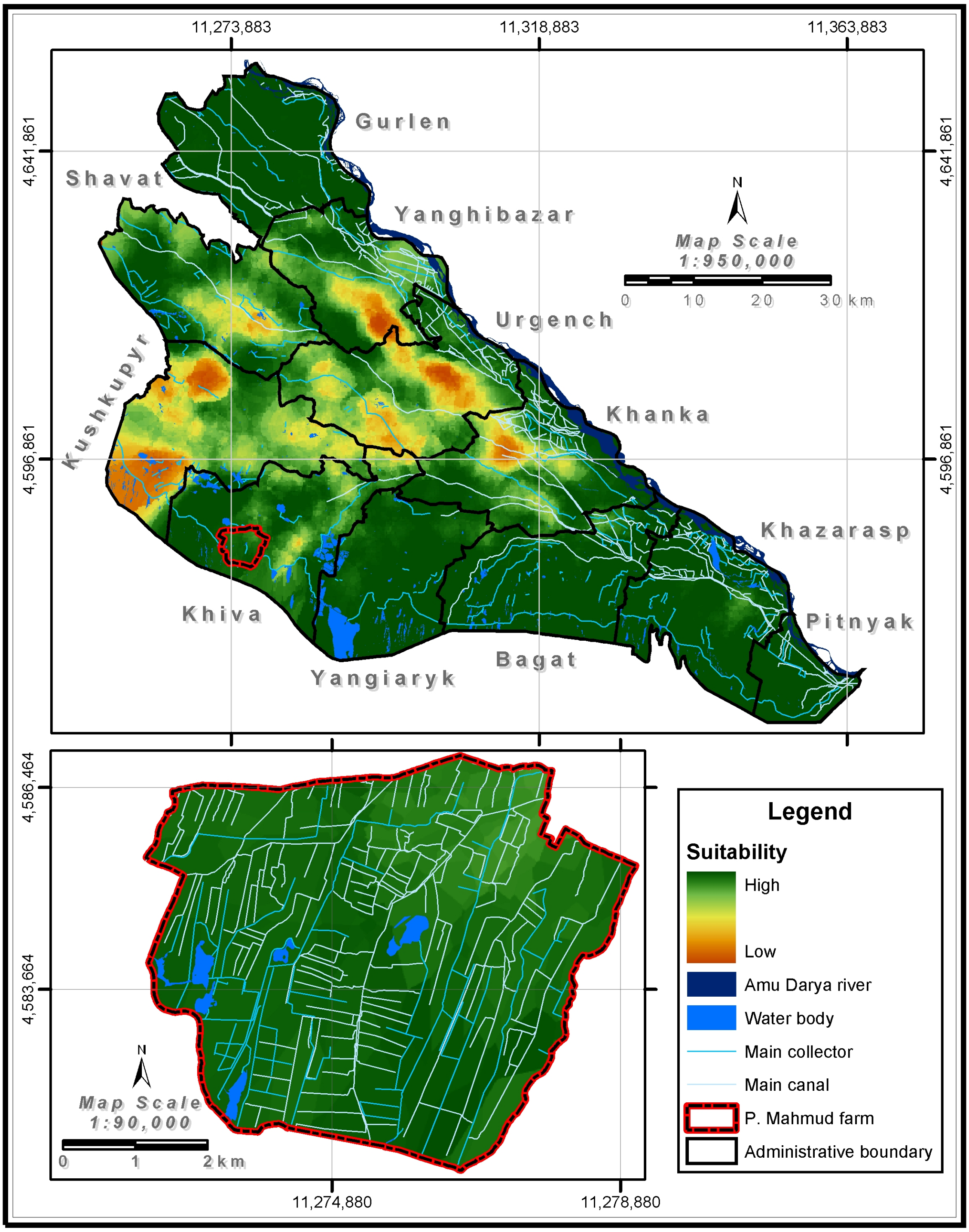


Figure 21 Criterion maps for water availability from groundwater

5.1.2.2 Water from the irrigation network

Rainfall is very little in Khorezm (90 to 100 mm) and evaporation rates are high which makes rainfed aquaculture that requires at least 300 to 400 mm (KAPETSKY ET AL. 1991) impossible in this region. Approximately 45 % (2753 hm²) of the agricultural land in Khorezm is irrigated. Irrigation infrastructure is therefore widespread and pond construction should be integrated within the existing network of irrigation and drainage canals, to support small scale aquafarming with economic limitations to construct additional water distribution infrastructure. One of the first steps within the evaluation of water availability from the irrigation network was to identify a certain distance to an irrigation canal that defines the boundary between suitable and unsuitable to build up ponds.

A linear distance surface was calculated for all canals and collectors to parameterise the proximity to canals (see chapter 4.2.5). Within the following fuzzy set membership an Euclidian distance of 1 km to the next water supplier was defined as maximum value for suitability.

At local scale this method was extended by hydrological network analysis incorporating the hierarchy of a certain canal segment and the distance to the four main irrigation canals that led into the farm. The latter are located in the north eastern corner and in the east of the P. Mahmud farm area (see figure 22). It was assumed that an increasing distance from the main water supplier results in increasing costs for water transportation in increasing water loss due to evaporation and seepage or rather decreasing water availability.

Starting from the location of these main irrigation canals entering into the farm a cost distance surface was generated along the buffered (100 m) irrigation canals. The hierarchy of a certain canal segment was represented by differences in their frictional effect. It was assumed that differences in the hierarchy result in a different amount of water that can be transported in a certain period. Accordingly, the higher the frictional effect of a canal segment the lower the water availability within the surrounding area.

The irrigation system of Khorezm and the hydrological network of the P. Mahmud farm are shown in figure 22.

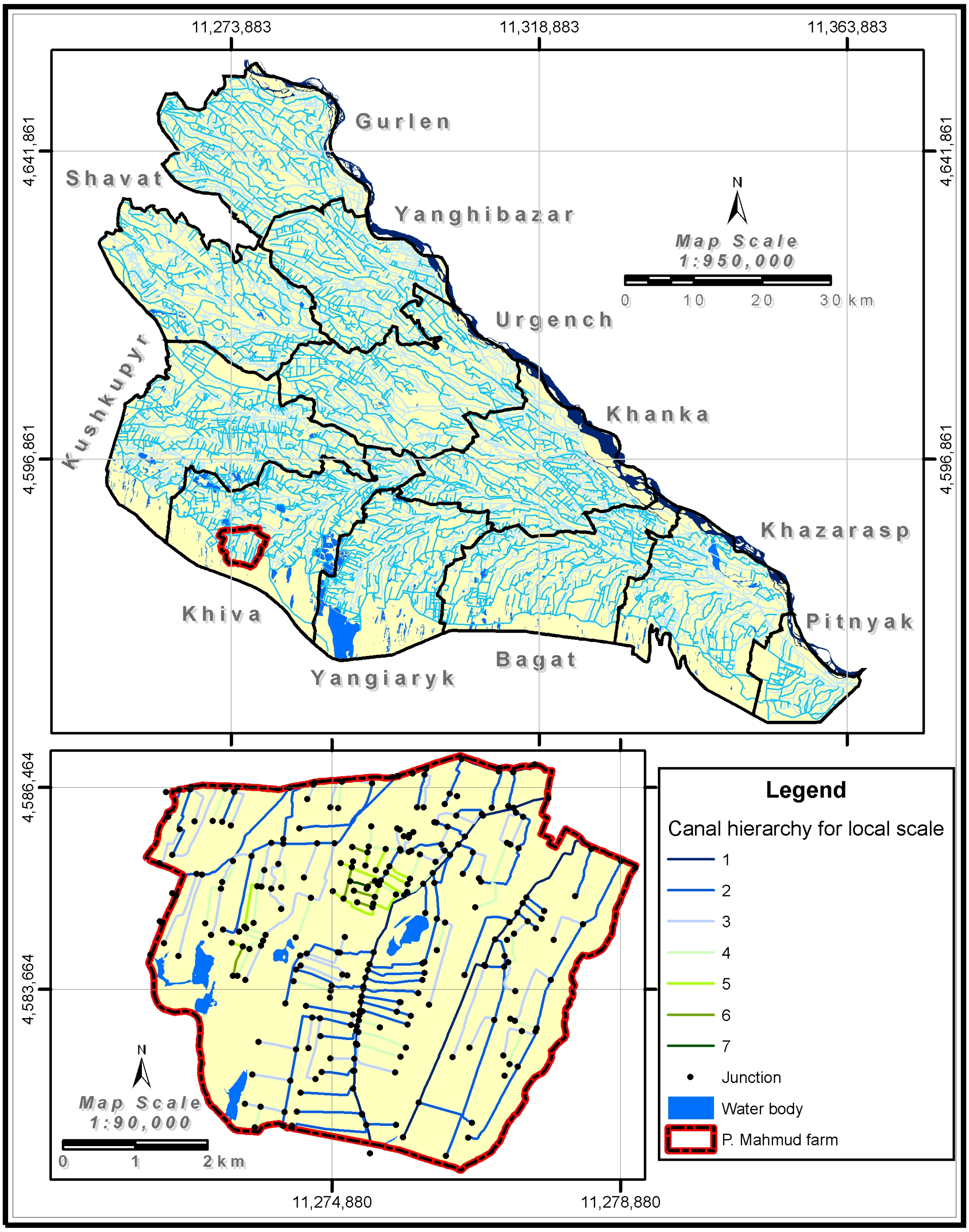


Figure 22 Irrigation network at regional and local scale

As shown in figure 22 the irrigation infrastructure with its dense canals and collectors is generally widespread over the whole area of Khorezm except for the desert areas in the far south. In addition, the suitability index depends on the category of the canals the water has been flown through. Thus, the junctions at the main canal have higher values than the junctions further west and east although the distance to the main supplier is the same. Besides the cost distance surface, the suitability value (0-255) at every junction ensures that the results can be used to estimate the water availability for a certain field that is supplied with water by the nearest junction. At locations with values of higher than 200 enough water to maintain fish ponds is available, the suitability can be defined as being very high. Values between 150 and 200 indicate good water availability as well while values less than 150 can be classified as moderately suitable for the purpose of the present study.

The described procedure was modelled as shown in figure 23 and mapped as shown in figure 24.

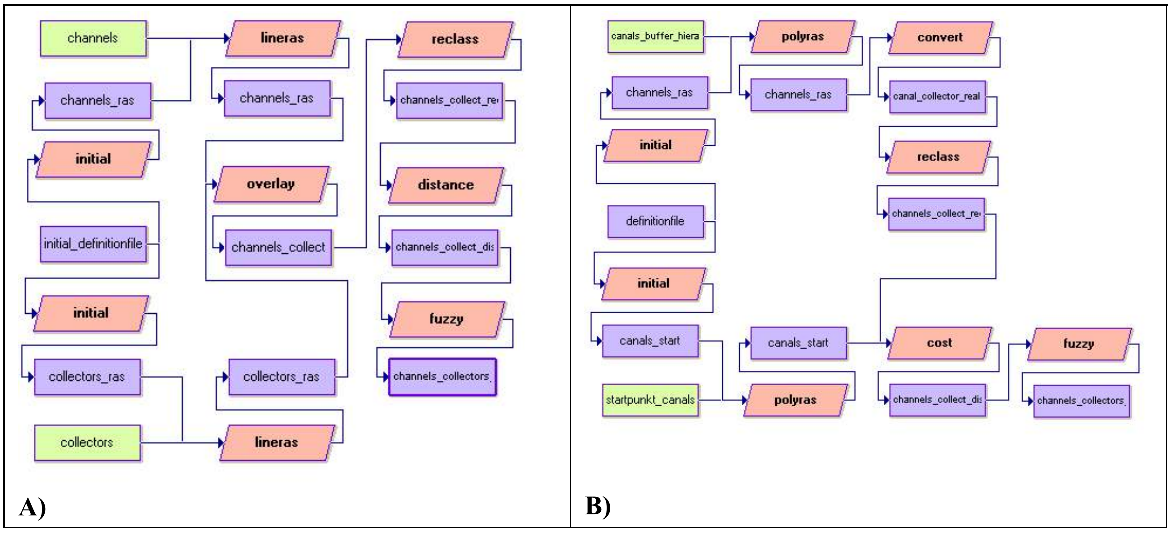


Figure 23 Cartographic model for water availability from the irrigation network, A) at regional scale, B) at local scale

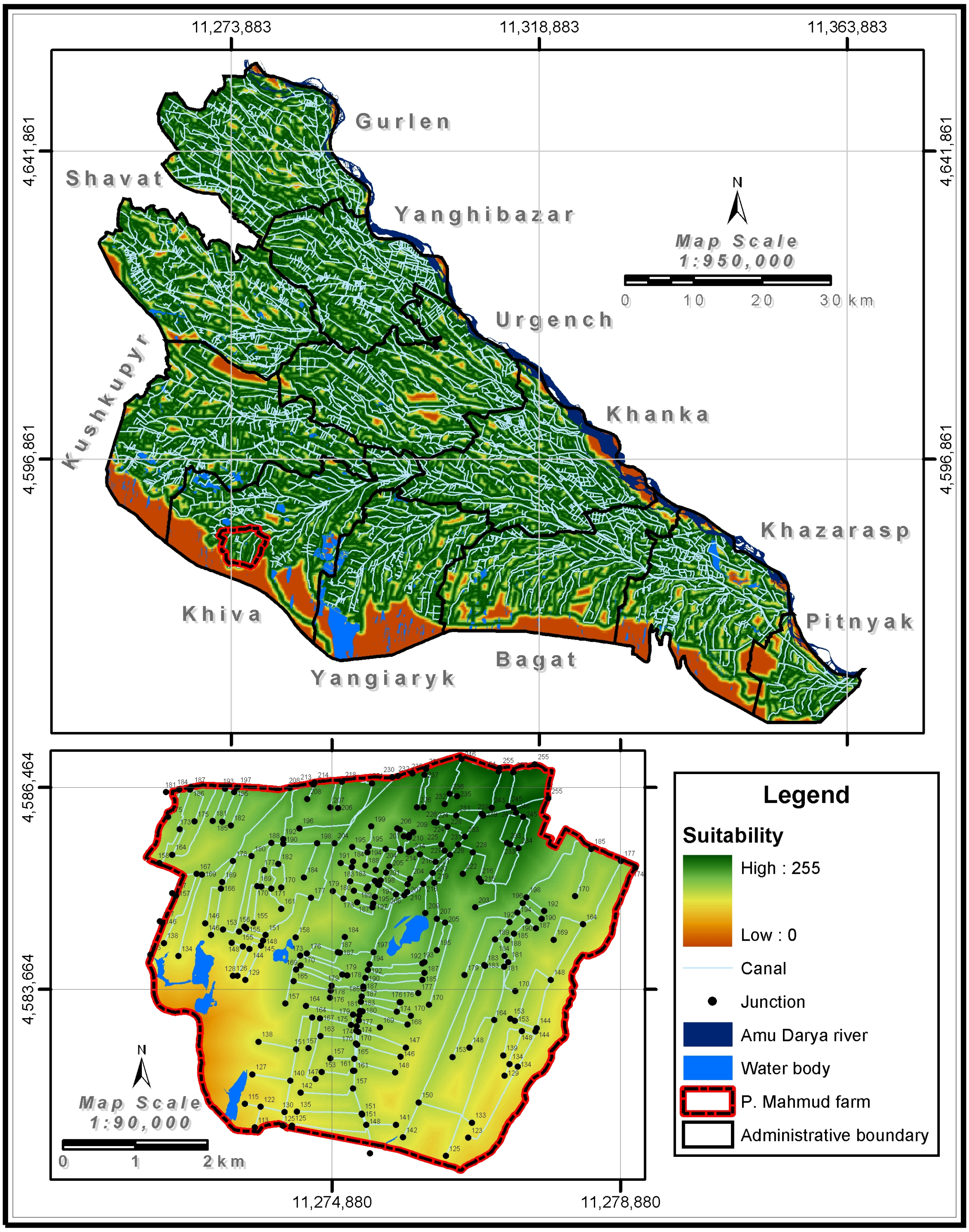


Figure 24 Criterion maps for water availability from the irrigation network

5.1.3 Water temperature

Water temperature is an important factor influencing the growth and survival of fishes. Different fish species have different optimal thermal ranges in which they grow best. In this study the conditions of the most commonly grown fish in Khorezm, the common carp, were considered. Due to the lack of spatially distributed data on water temperature in Khorezm, this criterion could not be used within the MCE. However, future refinement of the model may use the functional relationship between air and water temperatures to estimate pond water temperatures in regions where no pond exists so far (KAPETSKY 1994; MEADEN & KAPETSKY 1995; KAPETSKY & NATH 1997).

Figure 25 shows the graphs of water and air temperature at one selected location on P. Mahmud farm in the year 2003.

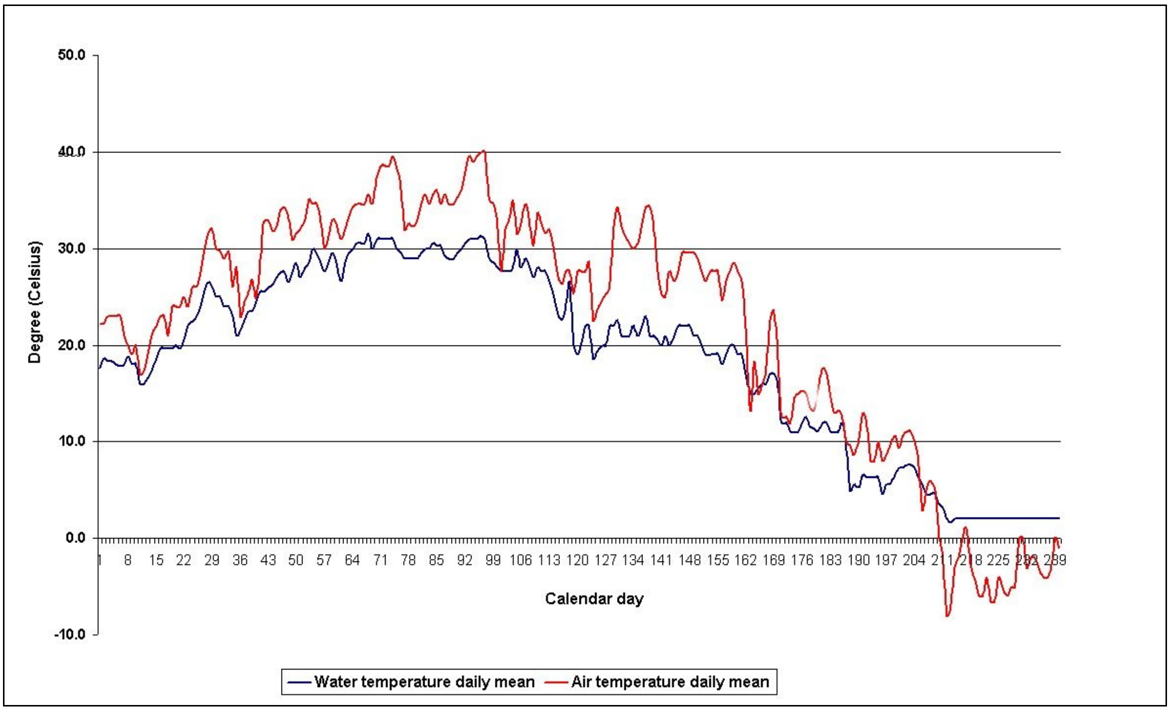


Figure 25 Comparison of air and water temperature for a selected site in Khiva in 2003

The Pearson correlation coefficient between the two data sets amounts to 0.97 which describes the strong relationship of temperatures of standing water and air temperature. Over Khorezm the three existing climatic stations may provide temperature data that could be spatially interpolated to a regional temperature surface, by applying robust thin-plate spline fitting technique (HUTCHINSON 1995), an algorithm that was designed specifically for data sparse environments. This relationship may be used as a rough guideline for decision makers to estimate fish production suitability during the reproductive period from April until early June.

5.1.4 *Engineering and terrain suitability*

5.1.4.1 Soil suitability

Soils develop from complex physical interactions of topography, geology, climate, vegetation and human influence and greatly vary at the macro-scale as well as at the micro-scale. For a successful aquaculture site selection soils and their characteristics are important factors to be considered. The relevant soil characteristics that define the overall soil suitability were modelled by MCE as well.

The most relevant parameters that define soil suitability in the Khorezm environment are soil texture, soil salinity, clay and skeleton content. The optimum soil texture is "clayey without swelling and shrinking, and not organic" while suitable to moderately suitable soils are characterised as "loamy and not organic". Sandy soils or clayey soils with swelling and shrinking or organic matter can be classified as unsuitable (KAPETSKY & NATH 1997). The parameters soil texture as well as clay content are important indicators for potential water loss due to seepage. It can be assumed that soils with high clay content can store the water without high rates of seepage unless the soil texture is sandy. Soil texture including the clay content was available for 30 cm, 1 m and 2 m soil depth. Although the grain size of a certain soil can be classified as loamy the water loss can be high in soils with high skeleton content. To take this into consideration the skeleton content was identified as an additional parameter for estimating the soil suitability for fish pond construction. Soil salinity is an important factor concerning an optimum fish growth. Although fish is much less sensitive for high salinity than crops the salinity of a certain soil type should not exceed a specified threshold because high salinity contents have negative influence on the salinity of pond water. Within the present study the threshold for salt capacity of a certain soil type was defined to be less than 200 which equals to moderately saline.

The most important soil parameters and their thresholds and weights for estimating the suitability of soils for fish pond construction are listed in table 11.

Table 11 Soil parameters for estimating the suitability for fish ponds

Parameter	Threshold for suitability	Parameter weight
Soil texture in 30 cm, 1 m and 2 m depth	Light to heavy loamy, not sandy	25 %
Clay content (included in soil texture)	> 45 %	--
Skeleton content	Not big or very big, fractions < 20 %	15 %
Salinity	None saline to moderately saline: Na+ cation < 6dS/m, salt capacity < 200	10 %

The selected data were derived from the central GIS database Khorezm (RUECKER ET AL. 2004), restructured and reclassified for standardisation. The cartographic model for this preprocessing is shown in figure 26.

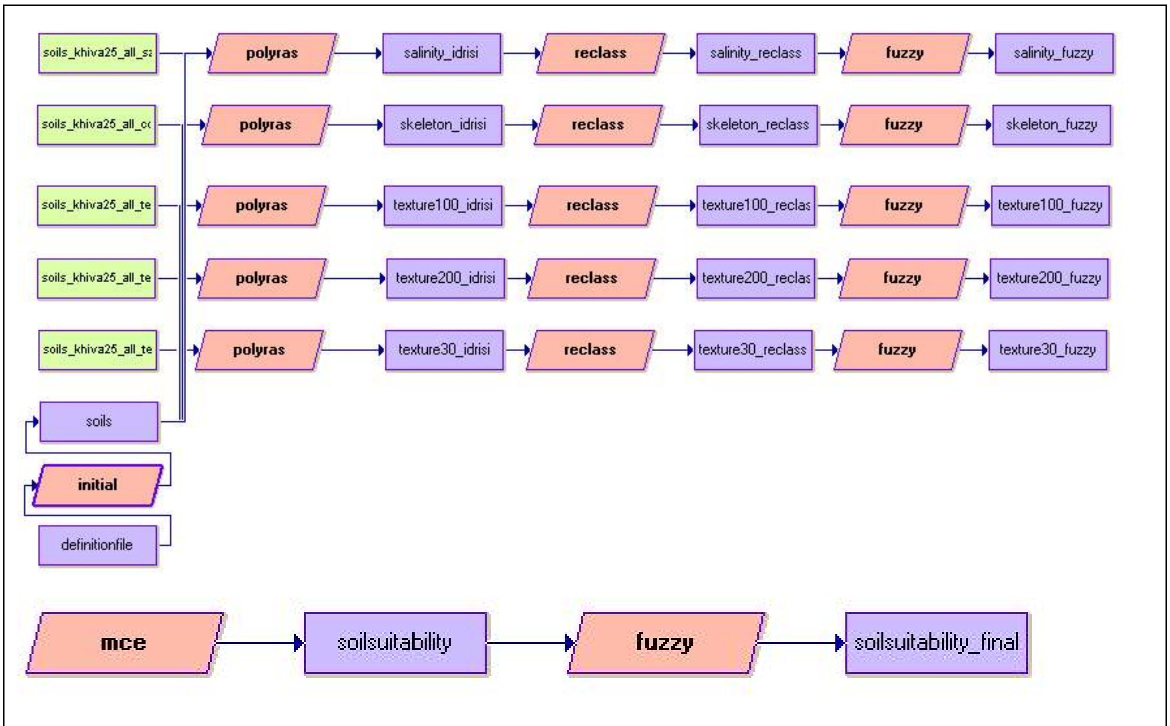


Figure 26 Cartographic model for soil suitability

For example, the soil texture classes were re-ordered to derive a continuous sequence from clayey over sandy to pebbles. The same was applied for the salinity content ranging from non-saline to soils with very high salinity. After standardisation, the data was imported to IDRISI vector format to serve as input for further processing steps including rasterisation, reclassification and fuzzy generation. The resulting maps for each soil parameter are displayed in figure 27.

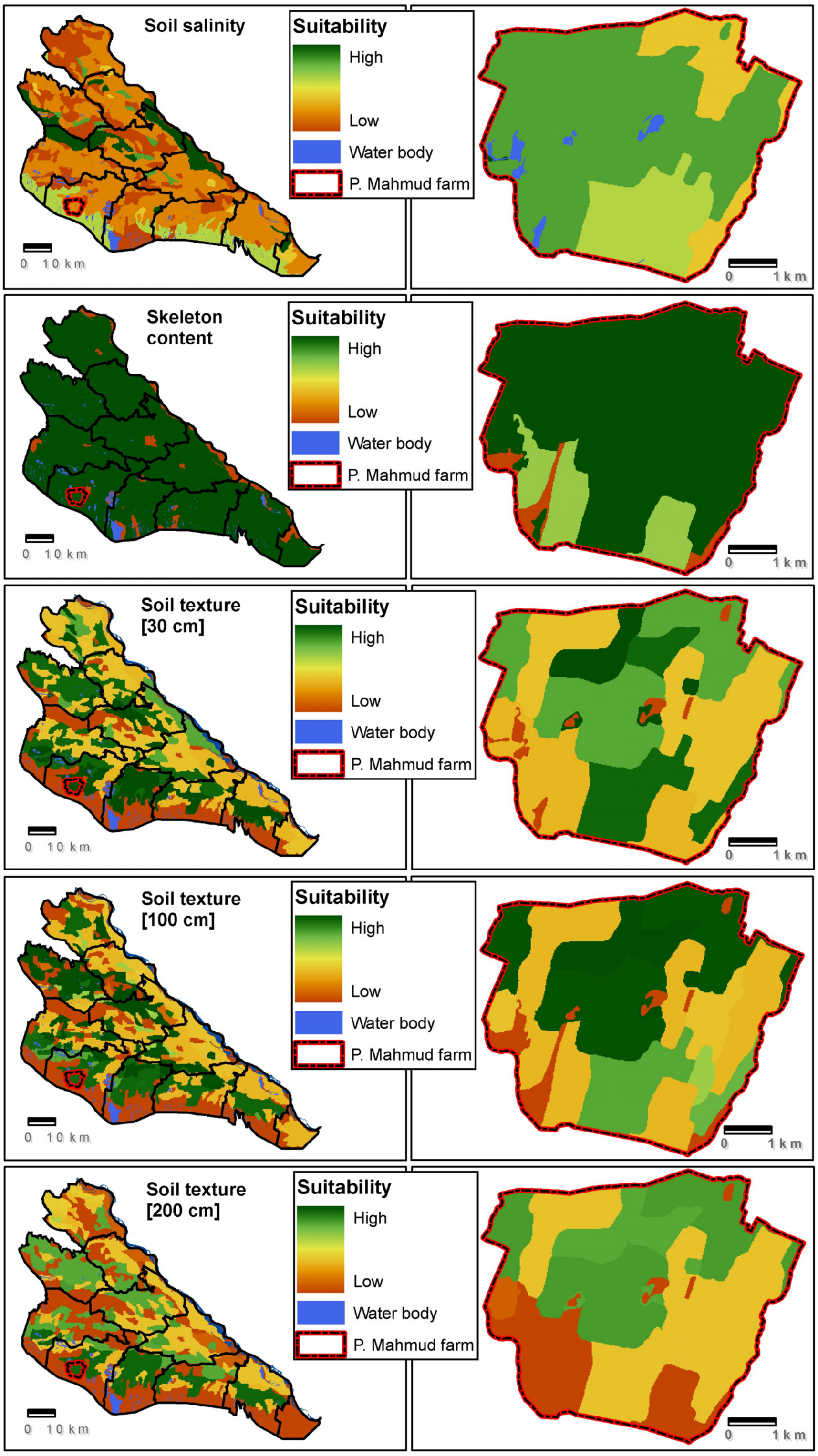


Figure 27 Soil characteristics at regional and local scale

Factor weights were then defined for the soil parameters to run the soil suitability MCE. It was assumed that the most important parameter is soil texture, including clay content. Accordingly, a weight of 25 % was applied to information about soil texture in 30 cm, 1 m and 2 m soil depth. The soils' skeleton content was weighted with 15 % while for soil salinity a weight of 10 % was assigned. The MCE analysis produced the following soil suitability map (see figure 28).

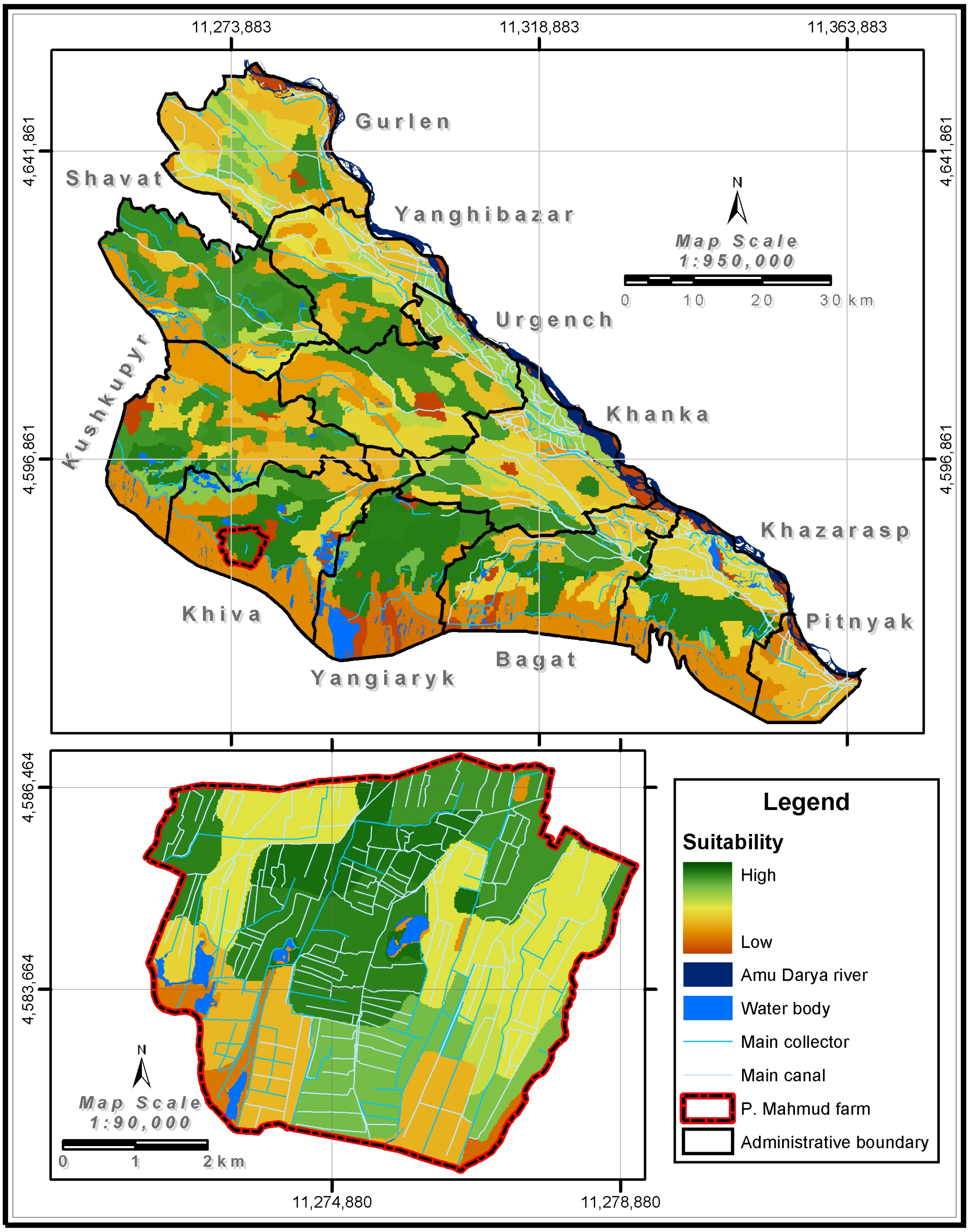


Figure 28 Criterion maps for soil suitability

Soil salinity is relatively high in Khorezm, which resulted in a low to very low soil salinity suitability index. Higher soil salinity suitability occurs mainly in small areas close to the Amu Darya river bed in the north of the rayons Urgench and Khanka and in the north of the Kushkupyr rayon. However, due to the lower weighting of soil salinity this pattern is only little represented in the criterion map of soil suitability shown in figure 28. Although the skeleton content rarely exceeds the defined threshold an area of low skeleton content can be observed in the southwest of P. Mahmud farm and due to the higher weight in the soil suitability map. However, this phenomenon might be supported by unsuitable soil textures, especially in depth of 1 m and 2 m. Generally, the area of low suitability soils concerning soil texture increases the deeper the soil is. Only the desert areas and a stripe in the north of the Kushkupyr rayon can be classified as less suitable independently from the soil depth. These two areas can also be observed in the criterion map of soil suitability (see figure 28). The same is true for areas with good suitability at regional scale as well as for the spatial pattern of soil texture as a whole. The main reason for this observation lies in the high weight which was applied to this parameter.

5.1.4.2 Topography

The topography, in particular slopes with a certain gradient are a limiting factor for pond construction. On the one hand steep slopes result in a lack of coherent areas for locating and developing fish ponds. Furthermore, transport accessibility is restricted by steep terrain which results in an isolation from markets. On the other hand excessively flat areas are characterised by poor drainage and low flow of water. Additionally, the risk of flooding is comparatively high and sluggish water flows are associated with low dissolved oxygen levels and high water temperatures (MEADEN & KAPETSKY 1991). The topography of Khorezm is modelled as elevation and is shown in figure 29.

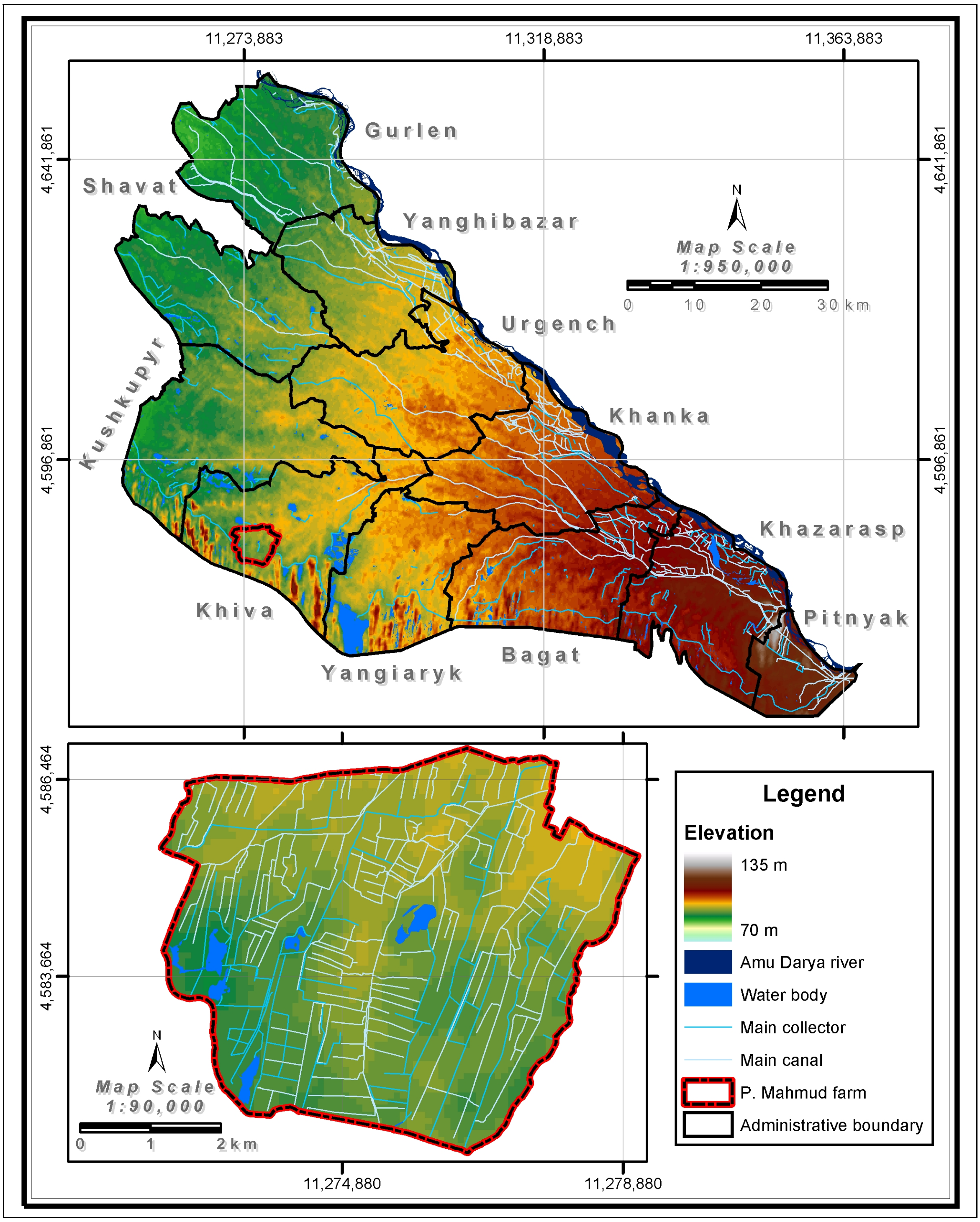


Figure 29 Topography at regional and local scale

The elevation of Khorezm increases continuously from the northwest (south of Gurlen rayon with about 75 m above seelevel) to the southeast (border between Khazarasp and Pitnyak with about 135 m above seelevel). At this peak markedly higher elevation with slopes exists as well as in some dunes in the south of Khiva, Yangiaryk and Bagat that could be modelled based on the 90 m resolution DEM.

After FAO (1995) guidelines for suitable fish ponds, most suitable areas are characterised by slopes of 0.5 to 3 % and slopes should not exceed 5 % to be at least moderately suitable fish pond sites. A more detailed guideline was developed by HAJEK & BOYD 1990 (after KAPETSKY 1994; AGUILAR-MANJARREZ & NATH 1998). Following this study slopes of 1-2 % are suitable for larger ponds (1 to 5 ha) while slopes up to 5 % can be used for constructing ponds of 0.01 to 0.05 ha. Terrain with dominant slopes above 8 % is mainly too steep for pond construction, except for valley bottoms. This suitability ranking is displayed in table 12.

Table 12 Slopes compared with suitability for fish ponds

Dominant slope [%]	Suitability for pond construction
<2	Most favourable for pond construction
2-5	Suitable for construction. Minor limitations can be overcome.
5-8	Moderate limitations for construction. Limitations may be overcome bay special design, construction, management or maintenance.
>8	Unfit for use, significant cost and efforts are required to compensate for limitations.

Source: HAJEK & BOYD (1990), after AGUILAR-MANJARREZ & NATH (1998)

The slope maps were calculated based on the 90 m pixel resolution DEM from data the Shuttle Radar Topography Mission (SRTM). Several filter algorithms provided by the software ENVI 4.1 (RESEARCH SYSTEMS, INC.) were used to correct DEM artefacts, such as no data or extreme values. Then slope values were calculated using the SLOPE module of the IDRISI Kilimanjaro GIS software (see figure 30).

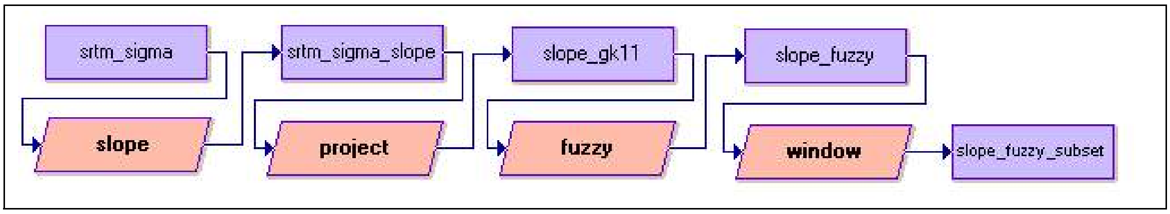


Figure 30 Cartographic model for slopes

The actual slope algorithm relied on the comparison of the elevation of cells to the neighbouring pixels followed by the determination of the gradient of the slope (EASTMAN 2003A). The slope is calculated as shown in the following equation:

$$tan\_slope = \sqrt{\left(\frac{right - left}{res * 2}\right)^2 + \left(\frac{top - bottom}{res * 2}\right)^2}$$ [Eq. 9]

where tan_slope = tangent of the angle with the maximum downhill slope
Left, right, bottom and top = attributes of the neighbouring cells
res = cell resolution

To produce a %-gradient as output tan_slope has to be multiplied by 100.

The number of surrounding pixels used for calculating slope and the weights given to each of the surrounding points in the calculation varied. Although an accurate projection system was defined in ENVI the DEM lost this information during the importing procedure to IDRISI Kilimanjaro. Accordingly, a correct projection system was defined after slope generation. Following the above mentioned guideline developed by HAJEK & BOYD 1990 slopes with less than 5 % were classified as very suitable within the standardisation procedure while slopes of more than 8 % were assumed to be to steep for pond construction. Using a linear function type (see chapter 4.3.4.2) this results in a linearly decreasing suitability between 5 % and 8 %. Due to the fact that the spatial extent of the SRTM DEM exceeded the extent of the study area, a subset was generated using the WINDOW module. Furthermore, this ensures the necessarily needed identical image dimension of all map layers included into the final MCE.

After applying the thresholds outlined above it was observed that slopes are no constraint for fish pond construction in Khorezm. Apart from local depressions the terrain in the irrigated areas of Khorezm can be characterised as smoothly undulating. Significant slopes occur only locally and can relatively easy be flattened. Slopes stepper than 2 % can only be observed in the south of the rayons Kushkupy, Khiva, Yangiaryk and Bagat as well as at the above mentioned hill located at the border of Khazarasp and Pitnyak (see figure 31).

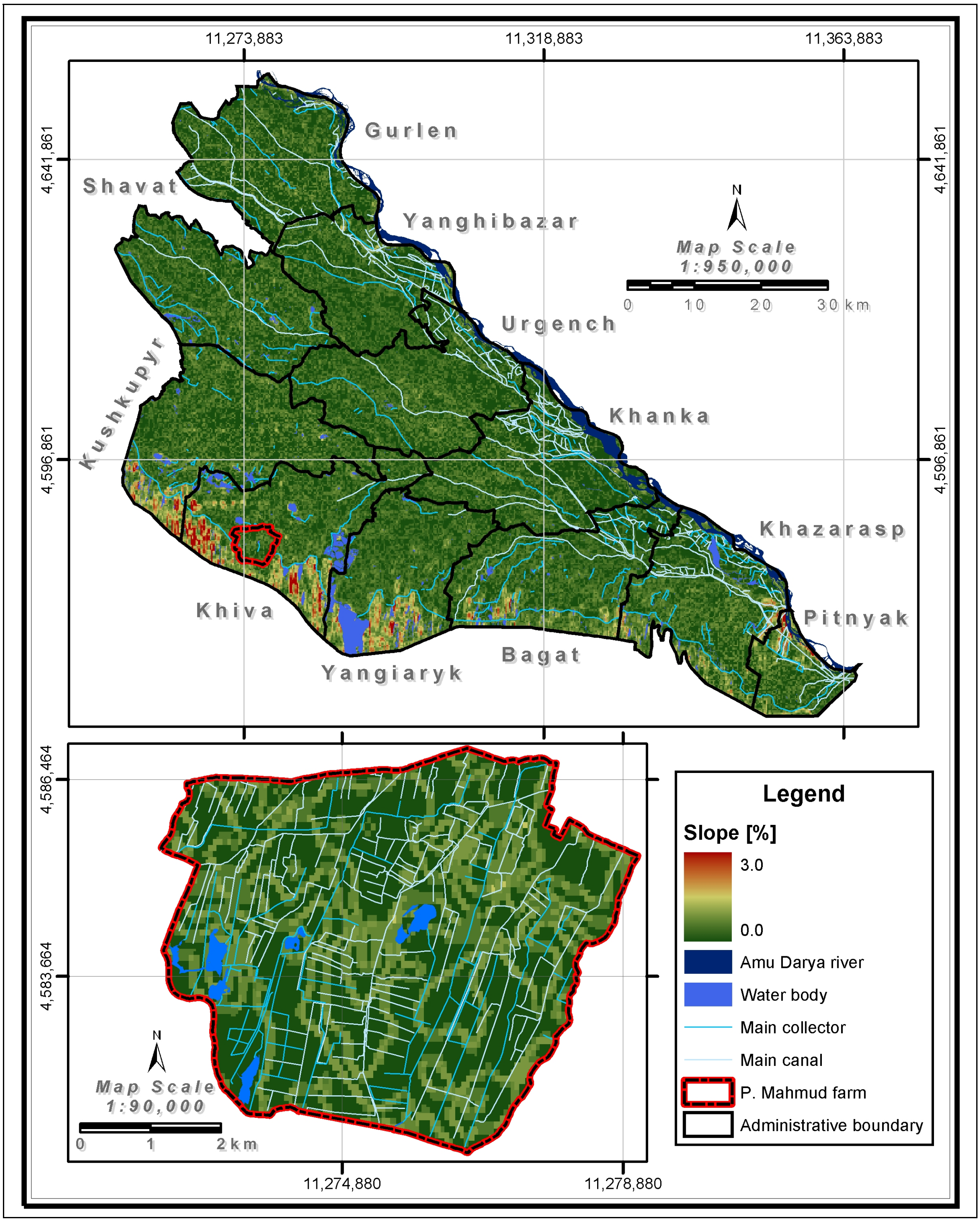


Figure 31 Slopes at regional and local scale

Regarding the local scale slope map shown in figure 31 it became obvious that the slopes derived from the SRTM DEM are relatively useless for an analysis at this scale due to its coarse spatial resolution of 90 m. Nevertheless, even at local scale the slope criterion map was included into the evaluation because of both to emphasize that slope is an important factor and to ensure reliable results when using high resolution slope data and changing the thresholds for suitability for future analyses.

Based on these facts the factor topography was weighted very low within the final MCE. Due to the fact that the standardised criterion map of slopes only consists of the value 255 and accordingly is unicolor this map is not shown.

5.1.5 Constraints for fish pond site selection in Khorezm

Constraints serve to limit the alternatives under consideration and are usually expressed in the form of Boolean (logical) maps. Boolean constraints are crisp set membership functions that can be classified exactly into suitable/unsuitable images with values 1 and 0, respectively. Areas excluded from consideration were expressed by the value 0 and those to be considered were represented by the value 1.

Four constraint categories which were divided into ten specific constraints were identified for fish pond site selection. These constraints were preprocessed according to the evaluation scale. The constraints are listed in table 13 and mapped in figure 32.

Table 13 Constraints and their characteristics for small, decentralised fish farms in Khorezm

Constraint category	Specific constraint	Minimum distance to constraint	Regional scale	Local scale
General Constraints	Fish ponds should have a specific minimum area size	1 ha	1:50,000	1:10,000
No urban development and settlements areas	Not in oblast capital	250 m	1:50,000	1:10,000 (no oblast or rayon centre in study area)
	Not in Rayon capital	200 m		
	Not in settlements and at a certain distance to them	150 m		
No infrastructure areas	Not on roads	30 m	1:50,000	1:25,000/1:10,000
	Not on irrigation and drainage network	10 m		
No ecological sensitive areas	Not on Amu Darya river	30 m	1:25,000	--
	Not on forest patches and at a certain distance to them	150 m	1:25,000	1:10,000
	At a distance to fields that are traditionally used for rice cultivation	60 m	1:50,000	1:50,000
	Not on protected Areas	Not available	Not available	Not available

The definition of a minimum area size for fish ponds ensures that the resulting suitability maps represent not only areas which are suitable for fish pond construction but also large enough to allow maintenance as well as moderate pond development. Due to uncertainty about the actual area needed in Khorezm to maintain a certain fish pond the minimum area size mentioned in table 13 is just a suggestion and was not implemented within this study. However, this threshold could be applied when the landscape for fish pond construction has been identified and the actual site needs to be determined.

Fish ponds should only be implemented in order to keep a certain distance from settlements, infrastructure, rice cultivation and ecologically sensitive areas, such as forest patches. A certain distance from settlements was selected to ensure urban development for future needs. The importance of a certain settlement was used to determine the distance to fish ponds to account for the future expansion of different settlements, with cities expanding generally more extensive than villages. Furthermore, a certain distance to settlements was specified to protect settlements from increasing moisture by raised groundwater level caused by nearby fish ponds. Areas cultivated with rice should be excluded from evaluation to ensure that enough water will be available for both agriculture and aquaculture. With two extremely water consuming land use types at the same site this is not assured, especially in an arid region such as Khorezm. The spatial maps of these constraints are shown in figure 32.

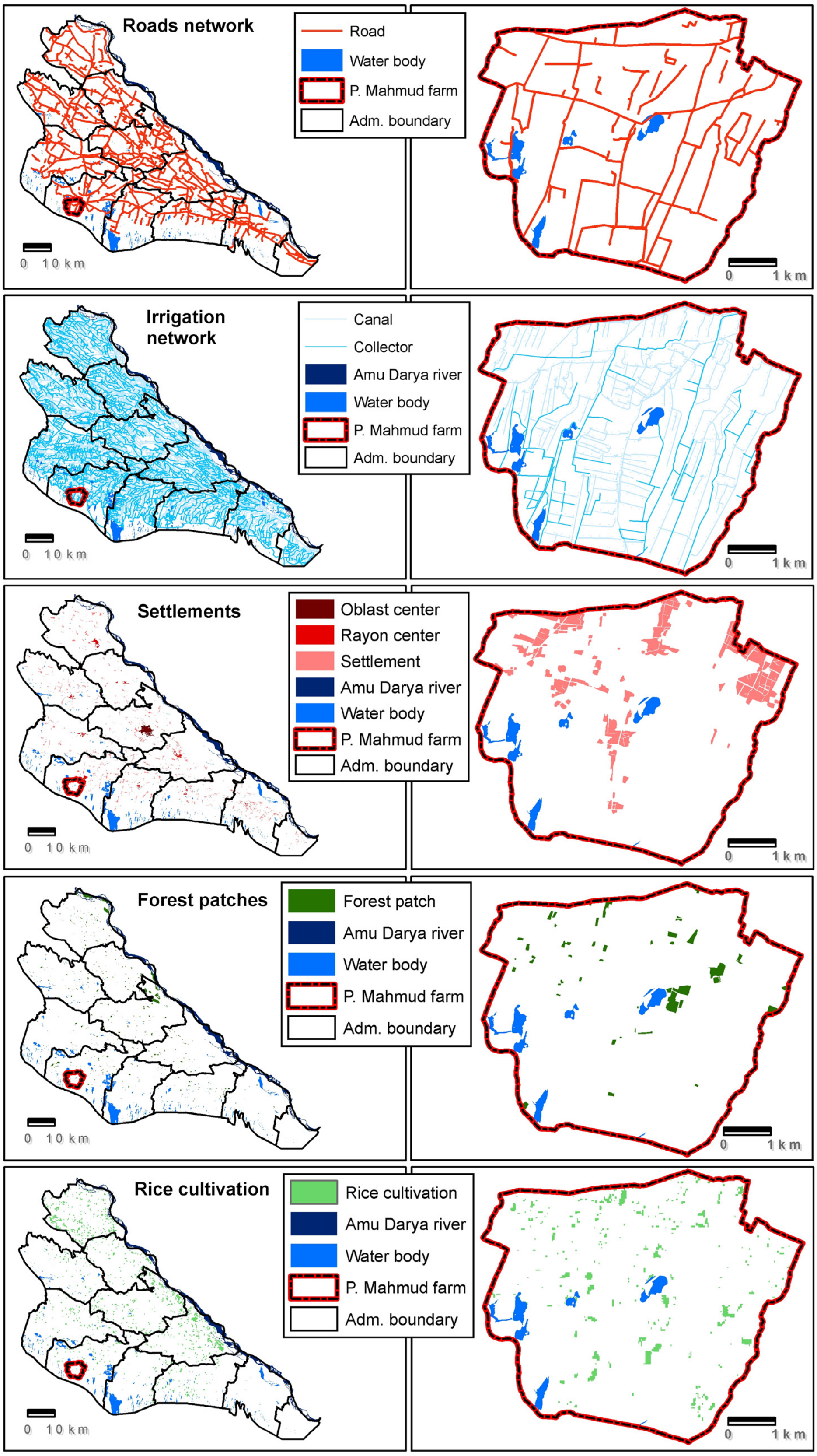


Figure 32 Constraints for fish pond site selection at regional and local scale

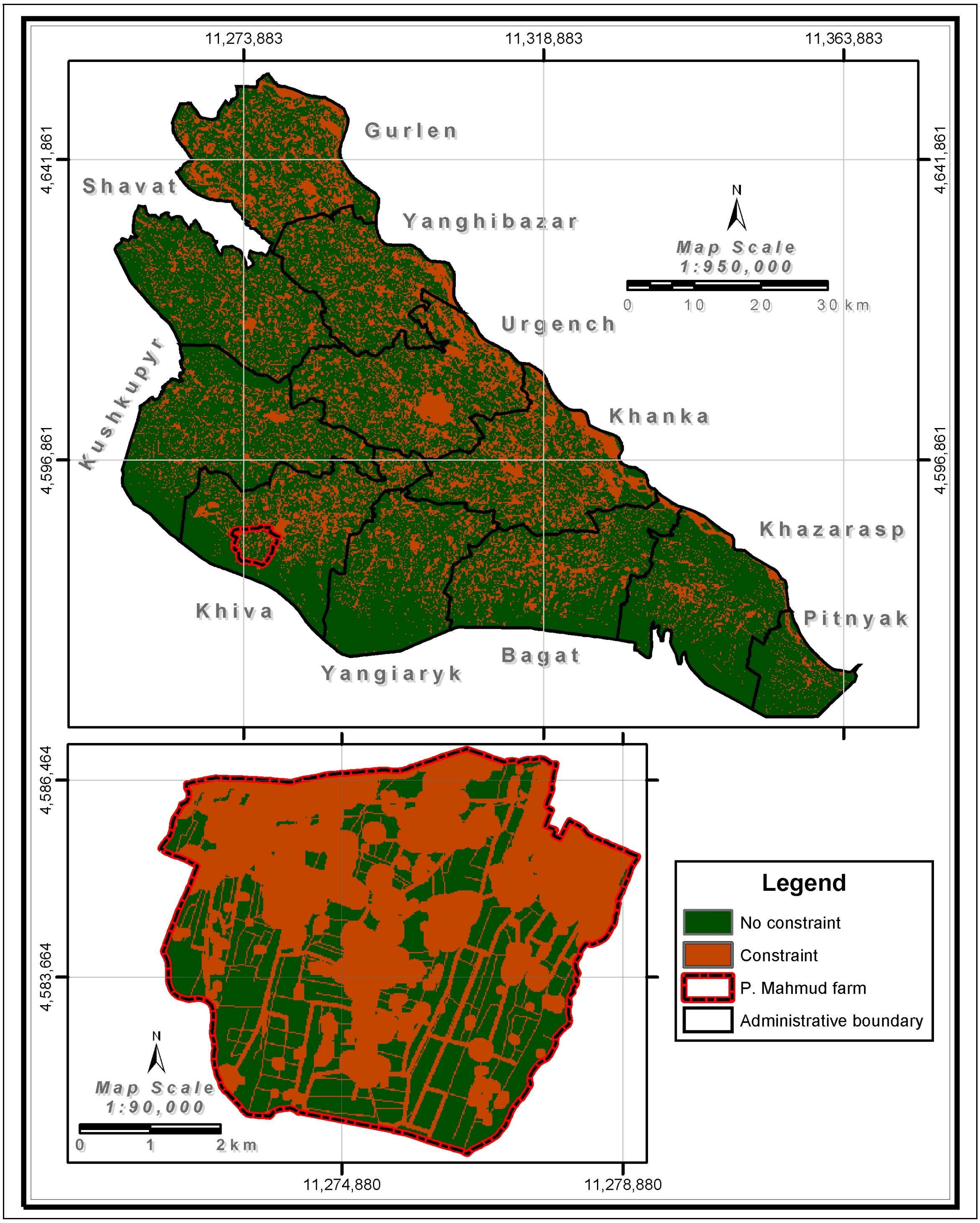


Figure 33 Criterion maps of constraints for fish pond site selection

Objects such as roads, irrigation canals and drainage collectors are represented as line features that are widely distributed over Khorezm, but that cover only a relatively small area. In contrast, settlements, forest patches and rice cultivation, are represented as polygon features and are relatively sparsely distributed but covering large areas.

However, these laminar constraints result in slightly larger areas to be excluded from site selection in the rayons Urgench, Khanka and Gurlen compared to all other rayons. Notably the city of Urgench, a wide riverbed of the Amu Darya river in Khanka and large areas of rice cultivation in Gurlen can be identified as main reasons for this unequal distribution. In contrast constraints are rare in the Pitnyak rayon due to the absence of large settlements, rice cultivation and forest patches. At local scale two main areas with different distribution of constraints can be observed. On the one hand there are many settlements and forest patches in the north and accordingly just a few areas that are unconstraint. On the other hand the south is characterised by mainly linear constraints that cover a relatively small area. The total area of constraints amounts to 1259 km² (27.1 %) for whole Khorezm and to 16.44 km² (58.8 %) at local scale. A detailed statistics focusing on each constraint individually is problematic due to overlapping areas and was therefore not implemented here.

5.2 Multi-scale land suitability assessment

The various factors and constraints were synthetisised to a single suitability map at each regional and local scale by MCE using the weighted linear combination algorithm. Two possible perspectives of decision makers with ecological and economical preferences were taken into account to result in two different scenarios for both scales. These preferences were modelled by different criterion weightings.

5.2.1 Regional scale land suitability assessment

At regional scale the identified factors and corresponding weights are listed in table 14. These factors and constraints including the course of the Amu Darya river, settlements, roads, the irrigation and drainage network, forest patches and areas with rice cultivation were input into the MCE.

Table 14 Factors and corresponding weights used at regional scale

Factor category	Specific factor	Factor weight	
		Economical perspective	Ecological perspective
Favourable economic conditions	Marginal agricultural sites indicated by soil bonitet and water mask	30.1 %	14.9 %
	Good road infrastructure and good proximity to markets	13.9 %	5.7 %
Adequate water availability	Water availability from groundwater table	20.9 %	40.8 %
	Water availability from the irrigation channel network	20.9 %	24.5 %
Engineering and terrain suitability	Soil suitability	10.5 %	9.8 %
	Slope	3.7 %	4.3 %

The crucial difference between the two decision makers' preferences is their opinion about the importance of the different factors expressed by the percentage of factor weight. It was assumed that the most important factor for a decision maker who favours economical site selection principles is to restructure marginal agricultural sites to profitable fish ponds. In an ecological perspective, good water availability was ranked highest to provide the necessary water input for the fish ponds. However, this water input should only be provided at an economically feasible price. Thus, the factor water availability was ranked highest in both preference rankings. Road infrastructure and proximity to local markets are much more important from an economical perspective than from an ecological one. The definition of the specific weights for the criteria concerning their relative importance for the stated objective was done by pairwise comparison matrices using the module WEIGHT in the IDRISI Kilimanjaro GIS software. The results are shown in table 15 and table 16.

Table 15 Pairwise comparison matrices to define factor weights from an economical perspective at regional scale

	Irrigation network	Groundwater	Road infrastructure, proximity to markets	Slope	Marginal land	Soil suitability
Irrigation network	1					
Groundwater table	1	1				
Road infrastructure, proximity to markets	1/2	1/2	1			
Slope	1/6	1/6	1/4	1		
Marginal land	2	2	2	6	1	
Soil suitability	1/2	1/2	1/2	3	1/2	1

Table 16 Pairwise comparison matrices to define factor weights from an ecological perspective at regional scale

	Irrigation network	Groundwater	Road infrastructure, proximity to markets	Slope	Marginal land	Soil suitability
Irrigation network	1					
Groundwater table	2	1				
Road infrastructure, proximity to markets	1/5	1/7	1			
Slope	1/6	1/8	1/2	1		
Marginal land	1/2	1/3	3	3	1	
Soil suitability	1/2	1/4	2	2	1/2	1

The calculated consistency ratio was acceptable with a value of 0.1 for the ecological weights and with a value of 0.2 for the set of weights based on the economical preference.

Based on these matrices and the factors and constraints the MCE was applied in the IDRISI Kilimanjaro software and overall land suitability maps for fish pond site selection representing the described decision makers' preferences at regional scale were generated. Afterwards a visual plausibility check was carried out by comparing the input criterion maps with the resulting suitability map. The maps were then exported to GeoTIFF format and imported to ESRI ArcGIS 9.0 for designing an attractive and easy interpretable layout. The continuous value range was classified into the following 5 discrete classes: very suitable, suitable, moderately suitable, less suitable and unsuitable to make sharp boundaries and to facilitate the map interpretation for decision makers in Khorezm. The corresponding area statistics of suitability classes are shown in table 17.

Table 17 Land suitability classes with area statistics at regional scale

Suitability Class	Suitability value	Ecological perspective, Area[km²]	Ecological perspective, Area [%]	Economical perspective, Area [km²]	Economical perspective, Area [%]
Very suitable	205 to 255	1570	33.7	430	9.2
Suitable	154 to 204	1460	31.4	2317	49.8
Moderately suitable	103 to 153	331	7.1	612	13.2
Less suitable	52 to 102	35	0.8	37	0.8
Unsuitable	0 to 51	1259	27.0	1259	27.0

The final land suitability maps at regional scale are shown in figures 34 and 35.

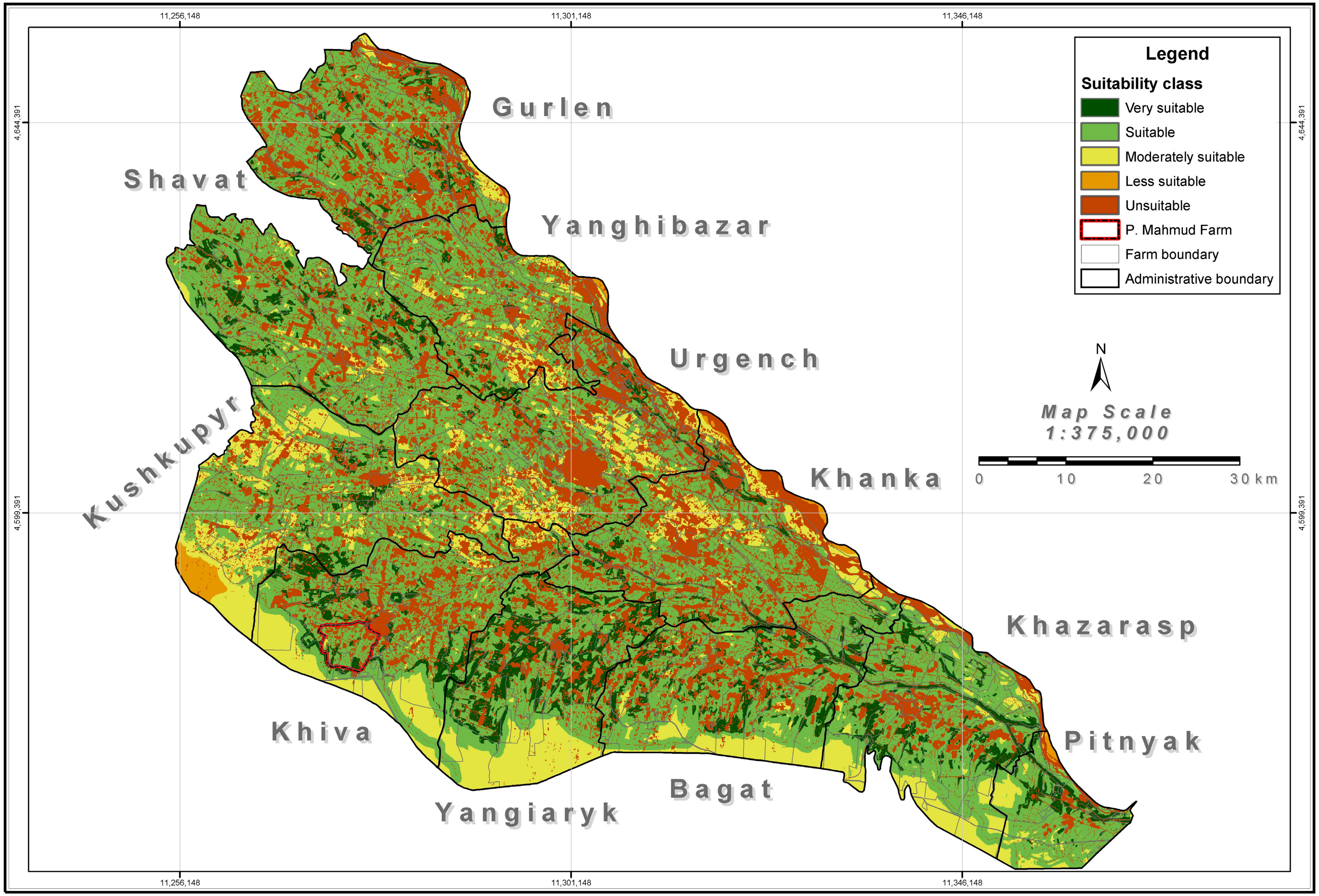


Figure 34 Land suitability map for fish pond site selection with economical preferences at regional scale

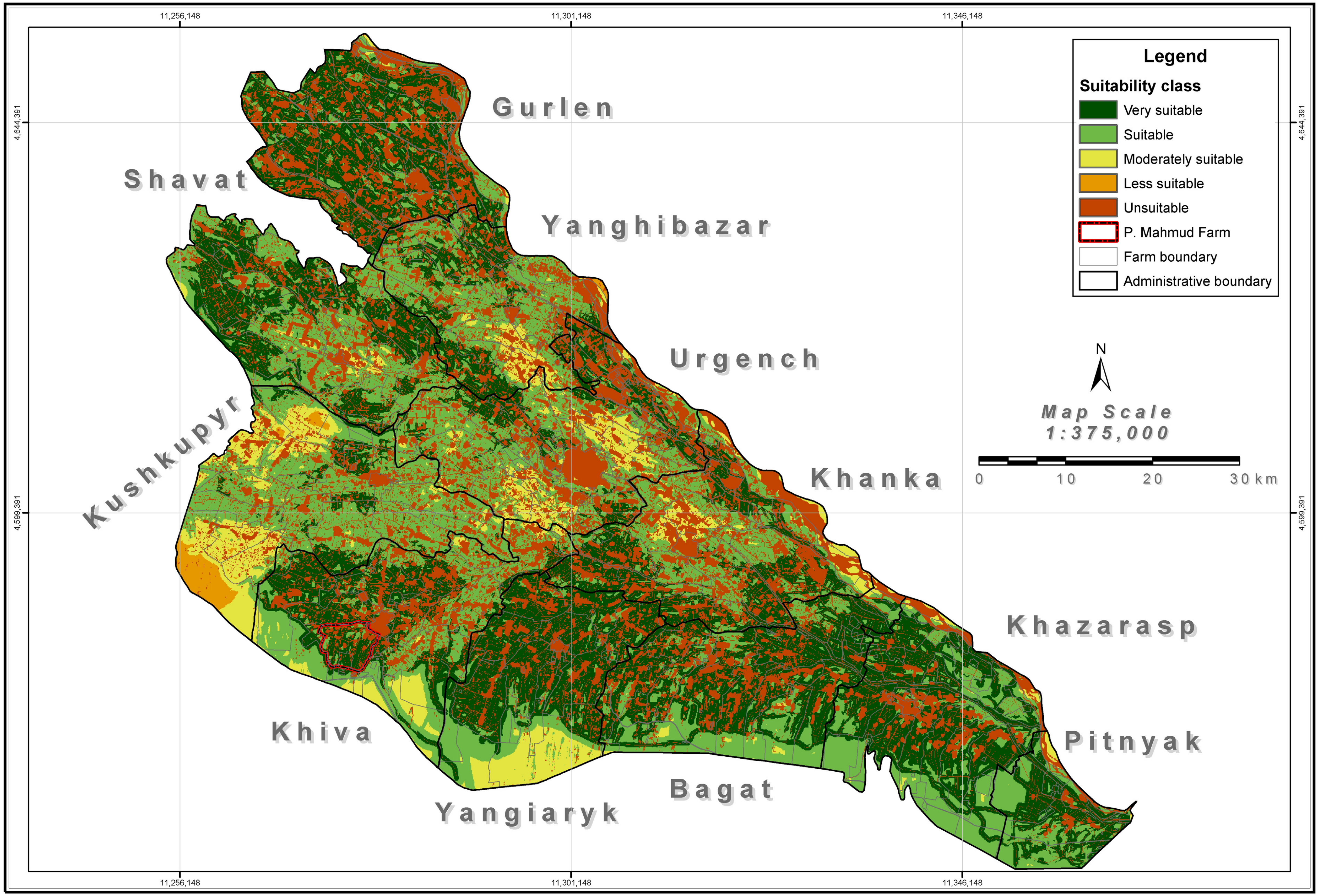


Figure 35 Land suitability map for fish pond site selection with ecological preferences at regional scale

Table 18 Land suitability classes and area statistics with economical preferences for each rayon

Rayon	Suitability class									
	Very suitable		Suitable		Moderately suitable		Less suitable		Unsuitable	
	km²	%	km²	%	km²	%	km²	%	km²	%
Gurlen	30.5	6.7	235.5	51.5	13.1	2.9	1.1	0.2	177.0	38.7
Shavat	45.2	10.0	283.7	63.1	18.2	4.0	0.01	0.0	102.8	22.8
Yanghibazar	14.5	4.1	191.6	54.0	32.1	9.0	1.6	0.5	115.1	32.4
Urgench	17.4	3.5	218.4	44.3	61.8	12.5	0.7	0.1	195.2	39.6
Kushkupyr	2.3	0.4	257.1	50.1	125.3	24.4	21.5	4.2	107.4	20.9
Khiva	46.6	9.8	218.6	46.2	86.1	18.2	0.8	0.2	121.2	25.6
Khanka	22.5	4.8	205.4	44.2	46.5	10.0	6.0	1.3	184.4	39.7
Yangiaryk	92.2	22.8	155.2	38.4	84.7	20.9	0.08	0.0	72.4	17.9
Bagat	63.1	14.0	232.5	51.5	51.0	11.3	1.7	0.4	102.9	22.8
Khazarasp	54.5	12.9	233	55.2	71.5	16.9	0.4	0.1	62.9	14.9
Pitnyak	20.4	13.8	85.9	58.2	21.0	14.2	2.7	1.8	17.5	11.9

Table 19 Land suitability classes and area statistics with ecological preferences for each rayon

Rayon	Suitability class									
	Very suitable		Suitable		Moderately suitable		Less suitable		Unsuitable	
	km²	%	km²	%	km²	%	km²	%	km²	%
Gurlen	224.6	49.1	53.5	11.7	2.1	0.5	0.0	0.0	177.1	38.7
Shavat	167.6	37.3	170.3	37.9	9.2	2.0	0.01	0.0	102.8	22.8
Yanghibazar	79.5	22.4	138.9	39.2	19.7	5.6	1.7	0.5	114.7	32.4
Urgench	69.3	14.0	173.6	35.2	54.4	11.0	0.9	0.2	195.2	39.6
Kushkupyr	41.4	7.8	247.5	46.4	105.6	19.8	31.7	5.9	107.7	20.2
Khiva	147.6	31.2	165.2	34.9	39.4	8.3	0.0	0.0	121.2	25.6
Khanka	124.9	26.9	127.3	27.4	28.2	6.1	0.08	0.0	184.4	39.7
Yangiaryk	208.2	51.5	67.5	16.7	56.4	13.9	0.0	0.0	72.4	17.9
Bagat	223.0	49.4	118.4	26.2	6.9	1.5	0.0	0.0	102.9	22.8
Khazarasp	214.8	50.9	139.1	32.9	5.5	1.3	0.0	0.0	62.9	14.9
Pitnyak	68.7	46.6	58.2	39.5	2.9	2.0	0.2	0.1	17.5	11.9

Generally, it can be stated that areas with high suitability are much more widespread when the decision makers' preferences are ecologically orientated. This might be the result of the high factor weight of water availability from groundwater. The data processing has shown that groundwater is available almost everywhere in Khorezm to a sufficient degree. Thus, the suitability values for this factor are predominantly very high. The same is true for about 33.7 % of all values in the final suitability map. In areas where the groundwater table is deep, mainly within the Urgench and the Kushkupyr rayon, the difference between both suitability maps becomes less marked. In summary, it can be noticed that the area of suitable and very suitable sites amounts to approximately 60 % of the whole area which is definitely more than expected.

Concerning the spatial distribution of sites suitable or unsuitable for fish pond construction in Khorezm the following can be observed. In general, the desert areas in the south of the oblast are mainly less to moderately suitable except for some collectors that represent higher water availability as in the surrounding areas. In particular, an area in the south-western corner of the Kushkupyr rayon is noticeable as a region with less suitability in both results. The relatively large size of this area results in relatively high values of less suitable areas in Kushkupyr compared to the other rayons (see table 18 and 19). The reason might be the comparatively low groundwater table. Furthermore, larger areas of unsuitability can be noticed in the centre of the Urgench rayon where the city of Urgench is located and along the Amu Darya river bed. Likewise, some rayon centres which were defined as constraints, such as Khiva in the northeast of the P. Mahmud farm can be identified. Altogether the area of unsuitability amounts to 27 % of the whole area in Khorezm. The fact that this value is the same for both suitability maps indicates that this is mainly a result of the defined constraints. Nevertheless, comparing the different rayons with each other some differences can be observed. There are three rayons with comparatively high amounts of unsuitable areas: Urgench, Khanka and Gurlen. The city of Urgench might be the reason for this in the Urgench rayon while large areas of rice cultivation and the Amu Darya riverbed result in a high percentage of areas classified as unsuitable in Khanka and Gurlen (see table 18 and 19).

The main differences between the two suitability maps occur where the different factor weights result in a different spatial pattern of the suitability classes.

5.2.2 Local scale land suitability assessment

The identified local scale factors and corresponding weights are listed in table 20 Together with the constraints including settlements, roads, the irrigation and drainage network, forest patches and areas with rice cultivation they were input into the MCE for demarcating suitable fish pond sites at local scale.

Table 20 Factors and corresponding weights used at local scale

Factor category	Specific factor	Factor weight	
		Economical perspective	Ecological perspective
Favourable economic conditions	Marginal agricultural sites indicated by soil bonitet and water mask	32.5 %	15.5 %
	Good road infrastructure and good proximity to markets	15.0 %	5.3 %
Adequate water availability	Water availability from the irrigation channel network	30.0 %	40.6 %
	Water availability from groundwater table	9.5 %	25.0 %
Engineering and terrain suitability	Soil suitability	9.3 %	9.4 %
	Slope	3.7 %	4.2 %

In correspondence to the regional scale, marginal agricultural sites were ranked highest from an economical point of view and water availability was ranked highest from an ecological perspective at local scale. However, due to the fact that groundwater data is available only at a coarse scale this factor was weighted much less than within the regional scale MCE. To compensate for this loss of importance concerning water availability, water from the irrigation network was weighted adequately higher. As at regional scale road infrastructure and proximity to local markets are much more important from an economical perspective compared to an ecological perspective. The pairwise comparison matrices in tables 21 and 22 show the relative importance of a certain factor compared to the other criteria.

Table 21 Pairwise comparison matrices to define factor weights from an economical perspective at local scale

	Irrigation network	Groundwater	Road infrastructure, proximity to markets	Slope	Marginal land	Soil suitability
Irrigation network	1					
Groundwater table	1/3	1				
Road infrastructure, proximity to markets	1/3	2	1			
Slope	1/8	1/3	1/5	1		
Marginal land	1	3	3	7	1	
Soil suitability	1/2	1	1/2	2	1/4	1

Table 22 Pairwise comparison matrices to define factor weights from an ecological perspective at local scale

	Irrigation network	Groundwater	Road infrastructure, proximity to markets	Slope	Marginal land	Soil suitability
Irrigation network	1					
Groundwater table	1/3	1				
Road infrastructure, proximity to markets	1/8	1/6	1			
Slope	1/8	1/6	1/2	1		
Marginal land	1/2	1/2	3	3	1	
Soil suitability	1/3	1/3	2	2	1/2	1

The calculated consistency ratio was acceptable with a value of 0.02 for the ecological weights and a value of 0.02 for the set of weights based on the economical point of view. Two final suitability maps for fish pond site selection representing the described decision makers' preferences at local scale were generated by MCE and a plausibility check was made analogous to the procedure described in the regional scale section. The discrete suitability classes and area statistics are shown in table 23 and are mapped in figure 36.

Table 23 Land suitability classes and their area statistics at local scale

Suitability class	Suitability value	Ecological perspective, Area [km²]	Ecological perspective, Area [%]	Economical perspective, Area [km²]	Economical perspective, Area [%]
Very suitable	205 to 255	0.18	0.6	0.13	0.5
Suitable	154 to 204	10.50	37.6	4.12	14.7
Moderately suitable	103 to 153	2.24	8.0	8.34	29.8
Less suitable	52 to 102	0	0	0.33	1.2
Unsuitable	0 to 51	15.03	53.8	15.03	53.8

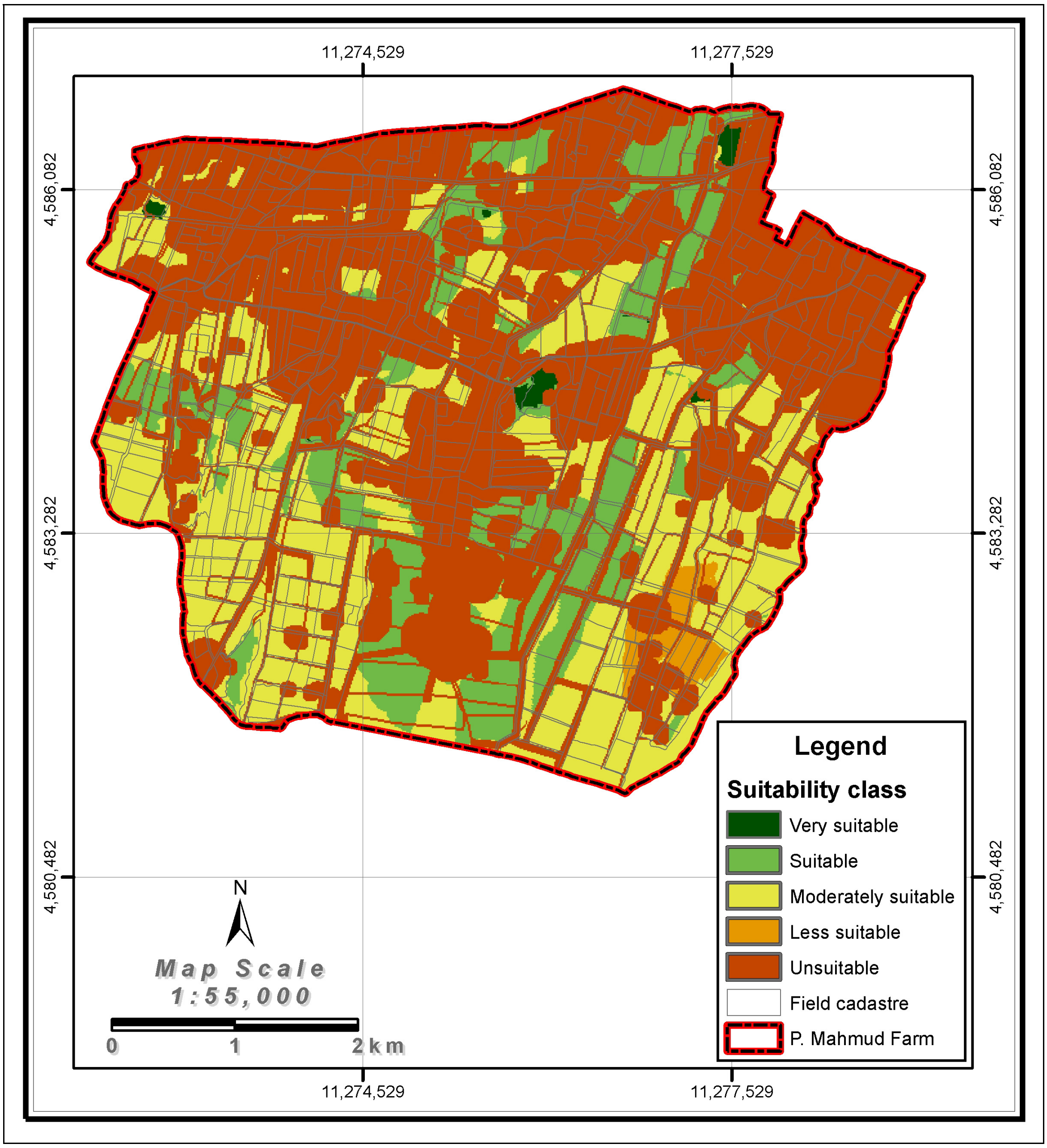


Figure 36 Land suitability map from an economical perspective at local scale

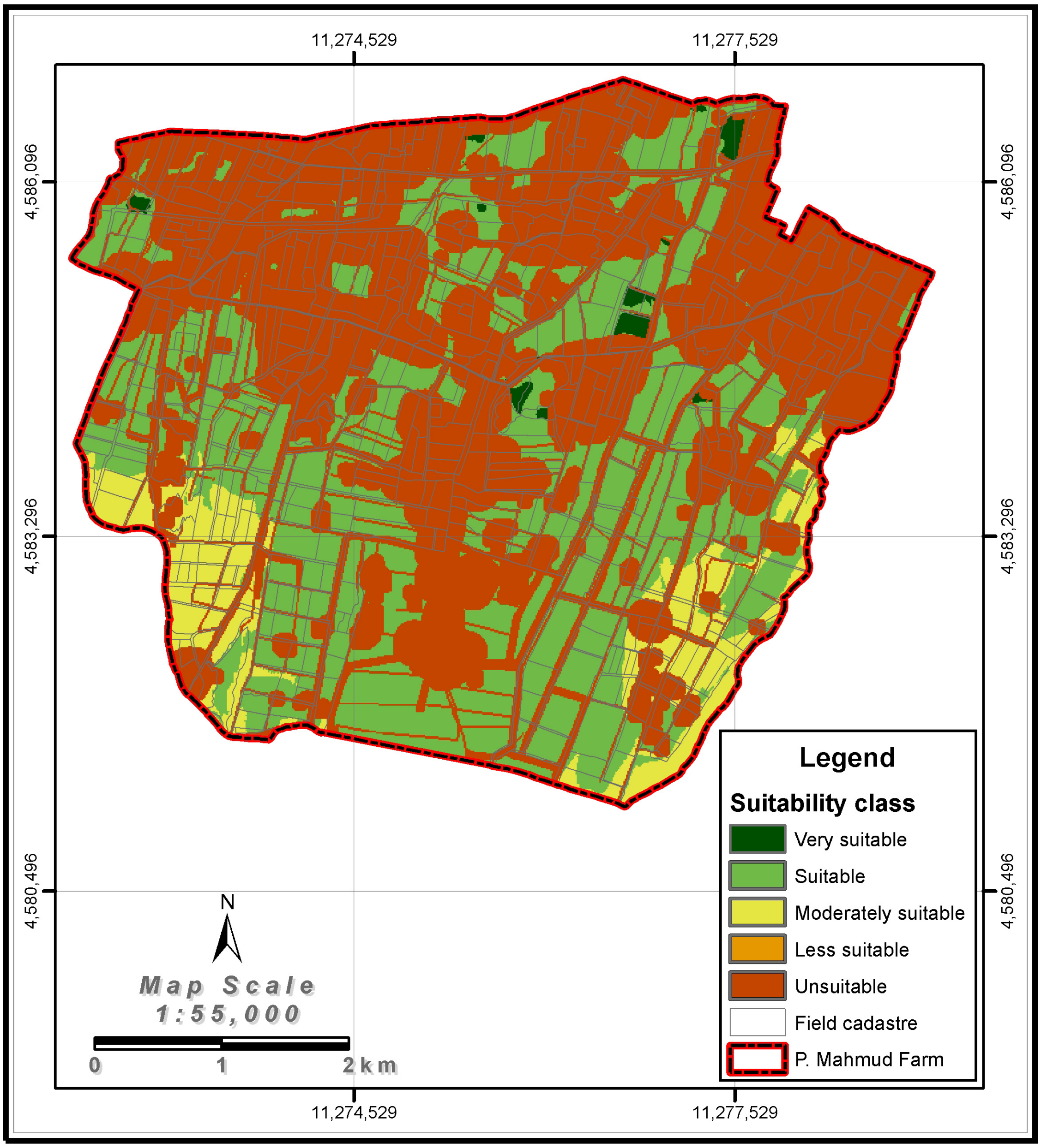


Figure 37 Land suitability map from an ecological perspective at local scale

Comparing both results at local scale with each other it can be stated that areas classified as suitable can be observed much more frequently in the ecologically weighted suitability map (see figure 36 and 37). In summary, it can be noticed that areas classified as suitable and very suitable amount to approximately 10.7 km² and 4.2 km² (entire farm area: 27.95 km²) depending on the decision makers' preferences. Compared to the results derived at regional scale this is much less.

5.2.3 Comparison of regional and local scale land suitability assessment

The comparison of the area statistics at regional and local scale highlights considerable differences in spatial pattern distribution. Areas classified as very suitable are rare on P. Mahmud farm independently from the decision makers' point of view. At local scale more than 50 % of the land is unsuitable for fish ponds, which is twice as large as at regional scale. During the data preprocessing steps it was noticed that the area of P. Mahmud farm can generally be divided into two parts. On the one hand the north with suitability values above average and on the other hand the south with relatively low suitability values. However, particularly in the north the most constraint areas can be observed. Large areas are covered by settlements, such as the village Urtasalma in the northeast or Serchalli in the centre. In addition, forest patches are noticeable constraints influencing the final suitability map impressively.

6 Conclusions and recommendations for further research

The introduction of fish ponds within the landscape of Khorezm, Uzbekistan was identified by the German-Uzbek Khorezm project as a promising strategy for restructuring the land use on marginal agricultural sites (VLEK ET AL. 2003).

This study developed a land suitability assessment approach to model potential sites for fish ponds in Khorezm. The model was applied at regional scale for the whole area of Khorezm and at local scale as a case study on P. Mahmud Farm in Khiva rayon, Khorezm. The inputs for the model consisted of spatially distributed and locally adjusted factors and constraints determining fish ponds. The inputs, which were generated by GIS-analyses, were weighted and combined in a multi-criteria evaluation (MCE). Economic and ecological preferences of local decision makers were modelled by different input weights. About 59 % (economic perspective) and 64 % (ecological perspective) of the whole area were classified as suitable for fish pond construction at regional scale. On the P. Mahmud farm, only 15 % and 38 % of the farm area were identified as suitable for fish ponds from an economical and an ecological perspective, respectively. The developed modelling framework is transparent and allows a rational decision making in site allocation. The framework is flexible for future adjustments in order to incorporate further data and site requirements as well as to apply it to other areas. The spatial patterns of the detailed input factors and constraints together with the final suitability maps which show the potential target areas for restructuring can guide policy makers, regional and local land use planners in land use decision making.

Recommendations for future research:

Three major areas for future research and application were identified.

Improved input data might be supportive to get more precise and better locally adjusted results, e.g. input data that were not yet available, such as more frequently groundwater observations, high resolution terrain data, a precise hydro network, water temperature and information on optimum growth parameters concerning different fish species might improve the results of the MCE, in particular at local scale. Especially, a detailed hydrological network analysis could be applied concerning the locally available water from the irrigation network instead of the implemented cost distance surface. This approach would ensure to consider the flow direction of the water and allow calculating the water availability for each irrigated field in more detail. Another example for further improvements based on specific input data is to consider agricultural by-products as locally available fish feed by detailed information on fish feeding strategies together with large scale data about the location of farm households and cattle dung production.

The second focus for further adjustments is to integrate a cost-benefit estimation into the land suitability assessment to identify farms (at regional scale) and fields (at local scale) with the least expenses for restructuring the given landuse into fish ponds, while providing a sustainable profit.

The third focus for future research and application is the integration of the locally adjusted modelling framework into a land use change model to balance and harmonize competing land use restructuring strategies in Khorezm.

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