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Habitat suitability for *Populus euphratica* in the Northern Amudarya delta - a fuzzy approach

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Zusammenfassung

Ziel dieser Diplomarbeit ist die Entwicklung eines Habitateignungsindex für die Euphrat-Pappel (*Populus euphratica*, syn. *ariana*) im nördlichen Amudarjadelta (Usbekistan). Die Euphrat-Pappel ist die dominante Baumart der Tugaiwälder, charakteristischer Auenwälder der Trockengebiete Zentralasiens. Im Amudarjadelta ist das fast vollständig anthropogen bestimmte hydrologische Regime der entscheidende Umweltfaktor für die Ökosysteme. Die drastische Abnahme des Wasserzuflusses zum Deltagebiet durch die Intensivierung der Bewässerungslandwirtschaft führte zu ihrer starken Degradierung und einer Vielzahl anderer ökologischer Probleme. Der Habitateignungsindex für *P. euphratica* soll ein Maß bereitstellen, um die Auswirkungen verschiedener zukünftiger Wassermanagementstrategien auf die ökologische Situation des nördlichen Amudarjadeltas zu bewerten.

Aus der verfügbaren Literatur und Expertenbefragungen wurde das vorhandene ökologische Wissen über die Umweltansprüche von *P. euphratica* und über die Zusammenhänge zwischen den verschiedenen Umweltvariablen zusammengestellt und ausgewertet. Als flussbegleitende Art in ariden Gebieten ist *P. euphratica* besonders abhängig von der Verfügbarkeit von Wassser der Flüsse und Kanäle sowie von Grundwasser. Daher wurden die folgenden Umweltvariablen als die Habitateignung maßgeblich beeinflussende Größen ausgewählt: Geomorphologie, Grundwasserflur- abstand und Überflutungsregime (Überflutungshäufigkeit, Zeitpunkt und Dauer der letzten Überflutung). Dabei ist die Überflutungshäufigkeit eine dynamische Größe, die die Überflutungsgeschichte des jeweiligen Standorts repräsentiert.

Um das vorhandene, z.T. semi-quantitative und qualitative Wissen zu formalisieren und die Berechnung der Habitateignung zu ermöglichen, wurde ein Ansatz der Fuzzy-Set-Theorie gewählt. Dabei liegt die Fuzzy-Menge der “geeigneten Standorte” zugrunde, zu der jedem Wert der einzelnen Umweltvariablen eine graduelle Zugehörigkeit zugeordnet wird. Die Zugehörigkeiten der einzelnen Umweltvariablen werden dann zu einem Gesamtindex, dem Habitateignungsindex, kombiniert. Für diesen Basisindex werden mögliche Erweiterungen vorgeschlagen, die zusätzliche Annahmen berücksichtigen.

Der so entwickelte Index wurde auf eine Testperiode (1991-1999) angewandt. Sowohl der Basisindex als auch die erweiterte Version beurteilen die Habitateignung für die Jahre 1991 bis 1997 als gering bis mittel. Nach einer Flut im Jahr 1998 steigt die Eignung der meisten überfluteten Gebiete. Etablierung ist nur 1998 möglich. Die Ergebnisse wurden auf ihre Plausibilität überprüft und mit der tatsächlichen Verteilung der Tugaiwälder im Jahr 2000 verglichen. Dabei zeigt sich, dass die berechneten Werte die Veränderungen des Grundwasserspiegels und der Überflutungsgeschichte erwartungsgemäß widerspiegeln und nur in Ausnahmefällen der Realität widersprechen.

So wurde ein “virtueller Experte” geschaffen, der die Habitateignung für *P. euphratica* schnell und einfach für ein großes Gebiet bestimmt. Dieses Habitateignungsindexmodell ist ein Modul eines GIS-basierten Simulationswerkzeugs, das einen qualitativen Vergleich verschiedener Wassermanagementszenarien hinsichtlich ihrer Auswirkungen auf die ökologische Situation im nördlichen Amudarjadelta ermöglicht.

Summary

The aim of this diploma thesis is the development of a habitat suitability index for the Euphratica poplar (*P. euphratica*, syn. *ariana*) in the Northern Amudarya delta (Uzbekistan). *P. euphratica* is the dominant tree species of the tugai forests, characteristic riparian forests of arid regions of Central Asia. In the Amudarya delta the anthropogenically managed hydrological regime is one of the main factors determining the ecological state of the ecosystems. The immense decrease of the water discharge to the delta area, due to the intensification of irrigated agriculture, led to a strong degradation of its ecosystems and numerous other ecological problems. The habitat suitability index for *P. euphratica* provides a measure that facilitates the assessment of future water management alternatives as to their effects on the ecological situation in the Northern Amudarya delta region.

To develop the habitat suitability index the existing ecological knowledge about habitat requirements of *P. euphratica* and the interrelations between the environmental variables was compiled by reviewing the available literature and expert interviews. As a riparian species of arid regions establishment and growth of *P. euphratica* especially depend on the hydrological regime of rivers and channels, as well as the availability of ground water. Therefore, the following environmental variables are chosen as determining parameters for the habitat suitability: geomorphology, ground water level, and flooding regime (i.e. flooding frequency, timing and duration of the last flooding). Here, the flooding frequency is a dynamic variable that reflects the flooding history of a given site.

The collected, partially semi-quantitative and qualitative, knowledge is formalized using an approach of the fuzzy set theory. The calculation of the habitat suitability is based on the fuzzy set of “suitable sites”. Each value of the environmental variables is assigned a gradual membership in this fuzzy set. The memberships of the different environmental variables are combined to an overall index, the habitat suitability index. Extensions of this base index are proposed that take into account additional assumptions.

The resulting index is applied to a test period (1991-1999). Both, the base index as well as the extended version yield low and intermediate habitat suitability values for the years 1991-1997. After a flood in 1998, the suitability values increase in most of the flooded areas. Establishment is only possible in 1998. The plausibility of the results is checked, and they are compared to the actual distribution of tugai forest in 2000. This reveals, that the index values respond in the expected way to changes of the ground water level and the flooding dynamics, and that the calculated values contradict to the reality only in very limited areas.

By these means a “virtual expert” is created which enables a fast and simple evaluation of the habitat suitability for *P. euphratica* over a large area. As one module of a GIS-based simulation tool it facilitates the qualitative comparison of different water management scenarios as to their effects on the ecological situation in the Northern Amudarya delta region.

Contents

1 Introduction **11**

2 Habitat Modelling **13**
2.1 Definition of “habitat” 13
2.2 Aims of habitat modelling 13
2.3 Habitat modelling approaches 14

3 The study area **19**
3.1 Geographical location 19
3.2 The Amudarya 19
3.3 Climate 20
3.4 Geology and soils 20
3.5 The intensification of irrigated agriculture 21

4 Tugai forests & *Populus euphratica* **25**
4.1 General description 25
4.2 Ecology 26
4.3 Ecological and economic value 27
4.4 Recent development of the tugai forests 28
4.5 *P. euphratica* as representative species 29
4.6 The Euphratica poplar (*P. euphratica*) 30

5 Habitat variables **33**
5.1 Climate 35
5.2 Geomorphology 35
5.3 Soil type 36
5.4 Ground water level 36
5.5 Flooding regime 36
5.6 Soil salinization 37
5.7 Ground and river water mineralization 38
5.8 Anthropogenic impacts 38
5.9 Summary 39

6 Geodata **41**

7 The habitat suitability index model **47**
7.1 General considerations 47
7.2 Construction of a fuzzy habitat suitability index 50
7.3 Description of the variables 52
7.4 Establishment 53
7.5 Adult formations 55

8 Possible extensions **59**
8.1 Additional floodings and establishment 59
8.2 Ground water level and flooding frequency 60

9 Results & Discussion **65**
9.1 Results of the index models 65
9.2 Comparison and test of the index results 69
9.3 Discussion of the results 73

10 Conclusions & Outlook **75**

Bibliography **79**

A Definition of fuzzy terms **83**

List of Figures

2.1 Theoretical variables and species performance 14

3.1 Map of Uzbekistan 20
3.2 The Amudarya delta 21
3.3 Climate diagram of Chimbay 22

4.1 Fragments of tugai forest 26
4.2 Traces of pasture in a tugai forest patch 29
4.3 An old Euphratica poplar and propagation through root-suckers 30

5.1 Influence diagram of habitat variables 34
5.2 Reduced influence diagrams 39

6.1 The geomorphology of the study area 42
6.2 Development of the ground water level from 1991-1999 43
6.3 Flooded areas during the flood in 1998 44
6.4 Distribution of woody tugai vegetation in the study area 45

7.1 Exponential decay of the impact factor of a flooding 53
7.2 Suitability curves of (a) flooding timing and (b) end of the flooding for establishment of *P. euphratica*. 54
7.3 Suitability curve of the ground water level for establishment of *P. euphratica*. . 55
7.4 Suitability curves of (a) the ground water level and (b) the flooding frequency for adult *P. euphratica* individuals. 56
7.5 Suitability curves of (a) flooding timing and (b) flooding duration for adult *P. euphratica* individuals. 57

8.1 Suitability curves for the flooding timing (a) and the flooding duration (b) of an additional flooding. 60
8.2 Fuzzification of (a) the ground water level and (b) the suitability of the flooding regime 62
8.3 Fuzzy sets representing the habitat suitability 63

9.1 Results of Index 1 (adult formations) for the years 1991-1999. 67
9.2 Results of Index 2 (adult formations) for the years 1991-1999. 68
9.3 Results of Index 1 (establishment) for 1998. 70
9.4 Comparison of index values and the distribution of tugai forests 70
9.5 Comparison of index values and the landscape map for 1991. 71
9.6 Comparison of index values and the landscape map for 1999. 71

9.7 Comparison of Index 1 and Index 2 72

Chapter 1

Introduction

"The rational use of natural resources in the deltaic plains of the rivers Amudarya and Syrdarya is one of the central problems of the Aral ecological crisis" claim Novikova et al. (1998) in view of the dramatic environmental changes in the Aral Sea region which became known as the Aral Sea crisis. The crisis even gave its name to one of 16 global disease patterns (syndromes) - the Aral Sea-Syndrome - which were introduced by the WBGU[1] (WBGU, 1996) to describe different global environmental and developmental problems. The causes that led to the ecological decline of the region can be found in the expansion and intensification of irrigated agriculture in the Central Asian Soviet Republics Kazakhstan, Turkmenistan and Uzbekistan during the last century. One centre of irrigated agriculture is the middle and lower reach of the Amudarya river. The high withdrawal of water, the construction of reservoirs, together with immense water losses due to evaporation and infiltration from non-sealed channels led to an extreme decrease of the water discharge of the Amudarya and to changes in its sedimentation and flooding regime. The consequences of these altered hydrological conditions for the delta area are (among others) a lowering of the ground water table, the desiccation of swamps, and the degradation of hydromorph ecosystems.

Numerous developmental projects have addressed the ecological and economic problems of the region, searching for solutions that might contribute to an improvement of the situation. In contrast, only few scientific projects study the complex interrelationships between socio-economic measures and their effect on the ecological situation. Within the scope of the INTAS-Project[2] "Restoration and management options for aquatic and tugai ecosystems in the Northern Amudarya delta region"[3] it is aimed to develop a computer-based simulation tool to evaluate different water management strategies as to their effects on the ecological conditions in the delta area. The habitat suitability for the characteristic tugai forests is chosen as an indicator of the ecological situation, because their development and viability strongly depends on the hydrological regime of the Amudarya and the canals, and because of their ecological and economic value for the entire Amudarya delta region. The tugai forests - fast growing, deciduous riverine forests of mainly poplars and willows - provide a valuable habitat for many wildlife species and render important ecological services (e.g. the formation of soil, the melioration of the microclimate and the preservation of biodiversity). They offer an indispensable resource for hunting, grazing

[1] Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (German Advisory Council on Global Change)

[2] International Association for the Promotion of Co-operation with Scientists from the New Independent States of the Former Soviet Union

[3] http://www.usf.uni-osnabrueck.de/projects/aral

and logging for the local population within an otherwise inhospitable desert landscape.
The Euphratica poplar (*Populus euphratica*, syn. *ariana*) is the dominating tree species of the tugai forests. It is selected as a representative species to determine the habitat requirements of the tugai forests and to develop a habitat suitability index. The habitat suitability for *P. euphratica* is used as a measure of the quality of the environmental conditions in the delta area, which enables a qualitative comparison of different water management alternatives.
Summarizing, the objectives of this study are the following:

1. Collection of the existing ecological knowledge regarding tugai forest ecosystems, with special attention to the Euphratica poplar (*Populus euphratica*).

2. Development of a habitat suitability index model for tugai forests, represented by *Populus euphratica*.

3. Testing of the index model.

By these means it is aimed to create a "virtual expert", which is able to assess the ecological situation, depending on the hydrological conditions, over a large area with relatively little effort. This tool should help decision makers who are not acquainted with the ecological requirements of the tugai forests to answer the question as to how to distribute the available water in the most effective way from the viewpoint of an improvement of the ecological situation.
On the long run, the habitat suitability index model will be part of an integrated simulation tool, which facilitates the evaluation of management decisions providing an ecologically sound basis to assist local and regional decision makers. It is intended to facilitate the management of water resources "in a way that ... balances the requirement of preserving or restoring ecosystems and their functions, in particular in fragile environments, with human domestic, industrial and agriculture needs ..." as envisioned by the Johannesburg Action Plan (United Nations, 2002).

Chapter 2

Habitat Modelling

2.1 Definition of “habitat”

The term “habitat” is used in scientific literature to describe living spaces with respect to several biological entities (e.g. organisms, populations, species or species communities). In the strictest sense the “habitat of an organism” is defined as “the locality or external environment in which a plant or animal lives” (Lawrence, 1989). The broader definition of a “habitat of a species” describes “the habitable part of space or area available for establishing a population” of a certain species (Lawrence, 1989). And often the term habitat is simply used to address the external environment, including biotic and abiotic factors, without reference to any biological entity. This variety of meanings leads to some confusion when referring to the term “habitat suitability”. If “habitat” is used in the sense of potential living space of a species, then “suitable habitat” would be a redundant phrase and “unsuitable habitat” would be a contradiction. In the context of this study clearly the last meaning of “habitat” as the sum of all environmental conditions has to be applied. To avoid terminological confusion it has been decided to use the term “habitat” only in this sense (unless indicated otherwise). Thus, the expression “habitat suitability” describes the possibility that an individual (or population) of a certain species can establish, survive, and reproduce under the given environmental conditions.

2.2 Aims of habitat modelling

Habitat models are often used to investigate the potential distributions of species or communities under changing environmental conditions, such as an intensified land use, different water management scenarios, etc. (Guisan and Zimmermann, 2000). They are utilized as parts of management tools or decision support systems to facilitate management decisions concerning the conservation or restoration of endangered species or ecosystems (Curnutt et al., 2000; Guisan and Zimmermann, 2000; Schultz and Wieland, 1995). Within those tools most habitat models are coupled with Geo Information Systems (GIS), which supply spatial data of the environmental variables and facilitate the visualization of results (Brooks and Temple, 1990; Curnutt et al., 2000; Debeljak et al., 2001; Dettmers and Bart, 1999; Glenz et al., 2001; Lutze et al., 1998). The investigated species or communities often serve as indicator species, because their environmental requirements reflect the requirements of a multitude of other species (Lutze et al., 1998), or because they reflect certain landscape characteristics of interest. Habitat suitability indices often serve as qualitative measures of the impacts of different management alternatives on the ecological situation (Curnutt et al., 2000). As experimental investigations are usually impossible at the spatial and temporal scales of interest, habitat models provide a means for a relatively simple assessment of the effects of environmental changes for large areas (Lutze et al., 1998).

2.3 Habitat modelling approaches

Habitat modelling can, partly due to the various meanings, address different problems. The investigated feature can either be a theoretical variable or a measurable expression of species performance (Fig. 2.1). Theoretical variables (e.g. habitat suitability, carrying capacity) are not directly measurable and express the potential of a given site to serve as habitat (in the sense of “living space”) for a species or species community. A unitless measure of habitat suitability which ranges between 0 and 1 is often called “habitat suitability index” (HSI) (Store and Kangas, 2001). Measurable expressions of species performance (e.g. biomass, abundance, presence/absence) also reflect the appropriateness of a given site from the viewpoint of a species or species community . Sometimes these different aspects are equated and, as an example, the

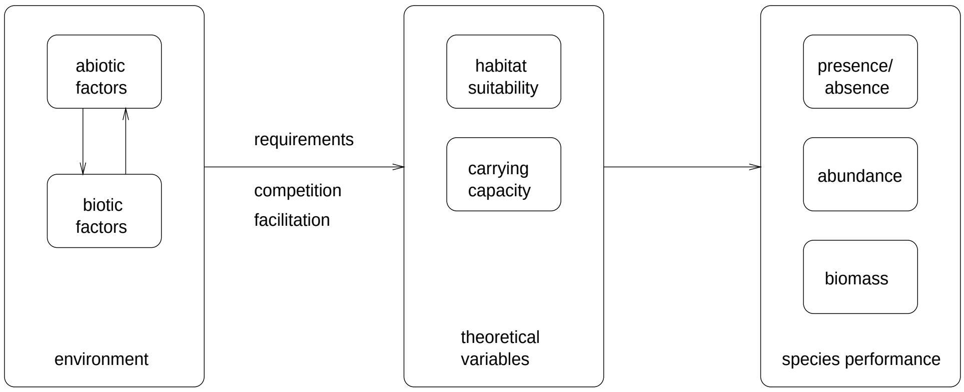


Figure 2.1: Relationship between the environment and its influence on different aspects of the performance of a species expressed by theoretical variables.

probability of presence of a species is interpreted as habitat suitability (Glenz et al., 2001), or vice versa the habitat suitability as the likelihood of occurence of a species (Store and Kangas, 2001).

Statistical approaches

In the case of modelling aspects of species performance, a wide variety of statistical approaches is used to relate the data on biological characteristics to the environmental parameters. Those statistical methods intend to investigate the species-environment relationships and, on their basis, to predict the potential distribution of a species or other aspects of species performance.

The simplest method are multiple linear regressions, which assume a linear dependency of the habitat suitability on the environmental variables, a normal distribution of the response variable, and independence of the input variables. The concept of linear regressions can be extended to Generalised Linear Models (GLM) (Guisan and Zimmermann, 2000). GLM´s relax some assumptions of the linear model. They allow other distributions of the response variable, and other than linear relationships between the predicted value and the systematic part of the model

(Guisan and Zimmermann, 2000). GLM´s include, among others, linear and logistic regressions as special cases. Other statistical approaches are Canonical Correspondence Analysis, Principal Component Analysis and Classification Techniques (Guisan and Zimmermann, 2000). Another formalism, that is based on measured data, are neural networks (Guisan and Zimmermann, 2000). Here, the type of relationship between the input variables and the output variable is not predefined, but "learned" from the data. Actually, neural networks perform multiple non-linear regressions.
For a detailed review on statistical habitat models see Guisan and Zimmermann (2000).

Bayesian Networks

Bayesian networks (also probabilistic networks, belief networks) are based on Bayes' theorem and have recently been applied in habitat suitability modelling (e.g. Marcot et al., 2001). Here, the variables of interest are depicted (from the experts) as an influence diagram where each node represents a random variable and each arrow a direct causal relationship. The strength of these influences is given by the *conditional probability*[1] which also has to be estimated by experts. For nodes without parents the *a priori probability*[2] has to be determined. Both probabilities can be expressed by probability tables or as bivariate functional relationships (Pearl 1999). From such a Bayesian network the *a posteriori probabilities*[3] of any of the variables under a given set of (possibly incomplete) information can be calculated. Bayesian networks represent one possibility to organize existing knowledge. The advantages of probabilistic reasoning are the explicit integration of dependencies between the variables and the semantic clearness of the formalism (Pearl, 1990). The uncertainty about the true value (or category) of a variable is expressed as probability or probability distribution. The drawbacks of Bayesian networks include the high costs of constructing and computing them (exact inference is NP-hard (Pearl, 1990)), as well as the elaborateness of the method which makes it difficult to handle by non-statisticians.

Rule-based approaches

Another possibility to incorporate expert knowledge and to deal with classification uncertainty provides the application of rule-based approaches. Those approaches use predefined rules about how the considered environmental variables affect the habitat suitability. Usually, the environmental variables are classified into two categories; deterministic vs. non-deterministic (Store and Kangas, 2001) (or binary vs. quantitative (Curnutt et al., 2000)) variables. The deterministic variables are used to model the "known or estimated limits of habitat" (Curnutt et al., 2000) and serve as exclusion criteria for areas that do not meet the basic requirements for tolerable environmental conditions. The non-deterministic variables are assigned suitability values, which express the suitability of a given value of the environmental variable. In the case of continuous variables, suitability functions are determined. These suitability curves or values are defined by experts or by the modeller, taking into consideration all available knowledge. These heuristic approaches are called rule-based (Curnutt et al., 2000) or multi-criteria evaluation (MCE) (Ressl, 1999; Store and Kangas, 2001).

[1] likelihood of the state of a parameter given the states of input parameters affecting it (Marcot et al., 2001)
[2] likelihood that some input parameter will be in a particular state (Marcot et al., 2001)
[3] likelihood that some parameter will be in a particular state given the input parameters, the conditional probabilities and the rules governing how the probabilities combine (Marcot et al., 2001)

Fuzzy techniques can also be classified as rule-based methods. They make use of fuzzy set theory or of fuzzy logic. The basic idea of fuzzy set theory is the possibility that an object can have a partial membership in a (fuzzy) set. This concept provides a means to deal with classification uncertainty by allowing statements such as: "The environmental conditions of the site X are suitable to a degree of 0.6". Contrary to probabilistic approaches, this means that the site *is* reasonably suitable. Whereas the probabilistic statement would read: The probability that the site is suitable is 0.6. The definitions of the fuzzy sets, which represent the suitability of the environmental conditions are identical to the suitability curves of the so-called rule-based approaches.

If fuzzy logic is applied rules are established (e.g. from expert knowledge), which represent the system's behaviour. The rules can have a truth value other than zero or one. These rules are than evaluated for the given environmental conditions by applying fuzzy reasoning.

An overview over recent habitat suitability models is given in Table 2.1.

Comparison of the different approaches

The mentioned approaches are based on hypothesis about how environmental factors control the distribution or performance of species and communities (Guisan and Zimmermann, 2000). Rarely the dynamic response on environmental changes is known in detail. Therefore, models rely either on data about species performance or on expert knowledge. Both, data and expert knowledge, are obtained under field conditions. That means, they reflect the outcome of interspecific competition. Hence, automatically the realized niche[4] is modelled. This results in limited applicability of the model to other regions, where species composition or interactions might be different (Guisan and Zimmermann, 2000).

The mentioned statistical habitat models are static. They look at the system at a certain point in time and are based on the assumption of equilibrium. That means, that the population density is neither increasing nor decreasing, on a longer time scale, but at steady state (Guisan and Zimmermann, 2000).

When modelling the theoretical variables one can refer to experts' judgements and qualitative knowledge on how the environmental variables affect the habitat suitability, and on experimental data on the species-environment relationships. One advantage of this approach is that no equilibrium assumptions have to be made, because only the potential of a given site to permit establishment, survival, and reproduction is evaluated.

Usually, the statistical modelling of species performance is more widely used to investigate the habitat or distribution of plant species, because plant presence and performance is easy measurable. Whereas for animal species it is much more difficult to collect data on presence, and especially absence, or species performance. Therefore, animal habitat models more commonly use the theoretical variables.

All of the statistical techniques have in common, that they require (preferably complete) data sets of the environmental parameters and the response variable. Often those data are not available and too time-consuming to collect. The statistical approaches do not allow to incorporate qualitative knowledge and do not permit to combine quantitative, semi-quantitative and qualitative knowledge. In contrast, Bayesian networks and rule-based approaches are designed for an explicit integration of qualitative and semi-quantitative expert knowledge.

[4]realised niche = the set of physical conditions and resources given which a species can survive and reproduce in the presence of the entire biological community (competitors, predators, facultative mutualists, etc.)

In our case the fuzzy approach is chosen to model the habitat suitability for *P. euphratica* in the Northern Amudarya delta. Since almost no data on species-environment relationships are available we have to rely mostly on expert knowledge. The fuzzy techniques provide a simple and extreme flexible method, which allows to integrate knowledge from different sources; qualitative, semi-quantitative, and quantitative knowledge. A procedure can be designed that fits the available data and is appropriate for the system (Silvert, 2000). Furthermore, fuzzy techniques provide a means to deal with uncertainty, which may arise from contradicting experts' assessments or observations.

Table 2.1: Some recent models covering different aspects of habitat suitability modelling. MCE=Multi criteria evaluation.

Method	Investigated species	Area of application	Reference
Logistic regression	Gray wolf (*Canis lupus*)	investigation of the potential for recolonization	Glenz et al. (2001)
Statistical method of presence-data evaluation using cumulative distribution functions	nine songbird species	prediction of the amount and spatial distribution of “good” habitat	Dettmers and Bart (1999)
Classification trees	Red deer (*Cervus elaphus*)	assessment of potential habitats	Debeljak et al. (2001)
Neural networks	fur seal (*Arctocephalus forsteri*)	prediction of the suitability of the coastline for breeding	Bradshaw et al. (2002)
Bayesian networks	Townsend´s big-eared bat (*Corynorhinus townsendii*)	habitat and population viability modelling	Marcot et al. (2001)
Rule-based	Cape Sable Seaside Sparrow, Snail kite, Long-legged wading birds	restoration of the fragmented Everglades ecosystem	Curnutt et al. (2000)
Rule-based	Loggerhead shrike (*Lanius ludovicianus*)	habitat suitability evaluation	Brooks and Temple (1990)
MCE	old-forest polypore (*Skeletocutis odora*)	protection of old-growth forest	Store and Kangas (2001)
MCE	rice, cotton	investigation of optimal cultivable land	Ressl (1999)
Fuzzy	different freshwater related species	restoration of riverine habitats	Duel et al. (1995)
Fuzzy + neural networks	Barn owl (*Tyto alba*)	assessment of effects of land use changes	Schultz and Wieland (1995)

Chapter 3

The study area

3.1 Geographical location

The Amudarya delta is located between 42,5° - 44° E and 58° - 60° N where the Amudarya used to drain into the Aral Sea. The major part of the delta lies within the Republic of Uzbekistan in the Autonomous Republic of Karakalpakstan (Fig. 3.1). The modern delta of the Amudarya streches from Nukus (the capital of the Republic of Karakalpakstan) in the south to Muinak, a former port of the Aral Sea, in the north. A smaller part of the delta belongs to Turkmenistan. Geographically, the delta is part of the Central Asian Turan lowland, the centre of which forms the Aral Sea (Ressl, 1999). In the north the delta adjoins to the former coast of the Aral Sea. In the west it is bound by the Ust-Yurt plateau, and in the east and south the delta is surrounded by the Kyzylkum and the Karakum[1] deserts (Ressl, 1999).
The southern part of the delta is mainly covered by irrigated fields. This work focuses on the northern part of the delta which is located approximately between Kyzyljar in the south and Muinak in the north (Fig. 3.2). The Northern Amudarya delta used to be covered by hydromorph ecosystems such as swamps, lakes, reed stands, and the typical riparian tugai forests (Ressl, 1999). The Northern Amudarya delta covers approximately 6400 km^2.

3.2 The Amudarya

The Amudarya river is the life vein of this dry desert region. It is the main contributory to the Aral Sea (besides the Syrdarya in the north) and has its source in the glaciers of the Hindukush and Pamir mountains in Uzbekistan (Ressl, 1999). On its way down it forms the border between Afghanistan and Uzbekistan before it crosses the Turan lowland and, finally, drains into the Aral Sea. Before the strong regulation of the river by dams and reservoirs beginning in the 1960s, and the expansion of irrigated land it brought appr. 50 km^3 water, rich in suspended matter, every year to the delta region. The Amudarya does not only provide surface water but it also feeds the ground water of this arid region where precipitation is negligible (mean annual precipitation is ca. 100 mm). Due to the melting of snow and glaciers in the mountains the highest river water levels were usually reached in July. They often resulted in inundations of the floodplains along the river reaches in the delta. Since 1980, the entire water supply to the delta area is regulated by the Tuyamuyun reservoir 200 km south-east of Nukus. The yearly water discharge in the northern delta now fluctuates between 0 and 20 km^3, and the natural flooding regime has

[1] In Turc languages Kyzylkum and Karakum means “red sand” and “black sand”, respectively.

Figure 3.1: Map of Uzbekistan. The rectangle indicates the Amudarya delta.

mostly stopped (Novikova, 2001). After 1978, only in 1998 and 2002 floods left large parts of the delta under water.

3.3 Climate

The Amudarya delta, like the whole Turan lowland, is located within the zone of arid continental climate which is characterized by very low precipitation, hot summers, and cold winters. The mean annual precipitation is approximately 100 mm, of which the main quantity falls in spring (Fig. 3.3). Temperature extremes reach -30 °C in winter and 45°C in summer. Because of the high dryness in summer every year around 25 severe dust storms take place (Létolle and Mainguet, 1996).

3.4 Geology and soils

The delta of the Amudarya and the surrounding deserts are alluvial plains. The thickness of the sediments amounts to 35-140 m (Ressl, 1999). The upper 12-15 m are recent Holocene deposits of silty sand or silty clay (Létolle and Mainguet, 1996). Consequently, the relief energy of the delta is low. The altitude difference between Nukus in the south of the delta and Muinak in the north is 8-10 m on a distance of 150 km.

The alluvial soils of the delta region were originally fertile, even if poor in humus, due to the fluvial sedimentation of loess, and hence, favourable for irrigated agriculture (Ressl, 1999). The hydromorph soils (permanently saturated with water) of the swamps and lake depressions are of different mineral origin and their desiccation led to the formation of Solontschaks (saline or alkaline soils with very low agricultural value) or Takyrs (often saline, uniform and compact clayey soils) (Létolle and Mainguet, 1996).

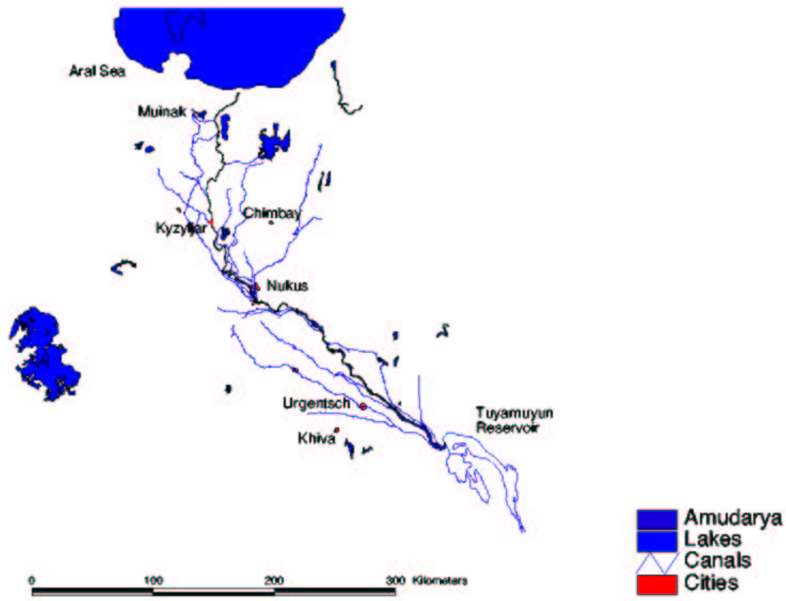


Figure 3.2: The Amudarya delta region. Source: Aral Sea Gis (Reimov, Ptichnikov, Novikova, Ressl) (1999) modified by Schlüter and Rüger.

3.5 The intensification of irrigated agriculture and its consequences

At the lower reach of the Amudarya river irrigated agriculture has a long tradition. Archaeological investigations date the beginning of intensive irrigation agriculture in the delta to 1500 BC (Ressl, 1999). But the efforts of the USSR to gain autarchy in cotton production in the thirties, the demand for higher food production and raising of new sources of foreign currency in the fifties and sixties of the last century led to an expansion of the irrigated lands and to an intensification of agriculture (Ressl, 1999). Rice, the main local food source, and cotton, the so-called "white gold", are both water intensive crops. To assure sufficient water supply to the irrigated fields, dams and reservoirs were built in the mountains of neighbouring Central Asian Soviet Republics, as well as at the lower reach (e.g. the Tuyamuyun reservoir was built in 1980). Additionally, in 1954 the construction of the 1400 km long Karakum Canal was initiated. Every year it takes 15 km^3 water from the Amudarya through Turkmenistan to the Caspian Sea.

Some consequences of the expansion of irrigated agriculture compiled from Kuzmina and Treshkin (1997), Ressl (1999), Treshkin (2001a) and WBGU (1997) are listed here.

1. The construction of regulating dams and reservoirs led to changes in river discharge and flooding regime. Salts that in the past were washed away by frequent floodings now accumulate in the delta area.

2. The sedimentation behaviour changed. Behind dams the river carries less suspended matter. That results in higher erosion of river banks and a deeper cutting of the river into its bed. This again leads to the disappearance of floodings.

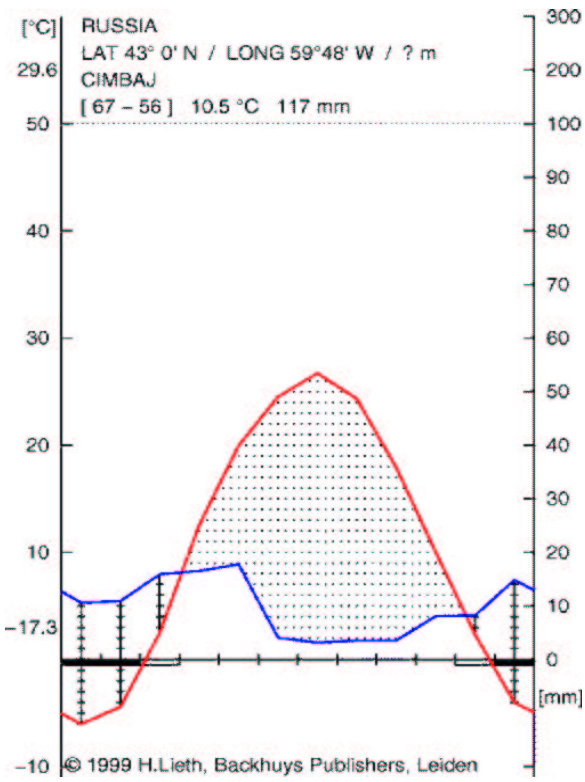


Figure 3.3: Climate diagram of Chimbay (Amudarya delta). The left scale indicates the monthly temperature averages of 67 years, the warmest month (29.6 °C) and the coldest month (-17.3 °C). The right scale indicates the monthly precipitation averages of 56 years. Source: Climate Diagram World Atlas, Lieth et al. (1999).

3. Another consequence is the considerable lowering of the groundwater table which in the delta region amounts to 3-8 m (Ressl, 1999), the drying out of lakes and wetlands. In the special case of the Aral Sea region it also resulted in the immense shrinking of the Aral Sea leading to its separation into two lakes with severe impacts on the regional climate, ecology and fishing industry.

4. On irrigated surfaces the rising of the ground water table, in contrast, leads to secondary salinization of the upper soil horizons due to the strong evaporation of capillary water. In order to prevent a decline of the agricultural production, fields are flushed several times per year. This in turn increases the water consumption and results in a high contamination of the drainage water, and subsequently the river water, with salts, herbicides and pesticides. The salt content of the Amudarya has risen from 0,4 g/l up to 1-2 g/l.

5. The water shortage and regulation of the water flow led to the degradation of hydromorph ecosystems (e.g. tugai forests, reed stands) and the loss of genetic and species diversity.

6. The deterioration of the natural vegetation and the drying out of the Aral Sea left bare soil behind, partly covered by a salt crust, that is susceptible to wind erosion and provides sources of dust and salt to the frequent dust storms.

7. The high risk of water bound diseases, due to the reduced flow velocity of the rivers, the

dusty air, the severe pollution of the drinking water, and the bad socio-economic situation are the reasons for the poor state of health of the population, the high infant mortality and malformation rate that are observed in the delta area.

8. Other social consequences of the overuse of water resources include high unemployment, due to the destruction of economical sectors (e.g. the fishing industry), and migration of the population.

Such a damage of the environment caused by planned management actions of natural areas within the framework of major projects was summarized by the WBGU under the term Aral Sea-Syndrome. Its symptoms - loss of biodiversity, local or even global climate change, lack of freshwater supply, degradation of soil, resettlement of the local population and the risk of interstate conflicts about the distribution of the water - also apply to other regions where the consequences of management actions were not preconceived due to the lack of understanding of the systems behaviour (WBGU, 1996).

Chapter 4

Tugai forests & *Populus euphratica*

Within the scope of this work the potential habitat suitability for tugai forests and *P. euphratica* will be used as an indicator of the ecological situation (hydrological regime, soils, soil salinization) of the Northern Amudarya delta. A site where the environmental conditions are favourable for establishment and growth of woody tugai is considered to be in a desired ecological state. The tugai forest ecosystem is chosen to accomplish this indicator function because of several reasons. First, the habitat suitability for tugai forest communities is closely related to the hydrology of the region (especially the ground water level and the flooding regime). Therefore, an estimation of the habitat suitability for tugai forests reflects the hydrological conditions, which in turn are crucial for the entire ecological situation. Second, there is relatively plenty knowledge available about the ecological requirements of tugai forests. They have been observed and studied during a long time. Another reason is their immense ecological and economic value, as well as their relevance being the historical vegetation of vast areas of the delta region. Finally, there are concrete plans to restore tugai forests, so that the results of this study, hopefully, can contribute to the facilitation of restoration attempts.

4.1 General description

Tugai forests (Desertsilveta) are desert floodplain forests typical for river valleys and deltas in arid regions (Fig. 4.1) (Treshkin et al., 1998). Under the name tugai they are mainly described for the floodplains and deltas of rivers in the former Central Asian Soviet Republics (e.g. the rivers Amudarya, Zeravshan, Tedjen, Murgab, Sumbar, Vakhsh, Syrdarya, Ili, Chu, Lepsa) (Treshkin, 2001b), but they also exist in Northern China (Sinkiang), Mongolia, Iran and other regions with continental arid or semi-arid climate. Typical tugais occur as narrow belts (from a few hundred meters up to several kilometers width (Novikova, 2001)) along river reaches or canals. They occupy sand banks, islands and low terraces (Kuzmina and Treshkin, 1997), where they are regularly flooded. In recent times they have also been found in dry river beds and on natural levees (Treshkin, 2001b).

Tugai vegetation is characterized by a high capacity to tolerate both very wet soil and very dry air, resistance to drought and salts, high transpiration intensity and the disposition to grow adventitious roots, typical for vegetative propagation (Treshkin et al., 1998). Most tugai plants are light dependent pioneer species. Their seeds can grow only on bare surfaces and loose their germinating ability in a dry state. Most tugai species do not have a summer dormancy period and vegetate from spring until late autumn, despite the arid climatic conditions (Treshkin, 2001b).

Figure 4.1: Fragments of tugai forest along a reach of the Amudarya.

Tugai vegetation can be divided into three groups: tree tugai, bush tugai and grass tugais. With more than 230 plant species the tugai vegetation can be considered as one of the most diverse vegetation types of the arid regions of Central Asia (Novikova et al., 2001).The main tree species of woody tugai are poplar (*Populus euphratica*, *P. pruinosa*), oleaster (*Eleagnus turcomanica*, *E. angustifolia*) and willow (*Salix songarica*, *S. wilhelmsiana*). They occur accompanied by bushes and tall grasses, such as tamarisk (*Tamarix ramosissima*, *T. laxa*), Halimodendron (*H. halodendron*), reed (*Phragmites australis*), reed grass (*Calamagrostis dubia*, *C. epigeios*, *C. pseudophragmites*), and herbs, like liquorice (*Glycyrrhiza glabra*) and *Apocymum scabrum* (Kuzmina and Treshkin, 1997). Under favourable site conditions tugai forests are characterized by a great species diversity and a complex vertical and horizontal structure providing diverse microhabitats for animal life (Treshkin et al., 1998).

Tugai forests undergo a typical series of transformations, because the development of the biocenosis leads to changes of the environmental conditions. The initial stage - characterized by relatively high ground water levels - is dominated by herb and willow-oleaster-poplar communities. At an age of 4 years the trees reach a height of 3-5 m and form poplar or mixed forests with a closed upper canopy. With the growth of the community the ground water level drops and poplar or poplar-tamarisk communities dominate. Due to the biological activity (i.e. the decomposition of salt containing litter) the soil salinization increases and tree tugai is replaced by bush tugai formations of mainly tamarisks (Treshkin, 2001b). This replacement may also be due to the short life span of the trees. Normally, by the age of 30-40 years the tree stands thin out and begin to die (Kuzmina and Treshkin, 1997). Usually, such a decline is not accompanied or followed by new establishment at the same site, because the conditions are not favourable anymore. Therefore, tugai forests die in one place and establish elsewhere, where the environmental situation is more suitable. On a long temporal scale, tugai forests alternate with meadows and tall-grass communities (Kuzmina and Treshkin, 1997).

4.2 Ecology

Due to the seasonal and yearly fluctuations of the ground water level in floodplains and deltas of arid regions the root system of many tugai species is large in size, branches and has several levels. The roots show high plasticity and are able to develop adventious roots on trunks and stems (Kuzmina and Treshkin, 1997). Therefore, they are able to germinate on various types of soil such as loamy, sandy loamy or sandy deposits with different depths of the ground water level (from 1 to 6 m) (Kuzmina and Treshkin, 1997; Treshkin, 2001b). The development and the existence of tugai forests is closely connected to the hydrological regime of the rivers. They depend on floodings for their establishment and the reduction of the soil salinity, as well as on access to ground water, which is also recharged by the rivers. With respect to optimal ranges of the ground water table it can be stated that both, very high and very low ground water levels, are restrictive for the comparative strength of the woody tugai vegetation. Intermediate ranges (2-5m) are most suitable for adult tugai forests.

Regarding the role that soil or river water salinization play for the degradation of the tugai forests only partial and contradicting knowledge is available. Kuzmina & Treshkin (1997) report that the stability of a typical woody tugai begins to decrease when an average salinization of 0.25 % in the uppermost 1 m of soil is reached. This destabilization leads to a greater susceptibility of the tree stand to diseases and infestations, to a drying of plants, to the disappearance of trees and the penetration of the community by halophytes. This process is accompanied by a reduction of species diversity in the community (Kuzmina and Treshkin, 1997). When the salinity further increases to 0.45 % trees disappear completely from tugai communities, as observed at the Atrek and Sumbar rivers in Turkmenistan. On the other hand they say, that tugai communities with the highest species diversity are found on non-saline or only slightly saline (up to 0.4 %) soils (Kuzmina and Treshkin, 1997). In opposition to both statements, Novikova (1998) found the highest species diversity at ground water levels between 2 and 4 m and intermediate salinity values (0.5-2 %).

4.3 Ecological and economic value

Tugai forest ecosystems play an important role for the ecological situation in the region. They protect against the high solar radiation and meliorate the microclimate. Compared to bush or grass tugai, air humidity is higher and temperature is usually 1-2 degrees lower. The daily temperature and humidity variations are smoother (Treshkin et al., 1998).

The forests serve as habitat for valuable, partly rare game species such as wild boar (*Sus scrofa*), tolai hare (*Lepus tolai*), Eurasian badger (*Meles meles*), foxes (*Vulpes sp.*), wild cats (*Felis sp.*), as well as the highly endangered Bukhara deer (*Cervus elaphus bacrianus*) and Khiva pheasant (*Phasanicus colchicus chroysomeles*). During the last decades their numbers have been reduced due to hunting and the disappearance of their habitat. One endemic species, the Turan tiger, went extinct in the 1950s (Treshkin, 2001b). Plant species that are endangered include *Sacharum spontaneum*, *Erianthus ravennae*, *Typha laxmanii*, *Apocymum scabrum,* and *Glycyrrhiza glabra* (Treshkin et al., 1998).

The tugai forests are a valuable element of the landscape. They contribute to the formation of soil, and improve its capacity to store water. They protect river banks and soil from erosion by water or wind, respectively (Treshkin et al., 1998). In addition, they serve as natural barriers against sand and dust storms retaining salt and dust, which originate from neighbouring degraded areas (Treshkin et al., 1998). Finally, they contribute to the improvement of the fertility of the soil by accumulating river alluvium during floodings (Treshkin et al., 1998).

Treshkin (2000) emphasises that the tugai forests “represent a unique ecosystem, which should be appreciated as a natural reserve of authentic flora and fauna; taking into account also their importance for the environment and water conservation, the protection of the tugai forest is of highest priority”.

Since the first colonization of the region the tugai forests have been used for multifaceted purposes. The trees are cut as construction or fuel wood. The undergrowth and the leaves of the trees are used for hay-making, and as pasture for sheep, goats, cattle, and camels, and the wildlife is hunted (Novikova et al., 1998; Runge et al., 2001; Treshkin et al., 1998; Treshkin, 2001a). In future the forests could also be used for cultivation of medical plants (e.g. liquorice (*Glycyrrhiza glabra*)).

4.4 Recent development of the tugai forests

Along with the environmental changes, described in 2.5, came the degradation and desertification of natural ecosystems that are closely connected to the hydrological regime, such as the tugai forests. This development is characterized by a reduction of biomass, the loss of biodiversity, the simplification of their structure and the invasion of desert species into the communities (Novikova et al., 1998; Treshkin et al., 1998). For example, the willow species (*Salix songarica, S. wilhelmsiana*) and the slightly less salt tolerant of the two poplar species *(Populus pruinosa)* have almost completely disappeared from the Amudarya delta. The bush species *Tamarix laxa, Halimodendron halodendron,* and *Lyceum ruthenicum* have been replaced by more dry resistant and salt tolerant species, such as *Tamarix hispida* and *Halostachys caspica*. Similar changes have taken place in the grass vegetation where *Typha laxmanii*, *Apocymum scabrum*, and *Glycyrrhiza glabra* are on the verge of disappearance, whereas desert species like the Camelthorn *(Alhagi pseudalhagi)* spread (Novikova et al., 1998). The vitality of the plants of most of the remaining forest fragments is low. Many plants are dry and seed renovation of tugai forests is rarely observed (Novikova et al., 1998; Treshkin, 2001b). A consequence of the degradation of the vegetation is also a degradation of the soils which is not compensated by a new formation (Novikova et al., 1998; Treshkin et al., 1998).

On most sites the tugai vegetation has not only changed and degraded, but completely disappeared. From originally 300,000 ha forest along the lower reach of the Amudarya in the 1930s only approximately 30,000 ha have been preserved. Most scientists name the lowering of the ground water table as the main reason for the disappearance of the tugai forests (Kuzmina and Treshkin, 1997). But also the increasing soil salinization is assumed to be a trigger of their degradation (Kuzmina and Treshkin, 1997; Treshkin, 2001b). Another important factor for the destruction of the forests is the anthropogenic use and overexploitation (Novikova et al., 1998; Treshkin et al., 1998). Many forests were cut or heavily destroyed by fires or overgrazing (Fig. 4.2). All of these impacts lead to the destruction of the surface vegetation and a degradation of the upper soil horizons (Kuzmina and Treshkin, 1997). The accelerated accumulation of salt due to an increased evaporation from the remaining bare surfaces and the absence of floodings inhibit a new establishment of young tugai forests (Kuzmina and Treshkin, 1997; Treshkin, 2001b). At present a successful natural establishment is possible only in small areas.

Consequences of the disappearing of the tugai forests are an expansion of the desert, a decreasing productivity of agricultural fields due to sand accumulation and an increased utilization pressure on the remaining forest fragments.

The National Biodiversity Strategy and Action Plan of Uzbekistan mentiones the tugai forest as the most endangered ecosystem in the country (Treshkin, 2001b). As no natural renovation of tugai forests can be expected under the present conditions (Treshkin, 2001b), scientists who are

Figure 4.2: Traces of pasture in a tugai forest patch near Kyzyljar (Amudarya delta).

acquainted with the ecological situation of the delta area demand for direct measures to preserve and restore the valuable tugai vegetation.

A first requirement for the preservation is strict protection of the remaining forest patches. Especially cattle grazing as one of the most severe anthropogenic impacts on the ecosystem must be controlled (Novikova et al., 1998). Second, active measures as to facilitate the renovation, as well as the preservation are required. The water must be rationally managed in the entire delta region. Suitable sites for renovation could be artificially flooded in order to enable an establishment of young tugais. Additionally, afforestation and the setup of tree nurseries are suggested (Novikova et al., 1998; Treshkin et al., 1998). It has to be noted that the present environmental conditions - the low ground water level and the progressive salinization of the soils - will make a restoration of tugai forests difficult (Kuzmina and Treshkin, 1997).

4.5 *P. euphratica* as representative species

The woody tugai vegetation of the Amudarya delta is classified into five formations (*Populeta euphraticae, Populeta pruinosae, Saliceta songaricae, Eleagneta angustifoliae, Eleagneta turcomanicae*), each named after its dominating tree species (Novikova et al., 1998). The most representative of the tugai formations is that of *P. euphratica*. It comprises the highest number of epi-associations and occupies by far the biggest territory (Treshkin, 2001b). Furthermore, the formation of *P. euphratica* contains the highest number of characteristic tugai species and has been revealed as the most valuable and prospective of the forest formations for preservation (Novikova et al., 1998). Therefore, its dominant species, *P. euphratica*, is chosen as representative species for the woody tugai vegetation. The habitat suitability assessment will be carried out for *P. euphratica*, bearing in mind its indicator function as representative for the entire woody tugai vegetation. It is assumed that the environmental conditions are favourable for tugai forest in general, provided they are suitable for establishment or growth of *P. euphratica*.

Figure 4.3: An old Euphratica poplar (Populus euphratica) at a canal in the Northern Amudarya delta (left) and propagation through root-suckers (right).

4.6 The Euphratica poplar (*P. euphratica*)

The Euphratica poplar (*Populus euphratica* OLIV., syn. *P. diversifolia* SCHRENK, *P. ariana* DODE) (Fig. 4.3) is a deciduous tree which is distributed in a discontinuous area from Northern Africa to China. It is adapted to continental arid and semi-arid climate with high solar radiation, extreme temperatures, high evaporation and low precipitation. It is resistant against frequent sand or dust storms (Han and Weisgerber, 1997). *P. euphratica* forests are found mainly in desert fringes and floodplains of rivers. In the floodplain of the Tarim river north of the Taklamakan desert in China, *P. euphratica* trees form an up to 100 km wide green belt (Han and Weisgerber, 1997), although their occurence is usually limited to a few kilometres width along river reaches or canals.

Like other tugai plants, *P. euphratica* is a light dependent pioneer species and usually establishes on fresh river alluvium. It grows fast in its juvenile phase and the growth rate culminates with 10-15 years (Han and Weisgerber, 1997; Weisgerber and Han, 2001). The life span of the trees seldom exceeds 80 years (Weisgerber and Han, 2001), although single individuals of more than 200 years have been found. Under optimal conditions *P. euphratica* trees can grow up to 30 m, but under poor conditions they stay shrubby and do not exceed 12-15 m (Weisgerber, 1994).

Varying with the regional climate, the growing period lasts from March or April to June or July (Liphschitz and Waisel, 1970), the trees flower in April or May and seed ripening starts in July, August, or September (Weisgerber, 1994) coinciding with the timing of the natural high waters of the rivers caused by snow melting. This way the floatable seeds can be transported long distances by the water without loosing their germination ability (Han and Weisgerber, 1997). Additionally to generative reproduction *Populus euphratica* shows a high potential to propagate through root-suckers (Fig. 4.3) (Weisgerber, 1994).

Generally, the very flexible root system of *P. euphratica* does not reach great depths (Han and Weisgerber, 1997), but under extreme arid conditions rooting depths of up 14 m (Weisgerber, 1994) and 23 m (Thomas, pers. comm.) were measured. In the latter cases it is assumed that the ground water slowly sank or the trees slowly grew higher with growing sand dunes. During the first years the root growth is favoured compared to the sprout. 6-8 cm high one-year-old seedlings are reported to have a root length of 20 cm (Weisgerber, 1994).

P. euphratica often is the only tree species growing in a region and natural forests, as well as artificial plantations are used as wind breakers to protect agricultural fields from sand drift, and from wind erosion by sand and dust storms. Without this protection huge areas of arable land would be lost to the desert. The trees are planted as natural drainage (because of their high transpiration) around irrigated fields to prevent the critical rise of the ground water level. The wood and the leaves of the trees are used for construction and pasture, respectively.

Summarizing its biological characteristics and economic, as well as ecological value Weisgerber and Han (2001) are convinced that *P. euphratica*, among other poplar species, “will be of considerable importance in the future for breeding and cultivation because of their quantitative and qualitative growth potential and also for ecological reasons.”

Chapter 5

Habitat variables

From a literature review, collected expert knowledge, and many interviews with biologists and geobotanists a list of potentially important environmental variables was compiled, that affect the habitat suitability of a given site for *P. euphratica*. This list consists of

- climate (temperature, precipitation, evaporation)
- geomorphology
- soil type
- ground water level
- flooding frequency
- flooding timing
- flooding duration
- soil salinization
- ground water mineralization
- river water mineralization
- anthropogenic impacts.

These environmental variables act on different spatial and temporal scales. Depending on the time horizon the environmental variables can be classified as static or dynamic variables. Over a period of a few decades, the scope of water management scenarios, geomorphology, soil type, and climate can be regarded as constant. All other factors vary on much shorter time scales. At the spatial scale of the study area only the climate can be considered as uniform.
The mentioned environmental variables are not independent from each other. Some dependencies are depicted in Fig. 5.1 and explained below.

1. The climate acts on a large spatial (regional) and a long time scale. The melting of the glaciers, the precipitation in the area and in the mountains, from where the rivers originate, determine the water availability, the fluctuations of the water level in rivers, the timing and frequency of floodings, and, as a consequence, the ground water level. The high evaporation, together with the chemical composition of the geological layers have an effect on the soil salinity and the mineralization of the river and the ground water.

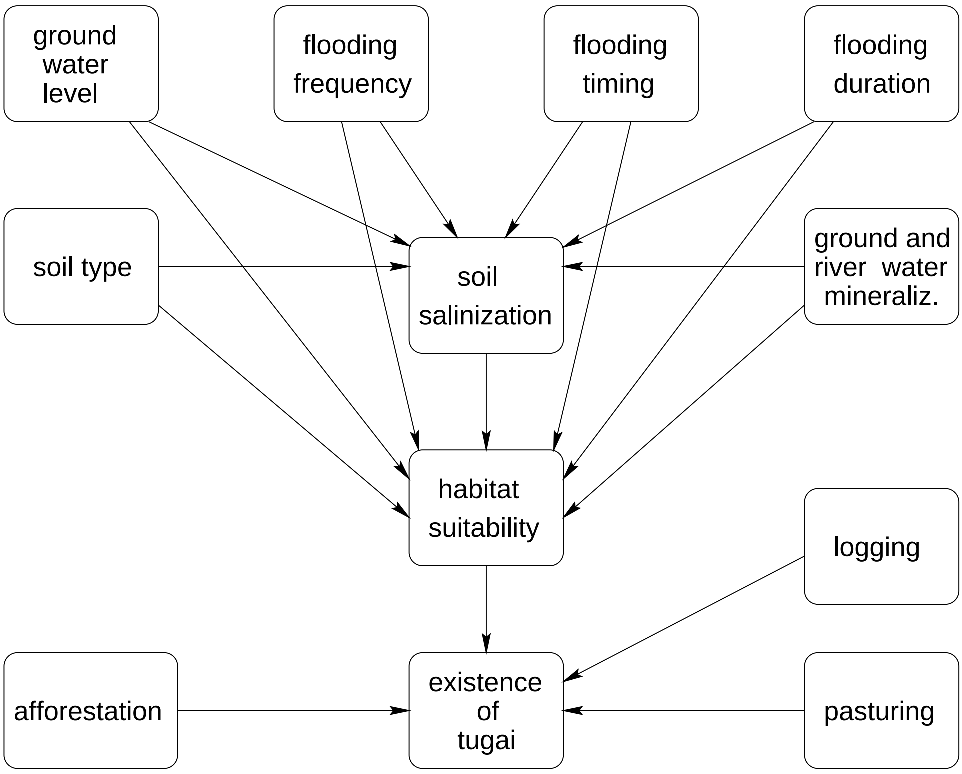


Figure 5.1: Influence diagram of some habitat variables that affect the habitat suitability or the existence of tugai forest on a local scale, as well as their dependencies from each other.

2. The geomorphology integrates some of the mentioned factors. Especially, the soil type is determined by the geomorphology due to deposition of different grain sizes at different locations in the relief. Other variables that are indirectly affected by the geomorphology include the ground water level (distance from surface), flooding frequency, and flooding duration.

3. The ground water level affects soil salinization. If the ground water level is higher than 3 m in loamy soil and 1.5 m in sandy soil, capillary rise of water leads to secondary salinization in the upper soil horizons. It is possible that the vegetation (especially tugai forests) lowers the ground water level during the vegetation period by its high evaporation, and thus reduces the probability of secondary salinization.

4. Depending on the ground water level also the ground water mineralization can influence the soil salinization.

5. Floodings reduce soil salinization, provided the water can drain off. The more often a site is flooded the lower is its soil salt content. The longer a flooding lasts the more salt remains on the surface due to the evaporation of the water. Floodings that take place in spring or autumn are more efficient in reducing the salinization, because of the lower evaporation.

In the following sections the impact of the different environmental variables on the habitat suitability for establishing and adult *P. euphratica* formations is described.

5.1 Climate

The Amudarya delta is situated within the distribution area of *P. euphratica*. The species, as well as the other tugai species, is adapted to the arid climate with high solar radiation, extreme temperatures, very low precipitation and high evaporation. *P. euphratica* tolerates temperature extremes of +40 °C and -40 °C, a mean annual precipitation of less than 50 mm (Han and Weisgerber, 1997). Thus, the present climate within the study area can be considered as suitable, and the climatic variability will be neglected. This decision can be justified with the limited extend of the study area and the high tolerance of *P. euphratica* to climatic features.

5.2 Geomorphology

The geomorphology of the study is classified by the regional experts into five categories: river bars, slopes of river bars, interfluve lowlands, floodlands and terraces, and lake depressions (Novikova, pers. comm.).
Tugai forests are mostly found on river bars or their slopes. But recently, together with the environmental changes, they are also found in dried out river beds. River bars and their slopes are characterized by regular floodings and a good drainage. Floodlands and terraces, as well as interfluve lowlands provide moderately suitable conditions, depending on the specific site.
To the contrary, lake depressions represent a combination of unfavourable conditions for both establishment and growth of tugai forest. In lake depressions usually the ground water level is very high. Together with the predominant clayey soils this leads to high salinization and bad aeration of the soil. Another drawback of lake depressions are the long flooding durations

and the lack of drainage. Therefore, the geomorphology classification is used as an exclusion criterion (or deterministic variable (Store and Kangas, 2001)). Lake depressions are classified as totally unsuitable for establishment and growth of *P. euphratica*.
The geomorphology is an indirect environmental variable which partially integrates other variables, that directly influence the performance of a species (e.g. ground water level, flooding dynamics). The use of indirect variables bears the risk of evaluating one factor several times (e.g. the geomorphology in lake depressions is judged as unsuitable and the duration of floodings is usually high in lake depression, which again has a negative impact on the plants). Additionally, the use of indirect variables diminishes the applicability of the model to other regions (Guisan and Zimmermann, 2000), where the environmental processes might be different and the indirect variable might resemble different conditions. Therefore, the geomorphology is not utilized further (except of the exclusion of lake depressions) for habitat suitability assessment. Instead it is referred to the direct variables such as the ground water level and the flooding dynamics.

5.3 Soil type

P. euphratica can grow on almost every soil type (Novikova, pers. comm.), although it prefers light soils such as sand or silt. It tolerates different values of field capacity[1] and is only moderately demanding for nutrient supply and aeration of the soil (Weisgerber and Han, 2001). At best, the establishment of *P. euphratica* takes place on fertile river alluvium, which is provided by a flooding.
It has been decided that the soil variability within the study area can (should) be neglected. There are two reasons to make this assumption. First, *P. euphratica* is not very demanding for special soil characteristics. And second, the lack of information about the soil parameters in the study area makes it difficult to incorporate the soil type into a habitat suitability index model.

5.4 Ground water level

A crucial environmental parameter for establishing as well as for adult trees is access to ground water. The soil moisture is usually very low so that the plants strongly depend on ground water for their living processes and to compensate the high transpiration losses. Intermediate ground water levels (1.5-5 m) are considered to be the optimum. Very high ground water levels prevent the supply of oxygen to the roots and bear the risk of secondary salinization. Thus, they have a negative impact on the habitat suitability. Very low ground water is hard to access, especially by young plants, and therefore unsuitable.

5.5 Flooding regime

The role that floodings play for adult trees is still doubtful and contradicting observations have been made. In the south-western Caspian Sea region a disruption of the natural flooding regime resulted in a fast degradation of tugai vegetation (Kuzmina and Treshkin, 1997). Thomas et al. (2000) could show that floodings of one or two days did not increase the productivity of the

[1]The field capacity is the maximum amount of water that a soil can retain after gravitational water has drained away.

trees, because the water did not reach the lower soil layers where the fine roots were developed near the ground water fringe. Contradicting to that, short floodings are reported to increase the vitality of tugai forests, as well as the diversity of herb species and the renovation of *Populus* and *Tamarix* by generative reproduction from seeds (Kuzmina and Treshkin, 1997). For longer floodings no experiments have been performed yet. So it is still questionable if flooding frequency and flooding timing have a direct impact on adult trees. On the other hand, the positive effect of floodings on the soil conditions (reduced soil salinization) is obvious.

Contrary to that, the importance of floodings for the establishment of *P. euphratica* seedlings is well known. A basic requirement is a flooding that coincides with the period of seed ripening in July or August. The seeds need wet soil at best during the whole summer to be able to germinate and develop. The seedlings are dependent on sufficient soil moisture during the first years of their life span in order to grow roots which reach the ground water. Under the arid climate conditions a sufficient soil moisture can almost only be achieved by floodings. Thus, it can be stated that a basic requirement for establishment of *P. euphratica* is a flooding at the 'right' time. Additional floodings during the subsequent years can facilitate a successful establishment.

The duration of floodings is also an important parameter. For both, adult and establishing formations, too long flooding durations prevent oxygen supply to the roots, and thus have a negative influence on the habitat suitability.

Treshkin (pers. comm.) states, that under the present environmental conditions (i.e. low ground water level) more frequent floodings are necessary to prevent tugai forests from degradation than under optimal ground water conditions. An evidence for this assumption is the natural reserve “Badai Tugai” south of Nukus, where an old tugai forest area is preserved. There the ground water level is intermediate and the vitality of the community is still high, although the last flood has taken place 20 years ago (Treshkin, pers. comm.).

5.6 Soil salinization

The available knowledge about the tolerance of *P. euphratica* for soil salinization and ground or river water mineralization is contradicting. In contrast to the low soil salinization values that are reported to affect tugai forests in a negative way (Kuzmina and Treshkin (1997), see 4.2), *P. euphratica* is known as a salt tolerant species (Novikova et al., 2001; Weisgerber and Han, 2001). The typical salt content of soils where *P. euphratica* is found is 1 %, but can reach 7 % (Ma et al., 1997). Han and Weisgerber (1997) state that it can grow in soils with 5 % salt content and in soils with a top salt layer of 2-5 cm thickness. Kuzmina and Treshkin (1997) mention that young plants only tolerate soil salinization up to 0.25 %, but adult trees can survive even in soils with up to 16 %. Weisgerber (1994) reports that a salt concentration of 2 % in the soil did not lead to growth inhibition and higher values of 5 % led only to slight inhibition of growth. In the Northern Amudarya delta the highest concentration of soluble salts is often found in a thin crust on top of the soil and the deeper layers contain less than 0.3 % salts (Novikova, 2001). Certainly, the salt tolerance of the trees depends on their age, the distribution of the salts in the soil (the soil content of the layer of the fine roots is the decisive factor), and the composition of different ions (Kuzmina and Treshkin, 1997).

It has been decided, that the soil salinization can be neglected within this work. This is a daring assumption and might cause some ecologists to frown. But there are several reasons that defend the decision not to explicitly consider the soil salinization. Besides the fact that *P. euphratica* seems to be relatively tolerant to soil salinization and the distribution of the salts in the soil is innocuous for adult trees, most of the parameters which affect the soil salt content (i.e. ground water level, flooding frequency, timing and duration, geomorphology) are included in the habitat suitability calculations. That means the soil salinity is indirectly included in the habitat suitability assessment. Another reason is the lack of the necessary parameters (i.e. soil characteristics, water quantities of floodings etc.) to actually calculate the soil salinization.

5.7 Ground and river water mineralization

As the plants vitally depend on the ground water, they also depend on tolerable values of the ground water mineralization, and hence, osmotic stress. There are indications (e.g. high salt content in leaves and xylem sap) that adult trees can tolerate high values of ground water mineralizations, but the exact relationship between water mineralization and vitality of the trees is not yet established. Kuzmina and Treshkin (1997) report that adult trees tolerate 10-16 g/l (1-1.6 %) ground water mineralization.

For young plants irrigation experiments have been performed which led to contradicting results. Ma et al. (1997) concluded, that one-year-old *P. euphratica* seedlings tolerate water mineralization of 1.2 % and soil salinization of 0.7 %. Whereas Liphschitz and Waisel (1970) found, that 0.79 % water mineralization was the upper limit that permitted growth of two-year-old saplings. This contradiction might be due to different durations of the treatments. In the first experiment the irrigation with saline water lasted for 21 days, and in the second experiment the treatment was performed during three months. For this reason it is possible that the soil salinization reached higher values during the second experiment, due to salt accumulation, and influenced the results.

The mineralization of the Amudarya and the major canals of 1-2 g/l, which is equivalent to 0.1-0.2 %, seems to lie within tolerable limits. The ground water mineralization ranges from < 1 g/l (0.1 %) up to > 50 g/l (5 %) (Novikova, pers. comm.). Those high values certainly are an important factor for the habitat suitability. But as there are no area-wide data available, nor assessable, the ground water mineralization has to be ignored in the habitat suitability evaluation. Therefore, it has been decided, that both river and ground water mineralization will be neglected.

5.8 Anthropogenic impacts

Beside the anthropogenically determined flooding regime and ground water level, establishment and growth of *P. euphratica* can be affected by other human impacts. It can be inhibited or prevented by logging, fires, or cattle grazing. On the other hand, it can be enhanced by artificial afforestation. Within the scope of this study it is aimed to assess the potential of a given site to serve as habitat for tugai forests, depending on the hydrological regime. Therefore, anthropogenic impacts (other than the results of water management strategies) are not considered. If a site is chosen for restoration or preservation, steps can be taken to protect it against anthropogenic exploitation.

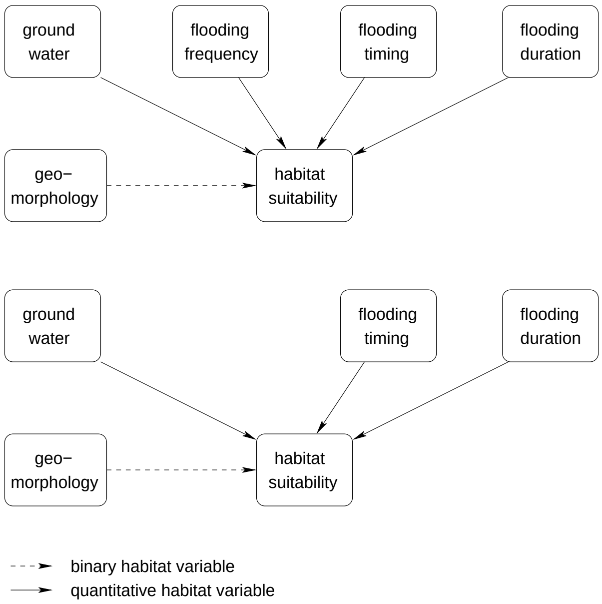


Figure 5.2: Reduced influence diagrams for adult (upper) and establishing (lower) tugai formations.

5.9 Summary

Departing from the described knowledge and the mentioned assumptions the geomorphology, the ground water level, as well as the flooding frequency, timing and duration are selected as important environmental variables that affect the habitat suitability for adult *P. euphratica* formations (Fig. 5.2).

For a successful establishment different requirements have to be met, but the important environmental variables are similar. Except of the flooding frequency, the same variables (i.e. geomorphology, flooding timing, duration and the ground water level) are considered as relevant environmental parameters determining the habitat suitability for establishment (Fig. 5.3). It is assumed that the flooding, which is required for an establishment, at the same time provides suitable soil conditions (e.g. reduces the soil salinization to a tolerable level).

Because of the different requirements of adult and establishing *P. euphratica* individuals it is necessary to evaluate the habitat suitability for both life stages separately.

Chapter 6

Geodata

Data about the selected environmental variables - geomorphology, ground water level, and flooding regime - are provided in the form of GIS-layers (shapefiles in Arcview).

Geomorphology

The geomorphology map (Fig. 6.1) was derived from a map which is available in the Aral Sea GIS (Reimov, Ptichnikov, Novikova, Ressl (1999)) and contains detailed descriptions about the geomorphological site conditions. These descriptions were classified by Schlüter (prep) into the five categories proposed by Novikova (pers. comm.): river bars, slopes of river bar, floodplains and terraces, interfluve lowlands, and lake depressions.

Calculation of the ground water level

The mean annual ground water table heights (Fig. 6.2) were interpolated by Schlüter (in prep.) on the basis of monthly measurements of the ground water level at 25 wells across the northern delta area and runoff values of the Amudarya and major canals for the years 1991-1999. More detailed information can be found in Schlüter (in prep.). As the water level heights in the Amudarya and the major canals are calculated using an estimate of the canal width, which is derived from slightly outdated maps, the results have to be considered as an approximation.

Determination of flooded areas

For the great flood in 1998 three previews of satellite images were available for both May 15 and June 19. The pictures were georeferenced and digitized by hand by Schlüter for each month (Fig. 6.3). It is known that the last flood before 1998 had occurred from June to August in 1978. For the lack of other possibilities it was assumed that the flooded area in 1978 is identical to the maximum extension of the flooded areas in 1998. On the basis of the delineation of the flooded areas the three variables that describe the flooding regime (i.e. flooding frequency, flooding timing, and flooding duration) are calculated (see section 7.3).

Future scenarios

For the development of future water management scenarios both the ground water level and the occurrrence, as well as extension of floodings will be derived from projected runoff data in the

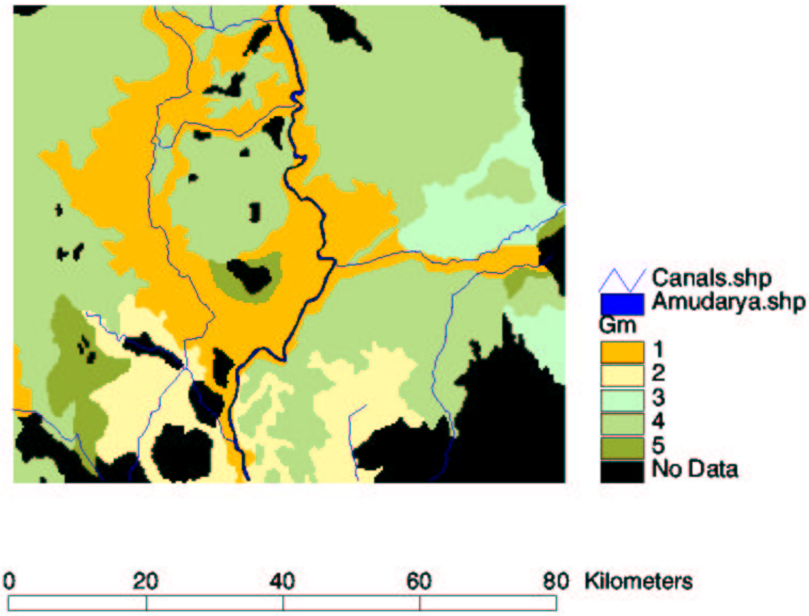


Figure 6.1: The geomorphology of the study area. The categories: 1 - river bars, 2 - slopes of river bar, 3 - floodplains and terraces, 4 - interfluve lowlands, 5 - lake depressions. Source: Aral Sea GIS (Reimov, Ptichnikov, Novikova, Ressl) (1999) classified by Schlüter (see also Schlüter, in prep.).

Amudarya and the main canals using a representative time series of 14 years of water supply to the delta. The ground water data will be provided as mean annual values. Information about floodings will be available in monthly resolution. For details both on the data of the environmental variables for 1991-1999, as well as the development of future management scenarios see Schlüter (in prep.).

Landscape map

For the comparison of the index calculations and the real distribution of woody tugai vegetation a landscape map is used, which was compiled from satellite images from the year 2000 by Novikova and colleagues. The descriptions of the vegetation by the authors were classified into six categories: no, normal adult, degraded adult, establishing, normal adult and establishing, degraded adult and establishing woody tugai. (Fig. 6.4).

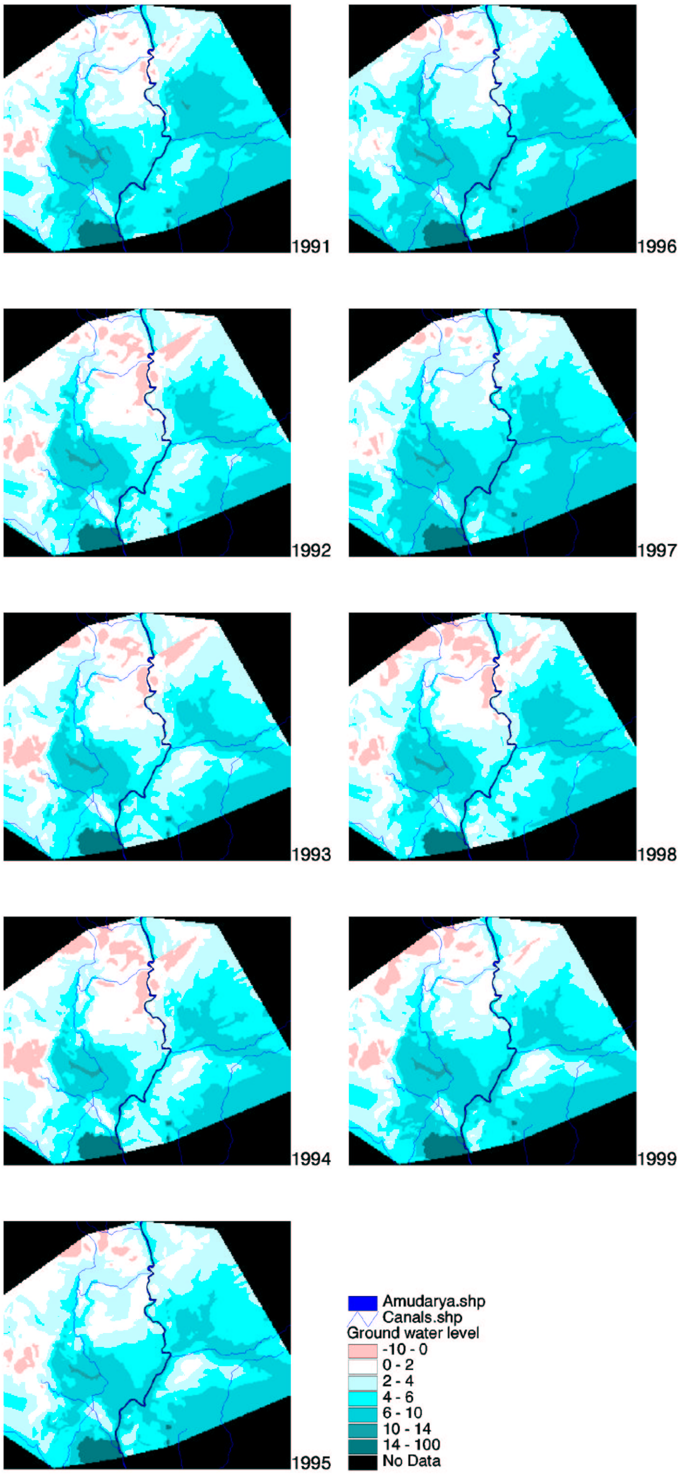


Figure 6.2: Development of the ground water level from 1991-1999. Data interpolated from measurements at 25 wells across the delta area and provided by Schlüter. For details about the interpolation see Schlüter (in prep.).

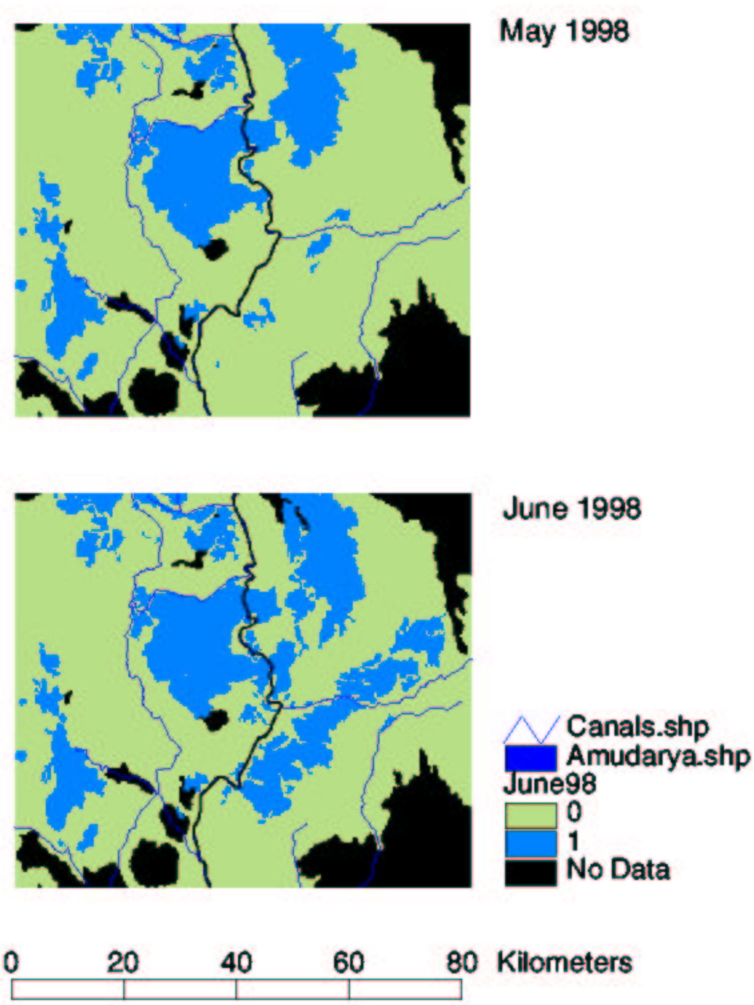


Figure 6.3: Flooded areas during the flood in May (above) and June 1998 (below). 0 - not flooded, 1 - flooded. Data provided by Schlüter.

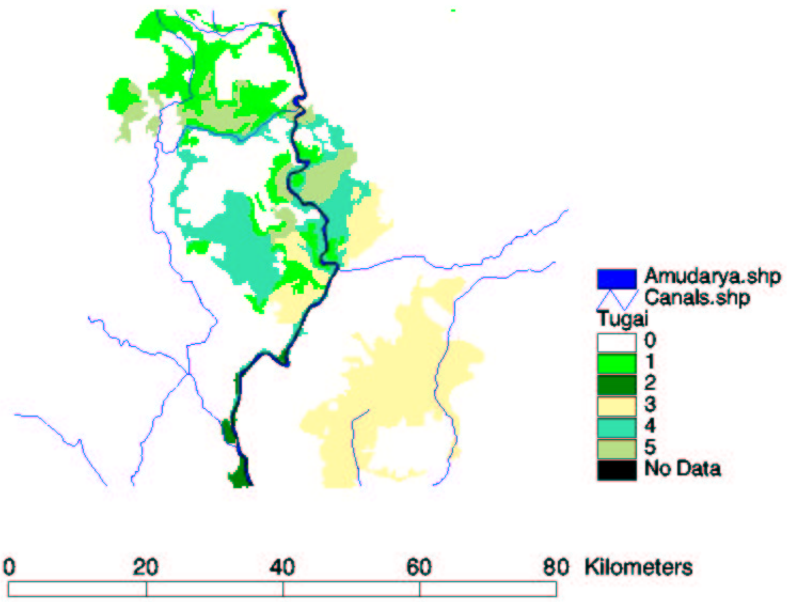


Figure 6.4: Distribution of woody tugai vegetation in the study area compiled from satellite images of 2000. Data provided by Novikova (2002). 0 - no woody tugai vegetation, 1 - establishing, 2 - normal adult, 3 - degraded adult, 4 - normal adult and establishing, 5 - degraded adult and establishing woody tugai vegetation.

Chapter 7

The habitat suitability index model

7.1 General considerations

Expert knowledge

In general, a habitat suitability index (HSI) aims to assess the suitability of a given site for a certain species or community by combining the influence of several environmental variables on the habitat suitability. Therefore, species-environment relationships have to be established on the basis of collected data or experts' assessments. This knowledge has to be structured and formalized to enable an automated evaluation procedure.

In our case, data on species-environment relationships are very scarce, but expert knowledge is available. Schlüter (in prep.) developed a questionnaire and interviewed experts about environmental requirements of establishing and adult tugai forest formations. Three of the experts (N.M. Novikova, Z.V. Kuzmina from the Institute of Water Problems, Russian Academy of Sciences Moscow, and S.Y. Treshkin from the Institute of Bioecology, Karakalpak Branch of the Uzbek Academy of Sciences Nukus) are well acquainted with the local conditions for more than 20 years. Another expert (H. Weisgerber, Germany) is internationally known for his research on *P. euphratica* in China. During many discussions it has been tried to clarify the impact of the environmental variables on the habitat suitability for *P. euphratica*, and tugai forests in general.

Table 7.1: Number of experts' ratings of the suitability of the flooding timing for establishing *P. euphratica* formations. Total number of experts = 2.

month / suitability	high	moderate	low	none
March	1			1
April	1			1
May	1		1	
June		1	1	
July	1	1		
August		1	1	
September			2	
October			1	1
November			1	1

Table 7.2: Number of experts' ratings of the suitability of the ground water level for establishing *P. euphratica* formations. Total number of experts = 2 (0.5-1.5 m classified twice by one expert).

range / suitability	high	moderate	low	none
0-0.5 m	1	1		
0.5-1.5 m	1	2		
1.5-3 m		1		1
3-5 m			1	1
5-15 m				2

Table 7.3: Number of experts' ratings of the suitability of the ground water level for adult *P. euphratica* formations. Total number of experts = 4 (one classification for 0-0.5 m missing).

range / suitability	high	moderate	low	none
0-0.5 m	1			2
0.5-1.5 m	1	1	2	
1.5-3 m	3	1		
3-5 m		2	1	1
5-15 m		1	1	2

Table 7.4: Number of experts' ratings of the suitability of the flooding frequency for adult *P. euphratica* formations. Total number of experts = 2.

range / suitability	high	moderate	low	none
once every 5 years	1			
two or three years in a row every 12 years	1	1		
once every 10 years		1		

Table 7.5: Number of experts' ratings of the suitability of the flooding timing for adult *P. euphratica* formations. Total number of experts = 4.

month / suitability	high	moderate	low	none
March	1			3
April	1		2	1
May	2		1	1
June	2	2		
July	3	1		
August	3	1		
September		2	2	
October			3	1
November			1	3

Table 7.6: Number of experts' ratings of the suitability of the flooding duration for adult *P. euphratica* formations. Total number of experts = 3.

value / suitability	high	moderate	low	none
1 month	3			
2 months	1	2		
3 months		1	2	
4 months			1	2
5 months			1	2
$\geq$6 months				3

Dynamic features

Until now, most HSI models are static and do not take into account changing environmental conditions. But trees have a long longevity and can persist despite adverse environmental conditions for some time. On the other hand, they can also benefit from past advantageous events. For these reasons, an evaluation of the environmental conditions must rely on both, the current conditions, as well as the development of the environmental variables in the past.

An example is the beneficial effect of floodings on the site conditions. The instantaneous consequence of a flooding is a reduction of water stress which leads to a higher vitality of an individual, and possibly, to a higher probability of reproduction through seeds. Other effects last longer. Depending on the soil type the flood water can be stored for some time (up to a few years) in the soil. The most enduring effect is the improvement of the soil due to the accumulation of fresh river alluvium and the reduction of the soil salinization due to the washing out of salts. The frequency by which floodings occur is an important characteristics and has a strong impact on the habitat suitability of the given site for tugai forests. Therefore, a variable (**flooding frequency**) has been constructed that reflects the flooding history of a site (cf. section 7.3).

Spatial scale and time step

The shapefiles of the habitat variables are converted to grids with a cell size of 300 × 300 m. This spatial scale is chosen as a compromise between resolution and computational time and space constraints. For the actual occurrence of tugai forests a finer spatial resolution could be applied, because they are usually limited to several hundred meters up to a few kilometers width along river reaches or channels. On the other hand, the variation of the available geodata is small within 300 m, and our aim is to provide a coarse evaluation of environmental conditions for a relatively large area.
The index calculation will be carried out in time steps of one year. In view of the long life span of the trees and the slow development of the ecosystems this time step seems to be appropriate. However, the monthly information about the flooding regime is crucial and will be represented in two variables (**flooding timing** and **flooding duration**). The dynamics of the ground water level, which is calculated on a monthly basis within the water management scenarios, is neglected. For the dry resistant trees the trend over a longer period is more important. Therefore the annual average is used for the index calculation average.

Again, the aim of the index models is not the prediction of presence or absence of tugai forests, but the evaluation of the environmental conditions as to their suitability for establishment or survival of woody tugai vegetation. The calculated index values can be used for a qualitative comparison of the impact of different water management scenarios on the ecological situation of the delta area.

7.2 Construction of a fuzzy habitat suitability index

In this section the procedure of constructing a fuzzy habitat suitability index is described. For the sake of readability you will find mathematical definitions in Appendix A.

Basic concepts of fuzzy techniques

The basic idea of the fuzzy concept is the extension of binary decisions to gradual statements, either about the membership of an object in a set (fuzzy set theory) or the truth value of a logical expression (fuzzy logic). In contrast to the classical set theory, an element can have a partial membership in a fuzzy set (cf. Appendix A). The membership function $\mu(x)$ assigns an object x of the domain X a real value between zero and one, which expresses the degree of membership of x in the fuzzy set A (Feuring, 1996).
In our case the fuzzy set could be the set of “suitable site conditions”, X could be the depth of the ground water level, and x could be any particular value of the ground water level. Each possible value of the ground water level is assigned a membership in the set of “suitable site conditions”. $\mu(4.5m) = 0.8$ indicates that a ground water level of 4.5 m is suitable, whereas $\mu(11.7m) = 0.2$ indicates a low suitability of a ground water level of 11.7 m.
Using classical set theory it would only be possible to classify a site as either “suitable” or “unsuitable”. Comparative statements, such as “Site A is more suitable than site B” would not be possible. If the threshold between “suitable” and “unsuitable” conditions was 6 m, 5.90 m and 6.10 would be classified differently, although they only differ by 20 cm.

Definition of the categories

The different possible states of a system have to be classified into one or more categories (e.g. suitable vs. unsuitable environmental conditions; no, low, moderate, and high suitability) depending on the resolution that is needed or the kind of results that are desired (Angel et al., 1998). Too many categories are impractical, and too few categories do not allow for a meaningful description of the state of the system. These categories are the underlying fuzzy sets, and a system can have a gradual membership in one or more of them.
In our case the state of the system will be defined only with respect to one category. The one fuzzy set that will be used is the set of “suitable environmental conditions”. A site will only be considered more or less “suitable” for growth or establishment of *P. euphratica*. The outcome will range between 0 (not suitable) and 1 (very suitable).

Choice of informative variables

The chosen input variables should be significant for the studied phenomenon, and they must be available in an appropriate resolution for the purpose (Angel et al., 1998). The variables can be discrete or contiuous. It is possible to assign weights to the variables that reflect the relative importance of the given input variable on the modelled feature. The weights can either be constant or depending on the value of the variable.
In our case the procedure of choosing input variables has been carried out in chapter 5. In the next section (7.3) it will be described how the input variables are derived from the available geodata.

Determination of association rules

For each input variable a function has to be defined, which assigns every possible value a partial membership[1] in each category. Depending on the type of input variable this function (or association rule) can be continuous or discrete. In ecological modelling those association rules are often established on the base of incomplete knowledge and subjective judgements, but they provide the possibility to integrate knowledge from different sources (e.g. observations, experts statements, experiments) and of different kind (qualitative, semi-quantitative, and quantitative) (Angel et al., 1998).
In our case knowledge from all three sources goes into the definition of the membership functions. However, the most important role plays the semi-quantitative expert knowledge collected with the questionnaires.
How the membership functions are defined for the different input variables is described in detail in section 7.4 (establishment) and 7.5 (adult formations).

Combination of the partial memberships

The partial memberships of each input variable have to be combined to an overall membership of the system in each category. The fuzzy theory provides a multitude of operators to combine two or more fuzzy sets. The most popular combination operators in ecological modelling include the minimum, the maximum, the arithmetic mean, the geometric mean, weighted linear combinations and the weighted symmetric sum (Silvert, 1997). The choice of the combination

[1] partial membership = membership in one of the fuzzy sets that describe the possible states of the system

operator should reflect the ecological context (e.g. compensatory effects between favourable and adverse conditions or the special significance of certain values) (Angel et al., 1998). For each purpose (i.e. ecological reality) an appropriate operator can be found, or if not, generated.

Defuzzification

If more than one categroy (i.e. fuzzy set) is used, the outcome of the index calculation are several numbers indicating the degree of membership in each category. However, for statistical analysis or visualization a single score is required. Therefore, a single numerical value should be produced, that is compatible with crisp approaches and can be understood by users or decision makers without reference to fuzzy set theory (Silvert, 2000). The most common method of defuzzification is the weighted linear combination of the memberships in the different fuzzy sets. Defuzzification usually means loss of information, and should therefore only be applied if necessary.
Since the result of the index computation with only one category is a single number between zero and one, no defuzzification is needed. The index value itself can be used for statistical analysis or visualization.

7.3 Description of the variables

In chapter 5 the choice of relevant habitat variables and in chapter 6 the available geodata of these variables were explained. Here the five selected input parameters for the HSI calculation and their derivation from the geodata is described.

Geomorphology - The geomorphology classification into river bars (1), slopes of river bar (2), floodlands and terraces (3), interfluve lowlands (4), and lake depressions (5) as provided by the GIS-map.

Ground water level - The distance of the ground water to the soil's surface in meters as provided by the GIS-map.

Flooding frequency - Floodings do not only have an immediate effect on the ecological conditions of the area by increasing the soil moisture or preventing oxygen supply to the roots of plants. They also have a long term impact, because moisture can be stored by the soil (depending on the soil type) and, even more important, the soil salinization is decreased by the "washing out" of salt. Therefore, the impact of floodings that took place in the past has to be taken into account. The effect of a flooding on the current situation is supposed to be the higher the more recently the flooding occurred. This is simulated as an exponentially decreasing effect with a 'half-life' of five years (Fig. 7.1). Departing from

$$f(x) = e^{-ax},$$

with x being the number of years since the flooding, it follows that the exponent a is 0.14:

$$\frac{1}{2} = e^{-a \cdot 5}$$

$$a = -\frac{ln(\frac{1}{2})}{5}$$

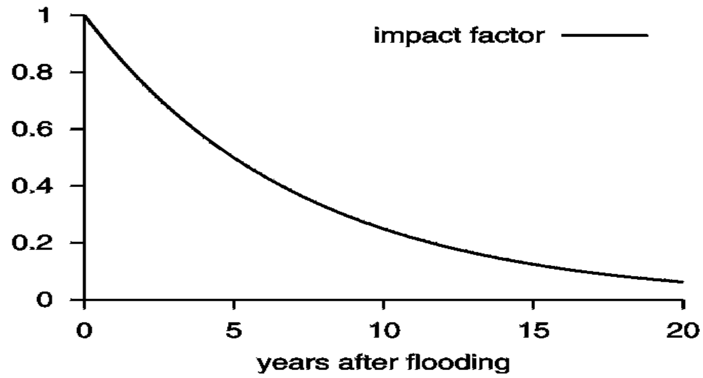


Figure 7.1: Exponential decay of the impact factor of a flooding. $f(x) = e^{-0.14x}$.

$$a = 0.14.$$

f(x) is called the *impact factor* of a flooding. An evaluation of the *impact factor* on the basis of the preceding year is possible as

$$\begin{aligned} f(x+1) &= e^{-0.14(x+1)} \\ &= e^{-0.14} \cdot e^{-0.14 \cdot x} \\ &= 0.87 \cdot f(x). \end{aligned}$$

A flooding, which occurred ten years ago, still has an *impact factor* of 0.25 compared to the *impact factor* of 1 of a current flooding. To capture the overall effect of all floodings that took place at a given site, their *impact factors* are added up and called *flooding frequency*.

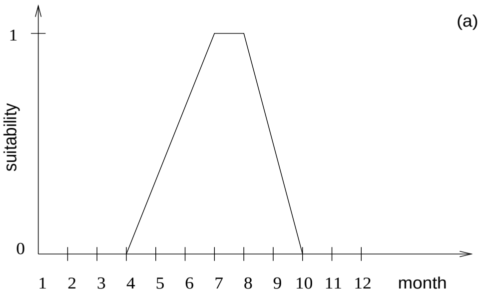
Flooding timing - The month of the beginning of the last flooding that occurred at the site under consideration. The probability of more than one flooding per year is very small. In this case also the begin of the first flooding is assessed. The number of the month (e.g. january = 1) represents the variable flooding timing.

Flooding duration - The duration of the last flooding that occurred at the site under consideration in months. If more than one flooding per year took place the sum of flooded months will be evaluated. Usually, the floodings last from one month at higher positions in the relief up to three months in depressions. Longer flooding durations are rare.

7.4 Establishment

In chapter 5 the geomorphology, the ground water level, and the flooding timing and duration have been identified as the most important habitat variables for an establishment of *P. euphratica*.

Here it is not taken into account that, depending on the ground water level, floodings in the years following a possible establishment can facilitate the survival of the seedlings and their definite



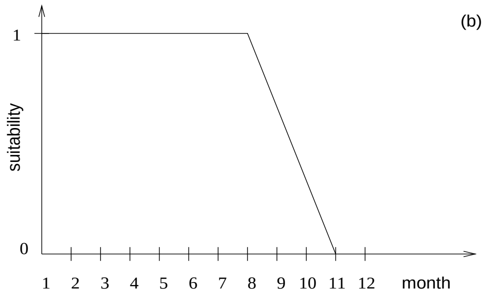


Figure 7.2: Suitability curves of (a) flooding timing and (b) end of the flooding for establishment of *P. euphratica.*

establishment by mitigating water stress and permitting root growth. It is only considered if the basic requirements for an establishment - a flooding at the "right" time of not too long duration and an "accessible" ground water level - are fulfilled and to which degree. In the following sections the definition of the association rules for the single environmental variables, as well as their combination is explained.

Flooding timing

Regarding the suitability of the flooding timing, the "local" experts assign the highest suitability values to the summer months. The German expert ranks the spring floodings higher (Tab. 7.1). But to allow an establishment of *P. euphratica* seedlings a flooding has to coincide with the timing of the seed ripening, which in the Amudarya delta usually happens in July or August. Therefore, July and August are assigned the highest suitability values (Fig. 7.2 (a)). May, June and September are judged less suitable, but still there might be establishment due to increased soil moisture or late availing trees. In the case that, for example, a flooding begins in June and ends in August, the most suitable month (in this case August) is used for the evaluation of the timing of the flooding.

Flooding duration

If a flooding occurs in August and the water remains until November, the germinating seeds have no possibility to establish. To provide optimal conditions, the flooding should end before September. To test this condition, a new variable *flooding ending* is calculated. It is defined as the begin of the flooding (number of month) + duration (in months) -1. An example: If a flooding occurs in July (7) and lasts two moths, the end of the flooding is August (8). If a flooding ends in September or October the remaining part of the vegetation period is shorter. Therefore, the suitability of late flooding endings is lower (Fig. 7.2 (b)).

Ground water level

The experts considered high ground water levels to be best suitable for establishment. Lower ground water levels are considered less suitable (Tab. 7.2). And the very low values are regarded as not suitable at all. These assumptions reflect the fact that establishment will be successful, if the young trees are able to grow roots that reach the ground water before they die of desiccation. In general it can be said, that the higher the ground water level is, the more suitable is the site for establishment.

According to the experts, high ground water levels (0-1 m) are judged as most suitable (Fig. 7.3), and a ground water depth of more than 6 m is classified as not suitable at all. A ground water depth of 6 m has been chosen as the limit of positive suitability values, because Treshkin (2001b) mentions this depth as the limit permitting establishment of tugai communities. In between, a linear decrease of the suitability of the ground water level is assumed.

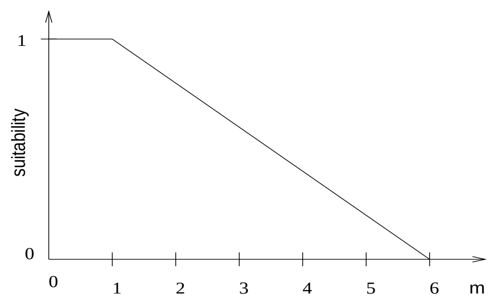


Figure 7.3: Suitability curve of the ground water level for establishment of *P. euphratica*.

Combination

If one of the three conditions is assessed as not suitable at all (suitability=0), the site should be classified as not suitable. Furthermore, the three variables are assumed to be of equal importance and not compensable (i.e. an unsuitable flooding timing or flooding duration cannot be counterbalanced by a suitable ground water level and vice versa). Therefore, the minimum operator is chosen to calculate the overall suitability ($suit_{total}$) of a site for establishment,

$$suit_{total} = min\left\{suit_{ft}, suit_{fd}, suit_{gwl}\right\},$$

with $suit_{ft}$ being the suitability of the flooding timing, $suit_{fd}$ the suitability of the flooding duration, and $suit_{gwl}$ the suitability of the ground water level.

7.5 Adult formations

Additionally to the environmental variables used for the evaluation of the habitat suitability for establishing *P. euphratica* formations the flooding frequency plays an important role for adult trees.

Ground water level

Consistently, the experts consider intermediate ground water levels (1.5-3 m) as highly suitable (Tab. 7.3). With increasing depth of the ground water the suitability decreases. In contrast, there is no agreement about relatively high ground water levels (0-0.5 m and 0.5-1.5 m). It is assumed that the "none"-rankings of the interval between 0 and 0.5 m are a result of the negative influence of the ground water on the soil salinization.
Extreme ground water conditions, such as ground water at or even above the ground, as well as very deep (> 14 m) ground water levels are considered not to be suitable at all. In the first case the oxygen supply to the roots is inhibited, and in the second case the accessibility of the ground

water is very low. 14 m is chosen as the limit of ground water levels that are assigned positive suitability values, although roots of *P. euphratica* have been found up to a depth of 23 m. But such extreme conditions do not permit an enduring preservation of woody tugai vegetation.
In agreement with the experts' statements and the fact that the highest diversity of tugai forests was observed between 2-4 m (Novikova et al., 1998), intermediate ground water levels (2 - 4 m) are assigned the highest suitability values (Fig. 7.4 (a)). From 1.5-5 m the suitability values are higher than 0.7. Higher ground water levels (0 - 2 m) are judged less suitable, because this is an indicator, that the site is a depression, where the soil salinity is usually higher. Under such conditions the competitive strength of *P. euphratica* is usually exceeded by reed (*Phragmites australis*) and cattail (*Typha laxmanii*). Low ground water levels (> 4 m) are increasingly difficult to access by the plants. Hence, the suitability values decrease exponentially with

$$suit_{gwl} = 0.8^{(gwl-4)}, gwl \geq 4m,$$

with *gwl* being the depth of the ground water in meters.

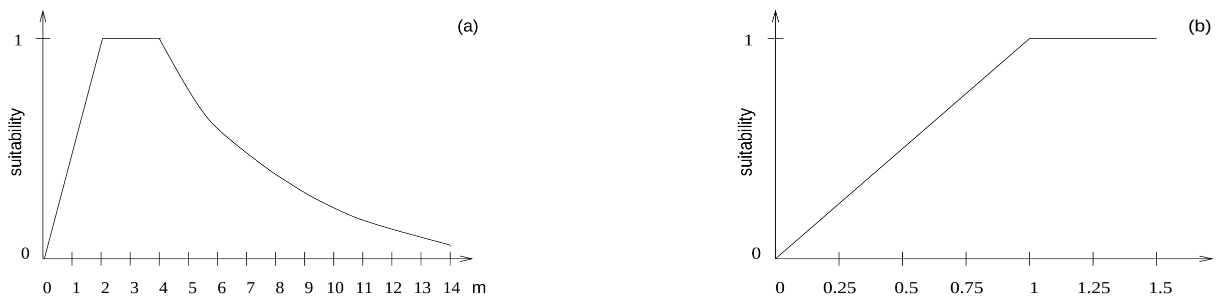


Figure 7.4: Suitability curves of (a) the ground water level and (b) the flooding frequency for adult *P. euphratica* individuals.

Flooding frequency

The more often floodings occur, the higher is the suitability of the site assessed by the experts (Tab. 7.4). There are no studies available on the relationship between flooding frequency and performance of *P. euphratica,* and the judgements of the experts have to be regarded as rough estimations.
One flooding every five years is considered to be sufficient for the preservation of *P. euphratica* stands or tugai communities. Thus, a *flooding frequency* of at least 1 is considered to represent a past that led to suitable soil conditions (Fig. 7.4 (b)). As an example: If 5, 10, 15, and 20 years ago floodings occurred at a site, the corresponding *flooding frequency* is 0.9. To the contrary, one flooding every 20 years (*flooding frequency* = 0.06) seems to be insufficient to preserve the tugai communities from degradation.

Flooding timing

Regarding the suitability of the flooding timing, the same pattern of experts rankings is revealed as for establishing formations. The inconsistencies in the assessment of the suitability of the flooding timing (Tab. 7.5) might be due to the fact that adult forests have been mentally assigned with their juvenile stage. Therefore, the summer months are ranked as highly suitable and spring

and autumn receive less appreciation. After consultation with the experts these estimations have to be considered as obsolete.
For adult *P. euphratica* trees, as well as for the entire tugai community, the positive effect of floodings is based on the washing out of salts from the upper soil layers and an increased soil moisture. These effects are better achieved in spring and autumn, when the evaporation is still relatively low. Therefore, floodings in spring and autumn are assigned higher suitability values than floodings in summer, being April and September the most suitable months (Fig. 7.5 (a)). It is rather unusual that floodings take place in the winter months, because there is no discharge from the mountains and temperatures are so low, that all the remaining water is frozen. But in early spring there can be floodings due to the melting of ice barriers. Those floodings would neither be very beneficial, nor adverse. Therefore, those months have been assigned intermediate suitability values.

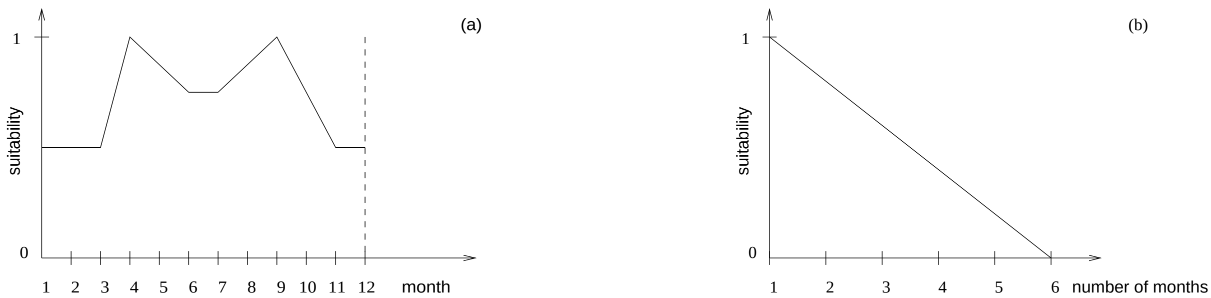


Figure 7.5: Suitability curves of (a) flooding timing and (b) flooding duration for adult *P. euphratica* individuals.

Flooding duration

Regarding the evaluation of the suitability of different flooding durations the experts agreed on the statement: The longer the flooding, the lower its suitability (Tab. 7.6). Floodings of one month are regarded as very suitable, and such of more than five months as not suitable at all. The other flooding durations are ranked in between.
According to these assessments a flooding duration of one month is regarded as the optimum and five months are considered as the limit of tolerable flooding durations (Fig. 7.5 (b)). For intermediate flooding durations the suitability decreases linearly the longer the flooding lasts.

Combination

It has been decided to calculate an overall suitability of the flooding regime, including flooding frequency, timing and duration. The suitability of the flooding frequency is regarded as the most important feature and represents the beneficial effects the floodings would have, if the timing and duration were ideal. The suitability values of the flooding timing and duration are used to lessen the suitability of the flooding frequency, when they are not ideal. To combine the values of flooding timing and duration the geometric mean has been chosen, because it possesses some desired characteristics. First, it fulfills the requirement that if one factor is zero the result will be zero. And second, the result is some kind of an average value of the arguments, very small values having a greater impact. This is a sensible feature, because a low suitability indicates a strong adverse effect on the plant community. Hence, the suitability of the flooding regime is calculated as

$$suit_{flood} = suit_{ff} \cdot \sqrt{suit_{ft} \cdot suit_{fd}},$$

being $suit_{flood}$ the overall suitability of the flooding regime, $suit_{ff}$ the suitability of the flooding frequency, $suit_{ft}$ the suitability of the flooding timing and $suit_{fd}$ the suitability of the flooding duration.
In the combination of the suitability of the ground water level ($suit_{gwl}$) and the flooding regime ($suit_{flood}$) two facts are taken into account. First, the ground water level is the more important variable, and second, the variables can partly compensate each other. A very deep ground water level can partly be compensated by frequent floodings, and tugai forests can endure long periods without floodings, when the ground water level is appropriate. Therefore, a linear combination operator is chosen, giving the ground water level the double weight compared to the flooding regime. The overall suitability ($suit_{total}$) is calculated as

$$suit_{total} = \frac{2 \cdot suit_{gwl} + suit_{flood}}{3}.$$

Chapter 8

Possible extensions

8.1 Additional floodings and establishment

Floodings during the years following a potential initial establishment event can facilitate a successful establishment. By providing water and reducing water stress they decrease seedling mortality and increase the probability that the seedlings can grow roots that reach the ground water.
That means that the environmental conditions have to be evaluated twice in every year when a flooding occurs at the site under consideration. The first evaluation judges the site conditions as prerequisites for an initial establishment. This evaluation is the same like in the base index described in section 7.4. The second evaluation assesses potential positive effects on previous establishment events due to new floodings. This step is described in this section. The maximum of both values is regarded as the current habitat suitability for establishment of *P. euphratica*.

Assessment of the past conditions

If it is desired to take into account the facilitation of a successful establishment by additional floodings the past environmental conditions have to be considered. For this reason an additional variable $suit_{past}$ is introduced, which describes the conditions for establishment during the past years. The shorter the interval between an initial establishment and a new flooding is, the higher is the probability that a high percentage of seedlings has survived and can be supported by the new flooding. Analogically to the impact factor of a flooding (see section 7.3) this is simulated as an exponential decrease with a 'half-life' of two years. This yields an exponent $a = 0.35$ and an annual decay factor of 0.7.
The initial value for the first year after the flood $suit_{past}(1)$ is defined as the result of the evaluation of the initial establishment conditions of the base index of the preceding year. For the following years $suit_{past}$ is calculated as $suit_{past}(x+1) = 0.7 \cdot suit_{past}(x)$, with x being the number of years since the flooding. If six years after the initial establishment event no new flood has taken place, it is assumed that the saplings have either successfully established or died. The variable $suit_{past}$ is then set zero.

Suitability of additional floodings

The important feature of an additional flooding is not the facilitation of germination of seeds, but the mitigation of water stress and the washing out of salts. Therefore, the effect of flooding timing and duration is judged differently than in the base index for establishment. Every flooding that occurs between April and October is judged as very suitable. The other months, when floodings are very unlikely to occur, receive lower suitability values (Fig. 8.1 (a)) . The flooding

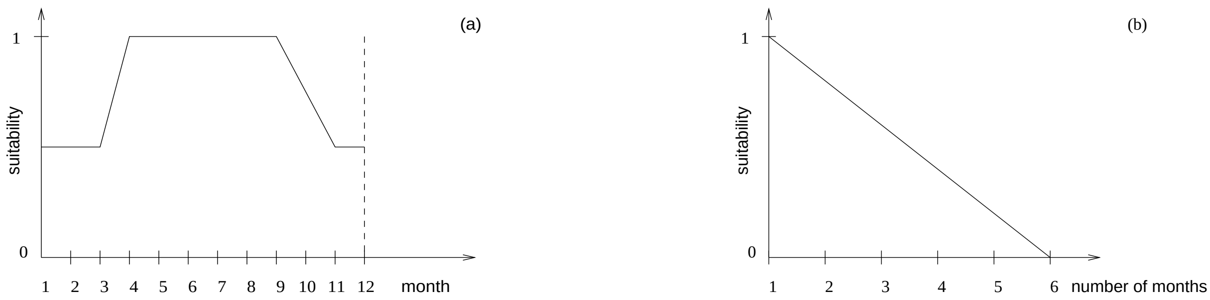


Figure 8.1: Suitability curves for the flooding timing (a) and the flooding duration (b) of an additional flooding.

duration is evaluated like for adult formations in the base index (Fig. 8.1 (b)).
The overall suitability of the flooding ($suit_{flood}$) is calculated as the geometric mean of the suitability of the flooding timing ($suit_{ft}$) and the flooding duration ($suit_{fd}$),

$$suit_{flood} = \sqrt{suit_{ft} \cdot suit_{fd}}.$$

Here the geometric mean is chosen because of the same reasons as mentioned before (section 7.5). If one of the arguments is zero, the suitability of the additional flooding will also be zero, otherwise the result is an average with lower values having a gretaer impact.

Combination

The suitability of the ground water level ($suit_{gwl}$) is assessed like in the base index version (see section 7.4). The calculation of the overall suitability of the site conditions for establishment after an additional flooding ($suit_{add}$) is calculated as

$$suit_{add} = \sqrt{suit_{past} \cdot \sqrt{suit_{gwl} \cdot suit_{flood}}}.$$

In contrast to the evaluation of the environmental conditions as prerequisites for an initial establishment, here not the minimum is chosen as combination operator. Like for adult tugai forest the negative effect of a low ground water level can be compensated by an additional flooding. Therefore, $suit_{gwl}$ and $suit_{flood}$ are combined using again the geometric mean. $suit_{past}$ is regarded as an additional environmental variable that is of equal importance as the current conditions $\sqrt{suit_{gwl} \cdot suit_{flood}}$.

8.2 Interrelation between ground water level and flooding frequency

In the base index for adult formations the interrelation and partial compensation of the flooding frequency and the ground water level is reflected in the choice of the combination operator. Another possibility to explicitly include the dependency of the suitability of the flooding regime from the ground water level is the use of a fuzzy rule-based system. Here, the assumption "The lower the ground water level, the more frequent floodings are necessary." (Treshkin, pers. comm.) can directly be modelled.

A fuzzy rule-based system (also knowledge-based system) works on the basis of linguistic rules of the form IF (A) THEN (B), where A is the premise and B the conclusion (Salski, 1992). In our case A is the description of the site conditions (e.g. "The ground water level is low and the suitability of the flooding regime is high."), and B the classification of the habitat suitability (e.g. "The habitat suitability is moderate."). The resulting linguistic rule reads: If the ground water level is low and the suitability of the flooding regime is high, then the habitat suitability is moderate.

Here "depth of the ground water level", "suitability of the flooding regime", and "habitat suitability" are linguistic variables (cf. Appendix A). A linguistic variable does not take numbers as values but linguistic constructs (Zimmermann, 1993). In this example "low habitat suitability", "moderate habitat suitability", and "high habitat suitability" are the values (terms) of the linguistic variable "habitat suitability". These expressions can be regarded as fuzzy sets, and each state of the system can be assigned a (gradual) membership in them.

Establishment of the fuzzy knowledge-base

The core of fuzzy rule-based modelling is the formulation of linguistic rules which describe the system to be modelled. Normally, these rules are defined by experts based on their experience with the system. The rules should cover the whole range of possible values of the input variables and provide a representation of the system's behaviour, which is as 'correct' as possible (Salski, 1992).

In our case the interrelation of the suitability of the flooding regime and the ground water level is to be modelled. More frequent floodings are needed, when the ground water level is low. It is supposed that unsuitably high or low ground water levels can be compensated by frequent floodings that either reduce the soil salinity or provide water (Treshkin, pers. comm.). At intermediate ground water levels floodings do not play an important role for the habitat suitability for adult trees. In a linguistic way, the dependency can be described as follows:

- If the ground water level is high and the flooding suitability is low, then the habitat suitability is low.
- If the ground water level is high and the flooding suitability is medium, then the habitat suitability is moderate.
- If the ground water level is high and the flooding suitability is high, then the habitat suitability is high.
- If the ground water level is intermediate and the flooding suitability is low, then the habitat suitability is moderate.
- If the ground water level is intermediate and the flooding suitability is medium, then the habitat suitability is high.
- If the ground water level is intermediate and the flooding suitability is high, then the habitat suitability is high.

- If the ground water level is low and the flooding suitability is low, then the habitat suitability is low.
- If the ground water level is low and the flooding suitability is medium, then the habitat suitability is low.
- If the ground water level is low and the flooding suitability is high, then the habitat suitability is moderate.

The assessment of the suitability of the flooding regime is exactly the same as in the base index (see section 7.5). Again, the single suitability values are combined as

$$suit_{flood} = suit_{ff} \cdot \sqrt{suit_{ft} \cdot suit_{fd}}.$$

Fuzzification

To translate the linguistic descriptions into fuzzy rules, the linguistic variables "ground water level" and "flooding suitability" have to be fuzzified (i.e. each crisp value of the input variables has to be assigned the degree of membership to the terms of the linguistic variable).
For the ground water level three fuzzy sets are defined: high, intermediate and low ground water levels. Like in the base index, extreme values of the ground water level (< 0 m or > 14 m) are excluded from the outset as not suitable at all. Ground water levels of < 2 m are classified as partly high and partly intermediate (Fig. 8.2 (a)). From 2 - 4 m the ground water level is assigned complete membership in the set of "intermediate ground water levels". Between 4 and 10 m the degree of membership in the set of "intermediate ground water levels" decreases while the degree of membership in the set of "low ground water levels" increases. From 10 m on the ground water is classified as "low".

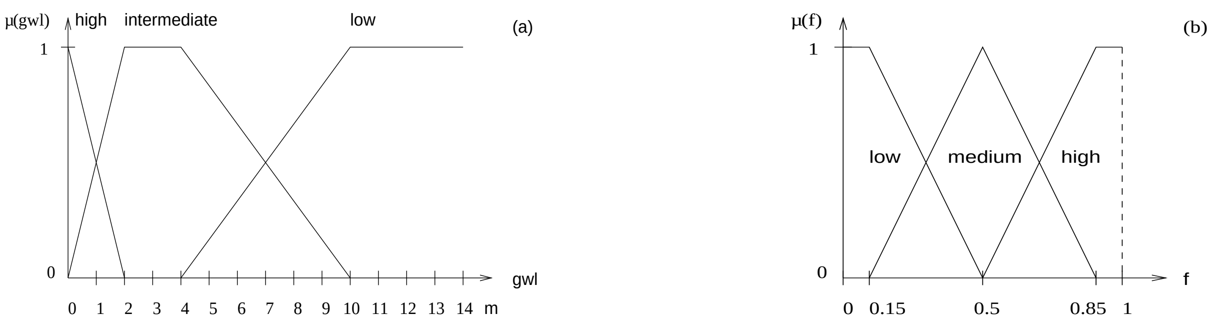


Figure 8.2: Fuzzification of (a) the ground water level (gwl) and (b) the suitability of the flooding regime (f).

Analogically, three fuzzy sets are defined for the suitability of the flooding regime: "high suitability", "medium suitability", and "low suitability" (Fig. 8.2 (b)). It was decided to define the fuzzy sets in a way that they cover almost equal areas. Therefore, the support[1] of the "medium suitability" set ranges from 0.15 to 0.85. The area covered by the "low" and "high suitability" set amounts to 0.325, and the area under the "medium suitability" set is 0.35.

[1] support of a set = range of elements with non-zero membership (cf. Appendix A)

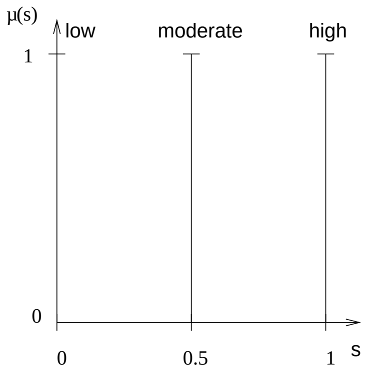


Figure 8.3: Fuzzy sets representing the habitat suitability (s).

Inference

Inference is the fuzzy evaluation of the linguistic rules according to the degree of fulfillment of their premises. It consists of the three steps aggregation, implication, and accumulation (Zimmermann, 1993).

Aggregation - The first step is to determine the degree to which the premise is fulfilled. The premise usually is a conjunction of logical expressions linked by logical operators (e.g. AND, OR). For each of the parts of the premise the degree of fulfillment has to be determined and the results have to be aggregated. For the logical AND and OR relations usually the minimum and maximum operators are used, respectively (Zimmermann, 1993). As the two parts of the premises in our case are linked with the logical AND, the minimum operator is applied to evaluate the degree of the fulfillment of the premise.

Implication - The second step is the so-called implication, which defines the degree to which the respective conclusion applies. In our case all the rules hold with a truth value of one. Therefore, the degree to which a conclusion applies is equal to the degree of fulfillment of its premise (Zimmermann, 1993).

Accumulation - Usually, more than one rule applies and consequently the outcomes of these rules have to be aggregated. If two or more rules yield the same result (i.e. low, moderate or high suitability), but to different degrees, the maximum operator is used to accumulate them.

Defuzzification

The outcome of the fuzzy inference are three values which describe the membership of the system in the fuzzy sets “low”, “moderate” and “high habitat suitability”. For the visualization a single numerical value is required. Therefore, the outcome has to be defuzzified, i.e. to be transformed into a crisp value.

To simplify the defuzzification, the three fuzzy sets representing the possible states of the habitat suitability are defined as singletons. Singletons are fuzzy sets that have one element (Fig. 8.3). The membership of this element is one (cf. Appendix A). Singletons represent the centre of gravity of triangular sets .

Among other defuzzification methods (e.g. Maximum, Mean of Maxima, Median) the Centre of Gravity (COG , also COA = Centre of Area)

$$COG = \frac{\sum x \cdot \mu(x)}{\sum \mu(x)}, x \in X,$$

for finite domains *X*, is one of the most popular. COG is chosen here as defuzzification method because of its robustness to small fluctuations and its computational efficiency. The habitat suitability index *(hsi)* is calculated as

$$hsi = \frac{0 \cdot \mu(moderate) + 0.5 \cdot \mu(moderate) + 1 \cdot \mu(high)}{\mu(low) + \mu(moderate) + \mu(high)}.$$

Chapter 9

Results & Discussion

For the testing of the basic index model and its extensions the period from 1991 to 1999 was chosen. For each year and environmental variable (except for the geomorphology) one grid was produced, which represents the site conditions. Based on these real data an index value was calculated for each year. Tests were performed to obtain a rough estimate of the quality of the results, e.g. a comparison of the index values for 1999 and the actual distribution of woody tugai vegetation provided by the landscape map (see chapter 6).
The base index is called “Index 1” and the second version of the index for adult formations presented in the preceding chapter (section 8.2) is called “Index 2” throughout the following chapters.

9.1 Results of the index models

Results of Index 1 (adult formations)

The results of the index calculation of Index 1 are displayed in Fig. 9.1. From 1991-1997 the index values are relatively low (from 0.0-0.7). Medium values dominate in most areas (green colour), which corresponds to medium or low ground water levels. The flooding frequency is very low everywhere, because the last flood occurred in 1978. It can be seen that the index values strongly depend on the ground water level. Where the ground water level is very high or very low the index value is very low (yellow colour). Only where the geomorphology is classified as “lake depression” or where the ground water level rises above the ground, the result of the index computation is zero. This can be attributed to the fact that the interpolated ground water data do not fall below 14 m, which was considered as the limit of tolerable ground water conditions (cf. Fig. 6.2).
In 1998 a flood occurs and its effect on the habitat suitability index is clearly visible. The flooded areas, where the ground water level did not rise close to the surface, are now judged as highly suitable (red colour). In the non-flooded areas the results do not considerably differ to the preceding years. In 1999 the portion of highly suitable areas even increases due to the fact that the ground water level has lowered in those areas where it had been close to the surface.

Results of Index 2 (adult formations)

Index 2 yields slightly lower suitability values (0.0-0.5) than Index 1 and differentiates less (Fig. 9.2). The main portion of the area is classified as moderatly suitable (green colour) and corresponds strongly to the ground water level. Unlike in Index 1 a value of zero is also reached, where the ground water level falls below 10 m. The impact of the flood in 1998 is also very noticeable. The index values increase up to 1. On non-flooded areas, like in Index 1, the results do not substantially change, compared to the preceding years. Again, in 1999 the index values increase and a big area in the middle of the study area is judged as very suitable, because the ground water level has fallen below 2 m.

Establishment

During the years 1991-1997 no flooding occurs in the study area. Therefore, no establishment is possible until the great flood in 1998. The results of the index calculation for 1998 (Fig. 9.3) vary between zero and one, with a big area in the middle of the study area with highly suitable conditions. In a second area, south-east of the centre, the index values are lower, because of the lower ground water level (cf. Fig. 6.2). Since no flood takes place in 1999, no new establishment is possible in this year.

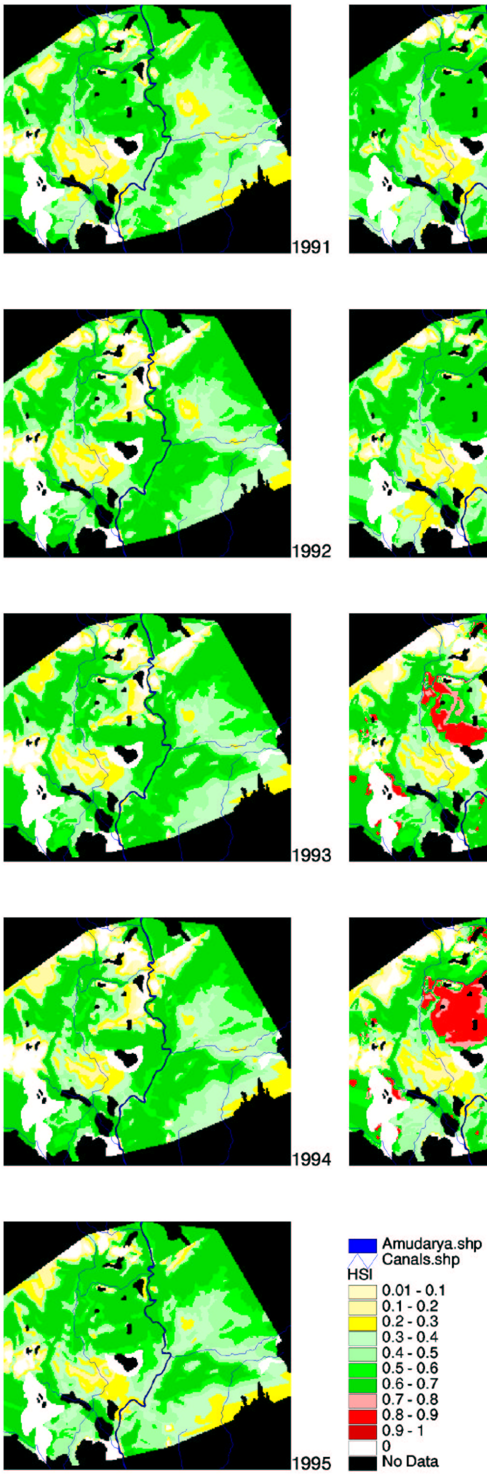


Figure 9.1: Results of Index 1 (adult formations) for the years 1991-1999.

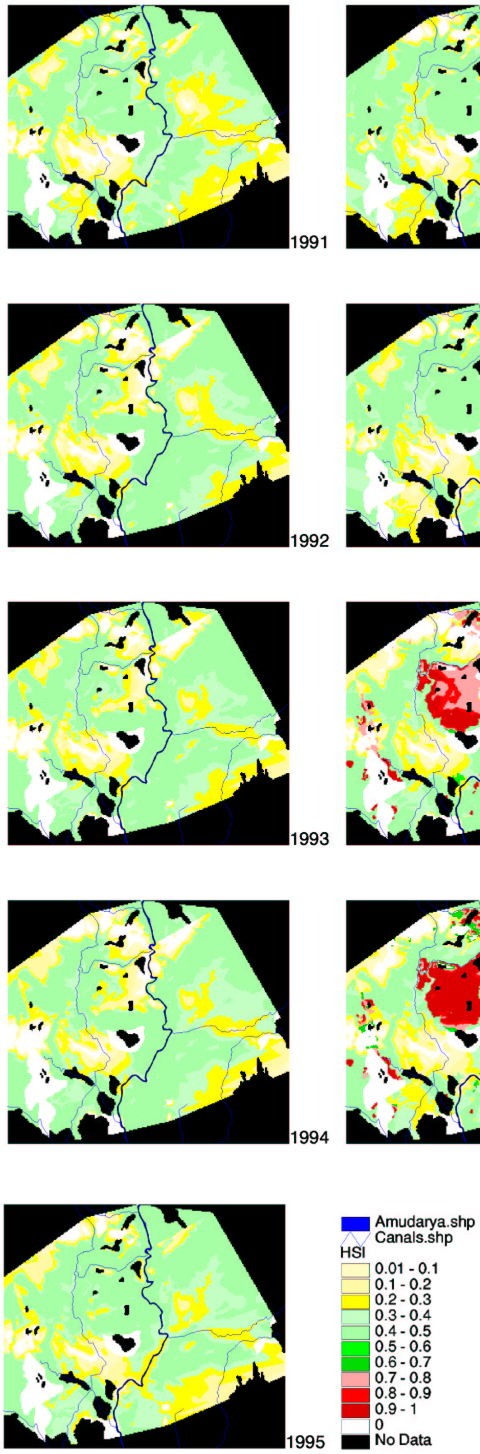


Figure 9.2: Results of Index 2 (adult formations) for the years 1991-1999.

9.2 Comparison and test of the index results

Comparison of low index values and existing tugai vegetation

As the landscape map (compiled from satellite images of 2000 and provided by Novikova and colleagues) also includes the results of anthropogenic impacts, which are not considered in the index models, it can be used only with limitations for an evaluation of the results of the index computation. Where the index models yield good habitat suitability values it cannot be concluded that it is probable to find tugai forests in reality. Forests can be logged or overgrazed, so that they disappear.

But in the opposite direction a comparison should be possible: Where the index models suggest that the environmental conditions are totally or very unsuitable, it can be expected not to find tugai forest in reality. For this comparison both the results of Index 1 and 2 (for adult formations) were evaluated as to the question, where the computed index values fall below 0.3 AND adult tugai forest exists (classes 2-5 of the landscape map) (Fig.9.4).

Both comparisons yield similar results. The index values contradict the reality along some segments of the river, in a lake depression in the centre of the study area, and in a north-eastern part. In the southern part along the river the ground water level is very low, which leads to low index values. Possibly the availability of water near the river is higher, even if the ground water level is low, than in more distant areas. In the centre of the study area the classification of the geomorphology as “lake depression” is the reason for the assessment of the area as “not suitable at all”. The existence of tugai forest at such locations questions the assumption made regarding the lake depressions. It seems that either the resolution of the geomorphology map is not appropriate so as to exactly identify lake depressions, or the assumption does not hold. In the northeast the ground water level is very close to the surface, and hence, the suitability of those areas is judged as low.

The results of Index 2 additionally conflict with the distribution of the woody tugai vegetation in a southeastern part, where the low ground water values determine the low index values. But the vegetation in this area is classified as “degraded” and therefore the index values at least qualitatively correspond to the state of the vegetation.

Summarizing the results of this comparison it can be stated that the results of the index models conflict with the real distribution of the woody tugai vegetation only in small areas.

Comparison of Index 1 and 2 to the landscape map

Another way of using the classifications of the landscape map for an evaluation of the index models is a direct comparison of the states of the vegetation with the calculated index values. For this reason, the states of the adult tugai vegetation were assigned numerical values (no=0, normal=1, and degraded=0.5) which can be compared with the index results. The index values were subtracted from the ’numerical’ landscape map. With this comparison it is not intended to ’validate’ the index models, because of the mentioned difficulties, but to analyze their outcomes. As exemplary years 1991 and 1999 are chosen to compare the results of the index calculation to the landscape map.

In 1991 (Fig. 9.5) the differences between the calculated values and the landscape classification are smaller, due to the fact that the index values are lower. Index 2 judges the center of the study area much less suitable than it seems to be. To the contrary, the same area was assessed in 1999, after the flood, approximatly ’right’.

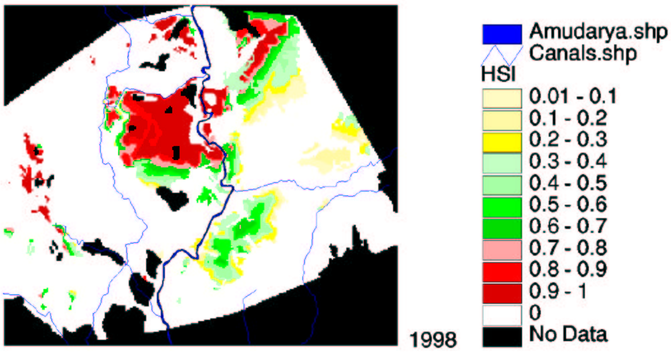


Figure 9.3: Results of Index 1 (establishment) for 1998.

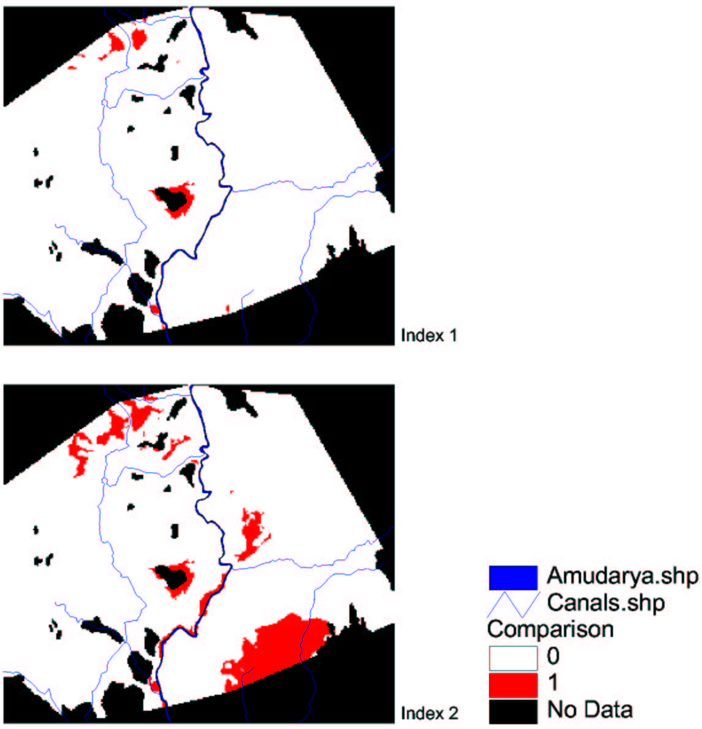


Figure 9.4: Comparison of the index values for 1999 and the real distribution of tugai forests (based on the landscape map (2000)). The red colour indicates areas with index values less than 0.3 and tugai forest.

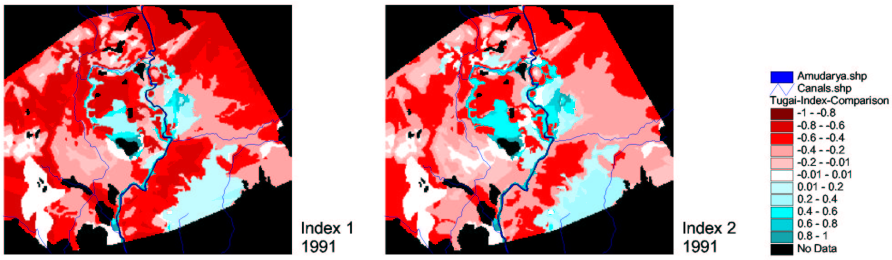


Figure 9.5: Comparison of index values and the landscape map for 1991.

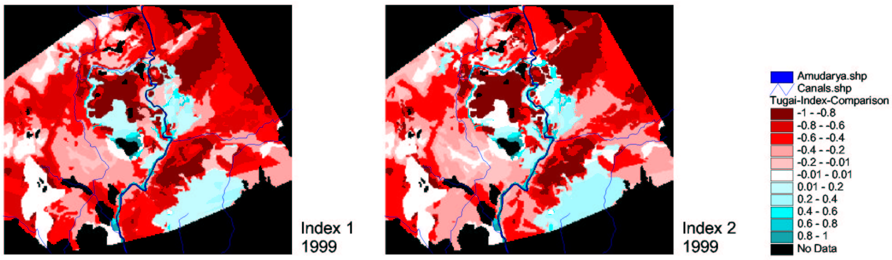


Figure 9.6: Comparison of index values and the landscape map for 1999.

In 1999 (Fig. 9.6) both indices yield intermediate or high results in big areas, where no tugai forest is found, especially in the flooded territories. This indicates that under protection the restoration of tugai forests could be promising. Along the river, in the centre, and the southeast of the study area the classification of the real vegetation exceeds the calculated values. The tugai vegetation in the southeastern area is classified as “degraded”. Therefore, the calculated index values of 0.3-0.5 might reflect the environmental conditions correctly.

Comparison of Index 1 and Index 2

To compare the results of both index models the values of Index 1 (for adult formations) are subtracted from the values of Index 2. In general, they differ only slightly from each other (Fig. 9.7). For the comparison the years 1991 - as a representative year for the years before the flood - and 1999 - the year after the great flood - are chosen.
In 1991 the results of Index 1 are up to 0.4 higher than Index 2 (red colour). Index 1 in general yields higher results than Index 2.
In 1998 again Index 1 judges the non-flooded areas up to 0.2 more suitable than Index 2. Index 2 is more sensitive to the flood than Index 1. It evaluates the flooded areas up to 0.4 more suitable than Index 1 (blue areas).

Comparison of the index scores with the ground water level

It should be presumed that a higher average ground water level in the study area is positively correlated with the development of the average index scores. Table 9.1 shows the development of the average ground water level and the average index scores of Index 1 and 2 (adult formations).
In 1994 the ground water average reaches the highest value of the test period with 3.99 m. Simultaneously, the averages of the index scores fall to their minimum. This can be attributed

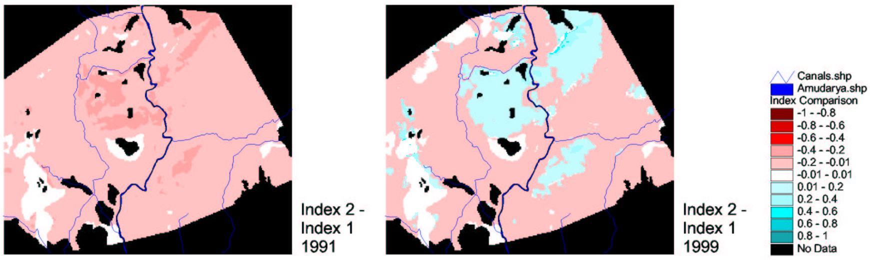


Figure 9.7: Difference between Index 1 and Index 2 (adult formations) for 1991 and 1999.

Table 9.1: Comparison of the development of the index values (averages over the entire study area) and the development of the ground water level (gwl) during the period from 1991-1999.

Year	Gwl in m	Index 1 (adult)	Index 2 (adult)
1991	4.83	0.45	0.33
1992	4.09	0.45	0.34
1993	4.02	0.46	0.34
1994	3.99	0.44	0.33
1995	4.54	0.46	0.34
1996	5.09	0.46	0.34
1997	5.03	0.45	0.33
1998	4.14	0.49	0.45
1999	4.49	0.50	0.45

to the low suitability of high ground water levels and the special sensitivity of the models in this range. The rise of the ground water in a region where it is already close to the surface is judged more critically, than the sinking of the ground water in a region where it is low anyway. In 1995 the lowering of the ground water average is accompanied by an increase of the index scores because of the same reason.

In 1998, the impact of the flood is obvious, both on the ground water average and on the average index scores. The average ground water level rises by almost 1 m to 4.14 m. The index models react to varying degrees to the flood. Index 1 is less sensitive to the improved conditions than Index 2. It increases from 0.45 to 0.49, while Index 2 jumps from 0.33 to 0.45. From 1998 to 1999 the average ground water level falls by 35 cm, which results in a slight increase of the average scores of Index 1. Index 2 does not change.

It can be concluded that the development of the average ground water level is not sufficient to explain the development of the index scores. Positive and negative effects of changing ground water levels even each other out. The impact of the flood is clearly visible. All this together reflects a behaviour of the index models, which was intended.

9.3 Discussion of the results

Range of results

The aim of the index models is a qualitative comparison of the effects of management alternatives among one another, but also of different sites within the study area. It is therefore desirable that the HSI scores take values across the entire spectrum from zero to one (Brooks, 1997). Both index models meet this requirement, ensuring a differentiated assessment of the study area.

Sensitivity analysis

Brooks (1997) suggests that “some form of sensitivity analysis should take place before major field testing or use” of habitat suitability index models. In this work the two index versions can be regarded as ‘some form of sensitivity analysis’. Both indices show the expected behaviour. The index scores are higher where the ground water is intermediate and at recently flooded areas.

Validation

A scientifically sound validation of the index models is not possible, because no human impact free data on the vitality, or another habitat suitability-related variable, are available for tugai forests or *P. euphratica*. As Brooks (1997) mentions, “it is unlikely that models for all species will be subjected to a full range of testing due to limitations in funding and time”. For the future it is desirable to subject the index models to more tests. Natural reserves, like the “Badai Tugai” reserve, could serve as suitable test areas.

Sources of error

A major source of uncertainty of the results are uncertain input data (i.e. data on the environmental conditions). The water level heights in the Amudarya and the major canals, which are used for the interpolation of the ground water data, are calculated using an estimate of the canal width, which is derived from slightly outdated maps. Therefore, the results have to be considered as an approximation. The satellite images, on the basis of which the flooded areas were determined, are snapshots. They only reveal the area, where the water remained for some time, but not the regions, which were inundated for a short time and then fell dry. For the development of future scenarios the situation will be even more uncertain. Both, the ground water level and the area of possible floodings will be predicted from prospective water discharge of the Amudarya and the major canals (Schlüter, in prep.).
Another source of error is uncertain expert knowledge. Expert knowledge reflects the experience of a person with the system of many years. It is mostly acquired in a particular area, and for both reasons subjective. When expert knowledge is used as the main source of knowledge one has to deal with several problems. In our case, one of the problems is the confusion between adult and establishing formations. Some experts ranked the suitability of July and August as flooding timing for adult formations high, because this is the time when seeds are ripe and establishment can take place. They did not take into account that for adult formations floodings in spring or autumn are more suitable due to the lower evaporation. After consultation with the experts this problem could be solved. Another problem are the dependencies between the

environmental variables. Sometimes experts included indirect effects in their judgement (e.g. the negative effect of a high ground water level on the soil salinization).

Resolution

The results of the index models represent a coarse estimation of the habitat suitability of a large area for tugai forests. If a more detailed assessment of a specific region is desired, it is possible to measure the soil parameters (e.g. salinity, particle size distribution) and to refine the index results on their basis. For artificial floodings it will be necessary to calculate the amount of water needed to ensure the survival of seedlings. Those data can only be calculated with the help of soil parameters of the specific site.

Chapter 10

Conclusions & Outlook

Comparison of Index 1 and 2 (for adult formations)

Both index models are developed on the basis of the same knowledge. The only additional feature of Index 2 is the joint evaluation of the ground water level and the suitability of the flooding regime. The incorporation of this additional assumption does not lead to substantially different results for the test period. But the qualitative behaviour is slightly different. Index 2 is more sensitive to floodings and judges low ground water levels more severe than Index 1. If these properties are desired, it is recommended to use Index 2. Otherwise the simpler Index 1 can be used. Since no real validation is possible it cannot be concluded that any of the index models is “better” than the other one.

Subjectivity

Theoretically, an automated definition of the fuzzy sets is possible and often applied (Zimmermann, 1993). To do this, either extensive data or knowledge on the desired outcomes depending on the environmental variables have to be available. This was not the case and the fuzzy sets had to be defined on the basis of the collected expert knowledge. The same applies to the combination operators and the definition of the rule set. On the other hand, this subjectivity gives the possibility to translate subjective expert knowledge into a formal algorithm. The fuzzy approach revealed as very helpful to formalize the available knowledge.

Uncertainty

The applied fuzzy techniques are capable to deal with uncertainty concerning the classification of a given site as suitable or not. But they do not account for the uncertainty of the input data. To account for the problem of uncertain input data the values of the input data could in turn be fuzzified[1]. A new procedure could be developed which processes fuzzy numbers (e.g. by using fuzzy arithmetic). The result of this new index calculation would be a fuzzy number representing the habitat suitability of a given site. Such a fuzzy number would provide more information about the uncertainty of the calculated result, depending on the uncertainty of the input data. In our case a fuzzy approach should be preferred to a probabilistic one, because the uncertainty of the input data cannot be easily estimated. Within this work it has not been possible

[1]The crisp input values can be transformed to fuzzy numbers, which are usually triangular fuzzy sets. The support of the fuzzy set reflects the degree of uncertainty.

to address this problem because of time constraints, but it would be interesting to consider it within future studies.

Loss of information

One can ask the question, why it is reasonable to construct an index that combines the effects of several environmental variables, while it is also possible to evaluate the single environmental variables separately. The advantages of such an aggregated measure are obvious. It is easier to grasp than several numbers or maps and, of course, the aggregation method aims to capture the ecological context, and thus, to provide a meaningful combination of the single environmental variables. That means, the index represents additional information. Nevertheless, every aggregation is accompanied by a loss of information. But in our case it is possible to go back to the original maps of the environmental conditions whenever needed.

Usefulness

An automated procedure, in contrast to an expert, is able to assess the suitability of a large area within a relatively short time. This facilitates the comparative evaluation of many different management scenarios. Due to the simplifications the models had to rely on, their results should always be judged and interpreted by local experts, and can only provide assistance and a rational basis for discussion. The integration of the model and the visualization of the results in a GIS facilitates the application by decision makers. The future has to show to what extent the whole simulation tool, including the index model, will be accepted by local experts and authorities.

Model improvement

The models represent a first attempt to automate the evaluation of the ecological situation in the Northern Amudarya delta under changing environmental conditions. They provide the best possible solution on the basis of the currently available data and knowledge. In future, the models can be refined, when new knowledge or data are available.

For future model refinement it can be suggested to explicitly include environmental variables that describe the salinity, such as soil salinization, ground water or river water mineralization. At the moment a GIS-map containing soil salinization is in preparation. Those additional data should be used to improve the model.

Further on it is recommended to amplify the model incorporating socio-economic features, because the incentive for a preservation or restoration of tugai forests will increase with the economic benefits that can be expected.

At the moment extensive studies regarding the physiology of *P. euphratica* and other desert species are carried out by German, Australian and Chinese scientists in the Tarim Basin in Sinkiang (China) (Thomas et al., 2000). The results of those studies, which also investigate the reaction of *P. euphratica* to short floodings, will hopefully contribute to an improvement of the model.

Integration into GIS-based simulation tool

Within the scope of the INTAS-Project “Restoration and management options for aquatic and Tugai ecosystems in the Northern Amudarya delta region” the index model will be integrated

in a GIS-based simulation tool. Different water management scenarios will be developed and qualitatively compared using the index model (Schlüter, in prep.). The results will be discussed with regional and local experts, and areas will be recommended for preservation or restoration of tugai forests. On those specific sites soil parameters can be measured to facilitate the calculation of concrete amounts of water that are required to preserve or restore healthy tugai forests.
This tool can hopefully support the restoration of tugai forests planned by organisations that are active in the field of environmental protection in Central Asia (e.g. UNDP[2]).

[2]United Nations Development Program

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Appendix A

Definition of fuzzy terms

Definition 1
*A **fuzzy set** A in the domain X is a set of ordered pairs*

$$A = \{(x, \mu_A(x)) \mid x \in X\},$$

where $\mu_A(x)$ *is a function with* $\mu_A(x) : X \to [0,1]$ *indicating the degree of membership of x in A.*
Note: A classical (crisp) set can be regarded as a special case of a fuzzy set, where the membership function (indicator function) can take only values from $\{0,1\}$.

Definition 2
*A **linguistic variable** is a variable with linguistic terms as values. Terms are defined as fuzzy sets on a base variable.*

Definition 3
*The **support** of a fuzzy set A is the crisp set of all points of the domain such that the membership function of A is non-zero.*

Definition 4
*A **singleton** is a fuzzy set whose support is a single point in the domain with a membership function of one.*

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