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A strategic reassessment of fish farming potential in Africa

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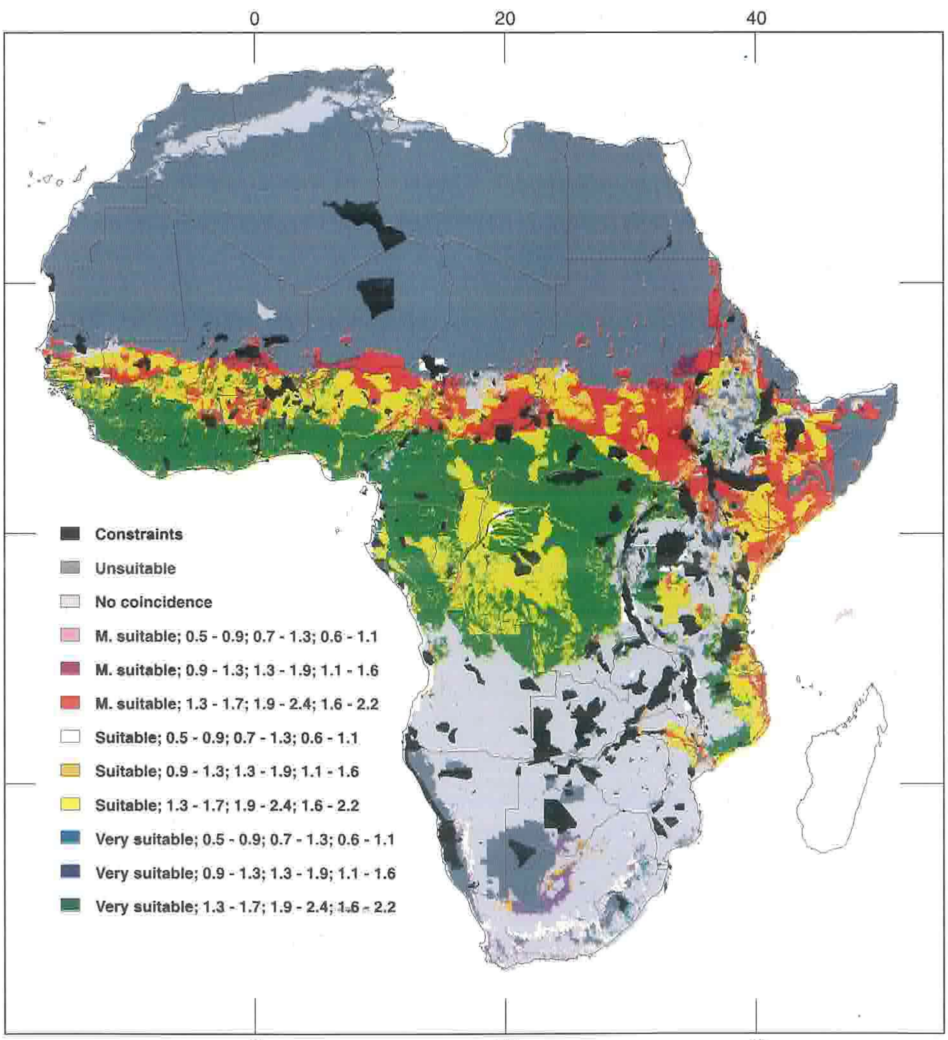

Suitability for small-scale farming and potential yield (crops per year) of Nile tilapia, African catfish and common carp

INTERNATIONAL YEAR OF THE OCEAN 98

Food and Agriculture Organization of the United Nations

A strategic reassessment of fish farming potential in Africa

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PREPARATION OF THIS DOCUMENT

This is the third study that evaluates inland fish farming potential at a continental-level. The study is a follow-up of an earlier assessment of warm-water fish farming potential in Africa by Kapetsky (1994). The overall purpose is to stimulate aquaculture development.

Work began in early January 1997 and the final document was completed just over a year later, by mid March 1998.

Compared with the earlier study, made for Africa, this study is considerably more refined and sophisticated. The most significant refinement was that the new data allowed a sevenfold increase in resolution over that used in the previous Africa study. Sophistication was added by incorporating, for the first time for Africa, a growth model into the GIS to make estimates of yield potential as the number of crops per year possible for three species over the entire African continent.

The present document was made possible through a coincidence of interests. FAO needed to bring up-to-date, the earlier Africa study, to benefit from the most recent and more accurate data available and to make better predictions of fish yield estimations. On the part of the Pond Dynamics/Aquaculture Collaborative Research Support Program (PD/A CRSP) it was an opportunity to enhance existing growth models used in an earlier study of fish farming potential in Latin America by Kapetsky and Nath (1997).

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ABSTRACT

The present study is an update of an earlier assessment of warm-water fish farming potential in Africa, by Kapetsky (1994). The objective of this study was to assess locations and areal expanses that have potential for warm-water and temperate-water fish farming in continental Africa.

The study was based on previous estimates for Africa by the above author, and on estimates of potential for warm-water and temperate-water fish farming in Latin America by Kapetsky and Nath (1997). However, a number of refinements have been made. The most important refinement was that new data allowed a sevenfold increase in resolution over that used in the previous Africa study, and a twofold increase over that of Latin America (i.e. to 3 arc minutes, equivalent to 5 km x 5 km grids at the equator), making the present results more usable in order to assess fish farming potential at the national level.

A geographical information system (GIS) was used to evaluate each grid cell on the basis of several land-quality factors important for fish-farm development and operation regardless of the fish species used. Protected areas, large inland water bodies and major cities were identified as constraint areas, and were excluded from any fish farming development altogether. Small-scale fish farming potential was assessed on the basis of four factors: water requirement from ponds due to evaporation and seepage, soil and terrain suitability for pond construction based on a variety of soil attributes and slopes, availability of livestock wastes and agricultural by-products as feed inputs based on manure and crop potential, and farm-gate sales as a function of population density. For commercial farming, an urban market potential criterion was added based on population size of urban centres and travel time proximity. Both small-scale and commercial models were developed by weighting the above factors using a multi-criteria decision-making procedure.

A bioenergetics model was incorporated into the GIS to predict, for the first time, fish yields across Africa. A gridded water temperature data set was used as input to a bioenergetics model to predict number of crops per year for the following three species: Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*) and Common carp (*Cyprinus carpio*). Similar analytical approaches to those by Kapetsky and Nath (1997) were followed in the yield estimation. However, different specifications were used for small-scale and commercial farming scenarios in order to reflect the types of culture practices found in Africa. Moreover, the fish growth simulation model, documented in Kapetsky and Nath (1997), was refined to enable consideration of feed quality and high fish biomass in ponds.

The small-scale and commercial models derived from the land-quality evaluation were combined with the yield potential of each grid cell for each of the three fish species to show the coincidence of each land-quality suitability class with a range of yield potentials. Finally, the land quality-fish yield potential combinations were put together to show where the fish farming potential coincided for the three fish species.

The results are generally positive. Estimates of the quality of land show that about 23% of continental Africa scored very suitable for both small-scale and commercial fish farming. For the three fish species, 50-76% of Africa's land has the highest yield range potential, and the spatial distribution of this yield is quite similar among the species and farming systems.

However, the spatial distribution of carp culture potential was greater than for Nile tilapia and African catfish. Combining the two farming system models with the favourable yields of the three fish species suggest that over 15% of the continent has land areas with high suitability for pond aquaculture.

The final fish farming potential estimates for the three species together show that about 37% of the African surface contains areas with at least some potential for small-scale farming, and 43% for commercial farming. Moreover, 15% of the same areas have the highest suitability score, and suggest that for small-scale fish farming, from 1.3 to 1.7 crops/y of Nile tilapia, 1.9 to 2.4 crops/y of Africa catfish and 1.6 to 2.2 crops/y of Common carp can be achieved in these areas.

Estimates for commercial farming range from 1.6 to 2.0 crops/y of Nile tilapia, 1.3 to 1.7 crops/y of Africa catfish and 1.2 to 1.5 crops/y of Common carp.

From a country viewpoint, the results are also generally positive. For small-scale farming of the three species, 11 countries scored very suitable in 50% or more of their national area. The corresponding results for commercial farming were that 16 countries scored very suitable in 50% or more of their national area.

Farm location data from Zimbabwe, Kenya, Uganda and Malawi were used to verify the GIS-based predictions of fish farming potential, from the standpoint of the farming system models combined with fish yields. This verification procedure indicated that the models used in the study are in general fairly accurate for strategic planning of aquaculture development.

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ABBREVIATIONS

AGLS	Soil Resources Management and Conservation Service
AGLW	Water Resources, Development and Management Service
AML	Arc Macro Language
AVHRR	Advanced Very High Resolution Radiometer
CIMMYT	International Maize and Wheat Improvement Centre
CR	Consistency ratio
CRES	Center for Resource and Environmental Studies
CRSSA	Center for Remote Sensing and Spatial Analysis
CSIRO	Commonwealth Scientific and Industrial Research Organization
DCW	Digital Chart of the World
DEIA	Division of Environmental Information and Assessment
DEM	Digital Elevation Model
DM	Dry Matter
DSMW	Digital Soil Map of the World
ECMWF	European Center for Medium Range Weather Forecasting
ESRI	Environmental Systems Research Institute
EROS	Earth Resources Observation Systems
ET0	Reference Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FTP	Anonymous File Transfer Protocol
GIS	Geographical Information System
GPS	Global Positioning System
GRID	Global Resource Information Database
GSI	Japan's Geographical Survey Institute
GTOPO30	Global Topography at 30 arc/seconds
GTZ	Deutsche Gesellschaft fur Technische Zusammenarbeit
IIASA	International Institute for Applied System Analyses
ICLARM	International Center for Living Aquatic Resources Management
IGBP	International Geosphere-Biosphere Program
INEGI	Mexico's National Institute for Statistics, Geography and Information
IUCN	International Union for Conservation of Nature and Natural Resources
LA	Latin America
LGP	Length of Growing Period
LUC	Land Use Change Project
MCE	Multi-Criteria Evaluation
MT	Metric tons
NASA	United States National Aeronautics and Space Administration
NCGIA	National Center for Geographic Information and Analysis
PET	Potential evapotranspiration
SSA	sub-Saharan Africa
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
W	Kendall coefficient of concordance
WCM	World Conservation Monitoring Center

1. INTRODUCTION

1.1 Overview and objectives

Overview

With the rapid increase in population and continuing expectations of growth in the standard of living, pressures on natural resources have become intense.

The World Food Summit in Rome, in November 1996 organized by the Food and Agriculture Organization of the United Nations (FAO) endorsed the previously agreed Summit Declaration and Plan of Action for a renewed global commitment to solve the problem of chronic food insecurity causing over 840 million people, mainly in developing countries, to remain undernourished (FAO, 1996a; Fertilizers and Agriculture, 1997).

Africa is an area of the world in which chronic hunger continuous to be widespread. Two hundred and four million people were affected in sub-Saharan Africa (SSA) by malnutrition in 1990. According to the Human Development Report (1996), 22.5 million African children are malnourished. It is estimated that 40 percent of the population of SSA goes hungry, and that the figure will increase by the year 2000 (FAO, 1996b).

Fish are an important source of both food and income to many people in developing countries. In Africa, as much as 5 percent of the population, some 35 million people, depend wholly or partly on the fisheries sector for their livelihood (FAO, 1996c). While capture fisheries based on species that are presently exploited seem to have reached their natural limits (FAO, 1996c), there is considerable potential to expand aquaculture in Africa in order to improve food security (Kapetsky, 1994, 1995; Engle, 1997).

Even though there is potential for fish farming in Africa, very few African countries have a quantified long term or even mid-term national plan (Coche, Haight and Vincke, 1994), it has therefore been difficult to develop production targets for their aquaculture sectors which could be used to set realistic actions and financial commitments. The only two regional assessments that may serve as a guidelines for strategic planning are those by Coche, Haight and Vincke (1994) and Kapetsky (1994).

The present study is based on the development of analytical strategies that could be used to stimulate improved planning for aquaculture development in Africa. This was done by developing Geographical Information System (GIS)-based models aimed to gain a better understanding among siting criteria required for fish farming. This study is built mainly on two GIS studies: the analysis of factors important for aquaculture development and operation (Kapetsky, 1994); and the development of farming system models and fish yield models in Latin America (Kapetsky and Nath, 1997).

Objectives

This study was aimed at stimulating and/or supporting the development of two important planning schemes:

- The development of national level studies which could improve planning in those countries with relatively large potential for fish farming development,
- The development of comprehensive plans for technical and financial assistance by FAO and other national and international organizations, as well as national governments and financing institutions for fish farming development.

1.2 Assessments of aquaculture potential in Africa

The first GIS study that evaluates inland fish farming potential in Africa was that by Kapetsky (1994), who found that 40 out of 49 countries, in the continent have areas with some potential for warm-water fish farming at small-scale and commercial levels. It was estimated that about 31% of the land area in Africa is potentially suitable for warm-water fish farming at a small-scale level, and that about 13% of the land area is suitable for commercial farming. These results clearly indicate that the availability of land area for warm-water fish farming is apparently not a constraint for aquaculture development.

Kapetsky (1995) estimated the potential contribution of African warm-water fish farming to food security by the Year 2000. He found that an increase in pond surface area per farm would provide a significant increase in fish production. Thus, warm-water fish farming could play an increasingly important role in filling the gap between fish supply and demand. Most certainly, it was concluded that, from those few countries where fish farming is already well established, significant contributions could be made to food security by warm-water fish farming by the Year 2000.

In addition to the above, economic studies for fish farming development in Africa have also proven that fish farming in African can be a good source of income. Findings by (Molnar, Rubagumya and Adjavon (1991) and Engle, Brewster and Hitayezu (1993) showed that fish production in Rwanda represented the main cash crop for over 50% of the group members and private pond holders. Engle, Brewster and Hitayezu (1993) indicate that fish farming provides cash to a family in addition to supplementing the diet of Rwandan farmers. Finally, Engle (1997) used a mathematical programming model to demonstrate how fish can be an important cash crop, even for limited-resource Rwandan farmers.

The above studies thus demonstrate that fish farming can be a viable enterprise for African producers and that gains in economic and food security goals can be achieved at reasonable costs.

1.3 Study justification and enhancements

The motivation for the current study was to provide a more thorough assessment of the potential for inland aquaculture in Africa compared to that provided by Kapetsky (1994) both by building upon the methodological framework developed by Kapetsky and Nath (1997) for Latin America, and by the use of more comprehensive spatial datasets currently available for Africa. Differences between the current study and the previous fish farming GIS effort for Africa (Kapetsky, 1994) are summarized in **Table 1.1**.

Table 1.1 Enhancements to the first African fish-farming study (Kapetsky, 1994). (See page xv for an explanation of the abbreviations used in the table)

SUBJECT	KAPETSKY (1994)	THIS STUDY
Resolution	10 minute grid (18 km x 18 km).	3 minute grid (5 km x 5 km).
Date range of data sources used.	1931 – 1988	1920 - 1997
Factors included in the analysis.	Water temperature (air temperature), water availability (water from rainfall runoff and water from streams and rivers), soils (texture and topography), inputs (LGP), local market demand (population density), and roads.	Water temperature (air temperature and wind velocity), water requirement (precipitation, potential evapotranspiration and seepage), soils (soil type and topography), inputs (manure and crops), farm-gate sales and urban market size (population density) and proximity (roads).
Constraints	Water bodies (main lakes).	Protected areas, water bodies (main lakes), and major cities.
Farming system analyzed	Small-scale and commercial.	Small-scale and commercial.
Farming System Models	Simple. Only farming system models. Factors are not assigned weights for integration of the models.	Complex. Based on experience from Latin America study (Kapetsky and Nath, 1997) and Sinaloa study (Aguilar-Manjarrez, 1996). Fish yield models, farming system models and overall models (fish yield models combined with farming system models). Factors assigned weights for model integration.
Bioenergetics model	Not used	Bioenergetic model adapted from the Latin America study (Kapetsky and Nath, 1997).
Fish species used	Nile tilapia (*Oreochromis niloticus*) and Catfish (*Clarias gariepinus*).	Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*) and Common carp (*Cyprinus carpio*).
Basis of water temperature estimates	Air temperature alone used to estimate water temperature using interpolation and regression. Annual estimate.	Air temperature and annual wind velocity data used as input variables into a simulation model to estimate monthly water temperatures.
Basis of fish yield estimates	Water temperature thresholds for the model species.	Water temperature, food consumption rates, feeding levels, feed composition, fish size, fish biomass and photoperiod.
Water requirement	Based on annual rainfall runoff, and water from perennial streams and rivers.	Function of monthly precipitation, monthly potential evapotranspiration, and seepage.
Soils	Soil texture and topography (slope), based on the FAO-UNESCO Soil Map of Africa at 1:5 million scale (FAO-UNESCO, 1977). Slope thresholds imposed by FAO-UNESCO soil classification.	Soil texture, effective soil depth, gravel and stones %, salinity and pH. Derived from DSMW, CD-ROM (version 3.5, FAO, 1995). Slope thresholds chosen from a 1 km DEM.
Inputs from agricultural by-products.	Crop yield and variety estimated using the LGP.	Inputs estimated by manipulating manure and crop data. Manure availability estimated from livestock data.Cropland areas extracted from a land cover image.
Local market demand	Function of population and the occurrence of fish farms.	Farm-gate sales of population size. Urban market size and proximity based on road conditions and population size respectively.
Road infrastructure (paved and motorable roads)	Important only for commercial fish farming.	Important only for commercial fish farming.

1.4 History of aquaculture in Africa

Although the history of aquaculture is relatively recent in sub-Saharan Africa compared to Asia, it is not new to the majority of the countries. In fact, most known aquaculture systems have been introduced over the last 35 years (FAO Fisheries Department, 1996a; 1996b).

During the 60's, aquaculture development not only stopped but regressed sharply. Most ponds were abandoned because of limited security of land tenures, reluctance of farmers to adopt technology, labor shortages, lack of stocking material, drought and political unrest (Harrison, 1994; Coche, 1994). It is since the late 60's that aquaculture has started to develop again, on more solid basis following the increased technical assistance financed by multilateral and bilateral donors.

To date, aquaculture in Africa is still essentially a rural, secondary and part-time activity taking place in small farms with small freshwater ponds. The continent contributes only 0.2 percent of total global production (FAO Fisheries Department, 1996a). Extensive to semi-intensive cultural systems produce limited fish yields which are mostly consumed directly, bartered or sold locally as cash crop. Almost all fish farming is carried out by rural small-scale operators in small freshwater ponds as a secondary activity to agriculture (Coche, Haight and Vincke, 1994).

Aquaculture development in most African countries has primarily had social objectives such as nutrition improvement in rural areas, generation of supplementary income, diversification of activities and income, and creation of employment especially in rural communities where opportunities for economic activities are limited. Only in recent years has aquaculture also been viewed (only on a relatively small scale) as an activity likely to meet national shortfalls in fish supplies thereby reducing fish imports, as well as a direct source of foreign exchange mainly through the production of high value marine finfish, crustaceans and molluscs.

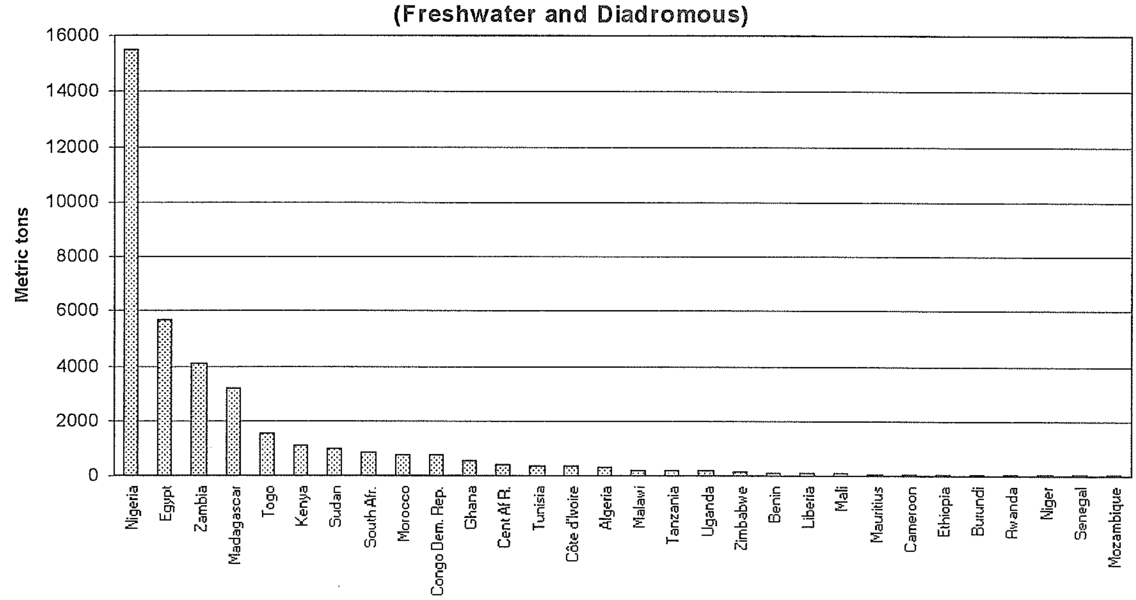
Aquaculture production in Africa has more than doubled during the period of 1985 to 1995, the year of the most recent data (**Figure 1.1**). However, the contribution of aquaculture production in absolute terms is still very small in comparison to that from inland fisheries. In 1995 inland aquaculture amounted to 35,000 tonnes, while mariculture provided less than half this amount (16,000 tonnes). Inland fisheries at 1,990,000 tonnes, exceeded both types of aquaculture by a wide margin.

Figure 1.1 Inland aquaculture, mariculture and inland fisheries production from Africa 1985 - 1995

Source: FAO Fishery Information, Data and Statistics Service (1997).

The major species cultured include finfish (tilapias, catfish, and carp), molluscs and shrimp. Freshwater fish make up over 80 percent of the total aquaculture harvests.Inland aquaculture is dominated by Nigeria (15,489 tonnes) and Egyt (5,645 tonnes) which together accounted for 56% of the total production in 1995 (**Figure 1.2**). There are only 5 additional countries (Zambia, Madagascar, Togo, Kenya and Sudan) that each produce 1,000 tonnes or more.

Figure 1.2 Inland aquaculture production by country in 1995 (Freshwater and Diadromous)



Source: FAO Fishery Information, Data and Statistics Service (1997).

1.5 Planning of aquaculture development

There is a lack of regular aquaculture development planning exercises in most African countries. However, there is a growing recognition of the need for proper planning of the fisheries sector in general and the aquaculture sub-sector in particular (**Text Box 1.1**).

Text Box 1.1 Growing needs for planning of aquaculture development in Africa.

- Need for improving the coordination between research and development as well as for a better system for using research as a support for development;
- Biased appreciation of the development priorities;
- Incomplete correspondence between identified development constraints and research priorities to alleviate these constraints;
- Need for direct access to past and up-to-date information is stressed to guide and support future aquaculture research programmes.

Source: Coche, Haight and Vincke (1994)

In 1983, the FAO Inland Water Resources and Aquaculture Service of the Fishery Resources and Environment Division embarked upon a medium-term programme to collect updated information useful in the preparation of national aquaculture development plans for 12 African countries with the highest potential for aquaculture (Coche, 1994). These 12 national reports are a good source of environmental and socio-economic information. However, they are essentially catalogues of information rather than a set of integrated information that can be used to develop clear policies and strategies for aquaculture development.

The national reports cited above have been assembled into a single document thus making a useful summary of the data collected in the original reports (Coche, 1994). Additionally, the original reports have been also used to develop an indicative plan for aquaculture development and research (Coche, Haight and Vincke, 1994). However, all of these studies could have or may still (i.e. since some data might still be useful if not outdated) benefit from the use of computers, particularly with regard to electronic databases and GIS. The former provide support for storing large and diverse kinds of information, and the latter a powerful mechanism of manipulating and integrating spatial information into a format that can be very useful for decision-making (Meaden and Kapetsky, 1991).

2. METHODOLOGICAL FRAMEWORK

2.1 Overview

The basis of the present study is in many ways similar to traditional studies for assessing aquaculture development (Muir and Kapetsky, 1988; Born, Verdegem and Huisman, 1994). The primary difference is that the use of a GIS in this case greatly enhanced the evaluation. Most certainly, one of the greatest advantages of GIS over manual techniques is the capability to quantify the predicted potential.

This study examines how well sites satisfy criteria for small-scale and commercial fish farming and how well three index fish species (Nile tilapia, *Oreochromis niloticus*; African catfish, *Clarias gariepinus* and Common carp, *Cyprinus carpio*) perform under such farming systems.

Two important limitations were placed on this study to save costs: firstly, only already digitized or computer ready data could be used for the analysis and secondly, field verification was limited to using the location of fish farms in four countries (Zimbabwe Kenya, Uganda, and Malawi). Another limitation was that the data had to be comparable for all countries. Consequently, because the most important gridded data sets for this study(mean monthly daily minimum and maximum air temperature, and mean monthly precipitation) were not available for Madagascar, it was not possible to include this country in the evaluation. Similarly, the main focus of the evaluation is "land-based" due to the dependency of the data available to it.

In overview, there are three major analytical procedures in this study:
a) Criteria score classification, standardization and thresholds;
b) Integration of primary criteria; and
c) Development of the models which manipulate and integrate the selected criteria together.

A summary of the terms and methodology used in this study are summarized in **Table 2.1**.

Table 2.1 A summary of the terminology used in this study.

CONCEPTS	DESCRIPTION
Data	Raw information, statistics, figures, materials.
Surrogate	Data which had been collected and which might appear to have little or no relevance to aquaculture or inland fisheries. Also called "proxy data" (Meaden and Kapetsky, 1991).
Production function	Those factors controlling economic activities have been called production functions since what is produced is a function of various combinations of the controlling factors (Meaden and Kapetsky, 1991).
Criterion	Synonymous to production function. Criteria are of two kinds: factors and constraints (Eastman, 1993; see below).
Factor	Criterion that enhances or detracts from the suitability of a specific alternative for the activity under consideration (Eastman, 1993).
Constraint	Criterion that serves to limit the alternative under consideration (Eastman, 1993).
Primary data	First manipulation and classification of data selected for spatial analysis (Aguilar-Manjarrez, 1992; Ross and Aguilar-Manjarrez, 1993).
Primary criteria	Criteria which have been manipulated and classified for spatial analysis, integration of some criteria into submodels (Aguilar-Manjarrez, 1996), initial stages of the GIS-based models in this study.
Secondary criteria	Renamed primary criteria after initial stages of the GIS-based models (Aguilar-Manjarrez, 1996). Secondary stages of the GIS-based models in this study.

a) Criteria score classification, standardization and thresholds

This first major analytical procedure was carried out by revising the primary spatial datasets for Africa whereby each factor was given a physical score from 1 to 4. Such a classification method was applied throughout this study in order to keep the analysis manageable and to make the results more easily comprehensible and comparable. Specifically, this classification system was used to standardize the different scales upon which raw data were measured.

The scoring levels (1 to 4) were: very suitable (VS), suitable (S), moderately suitable (MS) and unsuitable (US). This classification proved to be appropriate for three main purposes. Firstly, it was found that most raw data were classified within a range of four values. Secondly, such classification matched the FAO classification in terms of suitability of land for defined uses, and thirdly, it is the same methodology that has been used in previous GIS-aquaculture related studies (Kapetsky, 1994; Aguilar-Manjarrez, 1992;1996; Kapetsky and Nath, 1997). The level of suitability interpretation in the current study is similar to that of Kapetsky and Nath (1997), i.e., "the VS level provides a situation in which minimum time or investment is required in order to develop fish farming. For a level classified as S, modest time and investment are required, while if MS, significant interventions may be required before fish farming operations can be conducted. If the suitability level is US, the time or cost, or both, are too great to be worthwhile for fish farming".

In accordance with the suitability classification scheme, ranges of data (or thresholds) that pertain to a desired level of suitability for each criteria had to be selected. The selection of such thresholds involved interpretation of the data selected and such interpretation was guided with literature research (e.g. soils types) and opinions from expert staff at FAO. For example, for the farm-gate sales factor, the range that gives very suitable (VS) market opportunities for farmed fishes in this study, was 150-300 (inhabitants/km^2).

Certain factors shared two different classifications or interpretations. In the present study, factor interpretation was dependent on how these data were assessed, on a type of farming system (i.e. small-scale and commercial fish farming), and how the factor was integrated with other factors to model a particular query.

Constraints were developed as a Boolean map (image containing ones and zeros), and were incorporated in terms of the physical space available, meaning that there are many areas in Africa which are already being used for other purposes (for example, it would not be possible to construct fish ponds in large water bodies or in urban centres), and therefore these areas were considered to be constraints. Protected regions comprising areas of conservation, wildlife and additional forest, large inland water bodies and major cities were excluded from the evaluation.

b) Integration of primary criteria

The selected and scored criteria were developed into a series of submodels (Aguilar-Manjarrez, 1992; 1996; Aguilar-Manjarrez and Ross, 1993; 1995a; 1995b) or categories of criteria (Kapetsky, 1994; Kapetsky and Nath, 1997) which logically group certain factors together within a general model. For example, some factors were grouped to form sub-models naturally (e.g. in a FAO soil classification, soil texture and soil type factors were grouped into a submodel called soils), whilst some other factors were grouped into sub-models to enable a better understanding (e.g. precipitation, potential evapotranspiration and seepage were grouped to form a water loss submodel). Mathematical expressions were used to integrate the primary criteria in this study.

c) Development of the models

The third major analytical procedure involved the development and evaluation of the models. In this study, four GIS-based models were developed:

- Farming systems models were developed to estimate the quality of the land for small-scale and commercial fish farming in ponds irrespective of the fish farming system. The model was developed by using a multi-criteria evaluation technique through which five environmental and economic factors were combined.

- A bioenergetics model was used to estimate fish yield potential (in crops/y) for the three index species. Each grid cell was analyzed as to its production potential for the three species under small-scale and commercial farming conditions. The resulting output was exported to the GIS for further analysis and manipulation.

- The farming system models were used with the bioenergetics model to reach a combined evaluation that indicated the coincidence of each land quality suitability class with a range of yield potential.

- The land quality-fish yield outputs were combined together to indicate where fish farming potential coincided for the three species.

Finally, and as an important part of the whole procedure of using a GIS, existing fish farm locations were used to assess the accuracy of the results. A schematic of the analytical procedures used in the study is provided in **Figure 2.1**, which is followed by a brief description of these procedures. Detailed descriptions of the models and GIS procedures are provided in the appendix for readers interested in the methodology used.

A schematic diagram summarizing the steps involved in manipulating, classifying and integrating the data in this study are shown in **Figure 2.1**.

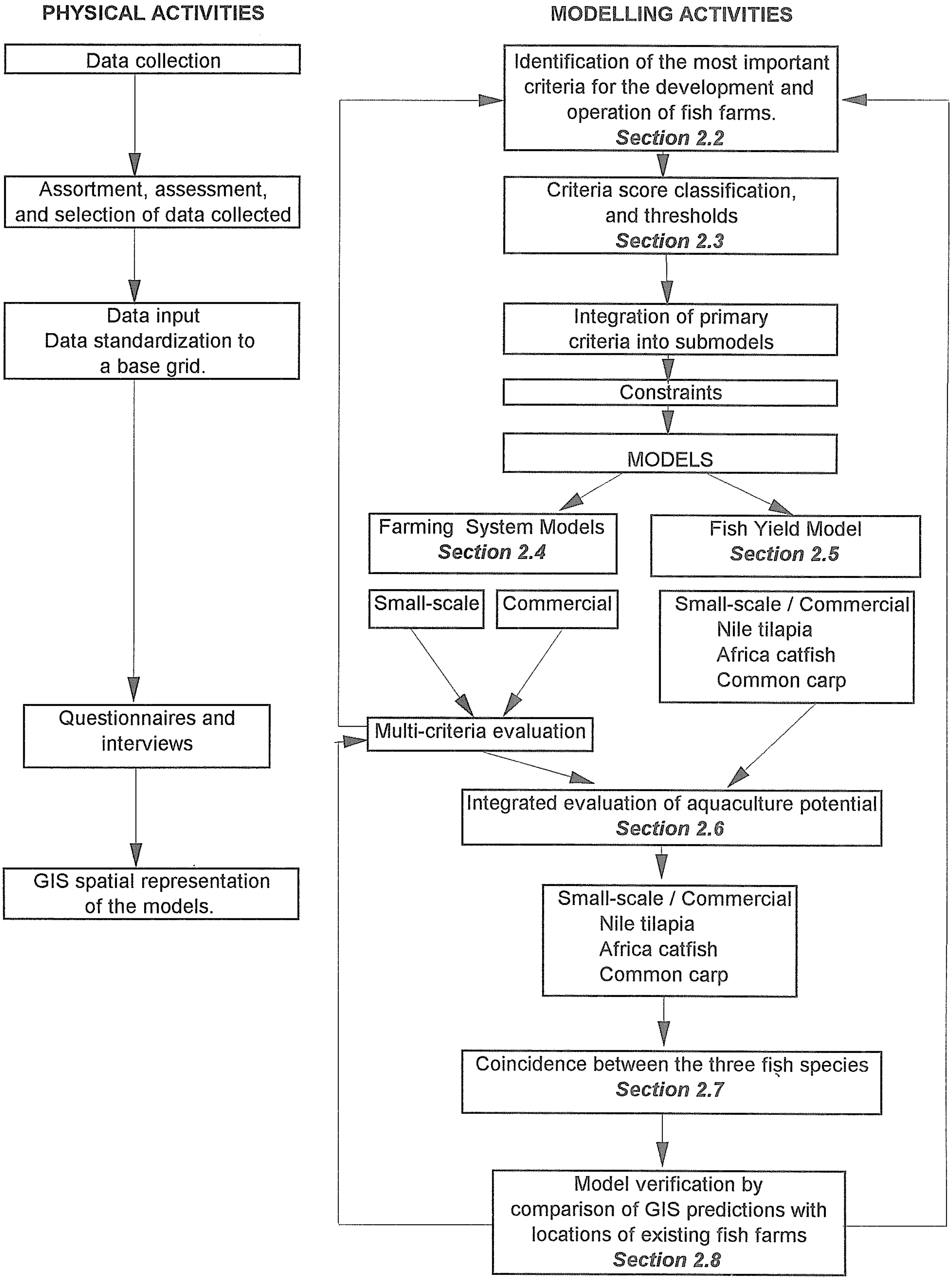


Figure 2.1 Schematic diagram of procedures that were involved in manipulating, classifying and integrating the criteria in this study

2.2 Identification of the most important criteria for the development and operation of fish farms

The selection of factors and constraints involved in a GIS is vitally important because they are the basis of the evaluation. To determine the suitability of locations for fish farming development in this study, it was necessary to establish the factors and constraints in Africa that were essential for the activity. It was also important to investigate whether the necessary data were available.

For clarity, the criteria were grouped into three categories (**Table 2.2**). The first category corresponded to the constraints. The second category was primarily concerned with the factors that assess the quality of the land for small-scale and commercial farming. This category was subdivided into two parts: physical and environmental factors, and land uses and infrastructure. Finally, the third category reviewed factors that dealt with the estimation of fish yields. Details regarding data sources for the various criteria are presented in **Table 2.3.**

Table 2.2 Criteria used to evaluate fish farming potential in Africa.

CATEGORY	CRITERIA	SUBMODELS FOR SMALL-SCALE AND COMMERCIAL FARMING
CONSTRAINTS	Conservation Wildlife reserves Forests Large inland water bodies Major cities	Constraints
FARMING SYSTEM FACTORS PHYSICAL and ENVIRONMENTAL RESOURCES	Precipitation Potential evapotranspiration Seepage	Water requirement
	Soils Slope	Soil and terrain suitability for ponds
LAND USES and INFRASTRUCTURE	Livestock wastes Agricultural by-products	Inputs
	Population density	Farm-gate sales
	Major cities (urban areas based on population density) Roads	Urban market size and proximity[2]
FISH YIELDS[1]	Minimum and maximum air temperatures Mean annual wind velocity	Water temperature

[1] Fish yields were predicted primarily as a function of water temperature, which in turn was estimated on the basis of air temperature and wind velocity data.
[2] Only used in the case of commercial farming potential.

Table 2.3 Sources of data for the African database.

CRITERIA CATEGORY AND ASSOCIATED FACTORS	NAME	DATA SOURCE	LOCATION	DATE	PROJECTION / COVERAGE	CELL SIZE (*minutes*) / FORMAT
CONSTRAINTS						
Protected areas	Protected areas of Africa (conservation, wildlife reserves and forests)	WCMC	United Kingdom	1997	Lat / long	Vector
Water bodies	Perennial inland water bodies	DCW	USA	1992	Lat / long	Vector
Major cities	Major cities	ARCWORLD - ESRI (Beta version)	USA	1992	Lat/long World	Vector
FARMING SYSTEM MODELS						
PHYSICAL & ENVIRONMENTAL RESOURCES						
Precipitation [mm]	Mean monthly precipitation	CRES	Australia	1995	Lat / long Africa	3 'x 3' ASCII
Potential evapotranspiration [mm]	Monthly potential evapotranspiration	IIASA	Austria	1997	Lat / long World	30' x 30' Raster
Soils	Digital Soil Map of the World (DSMW) CD-ROM (version 3.5)	FAO	Rome, Italy	1995	Lat / long World	5' x 5' Vector and Raster
Slope (%)	GTOPO 30	USGS-EROS Data Center	Sioux falls, USA.	1996	Lat / long	30 seconds Raster
LAND USES & INFRASTRUCTURE						
Livestock wastes (manure) [animal/km^2]	Cattle, goats, sheep and pigs [animal/km^2]	GlobalArc™ GIS Database. National Center for Atmospheric Research	U.S. Army CERL & CRSSA, Cook College, Rutgers University. USA	1996	Lat / long Africa	4'48" or finer Raster
Agricultural by-products (crops)	Land cover for Africa	USGS-EROS Data Center	Sioux falls USA	1996	Lambert Azimuthal Equal Area.	30 seconds Raster
Farm-gate sales [persons/ km^2]	Population density	NCGIA -ESRI	USA	1992	Lat/lomg World	
Major cities	Major cities with accompanying population classification.	ARCWORLD - ESRI (Beta version)	USA	1992	Lat/long World	Vector
Roads	Road types	ARCWORLD - ESRI	USA	1992	Lat/long World	Vector
FISH GROWTH						
Air temperature [°C]	Mean monthly minimum and maximum values.	CRES	Australia	1995	Lat / long Africa	3 'x 3' ASCII
Wind velocity [m/sec]	Mean annual wind velocity.	FAO/ESRI/UNEP/GRID	Geneva	1986	Lat / long Africa	2' x 2' Raster

2.3 Criteria score, classification and thresholds and integration of primary criteria

In all, five submodels (or categories of criteria) were considered to assess potential for small-scale fish farming:

1. Constraints
2. Water requirements,
3. Soil and terrain suitability,
4. Inputs, and
5. Farm-gate sales.

For commercial farming, an urban market size and proximity submodel was added.

CONSTRAINTS

2.3.1 Constraints

The constraints included in this study were geographical areas that were excluded for any fish farming development altogether, and were represented by the spatial area they occupied, which in turn was dependent upon the cell size used in this study (i.e. 5 km x 5 km). These areas were assigned a score of zero. The constraints were represented as a single submodel by combining all of them together.

Areas unavailable for inland fish farming development included protected areas (i.e. areas of conservation, wildlife reserves and forests), large inland water bodies and major cities, all of which were considered as constraints (see also **Appendix 8.2**).

FACTORS

PHYSICAL AND ENVIRONMENTAL RESOURCES

2.3.2 Water requirements

Water is essential for all forms of aquaculture and is a key factor in determining where aquaculture may develop. However, growing demands for water from an expanding aquaculture industry are resulting in increased competition with other water users for this limited resource (Muir and Beveridge, 1987; Phillips, Beveridge and Clarke, 1991; Nash, 1995).

The distribution of water in Africa represented a major determinant factor in the spatial analysis of this study. Latest predictions by the FAO (1996b) state that: "...by the year 2000, six out of seven East African countries and all five North African countries bordering the Mediterranean will face acute water shortages".

Water for levee and contour ponds may originate from several sources: precipitation, runoff, pumped or gravity water from perennial water bodies such as streams, rivers, lakes and reservoirs and pumped groundwater. However, to our knowledge, the data for these potential water sources are not available in a format that can be used to assess water requirements for a continental-level study of fish farming potential such as this one. An alternative approach (Kapetsky and Nath, 1997) with minor revisions was therefore used in the current study. This refined approach is summarized below.

Precipitation is considered the main source of water for small-scale fish farming. Other water resources such as perennial streams and rivers would exceed the economic

limitations associated with small-scale farming. Kapetsky (1994) estimated water availability for small-scale farming in Africa on the basis of annual rainfall. However, rainfall in Africa is variable throughout the year (Nicholson, 1981; Lamb, 1982; Nicholson, Kim and Hoopingarner, 1988; Encyclopaedia Britannica, 1993; Gommes and Petrassi, 1994), so it is difficult to know which areas would not have sufficient water during the dry months of the year. Therefore, for this study, an estimation of monthly net water requirement from ponds was used. The main objective of the water requirement estimation was to balance inputs from precipitation against losses due to evaporation and seepage from levee ponds.

The investigation is based on a study described in an internal FAO report (FAO Water Resources, Develoment and Management Service (AGLW), 1996). This approach has a three advantages. Firstly, with this method it was possible to identify critical areas, or periods of the year, in which there would be a water deficit. Secondly, the approach indicates the amount of water that would have to be supplied in order to keep the ponds full without pre-determining the source of water and thirdly, water requirement is estimated in centimetres and therefore no assumption about the area of the pond was necessary.

In comparison to the Latin America study (Kapetsky and Nath, 1997), this study did not use evaporation; instead, it used potential evapotranspiration estimates obtained from IIASA. These estimates are based on the Penman-Monteith method, which is the most widely accepted formula and yields errors below 10%. Reference evapotranspiration (ET0) is by definition the rate of evapotranspiration from an extended surface of an 8 - 15 cm tall green grass cover, actually growing, completely shading the ground and not short of water (Doorenbos *et al.* 1986). Methods to calculate ET0 are, among other, the Penman-Monteith method and the Pan Evaporation method. With the latter method, ET0 is estimated from the open water evaporation of an evaporation pan (which is a small pond). Typically, ET0 is calculated by multiplying the open water pan evaporation by a factor ("pan coefficient") of 0.75 (Table 17, *In*: Doorenbos *et al.* 1986). With the Penman-Monteith method, open water evaporation is to be estimated from ET0. For the current study, we multiplied ET0 estimated by the Penman-Monteith method by the reciprocal value of 0.75, i.e., 1.3 (J. Hoogeveen, pers. comm.). The latter value is higher than the factor of 1.15 used by Kapetsky and Nath (1997), but is expected to provide a better estimate of evaporative water requirement from shallow fish ponds. Data sources and procedures used for the water requirement submodel are briefly discussed below. Complete details are available in **Appendix 8.3**.

Precipitation

Mean monthly gridded values for precipitation created by CRES at the Australian National University were obtained in the form of ASCII files. The procedure to import these files into Arc/Info is similar to the one described for the air temperature data (see **Appendix 8.3**).

Potential evapotranspiration

GRID files containing monthly potential evapotranspiration values according to Penman-Monteith method for the whole world in ARC/INFO format were obtained from IIASA.

Seepage

Seepage can be one of the most important causes of water requirement from a pond (Yoo and Boyd, 1994). However, the amount of seepage will depend on the soil composition and on the structure of the pond bottom (Coche and Van der Wal, 1981). For example, if the composition of the soil is coarse, as in sandy soils, a great amount of water will be lost by seepage. To account for the importance of the water requirement and the uncertainty of the soil type, a trade-off was established by selecting a conservative seepage rate.

The same seepage coefficient used in the Latin America study (Kapetsky and Nath, 1997) was used. This corresponds to a loss of about 100 cm/y or approximately 8 cm/mo which is within the range of ponds that are categorized as having low seepage rates according to Yoo and Boyd (1994) (**Text Box 2.1**).

Text Box 2.1 Categories of monthly and annual seepage rates.

CATEGORY	RATES	
	cm/mo	**cm/y**
Low	0 - 14.7	0 - 176
Moderate	14.8 - 30.1	177- 362
High	30.2 - 45.6	363 - 546
Extreme	> 45.6	> 546

Source: Modified from Yoo and Boyd (1994).

Integrating the water requirement submodel

Water requirement for each month was estimated by using the following formula:

Water requirement = (Precipitation [mm] x 1.1) - (Potential evapotranspiration [mm] x 1.3) - Seepage ([8.0 cm/mo]).

In the above equation, the coefficient 1.1 accounts for the runoff from the pond side that is in excess of the rainfall that falls directly into the pond and 1.3 compensates for the higher evaporation from free surfaces such as small open ponds.

Using this approach, areas with two dry seasons could present a problem because the apparent net annual water requirement would be greater than either of the dry season losses. To evaluate the existence of two dry seasons a set of sample points was defined. These points were chosen to be at about 5° x 5° distance to sample the monthly estimates. Four areas of this type were found at 0° S and N, 10° W; 5° S, 15° W and 10° S, 20° W.

As the situation of two seasonal negative minima occurred in a localized area (close to the equator), it was reasoned that the effect is minor in a continental-level study of this type.

In order to estimate the total amount of water required for ponds during the dry season, the net annual water requirement was computed using the water budget equation above for each grid cell. Estimated water requirement was then divided into 4 equal-interval suitability classes which are presented in **Text Box 2.2**.

Text Box 2.2 Water requirement submodel.

VALUE [mm]	INTERPRETATION	SCORE
> 0	Very suitable as a water source for ponds.	4
-2,000 to -1	Moderately suitable for ponds and costs for deeper ponds.	3
-2,000 to -3,500	Very likely to encounter water availability problems and construction costs for deeper ponds.	2
< -3500	Unsuitable many problems problems to fill ponds. High costs for constructing deeper ponds.	1

2.3.3 Soil and terrain suitability for fish ponds

According to Yoo and Boyd (1994), soil properties most common to fish pond construction are: slope, texture, organic matter content and sulphide content. To evaluate the engineering capability for the construction of ponds two criteria, soils and slopes, were used as discussed below (see also **Appendix 8.4**).

Soils

The assessment and use of soils is a very important aspect of aquaculture site selection, development and management. This is particularly the case in pond farms, where soil quality has a great influence on construction and maintenance costs, and on productivity. It is also important in selecting sites and developing designs for ancillary components such as water supply channels. Excessive seepage often results from improper site selection, therefore soil properties should be clearly investigated and identified during site selection (Coche and Laughlin, 1985; Yoo and Boyd, 1994).

Suitable areas for the construction of ponds in Africa have been identified by Kapetsky (1994) on the basis of soil texture and topography. However, the approach did not take into account the effects of other factors that are also important to the soils evaluation (e.g. effective soil depth, gravel and stones percentages, salinity and pH). The FAO Land and Water Development Division (AGLS) have developed a Digital Soil Map of the World (DSMW) CD-ROM (version 3.5, FAO,1995) based on the FAO-UNESCO Soil Map of the World that enables the interpretation, extraction and manipulation of all of these factors on soils, and therefore a much more accurate account of soil suitability for fish pond construction in Africa.

The objectives of this soils investigation were to:

- identify the soils and terrain parameters of the DSMW most relevant to fish pond construction and operation, and
- define thresholds using the class ranges already established for each parameter in the original FAO-UNESCO Soil Map of the World (FAO-UNESCO, 1974).

The appropriate soil and terrain parameters selection, as well as threshold evaluations, were carried out by F. Nachtergaele (FAO-AGLS service).

The soil suitability ratings for fishpond construction were estimated from the soil information contained in the DSMW (FAO, 1995) at 1:5 Million scale, using a parametric approach (Sys, 1980) in which fishpond requirements were derived from limitation ratings elaborated by Hajek and Boyd (1990) as presented in **Table 2.4**:

Table 2.4 Soil limitation ratings for excavated fish ponds.

PROPERTY	Limitation Rating Slight	 Moderate	 Severe	Restrictive feature
Depth to sulfidic or sulfuric layer, ft.	>3	1.5 - 3	1.5	Potential acidity or toxicity.
Thickness of organic soil material, ft.	< 1.5	1.5 - 2.5	>2.5	Seepage; hard to compact.
Lime requirement, tons/acre.	< 2	2 - 10	>10	Mineral acidity.
pH of 1.5- to 2-ft layer of pond bottom.	>5.5	4.5 - 5.5	<4.5	Too acid.
Clay content, %.	>35 Clayey	18 - 35 Loamy	<18 Sandy/silty	Too sandy/silty; excessive seepage.
Depth to water table, ft.	>2.5	1 - 2.5	<2.5	Hard to drain; dilution.
Frequency of flooding[a]	None	Rare/occasio-nal	Common/ frequent	Flooding.
Small stones, %	<50	50 - 75	> 75	Small stones.
Large stones, %.	<25	25-50	>50	Large stones.
Organic matter, %.				
Low clay content soil. (<60% clay)	<4	4 - 12	>12	Excessive hums.
High clay content soil. (>60% clay)	<8	8 - 18	>18	Reducing environment.
Depth to rock, ft.	>5	3 -5	<3	Shallow; seepage.

Source: Hajek and Boyd (1990). Note: The slopes property included in the original table (Hajek and Boyd, 1990) is not presented in Table 2.3 (above) because slopes were evaluated separately in this study.

Note: [a] None: No possibility of flooding. Rare: 0 - 5 times in 100 years. Occasional: 5-10 times in 100 years. Frequent: >50 times in 100 years. Common: occasional and frequent combined.

The following limiting factors were considered: presence of a sulfidic layer, thickness of organic soil material, soil acidity, soil texture, depth and risk of flooding and soil depth.

The results (**Table 2.5**) have been presented as proportions of mapping units as having: only slight limitations (S4), only moderate limitations (S3), one moderate limitation plus a downgrade as given in Table 2.5 footnotes (S2) or one or more severe limitations (S1) for fishpond constructions. Using the FAO-UNESCO legend (FAO-UNESCO,1974) and based on adapted guidelines of Hajek and Boyd (1990) the information presented in **Table 2.5** was derived.

Table 2.5 Soil limitation table for fishpond construction in terms of FAO soil unit characteristics.

	S4	S3	S1
Acid sulfate layer	All other units	Not applicable	Thionic units
Organic layer	All other units	Not applicable	Histosols
Lime requirement	All other units	Ferrasols, Acrisols. Podzols	Not applicable
Clay content	All other units	Sandy topsoil*	Vertisols and vertic units, Dune sands.
Depth to water table	All other units	Gleyic Cambisols	Gleysols, Fluvisols
Salinity/Alkalinity Gypsum content	All other units	Saline Sodic**	Yermic units, Solonchaks, Solonetz. Petrogypsic
Soil depths	All other units	***	Not applicable

Notes: **S2**: * -1 class for sandy topsoil texture; ** -1 class for saline and sodic phases; *** -1 class for petrocalcic, duripan and petroferric phases.

An overall potential production index of the mapping unit for fishponds was calculated using the following formula:

$$ts = S4 + 0.6 \times S3 + 0.3 \times S2 + 0 \times S1,$$

where: ts = overall soil suitability using a weighted average approach.

Suitability values expressed as percentage of land area covered by soils VS, S, MS or US for fish ponds, were calculated by F. Nachtergaele as shown in **Text Box 2.3**.

Text Box 2.3 Soil suitability.

VALUE (%)	INTERPRETATION	SCORE
80 - 100	Very suitable	4
50 - 79.9	Suitable	3
20 - 49.9	Moderately suitable	2
0 - 19.9	Unsuitable	1

Slope

Pond layouts should account for the existing site topography in order to minimize pond construction costs , make use of gravity for water conveyance to and from the ponds, and enable efficient drainage.

The principal objective of slope evaluation was to identify areas suitable for the construction of fish ponds, the primary considerations being elevation and land slope.

An approach to the evaluation of slopes such as the previous African study (Kapetsky , 1994) was to use the slopes thresholds associated with the soils as defined in the FAO-UNESCO Soil Map of the World classification. This approach proved to be useful, but by using such data, it was not possible to select more precise slope thresholds. Moreover, the slopes resolution in the above map was found to be quite coarse for a study of this type.

Rather than having the slope thresholds imposed upon the soils classification, this study selected the desired slope thresholds by calculating slopes from a Digital Elevation Model (DEM). A new globally consistent 1 km resolution digital topographic database (the GTOPO30 or Global Topography at 30 arc-second) was used,. This dataset was obtained from USGS-EROS Data Center in the form of an IDRISI image file.

To convert the DEM into a slope image the SLOPES module was used in ARC/INFO (see **Appendix 8.4** for details of methods used). The grid was then reclassified based on thresholds determined by Hajek and Boyd (1990) for excavated fish ponds as presented in **Text Box 2.4**.

According to ICLARM and GTZ (1991), the most suitable slopes for large ponds (1-5 ha) in Africa should not exceed 1-2%. However, for small-scale farms where most ponds will be from 0.01-0.05 ha, slopes up to 5% are most favourable. These guidelines are reflected in Text Box 2.4.

Text Box 2.4 Slope suitability.

VALUE (%)	INTERPRETATION	SCORE
< 2	Most favourable for pond construction.	4
2 - 5	Suitable for construction. Minor limitations can be overcome.	3
5 - 8	Moderate limitations for construction. Limitations may be overcome by special design, construction, management or maintenance.	2
> 8	Unfit for use, significant cost and efforts are required to compensate for limitations	1

Source: Based on Hajek and Boyd (1990)

Integration of the soil and terrain submodel

To consider the combined suitability of soils and slopes, it was considered that the former were more important than the latter. This was because suitable soils would ensure two of the most important engineering capability factors for pond construction: good water retention and good pond fertility. In particular, according to Kapetsky (1994), soil texture in Africa is more limiting in comparison to slopes.

The following formula, which gives a higher weightage to soils, was used to combine the soils and slopes criteria in an engineering capability sub-model:

Soil and terrain suitability for fish ponds = (1.5 x Soils) + Slopes

The final scores derived from this formula were re-classified into 4 equal-interval suitability classes as shown in **Text Box 2.5**.

Text Box 2.5 Soil and terrain submodel.

VALUE	INTERPRETATION	SCORE
7.5 - 10	Very suitable	4
6.0 - 7.5	Suitable	3
4.5 - 6.0	Moderately suitable	2
< 4.5	Unsuitable	1

LAND USES AND INFRASTRUCTURE

2.3.4 Inputs

The main objective of this section was to pinpoint those sites in which livestock wastes and supplementary food such as agricultural by-products could contribute to the establishment of pond culture systems such as integrated agriculture-aquaculture farming.

Livestock wastes

Animal wastes are widely used as inputs in small-scale and commercial farming aquaculture systems. The objective of livestock waste estimation was to predict the amount of manure available for fish pond fertilization in Africa. Due to the lack of data on manure, we decided to use livestock numbers as a surrogate measure of manure availability.

Livestock population

Data for cattle, sheep, goats, and pigs were obtained from Rutgers University. This dataset is a global-scale environmental database, compiled from all the data contained in the Global GRASS™ CD-ROM datasets 1-5.

Amount of manure available (average livestock weights and manure production)

The total amount of manure produced daily by various animals depends mainly on their live weight (LW). Pigs, for example, produce a daily average of about one-tenth of their live weight in total wet wastes, consisting of solid wastes and urine (Coche, Muir and Laughlin, 1996).

Because of the increased demand of dissolved oxygen caused by the addition of organic matter to the pond water, the amount of organic manure to be applied at one time should be limited. This safe amount is usually expressed in kilograms [kg] of dry matter (DM) per hectare [ha] per day [d] abbreviated as [kg DM/ha/d]. Estimation of the DM content of a specific manure requires field measurements. Because collection of such data is impractical for continental-scale analyses, FAO estimates (Coche, Muir and Laughlin, 1996) on daily production of farm animal wastes were used in this study (**Table 2.6**). These authors provide a range of weights which correspond to typical livestock from which manure is commonly obtained. Values from Coche, Muir and Laughlin (1996) are intended to serve only as approximate estimates for planning purposes. For example, some variation can be expected due to animal species, age, feed ration, type of confinement and method of manure handling.

Table 2.6 Livestock weight estimates and manure production per kilogram biomass per day (adapted from Coche, Muir and Laughlin, 1996).

Animal type	Live weight LW]	Total wet wastes[1] per day		Solid wastes per day	Total fresh wastes[1] (Solids only)
	[kg]	% LW	[kg]	[%]	[kg/1000 kg LW/day]
Cattle	210	6.2	13	69	60
Sheep	30	7.0	2.1	47	70
Goats	30	7.0	2.1	47	70
Pigs[2]	54-72	6.0	3.5	54	60

[1]Solid wastes and urine.
[2] Also from Tacon (1989); Vincke (1985).
Note: To calculate solid manure from sheep: 1000/30 x 2.1 = 70 kg/1000kg LW/day.

Calculating the total amount of manure available

To calculate the amount of manure available the following formula was used:

Amount of manure available [tons] = Livestock number [1000] x Livestock weight [tons] x Solid manure/1000 kg of Livestock.

(Note: Solid manure in the formula refers to total fresh wastes (solids only) from Table 2.6 above).

The total amount of manure potentially available was estimated by adding the calculated amount of manure available for each livestock:

Total manure available [tons] = ma_{cattle} [tons] + ma_{sheep} [tons] + ma_{goats} [tons] + ma_{pigs} [tons],

where: ma = manure available.

Detailed descriptions of these calculations are presented in **Appendix 8.5**. The estimated total amount of manure available was divided into 4 equal-interval suitability classes which are presented in **Text Box 2.6**.

Text Box 2.6 Total amount of manure available.

VALUE [tons]	INTERPRETATION	SCORE
> 100, 000	Very suitable	4
30,000 - 100,000	Suitable	3
2, 000 - 30,000	Moderately suitable	2
< 2,000	Unsuitable	1

Agricultural by-products

Conditions encouraging agricultural production generally favour aquaculture and *vice versa*, and agriculture can be used as a good indicator of areas where aquaculture might flourish (Tacon, Maciocci and Vinatea, 1987; Little and Muir, 1987). In Africa, agriculture is by far the single most important economic activity and this is a good indicator of the potential to develop aquaculture (FAO, 1996a).

As noted by Kapetksy and Nath (1997), the presence of agriculture is an important indicator of aquaculture potential in two ways:

1. The development of agriculture implies that at least a minimum amount of infrastructure has already been developed, such as roads, local labour force, villages or towns for essential supplies.

2. Agricultural by-products can be a source of fish feed or fertilizer.

For small-scale farming, agricultural by-products can contribute to increase yields from the natural production of the pond. For commercial fish farming, such by-products can reduce feed costs by replacing some of the formulated feeds needed.

There are no digital maps of crop types for Africa that can be used to infer the availability of inputs. One approach (Kapetsky, 1994) involved assessment of the length of the growing period (LGP) and the variety of crops grown as indices of by-product availability. However, this approach is based on crop yield predictions and also does not account for inputs from livestock manure.

Crop data for this study were extracted from a land cover data set spanning April 1992 through March 1993. The dataset was obtained from the USGS-EROS Data Center. Although this land cover classification does not distinguish among different cropland types, the data are an indicator of actual cropland areas as opposed to predictions.

The land cover image contains 195 classes from which five data sets (or classifications) can be derived. Of the five data sets, the Olson Global Ecosystem (Olson and Watts, 1982) and the IGBP Land Cover Classification (Belward and Loveland, 1995) schemes were found to be the most complete in terms of extracting cropland areas. However, when comparing the classes of the original data source (i.e., 195 classes) with the classes corresponding to the Olson and IGBP schemes, areas classified as cropland areas in one data set were not similarly classified in another (e.g. forest and field in the Olson scheme classified as cropland in IGBP). More importantly, the 195 classes as well as their accompanying classification do not differentiate among cropland types. Therefore, only those areas which were classified as cropland areas in the raw data (195 classes) were selected for this study. The interpretation to score these land areas is presented in **Text Box 2.7**.

Text Box 2.7 Cropland areas.

INTERPRETATION	SCORE
Cropland	4
No cropland	0

Integration of the inputs submodel

In designing the inputs submodel, it was considered that livestock manure was more important compared to crops because African small-scale fish farmers usually employ manure and by-products are used only as a supplement. For example, Tacon (1991) found that from the 18 Kenyan fish farms visited, 83% used fresh cow manure for pond fertilization.

This submodel was integrated by combining the final manure scores with the cropland scores:

$$\text{Inputs} = (1.5 \times \text{Manure}) + \text{Crops}$$

Manure was multiplied by a coefficient of 1.5 in order to establish a higher ranking than crops. The interpretation for the final scores derived from this weighting scheme are presented in **Text Box 2.8**.

Text Box 2.8 Inputs submodel.

VALUE	INTERPRETATION	SCORE
7 - 10	Very suitable	4
5 - 7	Suitable	3
3 - 5	Moderately suitable	2
1 - 3	Unsuitable	1

2.3.5 Farm-gate sales

Population density

Based on the methodology developed in the Latin America study (Kapetsky and Nath, 1997), market potential as farm-gates sales was inferred from population density (in individuals/km^2 or i/km^2).

Population density data were obtained from NCGIA (Tobler *et al.*, 1995). The foundation of the analysis is based on the relationship among population size, density and surface area.

With territorial areas of around 30,000 km^2 each, Burundi and Lesotho are amongst the smallest countries of the entire African continent. In contrast, Zambia (753,000 km^2) and especially the Democratic Republic of the Congo (2,340,000 km^2) stand at the other end of this range (Reynolds, 1993).

Wide variations in population sizes and densities occur from country to country in Africa and within countries. In general, the most densely populated areas are found bordering the lakes, in the river basins (especially those of the Nile and Niger), along the coastal belts of North and West Africa, and in certain highland areas, while settlement is the most sparse in the desert and savanna areas. A striking contrast is shown by the case of Burundi, one of the smallest of all African countries, with a population density of 187 i/km^2 that is almost 19 times greater than that of Zambia (10 i/km^2) (Tobler *et al.*, 1995).

Clearly, differences in population size, density and surface area need to be interpreted in the context of availability of arable land and grazing areas, and the concentrations of people in places of high productivity and favourable climate or centres of industrial or commercial activity. In Burundi, for example, pressure on nearly all land resources is intense, whereas in Zambia, the very low density figure does not reflect the fact that high concentrations of people live in the industrial Copper Belt, nor that vast areas of the country comprise land of marginal agricultural utility (Reynolds, 1993).

Based on the background above, four assumptions were made for this analysis:

1. The greater the population density the better market opportunities for farmed fishes (Kapetsky, 1994);
2. From a land-cost land-use point of view, a very high population density may prohibit the use of such populated areas for fish farming (Kapetsky and Nath, 1997);
3. There is a tendency for products to flow towards concentrations of high population (Reynolds, 1993); and
4. Population figures and actual distribution of inhabitants in terms of economic resource bases must be seen in terms of population growth rates (Reynolds, 1993).

In a study on population growth and agricultural change in Africa, Turner, Hyden and Kates (1993) found rural districts of more than 200 i/km^2 uninfluenced in population density by urban concentrations within them.

Population density thresholds were based on a trade-off between the selection of a high population density as a potential market source and the limit at which population density in terms of land would be to expensive for small-scale fish farming. The same population density thresholds used in the Latin America study (Kapetsky and Nath, 1997) were used. The very suitable range corresponded to a range of 150 - 300 i/km^2. At the grid cell size of 25km^2 used herein, this density range corresponds to 3,750 – 7,500 individuals. The thresholds selected to indicate potential for farm-gate sales are given in **Text Box 2.9** (see also **Appendix 8.6**).

Text Box 2.9 Farm-gate sales submodel.

VALUE [i/km^2]	POTENTIAL MARKET [maximum total inhabitants]	SCORE
150 - 300	24,300	4
25 - 149	12,069	3
1 - 24	1,944	2
1 < and > 300	n/a	1

2.3.6 Urban market size and proximity

Urban market potential pertains only to commercial fish farming in this study. This is because we assumed that small-scale farmers consume part of their production and either sell or barter the surplus locally. The methodology developed by Kapetsky and Nath (1997) was used in this study to evaluate market potential as a function of travel time proximity and market size (in turn, a function of population levels). Complete details are available in **Appendix 8.7**.

Major cities (market size)

The spatial locations of major cities and accompanying population classifications were obtained from the ArcWorld datasets (ESRI,1992b).

To carry out the suitability analysis, the population dataset was re-classified into four classes as shown in **Text Box 2.10.**

Text Box 2.10 Major cities.

ARCWORLD	THIS STUDY	SCORE
> 5,000,000 1,000, 000 - 5,000,000	> 1,000,000	4
500,000 - 1,000,000 250,000 - 500,000	250,000 - 1,000,000	3
100,000 - 250,000 50,000 - 100,000	50,000 - 250,000	2
< 50,000	< 50,000	1

Roads (time proximity)

The methodology for estimating time proximity is presented in detail elsewhere (Kapetsky and Nath, 1997). The basic assumptions of the approach are as follows:

- The maximum time for a round trip from the farm to the market centre was 12 hours, to preclude the cost of the driver staying overnight away from the farm; and
- A speed of 90 km/h was set for a truck over motorable roads.

Time proximity was defined using the road system. Roads were re-classified in terms of cost (**Text Box 2.11**) according to ArcWorld's road type classification system. Main and feeder road travel combinations were then classified into five categories, with a maximum of six hours or less, in terms of one-way proximity.

Text Box 2.11 Roads.

ARCWORLD	THIS STUDY	SCORE
1 = High speed 2 = Hard surface	Very suitable (lowest cost)	1
3 = Gravel	Suitable	2
4 = Unsurfaced	Moderately suitable	3
3 = Track or trail	Unsuitable	4
6 = Under construction 7 = Undifferentiated	Not used	
No roads	Least suitable (highest cost)	5

Note: 6 and 7 were not used because they only represented 4 cells in total (combined).

Integration of the urban market size and proximity submodel

Market size and travel time, were combined into a submodel, whereby each of the five classes of proximity (road types) were combined with the four urban classes. The scoring interpretation of the final result is presented in **Text Box 2.12**.

Text Box 2.12 Urban market size and proximity submodel.

VALUE	INTERPRETATION	SCORE
0 - 5.9	Very suitable	4
6 - 11.9	Suitable	3
12 - 23.9	Moderately suitable	2
> 24	Unsuitable	1

2.3.7 Summary of criteria and their thresholds

The above categories of criteria and submodels together with their corresponding thresholds, are summarized in **Table 2.7**, and form the basis of evaluating small-scale and commercial fish farming opportunities in Africa.

Table 2.7. Summary of submodels and thresholds for small-scale and commercial fish farming. Note that the final category applies to commercial farming only.

N.	SUBMODELS or CATEGORIES of CRITERIA	Class 4 Very suitable	Class 3 Moderately suitable	Class 2 Marginally suitable	Class 1 Unsuitable
1	Constraints (area)				0
2	Water requirement [mm]	> 0	-2,000 to -1	-2,000 to -3,500	< -3,500
3	Soil & terrain suitability				
	Soils (%)	80 – 100	50 - 79.9	20 – 49.9	0 - 19.9
	Slope (%)	< 2	2 - 5	5 - 8	> 8
	Soil + slope (area)	7.5 – 10	6.0 - 7.5	4.5 - 6.0	< 4.5
4	Inputs				
	Livestock wastes [tons]	100,000	30,000 - 100,000	2,000 – 30,000	< 2,000
	Agricultural by-products (area)	Crops			No crops
	Livestock w. + Agricultural b-p. (area)	7 – 10	5 - 7	3 - 5	1 - 3
5	Farm-gates sales [i/km^2]	150 – 300	25 - 149	1 – 24	1 > and > 300
6	Major cities	> 1,000,000	250,000- 1,000,000	50,000 – 250,000	< 50,000
	Roads	Track or trail	Unsurfaced	Gravel	High speed & hard surface
	Major cities and roads combined (area).	0 - 5.9	6 - 11.9	12 - 23.9	>24

Note: Roads were scored in terms of cost, also, a fifth class was assigned to areas with no roads (i.e. highest cost).

2.4 Small-scale and commercial fish farming models

The overall objective of this section was to build models that combine the submodels described above according to their relative importance for the development and operation of small-scale and commercial fish farming systems in Africa. A schematic diagram of the procedures involved in creating these culture system GIS-based models is presented in **Figure 2.2**.

2.4.1 Multi-criteria evaluation (MCE)

Multi-criteria evaluation procedures have received considerable attention in the GIS literature (Jansen and Rietveld, 1990; Carver, 1991; Eastman, *et al.* 1993; Pereira and Duckstein, 1993; Banai, 1993). Nevertheless, very little attention has been paid to group decision-making problems despite the fact that spatial decision-making problems are invariably associated with several individuals characterized by conflicting preferences. Malczewski (1996) has developed a very useful GIS-approach to group decision-making. However, this approach was based on a hypothetical decision-making situation. Examples of real applications to GIS-based group decision-making are those by Eastman *et al.* (1993), Aguilar-Manjarrez (1996), and Kapetsky and Nath (1997). At present, IDRISI is the only commercially available GIS software that provides a module specifically designed to support multi-criteria evaluation decision-making.

Weighting procedure

The procedure to build the small-scale and commercial fish farming models in this study was based on IDRISI'S multi-criteria, single-objective decision-making technique (MCE) developed by Eastman (1993) and by Eastman *et al.* (1993), and therefore described only briefly here.

The development of weights is based on pair-wise comparisons (i.e. pairwise comparison matrix). The comparisons concern the relative importance of two criteria involved in determining suitability for the stated objective. In order to use this procedure, it is necessary for the weights to sum up to 1. Ratings are systematically scored on a 17-point continuous scale from 1/9 (least important) to 9 (most important) (Saaty, 1977) as in **Table 2.8**.

Table 2.8 The relative importance of two criteria.

1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
extremely		very strongly		strongly		moderately		equally	moderately		strongly		very strongly		extremely	
LESS IMPORTANT									MORE IMPORTANT							

2.4.2 Individual rankings

Choice of weights based on selecting scores

Based on the study by Aguilar-Manjarrez (1996), the relative ranking of the factors was made before completing the pairwise comparison matrix. Scores were assigned in rank order (**Table 2.9**) according to the number of factors involved in the evaluation for each type of culture system without repetition, such that a 1-4 score range was assigned for small-scale farming and 1-5 for commercial (i.e., a scale increase signifies an increase in suitability). The farming systems scores (1-4 and 1-5) assisted in the assignment of weights for each of the factors involved, but the real ranking among factors was derived from the weights obtained from the pairwise comparison matrices. Scores presented in this table should not be confused with the preceding suitability scores assigned (i.e., from 1 to 4).

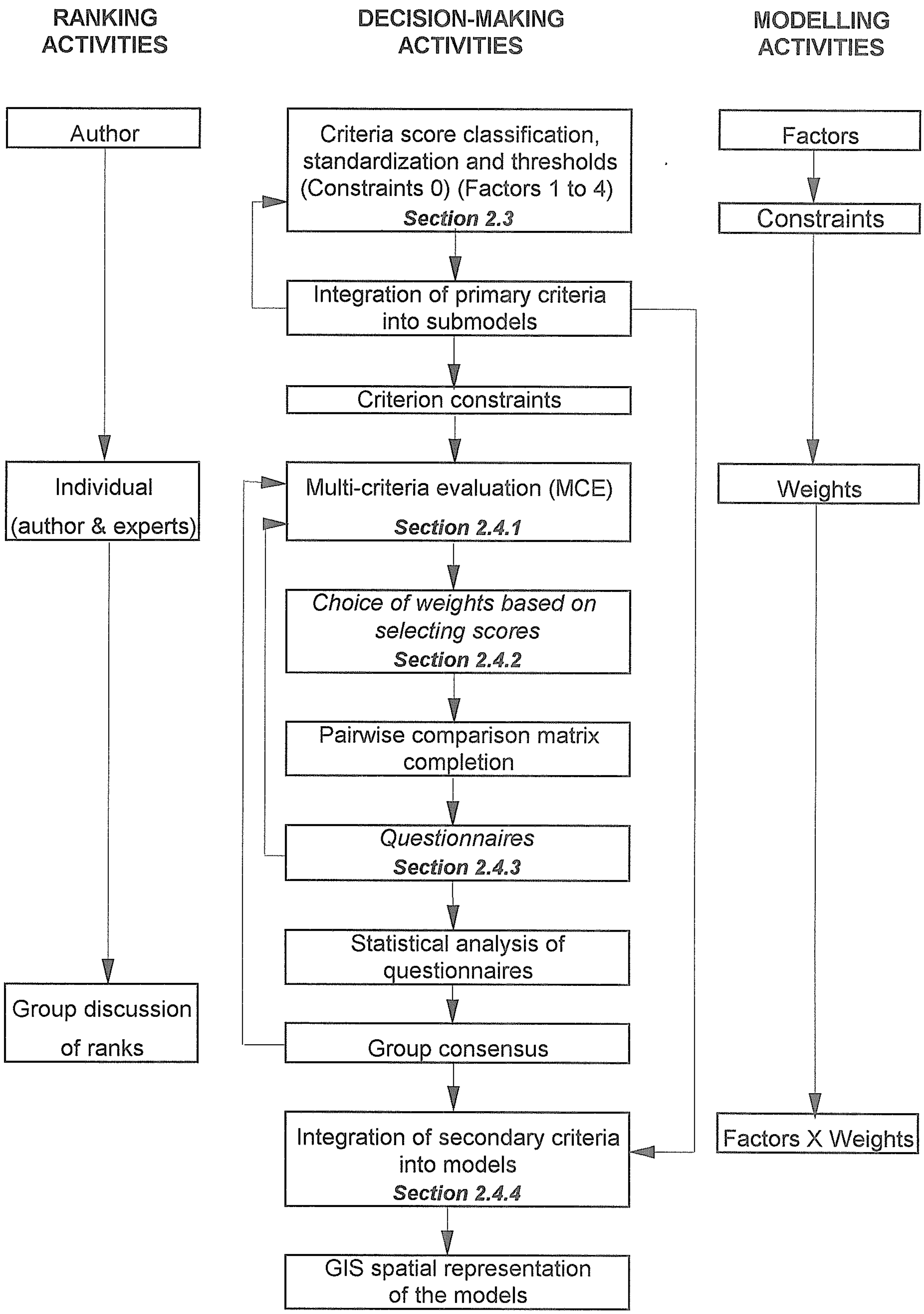


Figure 2.2 Schematic diagram describing the GIS procedures that were involved for multi-criteria group decision-making

Table 2.9 Factors interpretation and scores according to intensity of culture system.

FACTORS DEFINITION (DEFN) AND DESCRIPTION (DESC)	SMALL-SCALE FISH FARMING ENVIRONMENTAL (E) & SOCIO-ECONOMIC (S) INTERPRETATION	SCORE (1 TO 4)	COMMERCIAL FISH FARMING ENVIRONMENTAL (E) & SOCIO-ECONOMIC (S) INTERPRETATION	SCORE (1 TO 5)
Water requirement DEFN: Water is essential for all forms of aquaculture and is a key factor in determining where aquaculture may develop. DESC: Based on difference between precipitation, potential evapotranspiration and seepage. Calculations derived from monthly evaluations.	E: Water availability entirely dependant on potential evapotranspiration and seepage S: Low water demand, minimum costs involved, but may be too expensive for a small-scale farmer to replace water losses from potential evapotranspiration and seepage.	4	E: Water availability not necessarily dependent on rainfall and *runoff*. Water-pumping and piping are used to secure water supply. S: Largest demand on water and hence high costs involved in water supply.	4
Soil and terrain (slope) suitability for ponds DEFN: *Important for aquaculture site selection*, development and management. Great influence on construction and maintenance costs, and on *productivity. It is also important for designing* ancillary components such as water supply channels. DESC: Soils evaluation included: texture, effective soil depth, pH, salinity, and the presence of catclays and gypsum. Slope was derived from a 1 km digital elevation model in the form of percentages.	E: No *soil treatment*, highest dependency on natural state of the soil. Only moderate *limitations can be overcome without major* costs. Ponds are constructed in low lying impoundments. S: Minimum costs.	2	E: Moderate dependency on natural soil. Many limitations can be overcome (e.g. compaction, clay blankets, bentonite, waterproof lining). Not necessarily in low *lying impoundments*. S: *Capital and running costs tend to be high*, and hence, are important to consider.	3
Agricultural by-products and livestock wastes DEFN: Important as a source of fish feed and pond fertilizer. DESC: Agricultural by-products were defined by cropland areas extracted from a land-cover image (i.e. not defined by crop type, only defined as either crops or no crops). Livestock wastes were derived from livestock populations (i.e. cattle, sheep, goats and pigs).	E: Very important in order to achieve surplus yields. S: Minimum costs, especially when fish farming is integrated with other production activities (livestock rearing, agriculture).	3	E: *Less important, as formulated feeds* are mainly used. Only applied as a supplement to commercial feeds. S: Costs are minimum since feeds are rarely used.	1
Farm-gate sales DEFN: It was assumed that the greater the population density the better market opportunities for farmed fishes (Kapetsky, 1994). From a land-cost and land-use point of view, a very high population density may prohibit the use of such populated areas for fish farming. DESC: Derived from population density.	E: According to Kapetsky (1994), sales or barter of surplus production is an important consideration in small-scale fish farming in parts of Africa, where even modest amounts are sold or bartered. S: A high population density implied that the *land would be too expensive for this type of* culture system.	1	E: High volume sales at *urban markets are a* higher priority than farm-gate sales (Kapetsky and Nath, 1997). S: A high population density would not entirely prohibit the use of this land, but it would involve high costs and pollution risks.	2
Urban market size and proximity DEFN: The larger the population the greater the potential market for fish. Urban market centres are *potential locations for marketing* of the fish (Kapetsky and Nath, 1997). DESC: Derived from time proximity based on roads and urban market size based on population density.	Not used. It is assumed that production is sold or bartered locally.	**NOT USED**	E: High reliance on distant bulk. Mainly to *sell within the country and for exports*. S: *Capital and running costs are high* (e.g. transportation and fuel).	5

Definitions of the factors used in this study as well as a brief description of the primary data from which these factors were created are also provided in **Table 2.9** above. In addition, factors are interpreted according to each farming system from an environmental and socio-economic point of view. These interpretations are presented in separate paragraphs for clarity, but the score assigned was derived from a combined interpretation of environmental and socio-economic significance.

Completion of pairwise comparison matrix

The scores presented earlier (**Table 2.9**) were used to simulate the assignment of weights in a matrix, and each factor was accompanied by a careful definition of its importance and description (i.e., primary data used) to make the evaluation more comprehensive. The pairwise comparison matrices developed are shown in **Tables 2.10** and **2.11**. The consistency ratios (CR) of 0.04 for these tables were well within the ratio of equal to or less than 0.10 recommended by Saaty (1977), signifying a small probability that the weights were developed by chance.

Table 2.10 Weightings derived from the pairwise comparison matrix for assessing four factors relevant to small-scale fish farming in Africa (numbers show ratings of the row factor relative to that of the column).

FACTOR MAPS	Water	Soils	Inputs	Farm-gate	Weightings
Water	1				0.56
Soils	1/5	1			0.12
Inputs	1/3	3	1		0.26
Farm-gate	1/7	1/3	1/5	1	0.06
SUM					1.00

CR = 0.04

Abbreviations: Water = water requirement for shallow ponds; Soils = soil an terrain suitability for fish ponds; Inputs = Livestock wastes and agricultural by-products; Farm-gate = Farm-gate sales; Urban = Urban market size and proximity.

Table 2.11 Weightings derived from the pairwise comparison matrix for assessing five factors relevant to commercial fish farming in Africa (numbers show ratings of the row factor relative to that of the column).

FACTOR MAPS	Water	Soils	Inputs	Farm-gate	Urban	Weightings
Water	1					0.30
Soils	1/3	1				0.13
Inputs	1/7	1/4	1			0.04
Farm-gate	1/5	1/3	2	1		0.07
Urban	2	5	7	5	1	0.46
SUM						1.00

CR = 0.04

2.4.3 Questionnaires

Although factor scores were objectively based upon real data, the assignment of weights during MCE was considered partly subjective because it was entirely dependent upon decisions made by the first author. To help reduce some of this subjectivity, to verify the weights generated, and to reach a consensus for weights, two analytical procedures were considered: 1) the use of questionnaires without group discussion for final weight consensus (Aguilar-Manjarrez, 1996), and 2) group discussion for weight consensus without the use of questionnaires (Eastman *et al.*, 1993; Kapetsky and Nath, 1997). Because these procedures are complementary this study combined the two in order to achieve increased objectivity.

A group of four aquaculture experts from the FAO Inland Water Resources and Aquaculture Staff participated in the questionnaire (**Table 2.12**). The selection of these experts was based upon the following considerations: 1) similar aquaculture experience, 2) physically available to provide feedback through interviews during and after the evaluation had taken place, and 3) the same experts (except for one) involved in the Latin America study (Kapetsky and Nath, 1997) were used to benefit from the experience gained in that study.

Table 2.12 Expertise and international experience of FAO staff participating in the questionnaires and in the group discussion.

EXPERT	AQUACULTURE EXPERIENCE	INTERNATIONAL WORKING EXPERIENCE
1	General, projects, research	Latin America, Global
2	Small-scale rural development	Latin America
3	Nutrition	Latin America, Global
4	General, research	Pacific, Middle East, Global

During initial testing an additional decision-maker not included in the subsequent statistical analysis, served to adjust or amend the questionnaire prior to its application.

The questionnaires involved asking the four staff members to score factors important to commercial and small-scale farming systems (**Table 2.9**) and to assign weights to these factors (**Tables 2.11** and **2.12**), in a manner similar to that used by the first author prior to contacting the experts. In addition to providing the tables (Tables 2.9 to 2.11) for the experts to complete, spaces were also provided in the questionnaire for their comments.

Scores and weights assigned by the experts for small-scale and commercial farming systems are summarized in Tables 2.13 and 2.14. These tables indicate that there is general agreement among the experts because most of the important factors were assigned high scores. For example, water requirement in the small-scale evaluation and urban size and proximity in the commercial evaluation were assigned similar scores.

Table 2.13 Relative scoring and weighting of 4 factors for small-scale fish farming in Africa according to 4 experts.

DECISION-MAKER	A	B	C	D	E	MEAN	A	B	C	D	E	MEAN
	SCORES						WEIGHTS					
Water	4	4	4	4	4	4.0	0.56	0.45	0.41	0.6	0.47	0.498
Soils	3	2	3	3	2	2.6	0.26	0.2	0.29	0.3	0.18	0.246
Inputs	2	3	2	2	3	2.4	0.12	0.29	0.21	0.08	0.33	0.206
Farm-gate	1	1	1	1	1	1.0	0.06	0.06	0.09	0.02	0.02	0.05
Sum							1	1	1	1	1	1
CR							0.04	0.04	0.05	0.04	0.05	0.044

Terminology: A = Author; B,C,D and E = Experts.

Table 2.14 Relative scoring and weighting of 5 factors for commercial fish farming in Africa according to 4 experts.

DECISION-MAKER	A	B	C	D	E	MEAN	A	B	C	D	E	MEAN
	SCORES						WEIGHTS					
Water	4	2	5	4	5	4.0	0.3	0.12	0.36	0.3	0.45	0.306
Soils	3	3	3	5	3	3.4	0.13	0.16	0.18	0.45	0.14	0.212
Inputs	1	4	2	2	2	2.2	0.04	0.17	0.14	0.09	0.09	0.106
Farm-gate	2	1	1	1	1	1.2	0.07	0.06	0.08	0.04	0.02	0.054
Urban	5	5	4	3	4	4.2	0.46	0.49	0.24	0.12	0.3	0.322
Sum							1	1	1	1	1	1
CR							0.04	0.07	0.05	0.06	0.05	0.054

Terminology: A = Author; B,C,D , E = Experts.

There was general agreement that the factors chosen for the evaluation were relevant. Most importantly, none of the factors were considered to be unsuitable, or were rejected from the evaluation. Some of the experts wanted to include other factors that would enhance the evaluation. For example, if data were available, a fish consumption factor could be added since wide variations in population diets occur from country-to-country in Africa (Reynolds, 1993).

The advice from the experts was very useful in the evaluation in order to verify the weights assigned by the author. Moreover, as expected, most of the staff were familiar with the decision-making methodology used (Kapetsky and Nath, 1997) which resulted in many of their comments being GIS-oriented, and therefore very valuable.

It was found that there was a strong agreement in scores for the small-scale evaluation - only one staff member ranked one of the factors differently. A good, but lower agreement was met for the commercial evaluation and this was attributed to the fact that some experts had difficulty in assigning scores because this particular culture system has a relatively short history in Africa, so it was difficult to predict the range of culture practices that could evolve in this sector.

The decision-makers were greatly benefited by assigning scores prior to completing the pairwise comparison matrices. Although some changes were made to the matrices, all the adjustments (i.e. increasing or decreasing the numbers in the pairwise comparison matrix) to meet the CR required were based entirely upon the scores assigned by the decision-makers.

The consistency ratios (CR's) of the expert group were found to be satisfactory for both the small-scale and commercial evaluation (mean of 0.044 and 0.054). Overall, the CR's developed by the first author were slightly better when compared to the CR's from each decision-maker. For the small-scale evaluation, the CR of the author was the same or slightly better than the CR of the decision-makers. However, the CR of the author was much better in the commercial evaluation when compared to the rest of the group.

Statistical analysis of questionnaires

To assess questionnaire results, it was crucial to determine whether the rank scores of the first author matched the position of the rank score of the decision-makers. Based on the experience gained in the Sinaloa state study (Aguilar-Manjarrez, 1996), the Kendall coefficient of concordance non-parametric statistical analysis (Kendall, 1984a,b) was used as the basis for this study's evaluation.

The Kendall coefficient of concordance *W* measures the extent of association among several sets of ranking, or *m* entities. It is useful in determining agreement among decision-makers of the associations among several factors and has special applications in providing a standard method of ordering entities according to consensus (Siegel, 1965) (see also **Appendix 8.11**).

Group consensus

To identify the consensus ranking and the best alternative according to the collective preferences, the approach by Aguilar-Manjarrez (1996) was used whereby individual questionnaires were used to evaluate the decision-makers views and perceptions about their chosen scores and weights with those that were originally developed by the first author. This new approach also enables the experts to be more familiar with the technique, develop a more thorough evaluation and thus, arrive at a more comprehensive consensus.

A comparison of the results was achieved by rank ordering the scores and weights established initially by the author and comparing them against the rank position of the scores and weights found by the decision-makers (both ranks were ordered in descending order). Since the weights had to match the scores exactly, to make a logical assessment, the rank position of the weights was exactly the same as the rank position of the scores, and hence the result of the Kendall coefficient of Concordance test was exactly the same (e.g. for small-scale farming, water requirement was assigned the highest score and hence the highest weight).

For the small-scale analysis, **Table 2.15** shows that the author's results were very similar to the rest of the group. The value of the Kendall coefficient of concordance *W* was 0.56 and therefore the *m* sets of rankings were associated. In other words, the ranks established by the author agreed with those established by the decision-makers. As shown in this table, all factors matched the exact rank order when compared to the author. Clearly, both the author and the experts agreed that water requirement and soil/terrain suitability were the most important land-quality factors in this list.

Table 2.15 Consensus ranking of 4 factors for small-scale fish farming in Africa among 5 decision-makers.

	SCORES							RANK ORDER GROUP			RANK ORDER AUTHOR		
								MEAN		FACTORS			FACTORS
FACTORS	A	B	C	D	E	Rj	Rj^2	Rj	WEIGHT		SCORE	WEIGHT	
Water	4	4	4	4	4	16	256	4.0	0.498	Water	4	0.56	Water
Soils	3	2	3	3	2	11	121	2.6	0.246	Soils	3	0.26	Soils
Inputs	2	3	2	2	3	9	81	2.4	0.206	Inputs	2	0.12	Inputs
Farm-gate	1	1	1	1	1	4	16	1.0	0.05	Farm-gate	1	0.06	Farm-gate

W = 0.56; X^2 = 12; **Chi** = 9

Terminology: A = Author; B,C,D, E = Experts.

Abbreviations: Water = water requirement for shallow ponds; Soils = soil an terrain suitability for fish ponds; Inputs = Livestock wastes and agricultural by-products; Farm-gate = Farm-gate sales; Urban = Urban market size and proximity.

For the commercial evaluation, **Table 2.16** shows that the value of W (0.65) and therefore the ***m*** sets of rankings were associated; hence most of the ranks established by the decision-makers were in agreement. Overall, 3 out of 5 factors matched the exact rank position when compared to the author. Conversely, some factors such as farm-gate sales and nutrient inputs were not in agreement between the author and the decision-makers.

Table 2.16 Consensus ranking of 5 factors for commercial fish farming in Africa among 5 decision-makers.

	SCORES							RANK ORDER GROUP			RANK ORDER AUTHOR		
								MEAN		FACTORS			FACTORS
FACTORS	A	B	C	D	E	Rj	Rj^2	Rj	WEIGHT		SCORE	WEIGHT	
Water	4	2	5	4	5	20	400	4.2	0.322	Urban	5	0.46	Urban
Soils	3	3	3	5	3	17	289	4.0	0.306	Water	4	0.3	Water
Inputs	1	4	2	2	2	11	121	3.4	0.212	Soils	3	0.13	Soils
Farm-gate	2	1	1	1	1	6	36	2.2	0.106	Inputs	2	0.07	Farm-gate
Urban	5	5	4	3	4	21	441	1.2	0.054	Farm-gate	1	0.04	Inputs

W = 0.65; X^2 = 13; **Chi** = 9.5

Terminology:
A = Author; B,C,D, E = Experts.

At this stage of the evaluation, a group discussion should ideally take place to resolve differences in opinions. However, because the first author's results were in agreement with the staff and that valuable feedback had already been obtained through interviews during the development of the individual questionnaires, it was decided that the group consensus had already been reached and therefore, a group discussion was not necessary in this particular case.

2.4.4 Integration of secondary criteria into submodels

The main objective of this task was to integrate the secondary criteria to create two models (small-scale and commercial).

Since the CR's developed by the first author were slightly better than the CR's from most decision-makers, it was decided to use the weights (**Table 2.10** and **2.11**) found by the first author for both culture systems.

To create the small-scale fish farming model, the four submodels which had been already classified according to a suitability score from 1 to 4 were multiplied by the authors weights derived from **Table 2.10** and **2.11**, and then these values were added.

The commercial model was established in a similar way to that of the small-scale model, with the exception that an urban size and proximity submodel was added to the evaluation.

Since the MCE procedure required that the weights sum to 1, when the weights (**Table 2.10** and **2.11**) were multiplied by the submodels (scored from 1 to 4), the overall suitability maps for each type of culture system retained the 1 to 4 suitability score range.

2.5 Fish farming yield model of three species

2.5.1 Water temperature modelling

The fundamental factor at the macro-scale that determines the viability of an area for aquaculture is climate, because it is the primary source of water supply to ponds, and also dictates water temperature regimes, which in turn determine the species that can be cultured efficiently in a particular location (Coche, 1994; Kapetsky, 1994; Kapetsky and Nath, 1997).

Since fish are cold-blooded, their performance is directly related to water temperatures. Consequently, fish growth has been regarded as being directly proportional to the number of degree days within an optimal temperature range (ICLARM and GTZ, 1991; Kapetsky, 1994).

There are no geographically comprehensive data on pond water temperatures in Africa. One approach to estimating water temperature involves the use of air temperature because these two variables are closely correlated (Kapetsky ,1994; Webb and Nobilis, 1997). However, such approaches do not take into account the effects of seasonal variations in air temperature and other weather characteristics (solar radiation, cloud cover, wind speed and relative humidity). Heat balance models (e.g., Fritz, Meredith and Middleton, 1980) account for the effects of these variables on pond water temperature, and have been successfully applied for pond aquaculture systems (Nath, 1996). The latter model (based on gridded datasets of seasonal air temperature and mean annual wind velocity, as well as a simple generator for other weather variables) was adapted for use in this study with the intention of estimating water temperature for the entire African continent.

Index fish species

The fish species selected to portray yield potential in Africa were Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*) and Common carp (*Cyprinus carpio*). These species are widely distributed and have already performed well for fish farming in the continent (Coche, Muir and Laughlin, 1996).

Air temperature

Mean monthly gridded values for minimum air temperature and mean monthly gridded values for maximum air temperature created by CRES at the Australian National University were obtained in the form of ASCII files which were easily converted into ARC/INFO format.

Wind velocity

Mean annual wind velocity was provided by UNEP/DEIA/GRID-Geneva, in the form of an IDRISI image file. The image file was exported into ARC/INFO and converted into an ASCII file.

Water temperature estimates

Estimation of water temperature across the African continent followed the same approach used previously (Kapetsky and Nath, 1997), with the exception that annual wind speed data (UNEP/GRID) were used as input to the model, instead of a constant value as assumed by the above authors. Details regarding the water temperature simulation model itself are available in Kapetsky and Nath (1997) and in Nath (1996).

2.5.2 Fish growth modelling

Integration of fish growth models within GIS has previously been shown to be a valuable mechanism of evaluating spatial variability in production for different culture species (Kapetsky and Nath, 1997). Fish yield estimation in the current study followed analytical approaches similar to those used by the above authors. However, different specifications (see below) were used for small-scale and commercial farming scenarios to reflect the types of culture practices found in the continent. Moreover, the fish growth simulation model documented in Kapetsky and Nath (1997) was refined in the current study to enable consideration of feed quality and high fish biomass in ponds. Model refinements and verification results are fully documented in **Appendix 8.8** of this report.

To achieve the overall objectives of this study and for easy interpretation of the results, it was necessary to aggregate crops/y outputs from the simulation runs into four classes. However, specification of rigid classes that pre-judge the output values without accompanying production cost and marketing data is inappropriate. Furthermore, differences in model output were expected depending on the particular species and harvest sizes. To avoid these problems, output for each scenario within the commercial and small-scale categories was divided into equal quarters of the range of crops/y. These outputs were designated as 1st quarter (highest crops/y) (1^{st}Q), 2^{nd} quarter (2^{nd}Q), 3^{rd} quarter (3rdQ), and 4^{th} quarter (lowest crops/y) (4^{th}Q).

Small-scale farming

As previously noted (Kapetsky and Nath, 1997), it is difficult to precisely define "small-scale" aquaculture systems because of the wide diversity in culture conditions. For conditions in Africa, small-scale inland aquaculture will most likely be confined to fertilized ponds, and will involve harvest of relatively small fish. Therefore, small-scale farming scenarios in the current study were restricted to simulation of Nile tilapia, African catfish and Common carp growth performance under conditions where natural food in ponds was the only source of nutrition. Natural food availability was modelled as a function of fish biomass, and involved the use of the critical standing crop parameter CSC_{fert} (Nath, 1996; see also commercial farming section below). An annual mortality rate of 20% and a stocking weight of 25g were assumed for all simulation scenarios.

Other simulation settings for the three species under small-scale farming conditions are indicated in **Table 2.17**. A higher stocking density was used for Nile tilapia (because of the lower harvest size) and for African catfish (because of its tolerance to crowding) compared to Common carp (**Table 2.17**). The CSC_{fert} value for Nile tilapia was assumed to be higher than that for the other two species (**Table 2.17**) because Nile tilapia exploits this food resource very efficiently.

Table 2.17 Stocking densities, harvest sizes and critical standing crops assumed for small-scale farming of Nile tilapia, African catfish and Common carp.

Species	Stocking [fish / m^2]	Harvest Size [g]	Standing Crop (CSC_{fert}) [kg / ha]
Nile tilapia	1	150	400
African catfish	1	250	300
Common carp	0.5	250	300

Commercial farming

Kapetsky and Nath (1997) used a wide range of farming scenarios (i.e. four fish species each with two feeding levels and two harvest weights) in an effort to fully represent the diversity of commercial aquaculture possibilities in Latin America. However, because commercial aquaculture has a relatively short history in Africa (Pedini and Shehadeh, 1997), it is difficult to predict the range of culture practices that might eventually evolve within this sector.

Based on current knowledge, it appears that most commercial culture operations in Africa will involve the use of both pond fertilizers as well as supplemental feed. Consequently, the commercial farming scenarios for Nile tilapia, African catfish, and Common carp in the current study assumed that natural food availability is a function of fish biomass (Bolte, Nath and Ernst,1995). It was also assumed that supplementary feeding for all three species would commence only after the amount of natural food dropped below a target satiation feeding level of 75%. Estimation of natural food availability requires definition of the critical standing crop for ponds (CSC_{fert}; in [kg / ha]), a parameter that is species dependent. An additional parameter is the critical standing crop for fed ponds (CSC_{feed}; in [kg / ha]), which is used to account for the effects of crowding under high fish biomass conditions (see also **Appendix 8.8**). An annual mortality rate of 20% and a stocking weight of 50g were assumed for all simulation scenarios. Further, supplemental feed protein and gross energy contents (dry matter basis) were assumed to be 25% and 3.0 kcal/g respectively. Fish feed was assumed to contain 10% moisture.

Other simulation settings for commercial farming of the three target species are listed in **Table 2.18**. Compared to African catfish and Common carp, a higher stocking density was used for Nile tilapia because the harvest size was lower (**Table 2.18**). The critical standing crop parameter used to estimate natural food availability (i.e., CSC_{fert}) for Nile tilapia was assumed to be higher than that for the other two species (**Table 2.18**) because Nile tilapia exploits such food resources very efficiently. The critical standing crop parameter used to account for poor water quality and crowding effects in fed ponds (i.e., CSC_{feed}) was assumed to be higher for African catfish than for the Nile tilapia and Common carp (**Table 2.18**) because this species is very tolerant of poor water quality (Haylor, 1993).

Table 2.18 Stocking densities, harvest sizes and critical standing crops assumed for commercial farming of Nile tilapia, African catfish and Common carp.

Species	Stocking [fish / m^2]	Harvest Size [g]	Critical Standing Crops [kg / ha]	
			CSC_{fert}	CSC_{feed}
Nile tilapia	3	300	1000	3500
African catfish	2	600	750	3500
Common carp	2	600	750	4000

2.6 Combination estimates of potential from small-scale and commercial models with the species yield models

As shown throughout this study, because of the different scale upon which data is measured, it was necessary to adopt a standard classification method (or threshold). Both the farming system suitability maps and the crops/y results from the fish growth models have been scored into four suitability classes from very suitable to unsuitable (i.e. 1 to 4). These outputs were combined to make maps showing the coincidence of each culture system suitability map class with each class of the crops/y output (i.e. 1^{st}Q to 4^{th}Q). Model details are fully documented in **Appendix 8.9**.

2.7 Coincidence between fish species

To enhance the results found by the combined models in the preceding section, the results of the small-scale model for the three fish species were combined in order to establish where the best yields for all three species coincided. Similarly, the commercial models for the three fish species were combined to find such coincidence (see also **Appendix 8.9**).

2.8 Verification

The overall goal of this section was to test the predictions of aquaculture potential made by the use of the culture systems models in combination with the fish yields models, in terms of suitability of the site and the yield in crops/y. The verification study was confined to Zimbabwe, Kenya, Uganda and Malawi due to data availability (**Table 2.19**), and financial constraints. Nevertheless, these four countries are important producers of cultured fish from the inland waters of Africa.

Table 2.19 Data availability for verification by country.

DATA	ZIMBABWE	KENYA	UGANDA	MALAWI
Year	1997	1996	1997	1997
Author	Balarin[1]	Marquet [2]	Candia	Brooks[3]
Location by district	Yes	Yes	Yes	Yes
Lat/Long location	Yes	Yes	No	No
Fish species	Nile tilapia, Common carp & African catfish	Nile tilapia	Nile tilapia	Tilapia & African catfish
Culture system	Small-scale & commercial	Small-scale	Small-scale & commercial	Small-scale
Production	Yes[4]	No	No	No
Number farms	6	31	203	No
Number & size of farms	Yes	No	Yes	No
Farm characteristics	Yes (various)	Water quality	None	Water quality

[1]Balarin, Chisawa and Evans (1997); [2]Marquet, Achieng and Obuya (1996); [3] Brooks and Maluwa (1997); [4]Total production by species [t/y] and annual yields [t/ha/y].

Based on the data available for each country, it was necessary to carry out four different types of evaluations (see also **Appendix 8.10**):

a) Zimbabwe proved to be optimum for verification, due to the large amount of data available. Farm characteristics data by Balarin, Chisawa and Evans (1997) were enhanced and expanded to suit this studies results by means of interviews and locations of farms using a Global Positioning System (GPS) for 6 farms. Data were collected and compiled by F. Zimudzi from 11-24 November, 1997.

b) For Kenya, existing Lat/Long locations of fish farms were used for verification. The water quality data available (i.e. only available for July, 1996) served to verify the water temperature predictions.

c) For Uganda, there were no accurate geographical locations of fish farms and no farm characteristics available. However, data for this country were found useful for general verification by using the numbers of farms at a district level.

d) For Malawi, data on water quality were available (i.e. annual data) for verification of the water temperature predictions.

3. RESULTS

3.1 Overview

Key results of the GIS analyses are presented in this section. The results are classified into the following categories: VS (very suitable), S (suitable), MS (marginally suitable), and US (unsuitable). In order to provide a comprehensive analysis, the results are presented separately by country and continental levels. Furthermore, in order to follow the structure of the preceding methods section, results have been partitioned by fish farming system and by fish species. In other words, factors important for the development and operation of fish farms are evaluated separately from the crops/y results. This results layout is similar to that used by Kapetsky and Nath(1997), and allows examination of the estimates of the quality of land for fish farming in ponds irrespective of the species used. Conversely, the same rationale applies for a separate evaluation of the crops/y potential of each fish species. Finally, the combined models and the overall coincidence among them for the three fish species are also considered separately. Procedures for the statistical results and grid outputs are available in **Appendix 8.11** and **8.12** respectively.

Result descriptions include 49 African countries. However, for simplicity and clarity, only those countries where inland fish farming is most favourable are presented in all histograms below (i.e. 30 are presented).

Differences in thresholds, models and data used between the previous African study (Kapetsky, 1994) and the present one do not allow direct comparison of the factors used in the evaluation. Nevertheless, it was possible to make a general comparison among submodels, because they were developed to meet the same objectives (e.g. to identify areas where water was most available).

3.2 Small-scale and commercial models

<u>Continental overview</u>

Constraints

Constraints were identified in all African countries. The largest constraint area is occupied by the protected areas, about 6 % of continental Africa (**Table 3.1**). These are distributed across Africa, with the largest surface areas in South-eastern Africa, and with the smallest surface areas located west and north of the equator (**Figure 3.1**).

Table 3.1 Area distribution of constraints as a percentage of the surface area in continental Africa.

CONSTRAINTS	Area (%)
Protected areas	6.0
Inland water bodies	0.8
Major cities	0.1

Large inland water bodies occupy about 0.8% of Africa, and are distributed across the entire continent. However, water bodies with the largest surface area occur in South-eastern Africa.

Major cities take up only 0.1% and are distributed across the continent. The highest density of major cities is in the Northwest part of Africa.

Factors for fish farming development and operation

Water requirement is the most limiting of all submodels at the very suitable level, with about 0.6% of the African surface being classified as VS; however an additional 27% is rated S (**Table 3.2**). The coastal fringes of NW Africa and Central Africa have the highest potential for pond water supply (**Figure 3.2**). This is particularly significant since water requirement was the most important submodel in the small-scale model and was ranked second in importance for the commercial model. The spatial distribution of water availability is similar to that in the previous African study (Kapetsky, 1994).

Except for cities and roads, soils are the most limiting factor at the VS level (about 1.6%) of the African surface (**Table 3.3**), but 42.5% of the surface area rates suitable. Slope is the least limiting factor with about 93% of the African surface area being rated as VS (**Table 3.3**). The combination of soils and slopes (soil and terrain submodel) suggests that about 40% is very suitable and 41% suitable (**Table 3.2**). Very suitable soils and terrain are distributed throughout continental Africa and only a small surface area (about 0.7%) was found to be unsuitable (**Figure 3.3**). The overall soils results are comparable to the previous African study (Kapetsky, 1994; **Table 3.2**).

Table 3.2 Suitability of submodels for fish farming development and operation as a percentage of the surface area in continental Africa. Note: OLD refers to the previous African study (Kapetsky, 1994) and NEW to the present study.

SUBMODELS	Very suitable		Suitable		Moderately suitable		Unsuitable	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
Water	29.1	0.61	13.6	26.5	11.9	32.3	45.4	40.7
Soils	35.7	40.3	39.1	40.9	11	18.2	14.2	0.5
Inputs	20.2	11.5	32.6	20.6	7.3	21.7	39.9	46.3
Farm-gate	38.8	1.7	16.3	16.3	9.5	45.8	35.4	36.2
Urban market	5.6	49.1	15.7	6.6	2.9	1.6	75.8	42.7

Abbreviations: Water = water requirement for shallow ponds; Soils = soil an terrain suitability for fish ponds; Inputs = Livestock wastes and agricultural by-products; Farm-gate = Farm-gate sales; Urban = Urban market size and proximity.

Table 3.3 Suitability of factors for fish farming development and operation as a percentage of the surface area in continental Africa.

FACTORS	Very suitable	Suitable	Moderately suitable	Unsuitable	Total
Soils	1.5	42.8	38.7	17.0	100
Slope	93.2	5.8	0.8	0.2	100
Manure	20.7	25.1	19.1	35.1	100
Crops	18.5	--	--	81.5	100
Cities	0.002	0.006	0.013	0.036	0.06
Roads	3.7	1.7	2.2	2.4	10.0

Notes:

- Manure = livestock wastes; Crops = agricultural by-products.
- Cities and roads factors do not total 100% because they are point and line features and not polygons. If road or cities density covered the entire African surface area, then these factors would also total 100.

21% of the surface area in Africa rates VS in terms of livestock waste potential; an additional 25% rates S (**Table 3.3**). Cropland areas that were classified as VS total about 19% of the African surface area (Table 3.3) and occur in broad bands across the continent,

particularly throughout a large part of Southeast Africa. Combining manure together with the crops resulted in 12% and 21% of the area being respectively classified as VS and S (**Table 3.2**). Clearly, the spatial distribution of the very suitable areas in this submodel was greatly influenced by the crops distribution (**Figure 3.4**). Despite the percentage area differences between the current study and the previous one (Kapetsky, 1994; **Table 3.2**) it was confirmed that the very suitable areas in both studies were similar.

Farm-gate sales is the second most limiting submodel at the VS level, with only 1.7% of the area capable of supporting markets for farm-gate sales; further only an additional 16% rates suitable (**Table 3.2**). Areas with very suitable markets are patchily distributed in Morocco, West Africa, Central Africa south of the equator and South-eastern Africa (**Figure 3.5**). Large differences were found for the farm-gate sales factor between the present and the previous study except for areas classified as suitable (**Table 3.2**).

Most major cities in Africa are ranked as unsuitable (**Table 3.3**) with regard to supporting a high market potential. However, this is not the case for roads, because a highest percentage of the surface area was ranked VS (**Table 3.3**). When these two factors are combined to assess the urban market potential, results suggest that this submodel was the least limiting, with 49% of the African surface area being rated VS (**Table 3.2**). In other words, 49% of the continent is within reasonable proximity of large urban centres that could be important for commercial fish farming development. As was the case with farm-gate sales, this submodel also has a patchy distribution attributable to the spatial distribution of the major cities and roads (**Figure 3.6**). Significant differences were found between the present study and the previous one, both in terms of area and spatial distribution (**Table 3.2**).

Small-scale and commercial farming

Results from the farming system models (**Table 3.4**) show that both small-scale and commercial models present similar areal distributions (i.e. in terms of percentages) for each of the four suitability classes. Both models show that very suitable sites occur in about 23% of the surface area across the continent, particularly in many parts of Southeast Africa; however, there are some clear spatial distribution differences (**Figure 3.7 and 3.8**). This is because the small-scale model is clearly influenced by the importance of the water requirement submodel, whereas the commercial model is influenced by the urban market size and proximity submodel. The latter influence is evident in the patchy distribution of some suitable areas.

Table 3.4 Suitability of models for fish farming development and operation as a percentage of the surface area in continental Africa.

MODELS	Very suitable	Suitable	Moderately suitable	Unsuitable
Small-scale	22.6	20.5	16.9	40.0
Commercial	23.0	23.3	18.0	35.8

In comparison to the results obtained herein, Kapetsky (1994) found that 31% of the African surface contains areas that are apt for warm-water fish farming at a small-scale level and 13% at a commercial level. For both studies, very suitable sites occur across Africa, north and south of the equator. However, because the previous study was limited to warm water fish species (Nile tilapia and African catfish), it did not show any fish farming potential in Morocco and Southeastern Africa, unlike the current study.

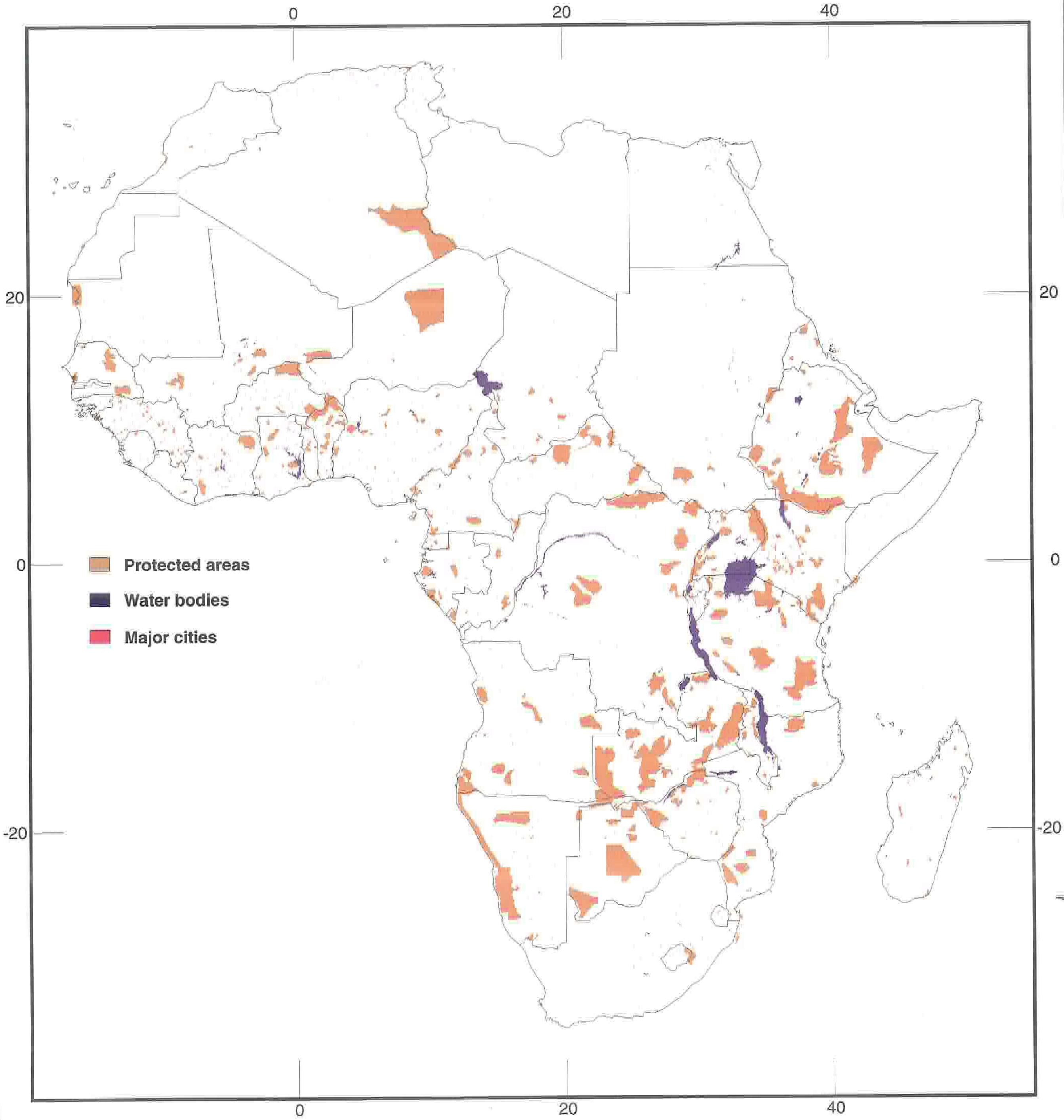


Figure 3.1
Spatial distribution of constraints

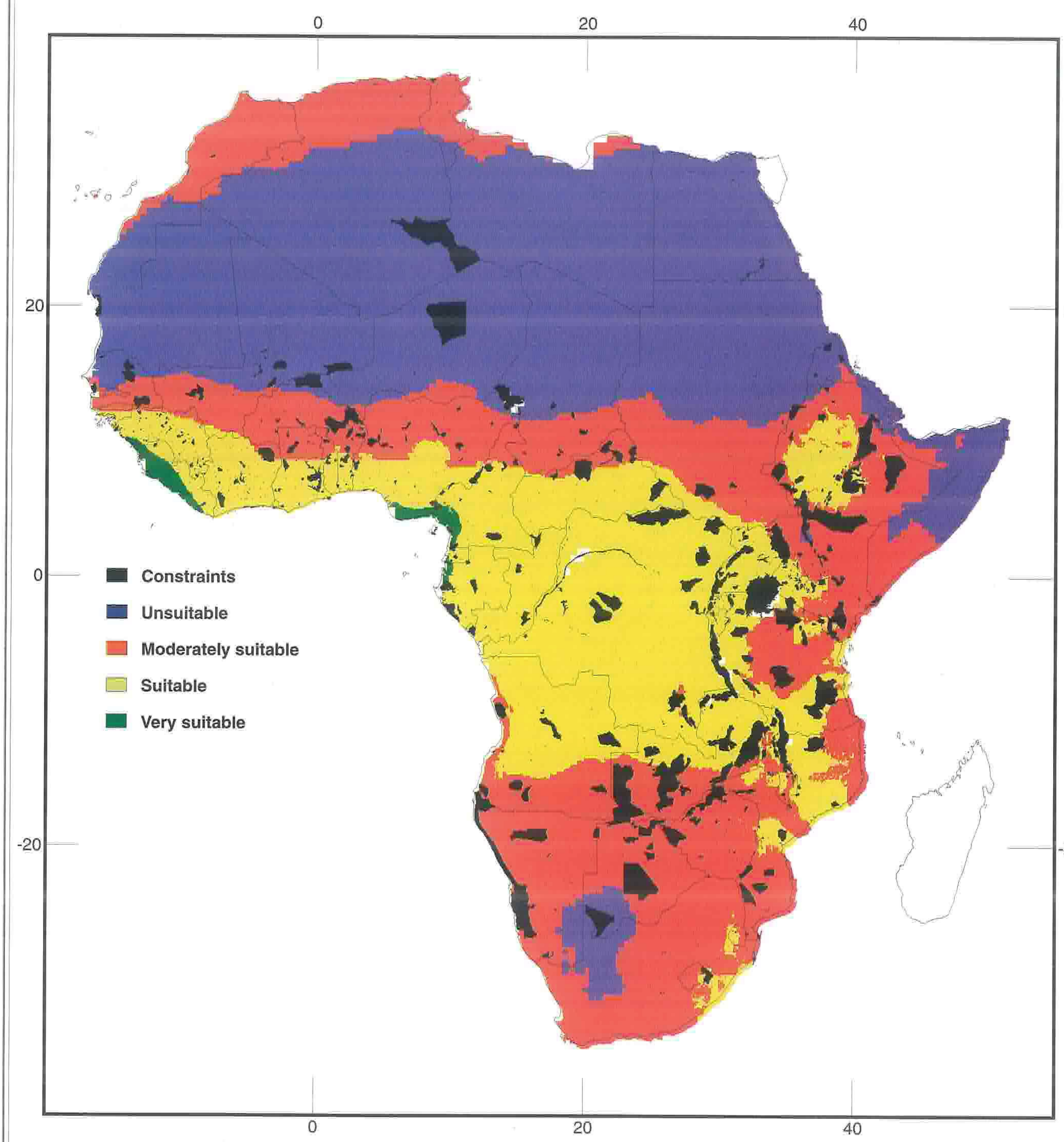


Figure 3.2
Net annual water requirement for shallow ponds

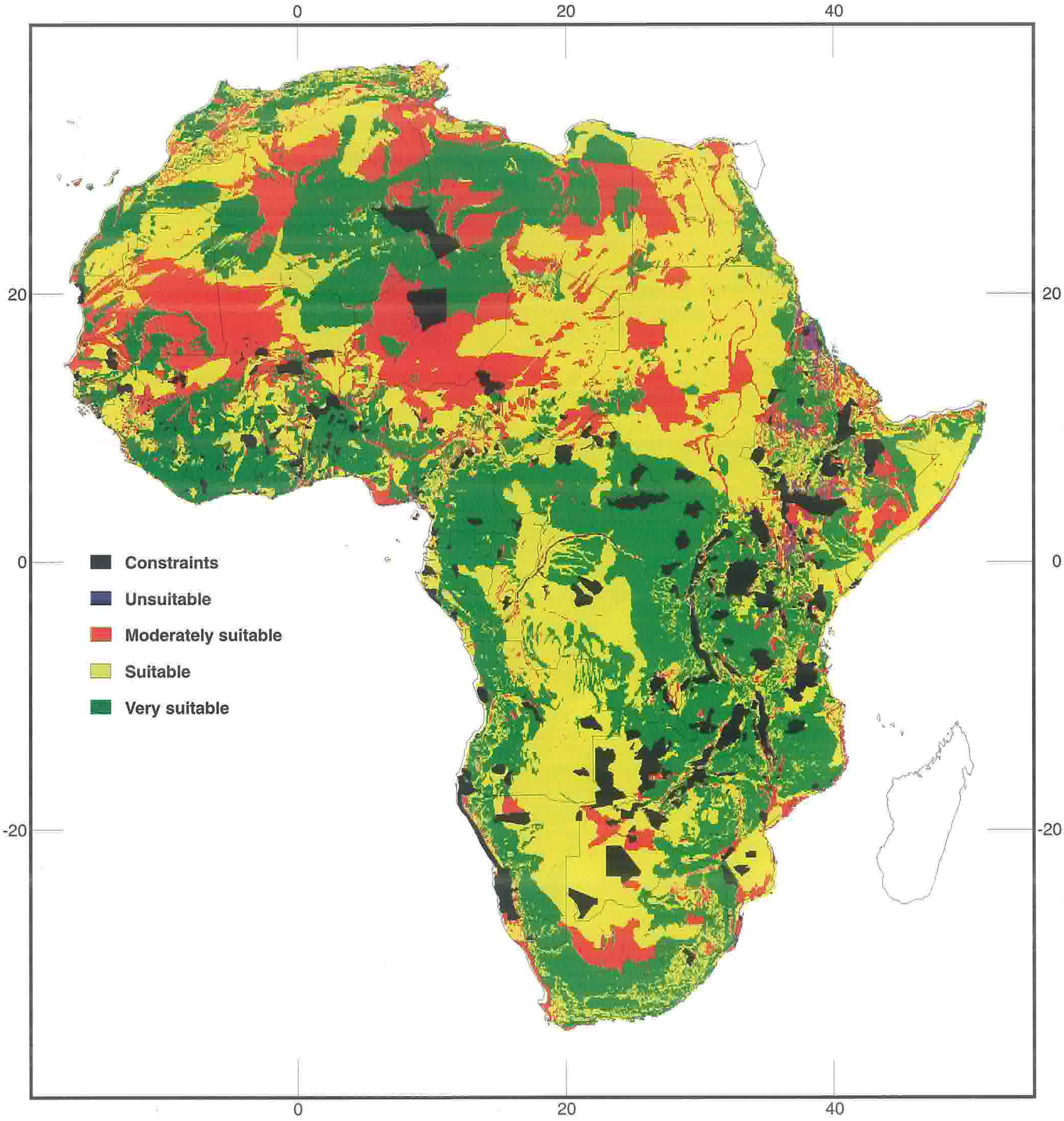


Figure 3.3
Soil and terrain suitability for ponds

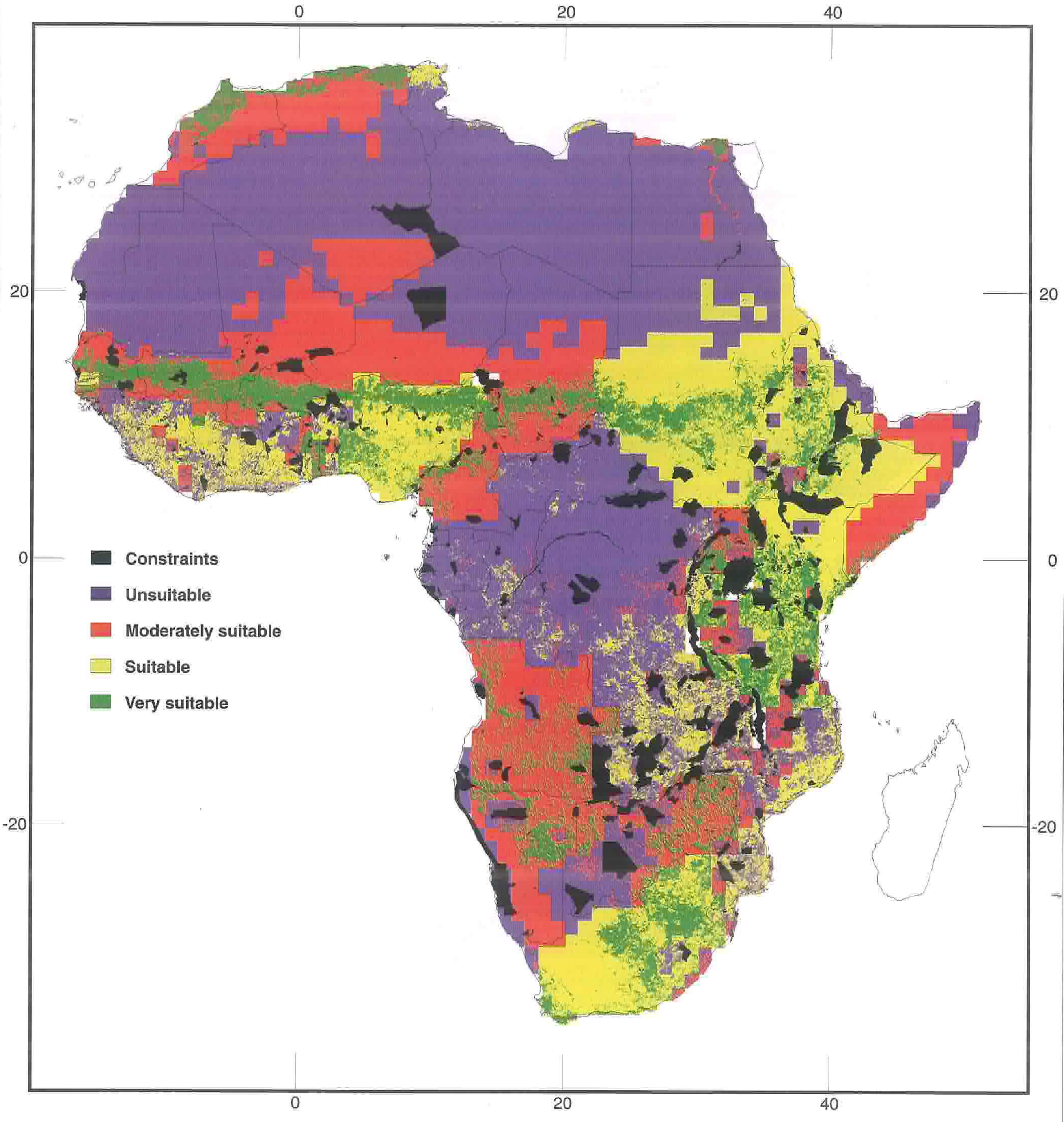


Figure 3.4

Potential livestock wastes and agricultural by-products as feed and fertilizer inputs

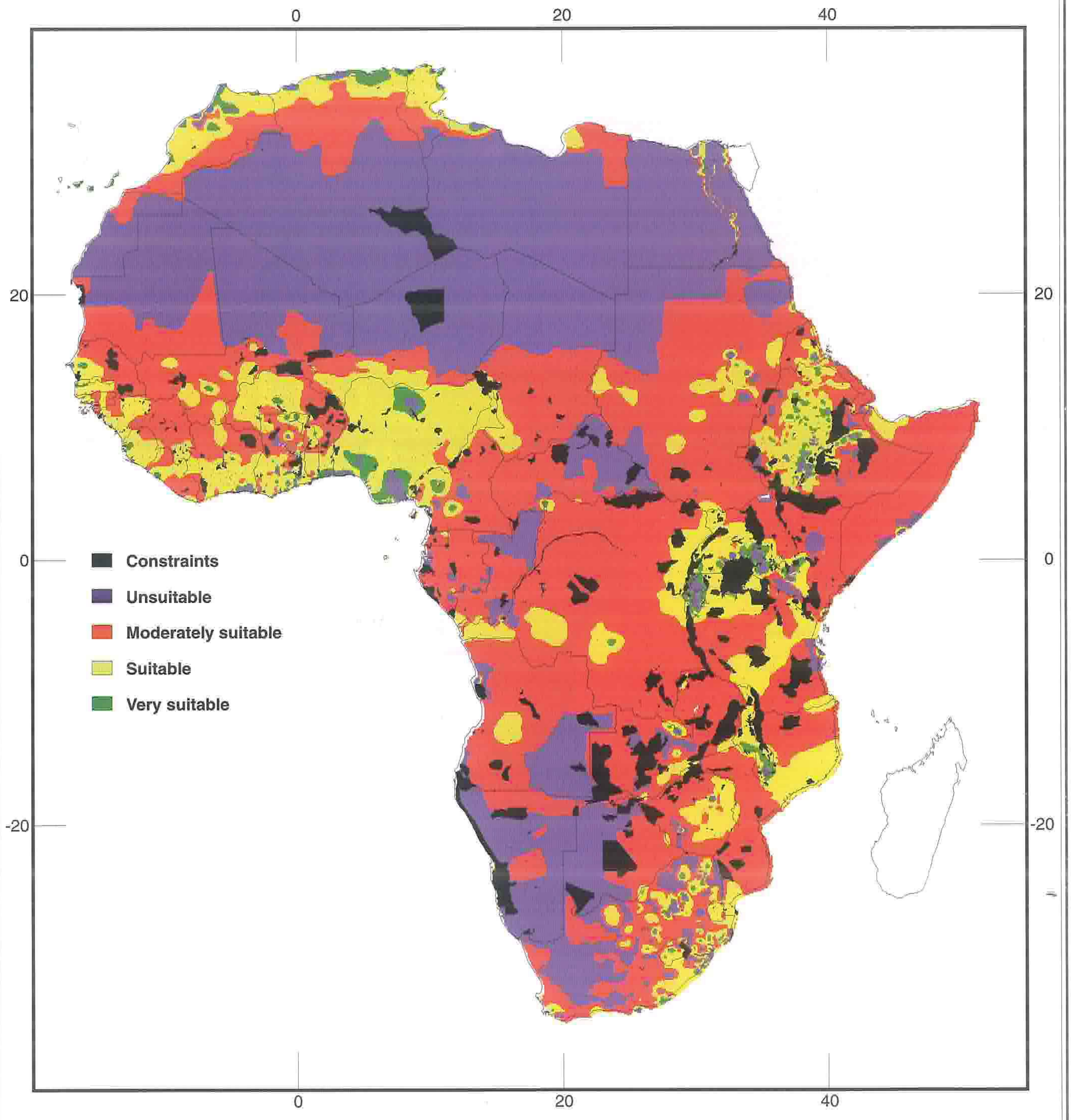


Figure 3.5
Potential for farm-gate sales

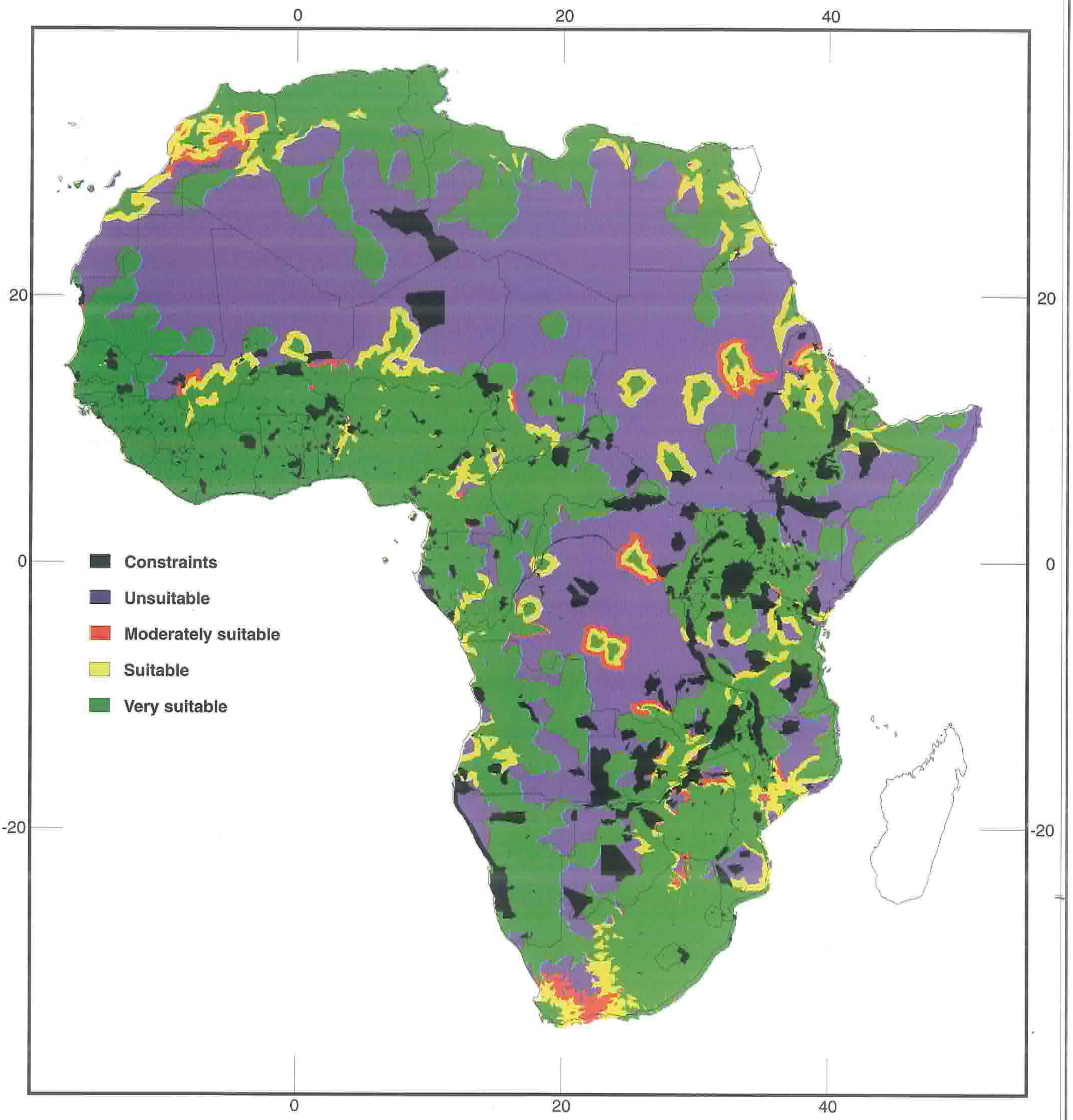


Figure 3.6
Potential market demand: commercial fish farming

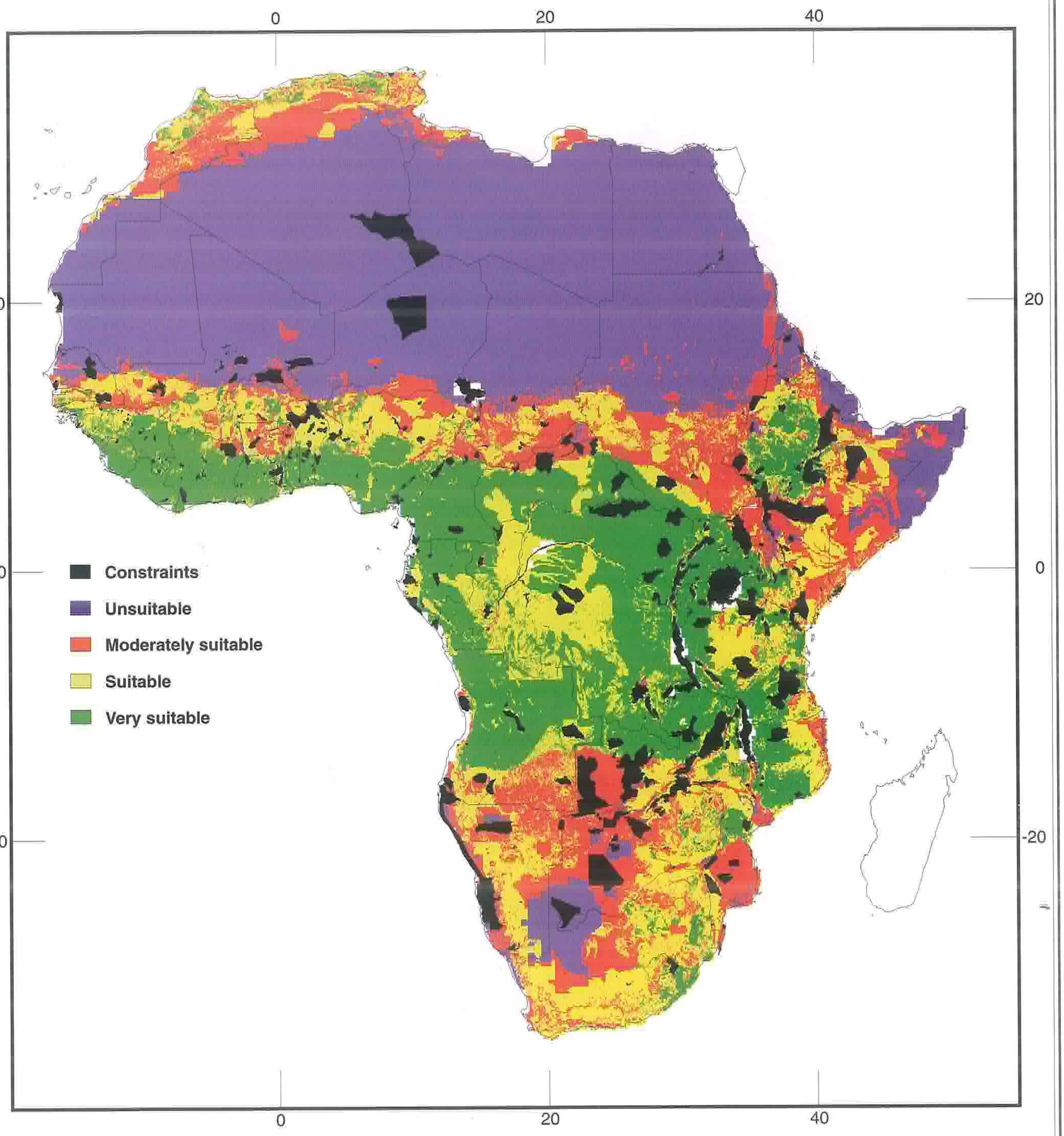


Figure 3.7
Suitability for small-scale fish farming

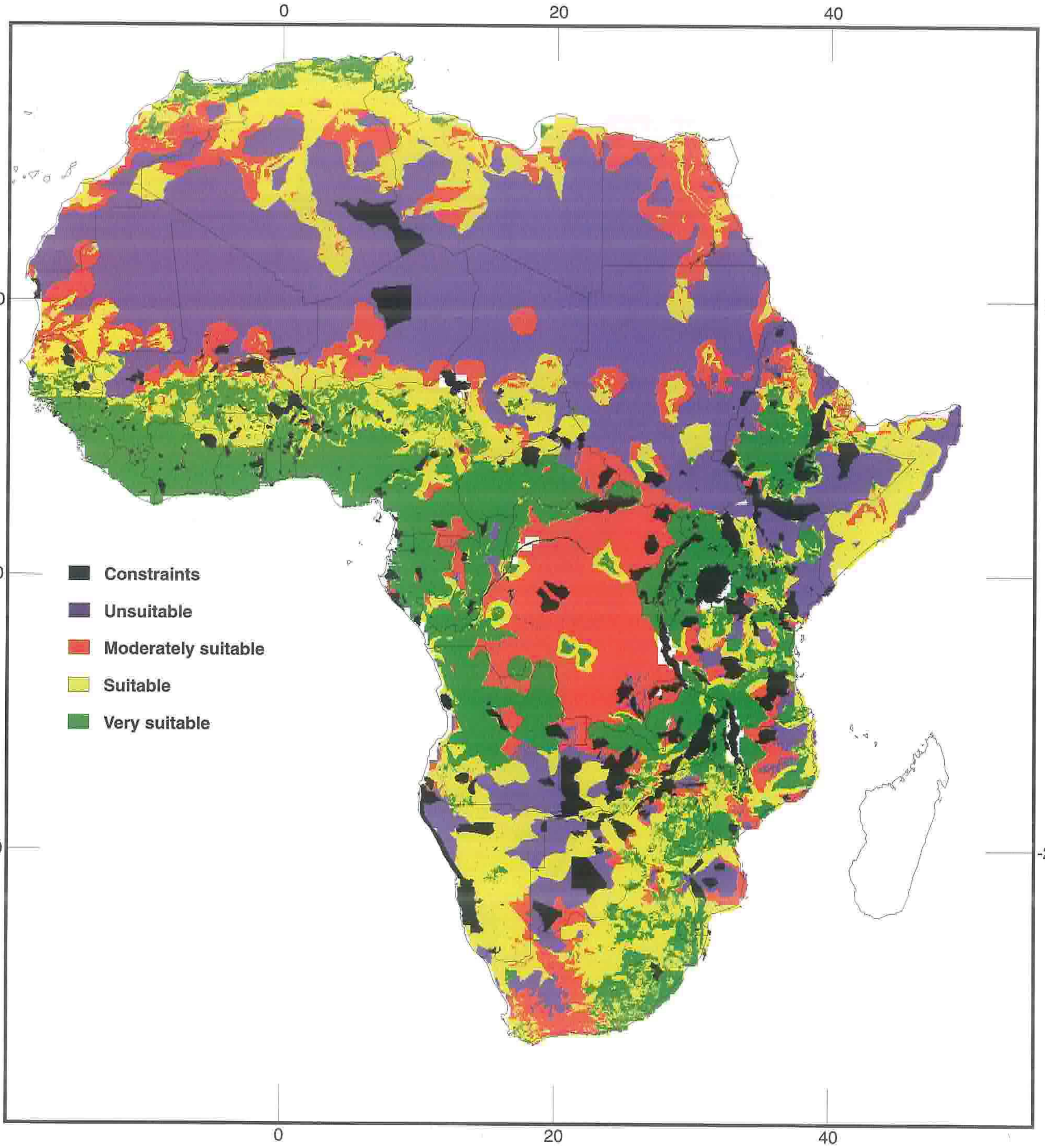


Figure 3.8
Suitability for commercial fish farming

Country-level overview

Constraints

Uganda, Zambia and Malawi stand out as countries with the largest extent of constraint areas (**Figure 3.1** and **3.9**). Zambia has the highest portion of protected areas (about 30% of its surface; **Figure 3.9**). Three countries (Malawi, Uganda and Burundi) have about 10 - 16 % of their areas containing large inland water bodies. Finally, Gambia, Burundi and Rwanda are countries with the highest concentration of major cities.

Factors for fish farming development and operation

Water requirement

Only one country, Sierra Leone, has a large area (about 60%) that is VS for water requirement and only 6 other countries score VS for 3 to 40% of their area (**Figure 3.2 and 3.10**). However, there are 25 countries that have 25% or more of their areas classified as S. Thirteen countries have no areas that score VS and relatively small areas that score S to MS for water requirement. In this regard, Egypt and Mauritania stand out as countries with 100% of their area classified as US, implying that water availability is likely to be a serious constraint in these countries (**Figure 3.10**).

Soil and terrain suitability for ponds

24 countries score VS (50% or more of their area) and 16 others score VS (25-50%) for this category of factors (**Figure 3.3 and 3.11**). Only five countries(Sudan, Egypt, Botswana, Chad and Djibouti) have very small surface areas that score VS (less than 15%; Figure 3.11).

Inputs

Burkina Faso and Togo are particularly favoured for inputs (**Figure 3.4**) and have about 50% of their area scored as VS. Eight additional countries have areas from 30 to 40% that score VS (**Figure 3.12**). Twenty-one countries have 25% or more of their areas that score S. However, 40 countries possess areas (10% or more) where inputs are potentially insufficient. Libya and West Sahara stand out as having nearly 100% of their area scored as US.

Farm-gate sales

Farm-gate sales seem to be limiting at the VS level (**Figure 3.5**), with only Burundi having 40% of its national area scored as VS (**Figure 3.13**). Only five countries (Rwanda, Malawi, Gambia, Nigeria and Uganda) have from 10 - 31% or more of their area scored as VS (**Figure 3.13**). Nevertheless, 24 countries have 25% or more of their areas scored as S. Egypt, Libya and West Sahara are notably lacking in market opportunities for farmed fish .

Urban market size and proximity

A large number of countries seem to be within reasonable proximity to large urban centres where there could be important markets for commercial fish farming development (**Figure 3.6**). 12 countries have 100% and eight additional countries have nearly 100% of their national areas scored VS for this factor (**Figure 3.14**). Most of the other countries have between 15 to 90% of their area scored as VS. Sudan was the only country with less than 15% of its surface area categorized as VS (**Figure 3.14**).

Small-scale and commercial farming models

Small-scale model

Of the 49 countries included in this study, 42 possess at least some land scored as VS (**Figure 3.7**). Among these, 16 countries that have 50-97% of their areas scored as VS. Liberia, Sierra Leone, Burundi, Rwanda and Côte d'Ivoire stand out as the top five countries within this category (**Figure 3.15**). In addition, nine countries have 30-50% scored as VS and another 22 countries have 25% or more of their areas scored as S (**Figure 3.15**).

Commercial model

In all, 46 countries have at least some of their land scored as VS (**Figure 3.8**). Among these, 21 countries have between 50% and 99% of their areas classified as VS. The top six countries for the VS category were: Liberia, Sierra Leone, Equatorial Guinea, Rwanda, Burundi and Uganda (**Figure 3.16**). Nine countries were found to have 30-50% scored as VS and another 19 have 25% or more of their areas scored as S (**Figure 3.16**).

Table 3.5 summarizes results of the farming system models, in terms of the number of countries with corresponding percentages of land area in the different suitability levels. **Table 3.6** lists the top ten countries (in rank order) that were found to possess the highest potential in terms of the quality of land for fish farming in ponds irrespective of the species used.

Table 3.5 Summary of farming system model results as number of countries by percentage land area by scoring levels (VS, S, MS and US).

SUBMODEL / AREA	VS 50% or more	S 25% or more	MS 25% or more	US 10% or more
Water	1	25	26	16
Soils	24	36	9	1
Inputs	2	21	14	40
Farm-gate	1	24	32	21
Urban	36	1	0	25
Small-scale	16	22	16	17
Commercial	21	19	5	20

Abbreviations: Water = water requirement for shallow ponds; Soils = soil an terrain suitability for fish ponds; Inputs = Livestock wastes and agricultural by-products; Farm-gate = Farm-gate sales; Urban = Urban market size and proximity.

Table 3.6 Top ten countries from farming system model results.

WATER	SOIL	INPUTS	FARM-GATE	URBAN	SMALL-SCALE	COMMERCIAL
Sierra Leone	Liberia	Burkina Faso	Burundi	Burundi	Liberia	Liberia
Liberia	Benin	Togo	Rwanda	Djibouti	Sierra Leone	Sierra Leone
E. Guinea	Côte d'Ivoire	Senegal	Malawi	E. Guinea	Burundi	E. Guinea
Cameroon	Rwanda	Tanzania	Gambia	Gambia	Rwanda	Rwanda
Guinea	Burundi	Nigeria	Nigeria	Côte d'Ivoire	Côte d'Ivoire	Burundi
Nigeria	Uganda	Burundi	Uganda	Lesotho	E. Guinea	Uganda
Gabon	Cameroon	Zimbabwe	Lesotho	Liberia	Uganda	Côte d'Ivoire
Congo, Rep.	E. Guinea	Gambia	Morocco	Rwanda	Cameroon	Guinea
Burundi	Gabon	Uganda	Ghana	Sierra Leone	Gabon	Gabon
Rwanda	Cent.Afr.Rep.	South Africa	Ethiopia	Togo	Congo, Dem. Rep. of	Togo

Figure 3.9 Relative surface area with constraints

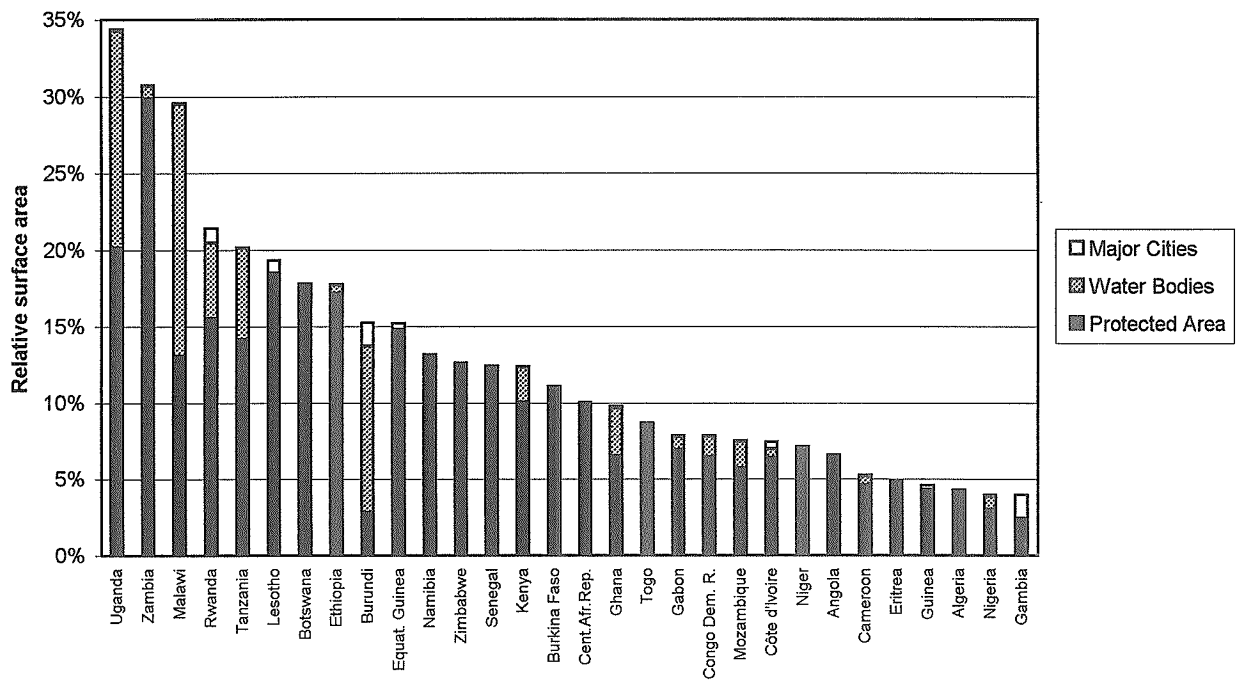
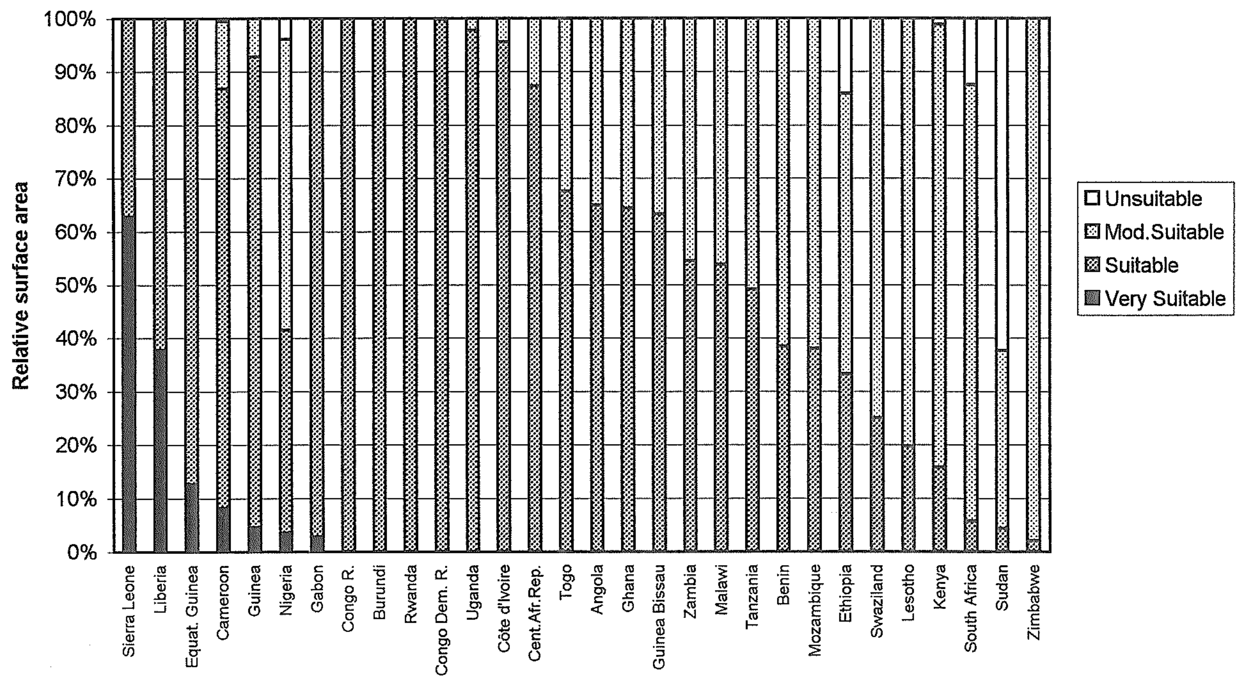


Figure 3.10 Relative surface area with net annual water requirement for shallow ponds



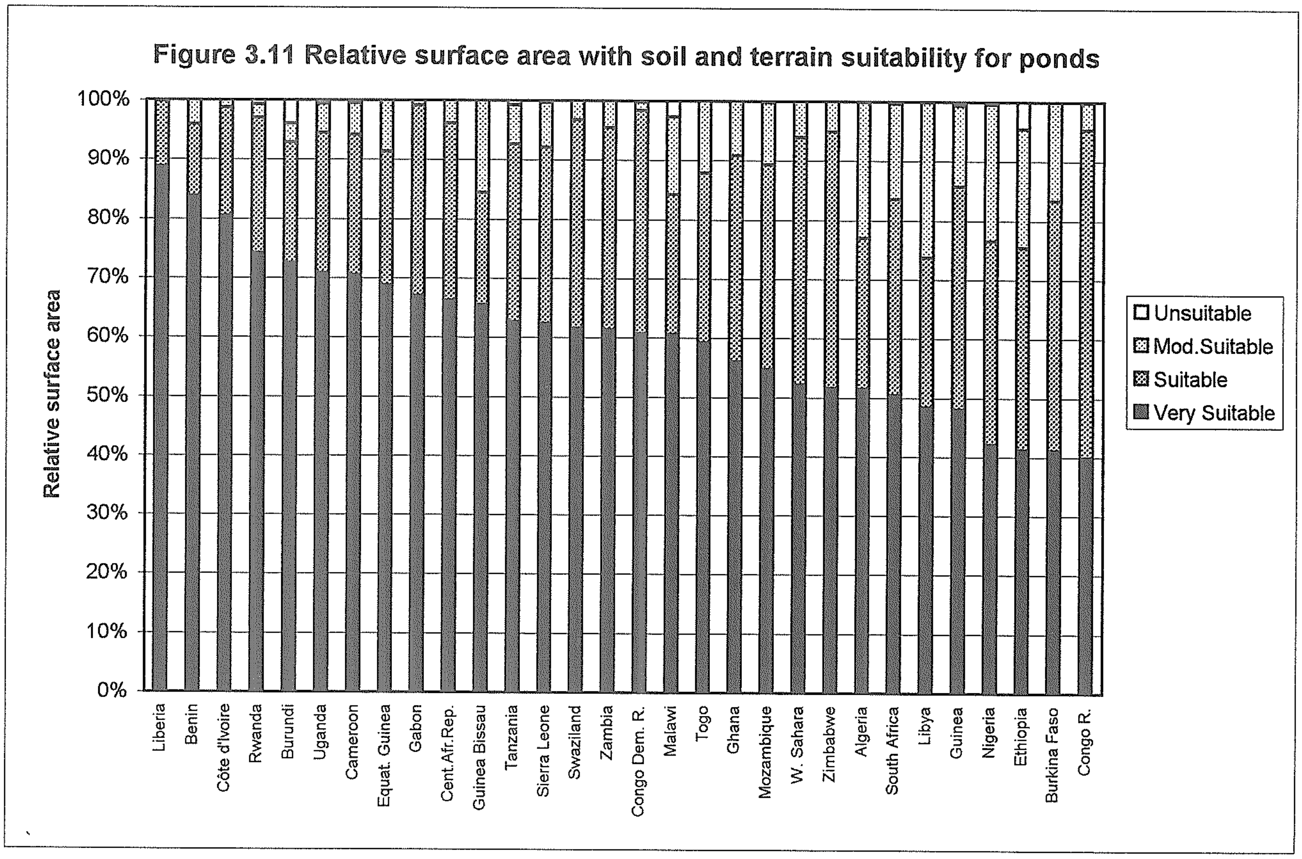


Figure 3.11 Relative surface area with soil and terrain suitability for ponds
Relative surface area
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Liberia
Benin
Côte d'Ivoire
Rwanda
Burundi
Uganda
Cameroon
Equat. Guinea
Gabon
Cent.Afr.Rep.
Guinea Bissau
Tanzania
Sierra Leone
Swaziland
Zambia
Congo Dem. R.
Malawi
Togo
Ghana
Mozambique
W. Sahara
Zimbabwe
Algeria
South Africa
Libya
Guinea
Nigeria
Ethiopia
Burkina Faso
Congo R.
Unsuitable
Mod.Suitable
Suitable
Very Suitable

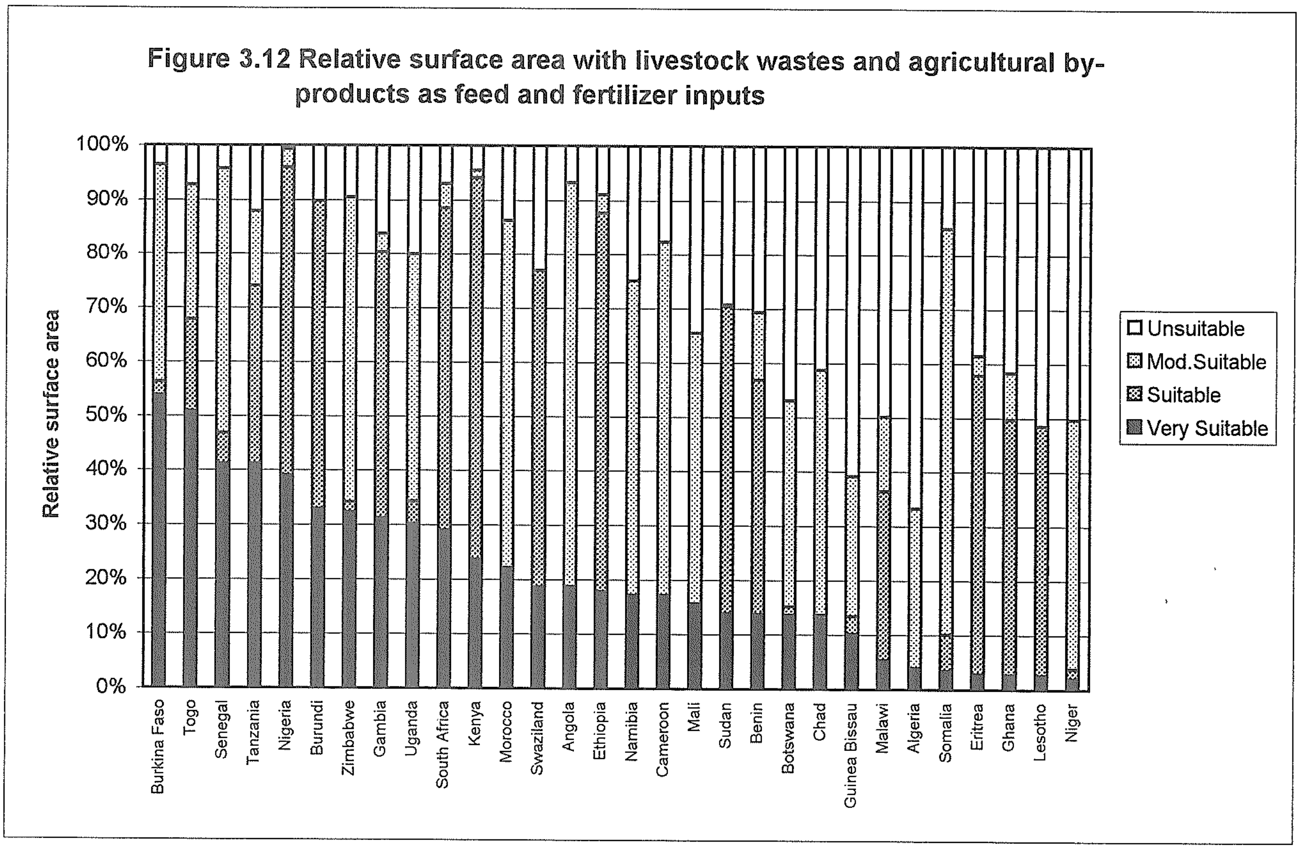


Figure 3.12 Relative surface area with livestock wastes and agricultural by-products as feed and fertilizer inputs
Relative surface area
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Burkina Faso
Togo
Senegal
Tanzania
Nigeria
Burundi
Zimbabwe
Gambia
Uganda
South Africa
Kenya
Morocco
Swaziland
Angola
Ethiopia
Namibia
Cameroon
Mali
Sudan
Benin
Botswana
Chad
Guinea Bissau
Malawi
Algeria
Somalia
Eritrea
Ghana
Lesotho
Niger
Unsuitable
Mod.Suitable
Suitable
Very Suitable

Figure 3.13 Relative surface area with potential for farm-gate sales

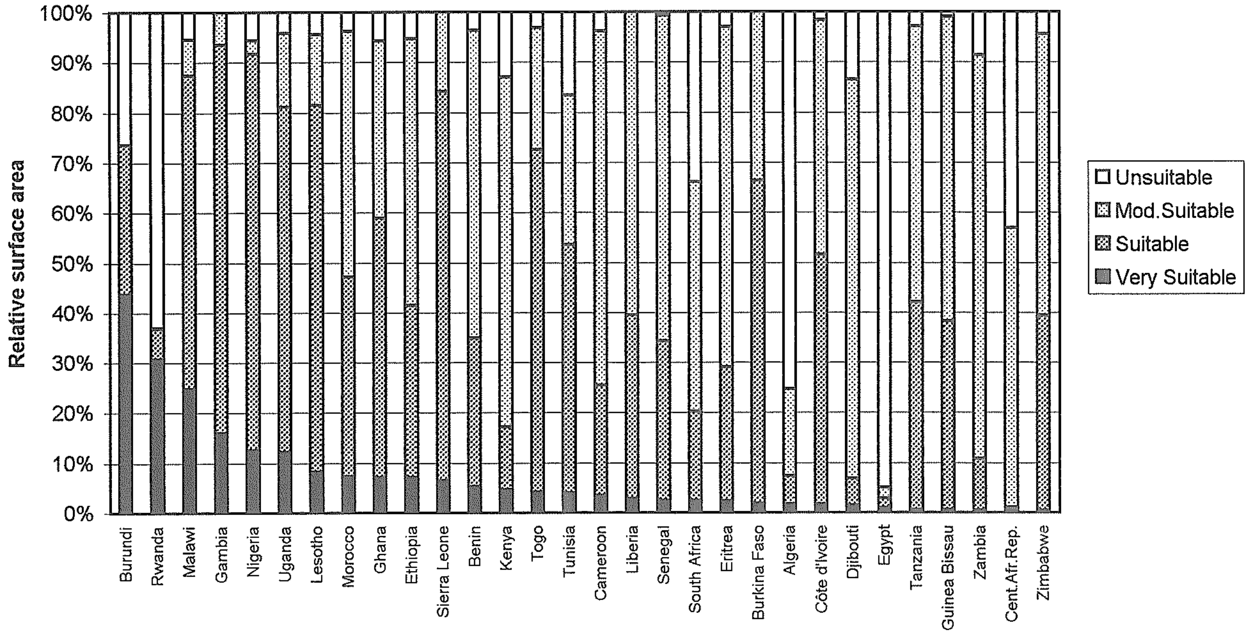


Figure 3.14 Relative surface area with market demand for commercial fish farming

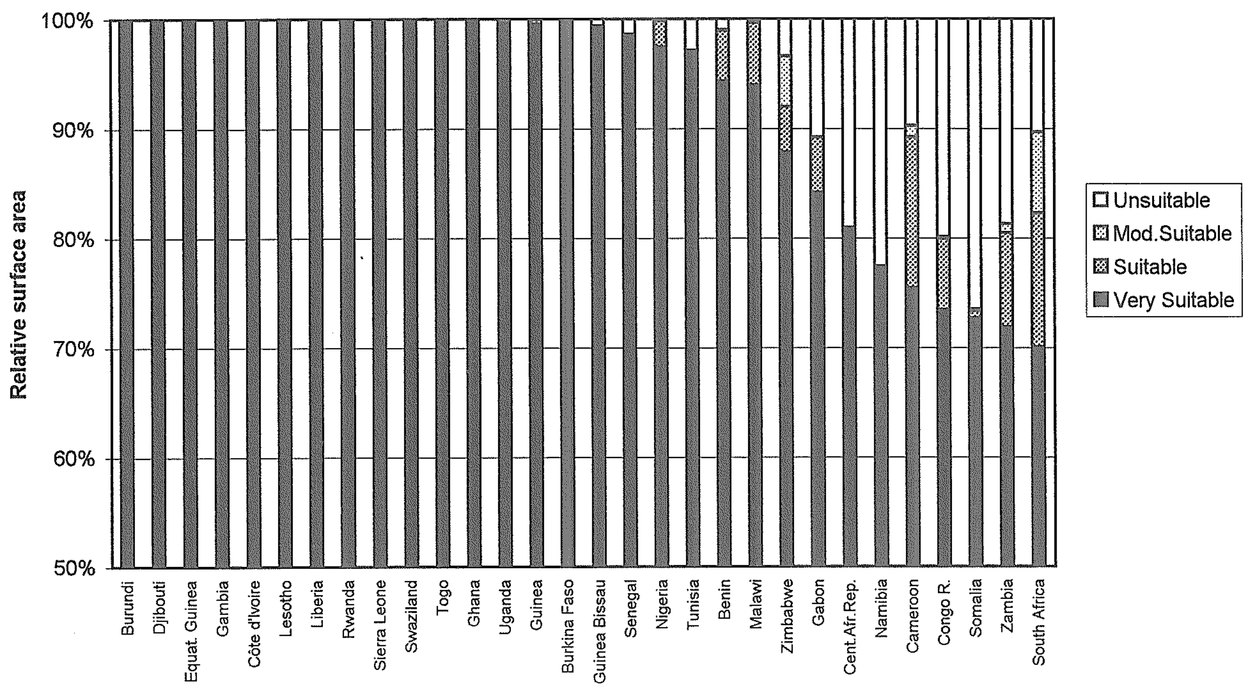


Figure 3.15 Relative surface area with suitability for small-scale fish farming

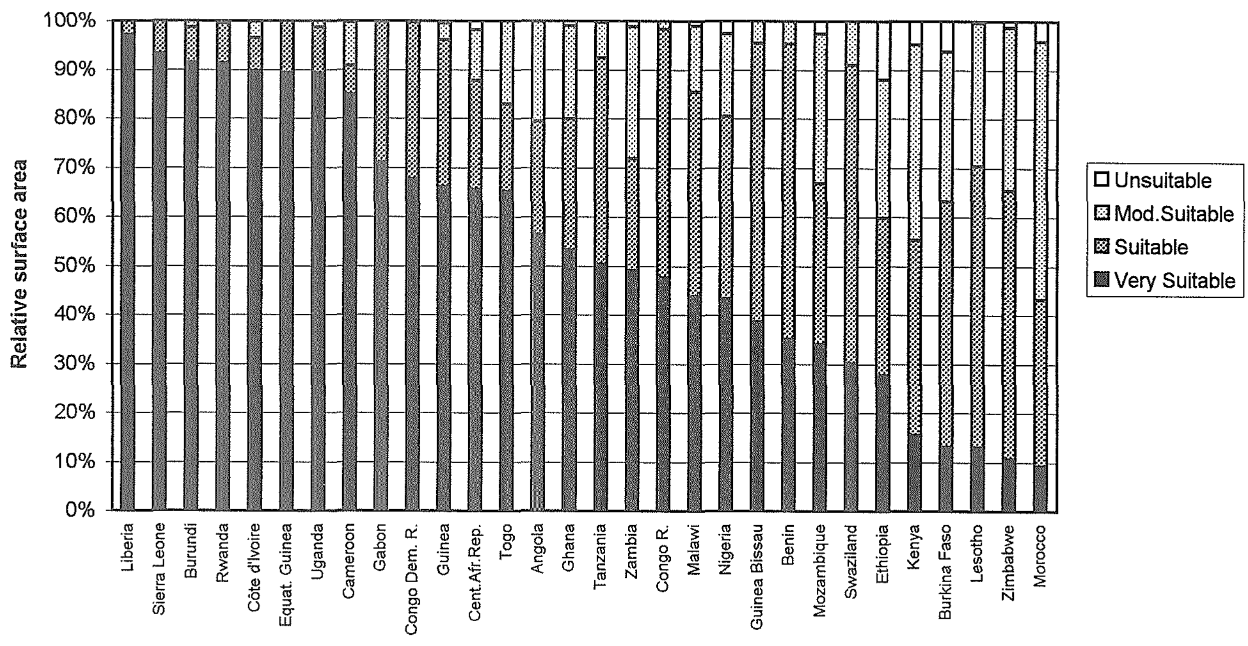
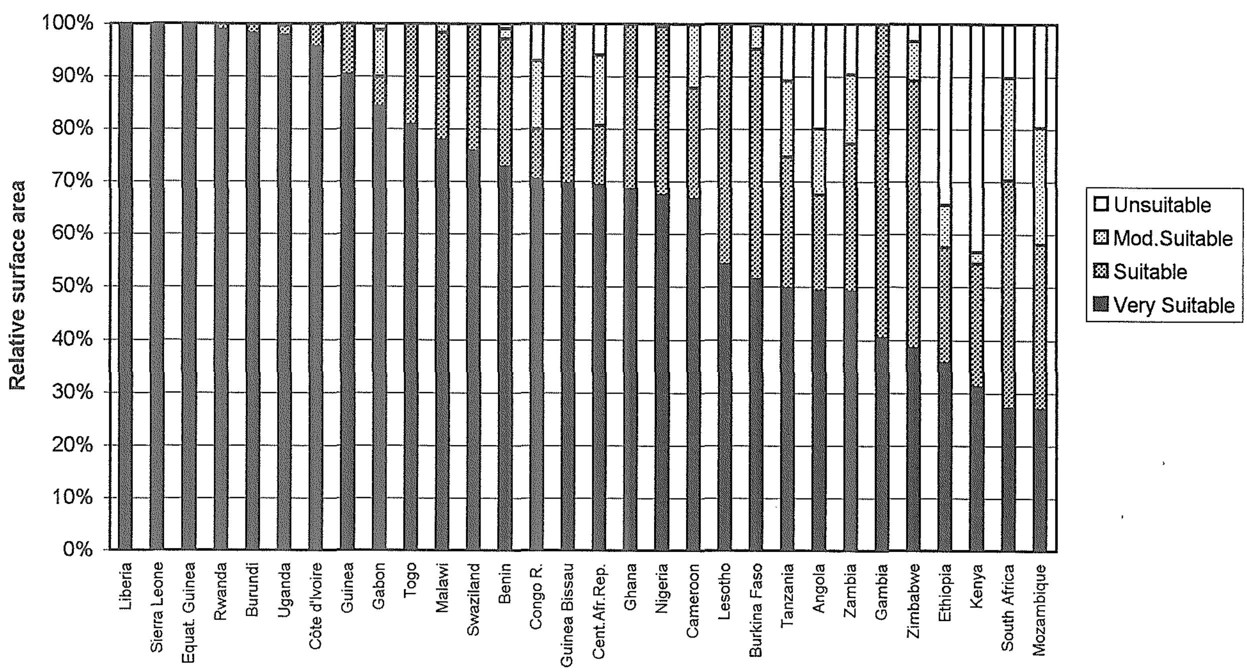


Figure 3.16 Relative surface area with suitability for commercial fish farming



3.3 Fish growth modelling

Continental overview

Statistical results of the fish growth models are presented for reference in **Table 3.7**. However, the primary output from the growth model that is of interest in the current study is the yield (in crops/y) for the three different fish species in different regions. Hence, these outputs are discussed below for each of the scenarios used to define commercial and small-scale aquaculture operations. For simplicity, crops/y results are separated into quarter (Q) parts of the ranges obtained for small-scale and commercial operations.

Table 3.7 Summary of statistical results for fish growth models (SD = Standard Deviation). Note that the feed requirement is not an output from the small-scale model, because we assume that fish subsist on natural food resources in small-scale operations.

		SMALL-SCALE		COMMERCIAL		
		Crops/y	Yield [kg/ha/y]	Crops/yr	Yield [kg/ha/y]	Feed [kg/ha/y]
Tilapia	Minimum*	0.1	122	0.1	721	780
	Maximum	1.7	2019	2.0	14454	23441
	Mean	1.2	1438	1.4	10307	17533
	SD	0.4	523	0.4	3225	5536
Catfish	Minimum*	0.1	101	0.1	963	454
	Maximum	2.4	2426	1.7	17484	24907
	Mean	1.9	1922	1.4	14331	20047
	SD	0.5	459	0.3	3285	4882
Carp	Minimum*	0.1	101	0.1	980	489
	Maximum	2.2	2314	1.5	13929	23009
	Mean	1.8	1836	1.1	11524	19584
	SD	0.4	430	0.2	2495	4170

* Minimum values for crops/y are the immediate values after zero (0.0 or No crops).

Over 50% of Africa has land areas with 1stQ yields for the three fish species and for both types of farming systems. The largest surface areas scored in the 1stQ yield range were found for Common carp and African catfish (**Table 3.8**). For small-scale farming, Common carp stands out as having the largest surface area scored in this yield range (about 76%) and for commercial farming African catfish and Common carp have similar surface areas (70 and 66% respectively).

Table 3.8 Suitability of fish yields (crops/y) for fish farming development and operation as a percentage of the surface area in continental Africa.

FARMING SYSTEM / FISH SPECIES		1stQ	2ndQ	3rdQ	4thQ	No Crops
Small-scale	Nile tilapia	51.6	17.3	22.8	8.3	0.07
	African catfish	53.5	33.4	12.5	0.60	0.02
	Common carp	76.3	19.0	4.5	0.09	0.02
Commercial	Nile tilapia	53.0	27.9	15.5	3.5	0.21
	African catfish	70.4	21.6	7.5	0.5	0.03
	Common carp	66.5	26.4	6.1	1.0	0.02

The spatial distribution of the 1stQ yield ranges are very similar for the three fish species (**Figures 3.17** to **3.22**) with most of these sites distributed across Africa, north and south of the equator. Common carp and African catfish have similar results for both small-scale and commercial systems; however, the primary difference is that areas with 1st Q suitability are higher for the former under small-scale conditions (**Table 3.8**). For commercial systems, African catfish apparently have higher potential compared to Common carp. The spatial distributions for the two types of farming systems for Nile tilapia (Figure 3.17 and 3.20; Table 3.8) are similar. However, the small-scale system does show larger spatial areas in the 4thQ yield range for this species (Table 3.8). When comparing Common carp and African catfish to Nile tilapia, more surface areas in the 4thQ yield range for the latter species appear in North Africa (Morocco and Algeria), Southern Africa (Namibia) and in East Africa (Ethiopia, Kenya, Uganda and Tanzania).

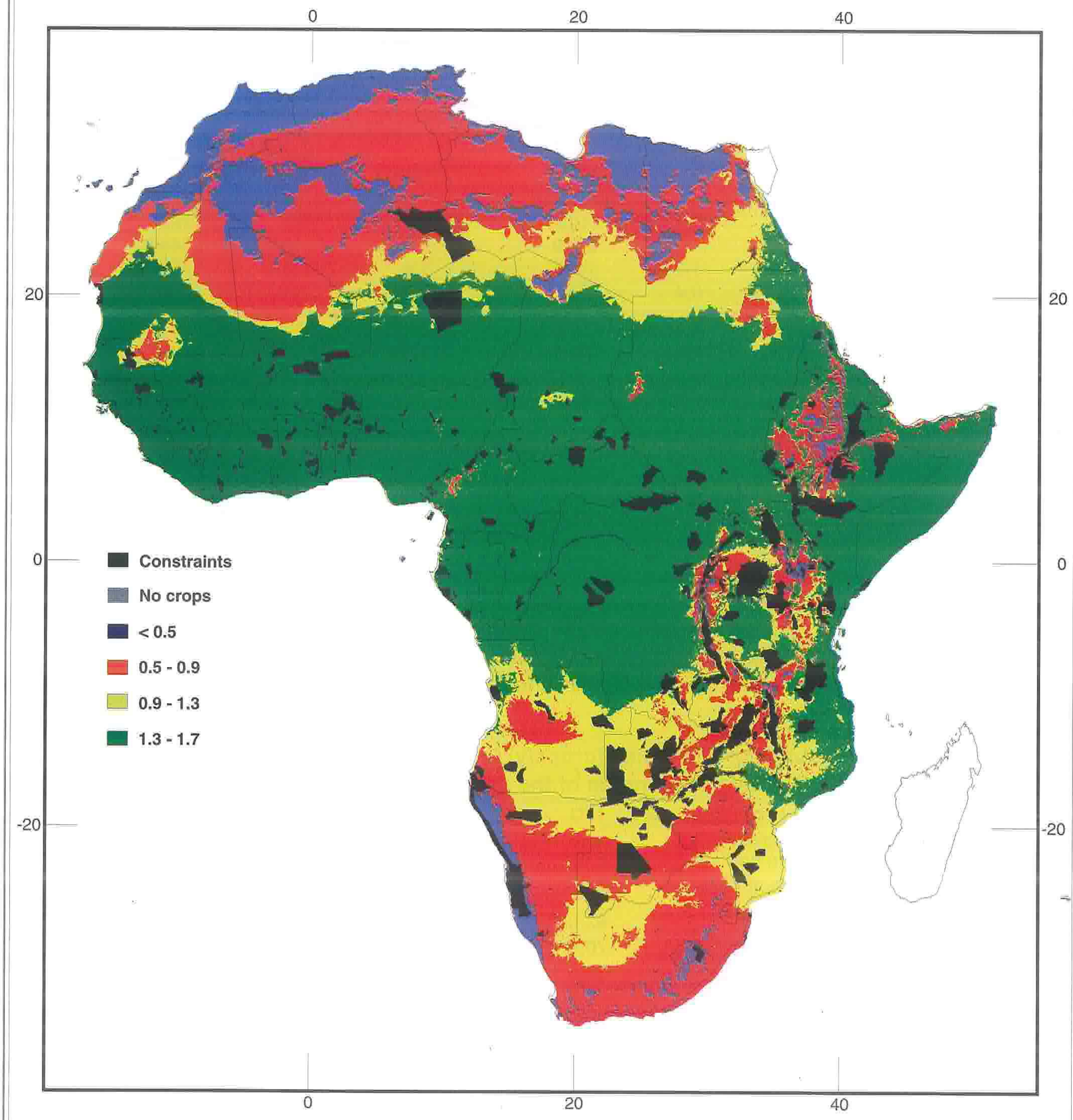


Figure 3.17
Potential yield (crops/y) of Nile tilapia - Small-scale farming

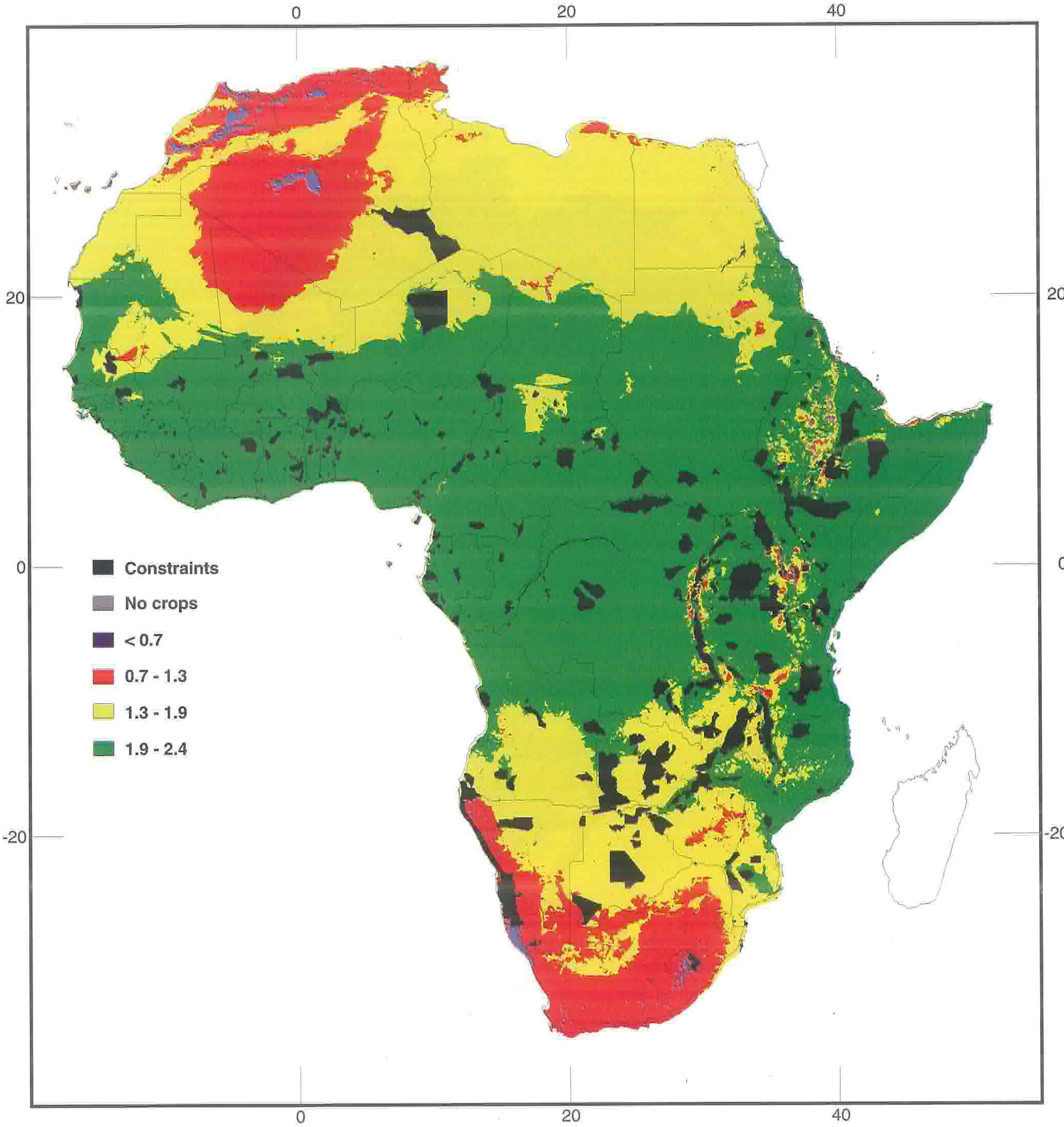


Figure 3.18
Potential yield (crops/y) of African catfish - Small-scale farming

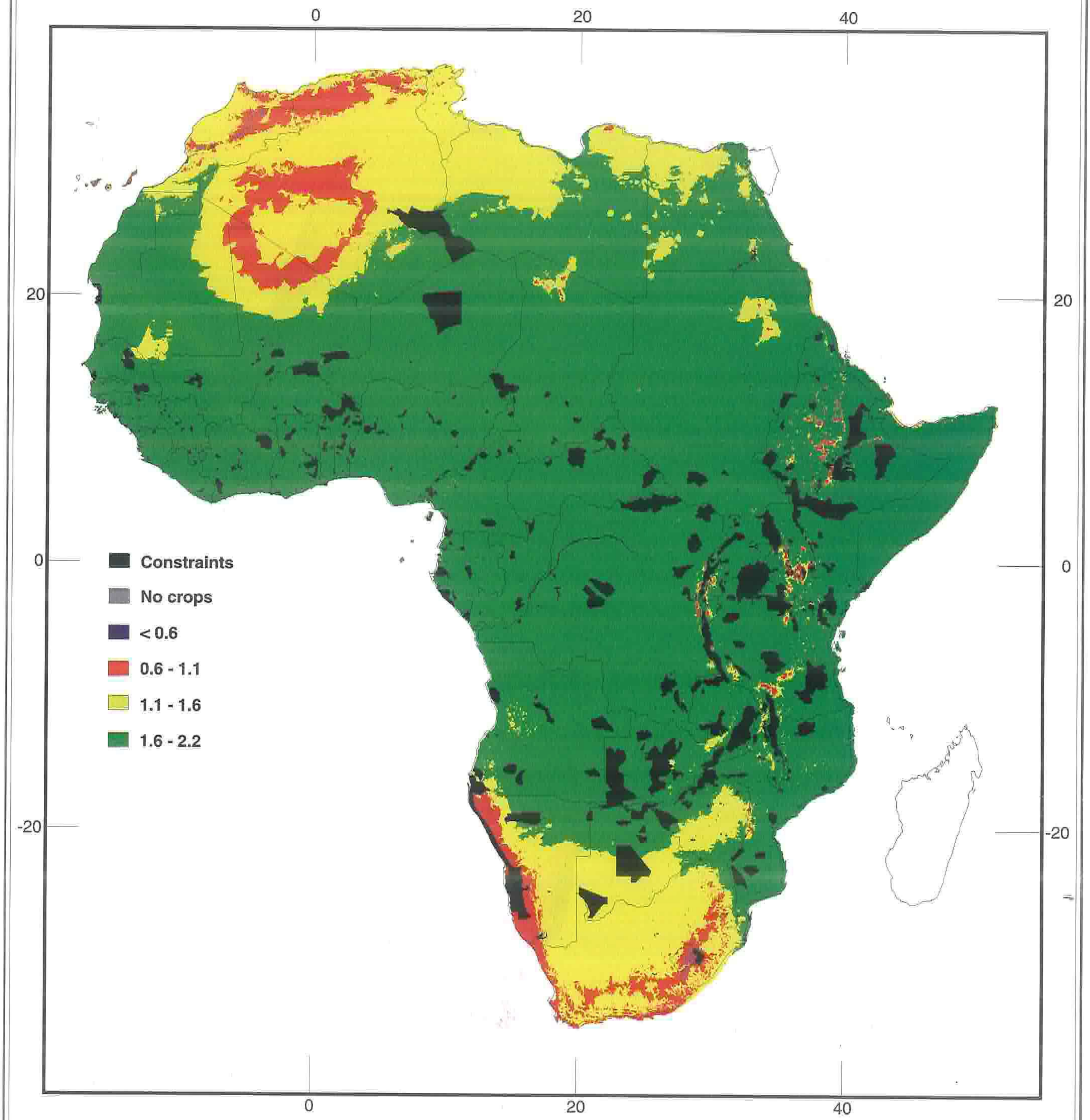


Figure 3.19
Potential yield (crops/y) of Common carp - Small-scale farming

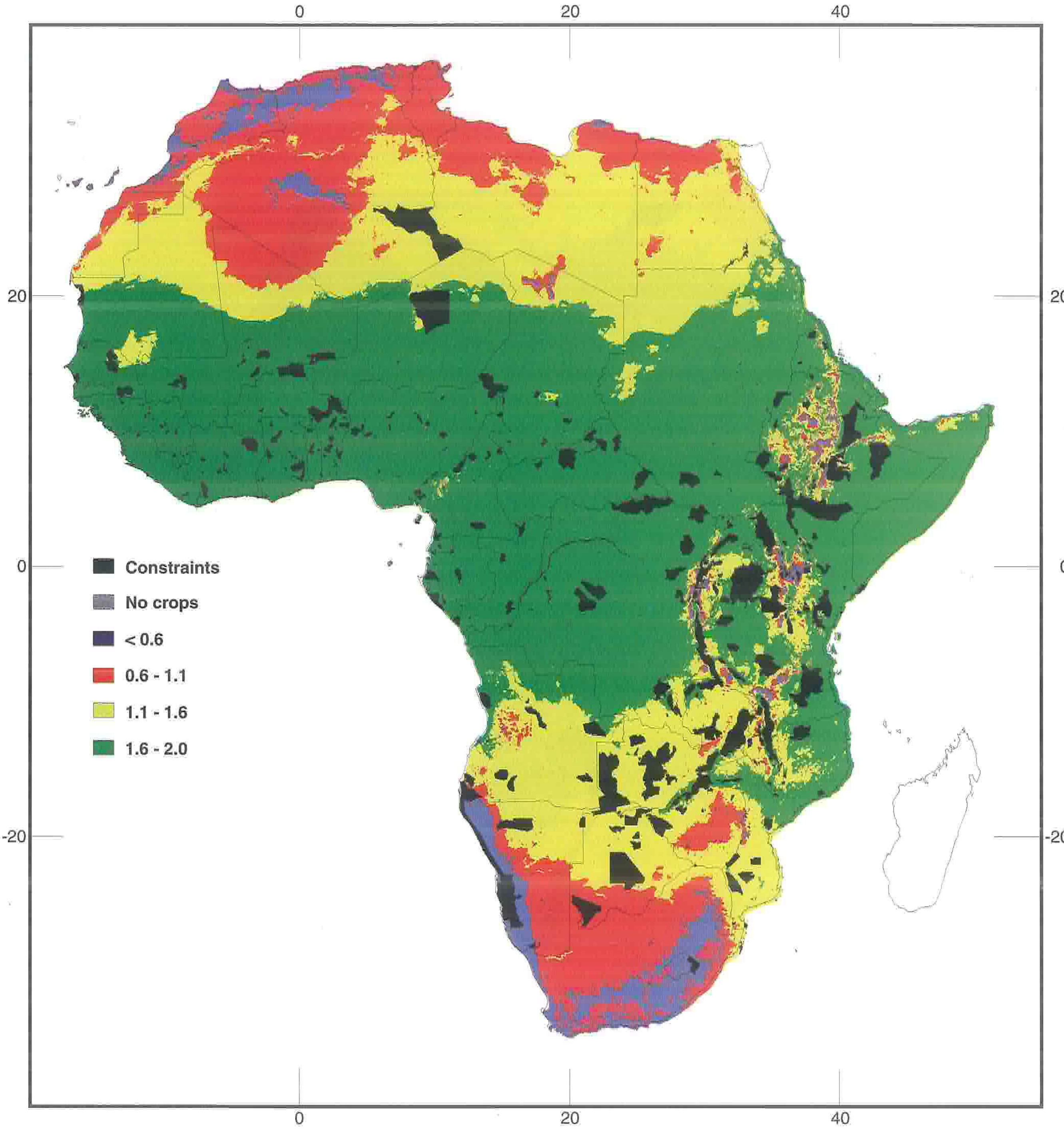


Figure 3.20
Potential yield (crops/y) of Nile tilapia - Commercial farming

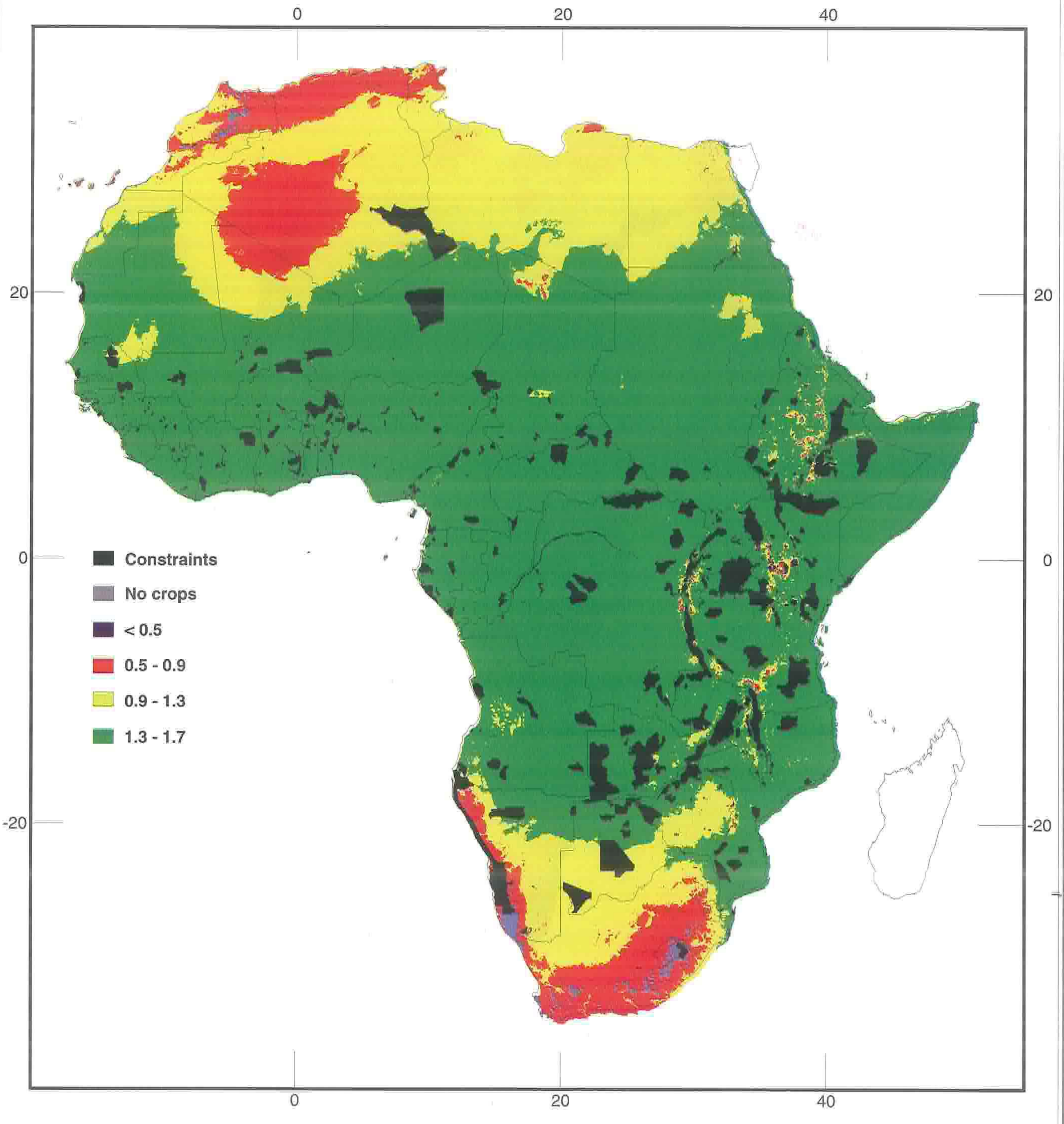


Figure 3.21
Potential yield (crops/y) of African catfish - Commercial farming

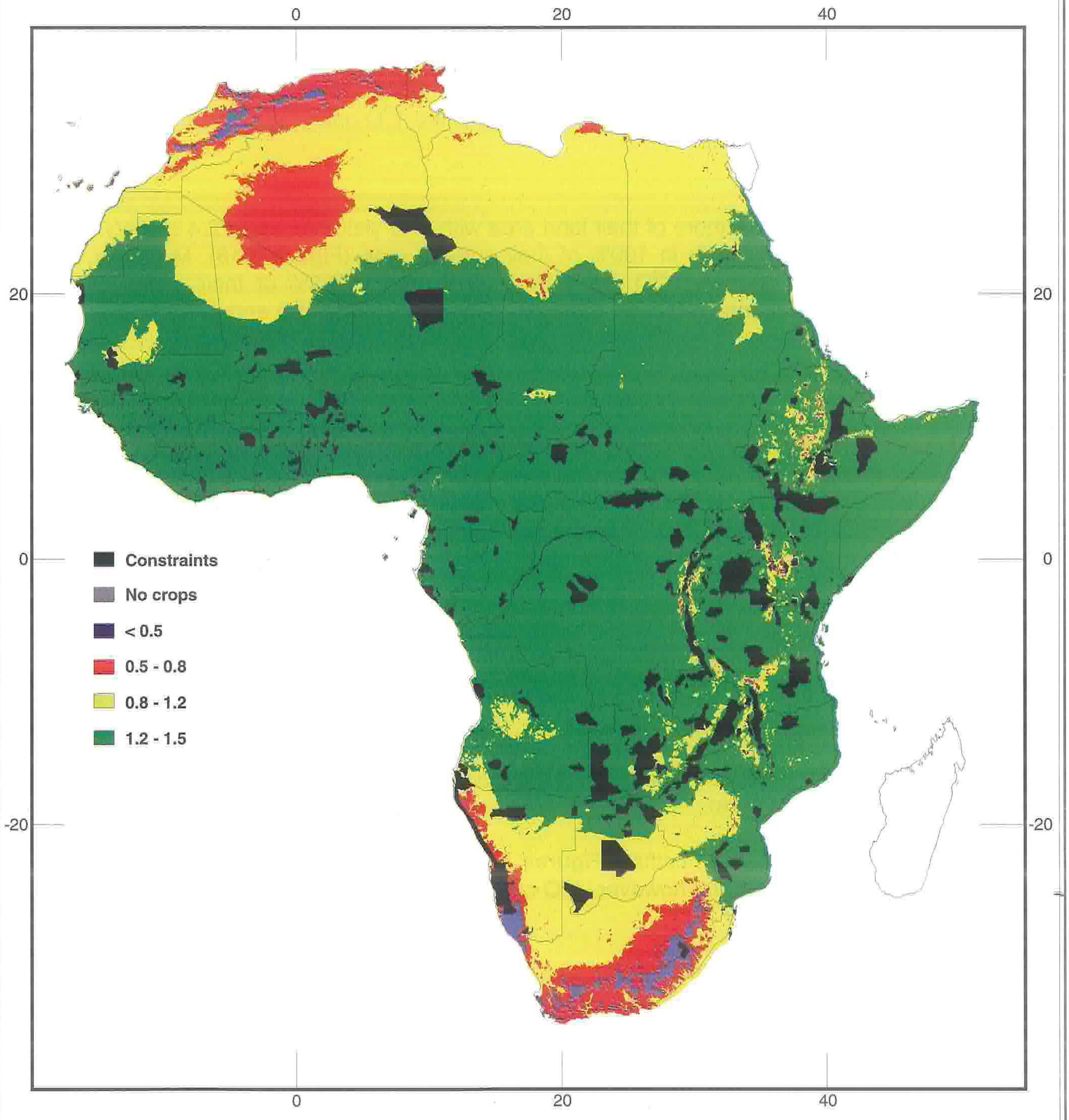


Figure 3.22
Potential yield (crops/y) of Common carp - Commercial farming

Country-level overview

Small-scale farming

Nile tilapia

The spatial distribution of small-scale culture opportunities for Nile tilapia (**Figure 3.17**) is considerably more restrictive compared to the other two species (**Figure 3.18, 3.19**). However, 1^{st}Q yields of 1.3 to 1.7 crops/y can be obtained in 50% or more of 29 countries, eight of which possess 1^{st}Q yields in 100% of their surface area (**Figure 3.23**). Zambia, Angola and Mozambique stand out as having 2^{nd}Q yields from 50 to 70% of their area. Only Lesotho and Tunisia offer no possibilities for yields in the 1^{st}Q and 2^{nd}Q ranges.

African catfish

32 countries have 50% or more of their land area with 1^{st}Q yields of 1.9 to 2.4 crops/y. Ten countries possess 1^{st}Q yields in 100% of their surface area (**Figure 3.18**). Moreover, an additional 12 countries have 2^{nd}Q yields from 50 to nearly 100% of their surface area (**Figure 3.24**). Only Lesotho offers no possibilities for yields in the 1^{st}Q and 2^{nd}Q ranges.

Common carp

Opportunities for small-scale farming of Common carp are extensive (**Figure 3.19**). 39 countries possess 50 to 100% of their land area with 1^{st}Q yields of 1.6 to 2.2 crops/y, 16 of which have 1^{st}Q yields in 100% of their surface area (**Figure 3.25**). An additional seven countries contain 2^{nd}Q yields in 50% or more of their area (**Figure 3.25**). Lesotho is the only country with no possibilities in the 1^{st}Q range.

Commercial farming

As was the case for small-scale farming, the spatial distribution of Nile tilapia (**Figure 3.20**) is more restrictive compared to the other two species (**Figure 3.21, 3.22**). However, the same group of Central African, SE and NW African countries maintain 1^{st}Q crops/y potential. With the exception of eight countries, all African countries are disadvantaged at the 1^{st}Q range (**Figure 3.26**).

The spatial pattern of African catfish (**Figures 3.21 and 3.27**) is similar to that of Common carp (**Figures 3.22 and 3.28**); however, 1^{st}Q crops areas are larger for African catfish.

In summary, as would be expected for a species with a relatively wide temperature range for growth, the spatial distribution of Common carp culture is greater compared to the other species (**Table 3.9**). Common carp and Nile tilapia contrast greatly in the spatial distribution of fish yield potential for both types of culture systems. Nile tilapia is apt for small-scale and commercial farming in as many countries as Common carp and African catfish, but Nile tilapia potential extends over a much smaller area (**Table 3.9**). The countries which possess 1^{st}Q yields in 100% of their surface area are listed by species in **Table 3.10**.

All countries have at least some capability to support a reasonable range of yields except for Lesotho which offers no possibilities in the 1^{st}Q and 2^{nd}Q yield ranges.

Table 3.9 Summary of fish yields results as number of countries by percentage land area for the 1stQ and 2ndQ crops/y range.

	1stQ RANGE			2ndQ RANGE
AREA	50% or more	100%	90 - 99%	50% or more
Small-scale				
Tilapia	29	8	9	3
Catfish	32	10	11	12
Carp	39	16	16	7
Commercial				
Tilapia	31	9	11	9
Catfish	37	15	16	8
Carp	36	14	14	9

Table 3.10 Top countries with fish yield potential (1stQ crops/y) in 100% of their land area.

SMALL-SCALE			COMMERCIAL		
TILAPIA	**CATFISH**	**CARP**	**TILAPIA**	**CATFISH**	**CARP**
Benin	Benin	Benin	Benin	Benin	Benin
Burkina Faso	Congo, Rep.	Burkina Faso	Burkina Faso	Burkina Faso	Burkina Faso
Congo, Rep.	E. Guinea	Cent.Afr.Rep.	Cent.Afr.Rep.	Cent.Afr.Rep.	Centr.Afr.Rep.
Gambia	Gabon	Congo, Rep.	Congo, Rep.	Congo, Rep.	Congo, Rep.
Ghana	Gambia	E. Guinea	Gambia	E. Guinea	E. Guinea
Guinea Bissau	Ghana	Gabon	Ghana	Gabon	Gabon
Côte d'Ivoire	Guinea Bissau	Gambia	Guinea Bissau	Gambia	Gambia
Togo	Côte d'Ivoire	Ghana	Côte d'Ivoire	Ghana	Ghana
	Liberia	Guinea	Togo	Guinea	Guinea
	Togo	Guinea Bissau		Guinea Bissau	Guinea Bissau
		Côte d'Ivoire		Côte d'Ivoire	Côte d'Ivoire
		Liberia		Liberia	Liberia
		Niger		Nigeria	Sierra Leone
		Nigeria		Sierra Leone	Togo
		Sierra Leone		Togo	
		Togo			

Figure 3.23 Relative surface area with potential yield (crops/y) of Nile tilapia - Small-scale farming

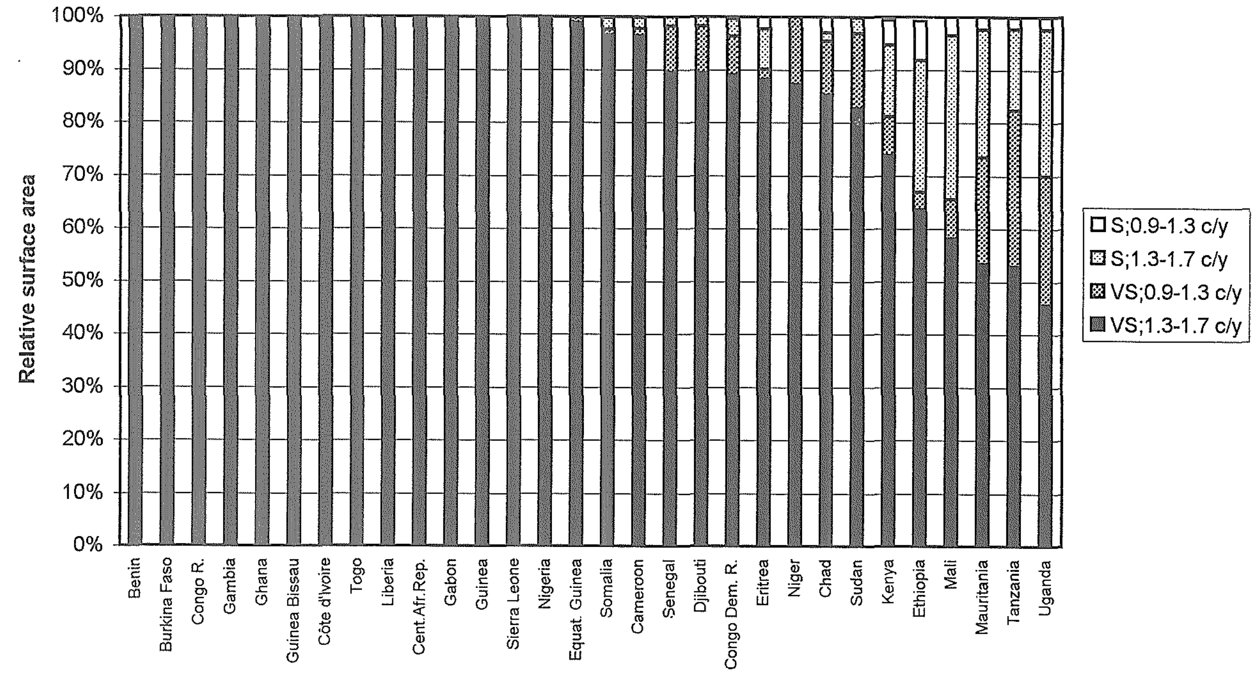


Figure 3.24 Relative surface area with potential yield (crops/y) of African catfish - Small-scale farming

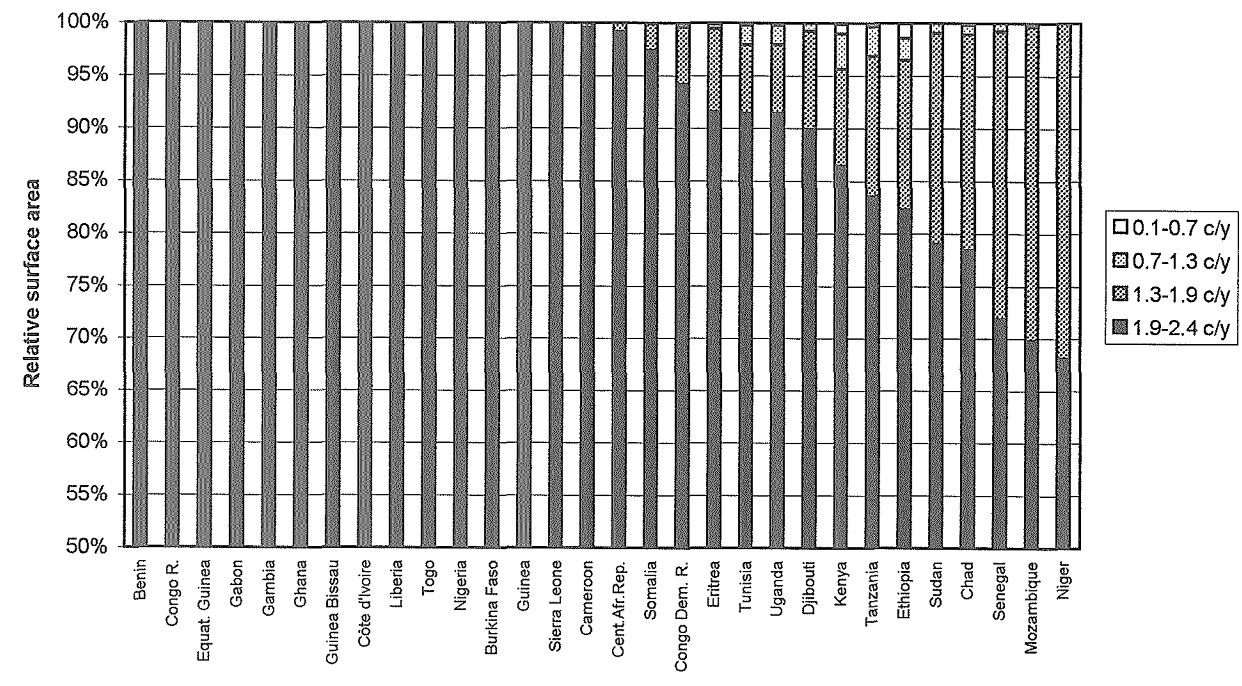


Figure 3.25 Relative surface area with potential yield (crops/y) of Common carp - Small-scale farming

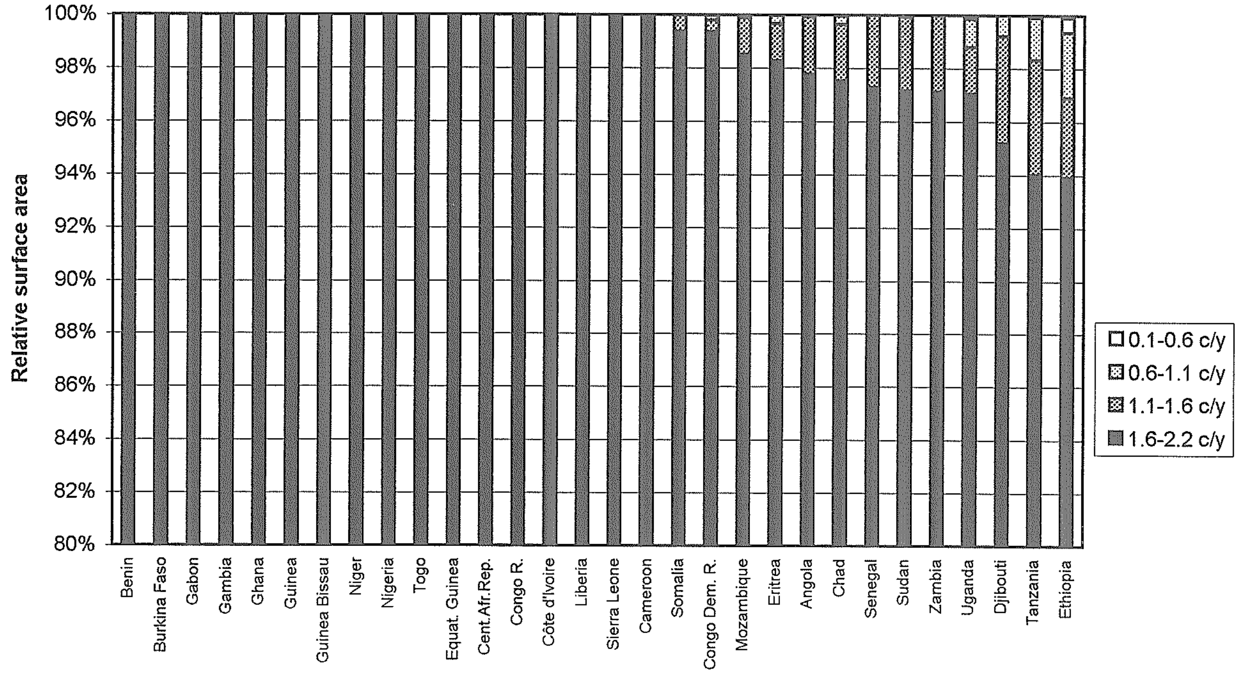


Figure 3.26 Relative surface area with potential yield (crops/y) of Nile tilapia Commercial farming

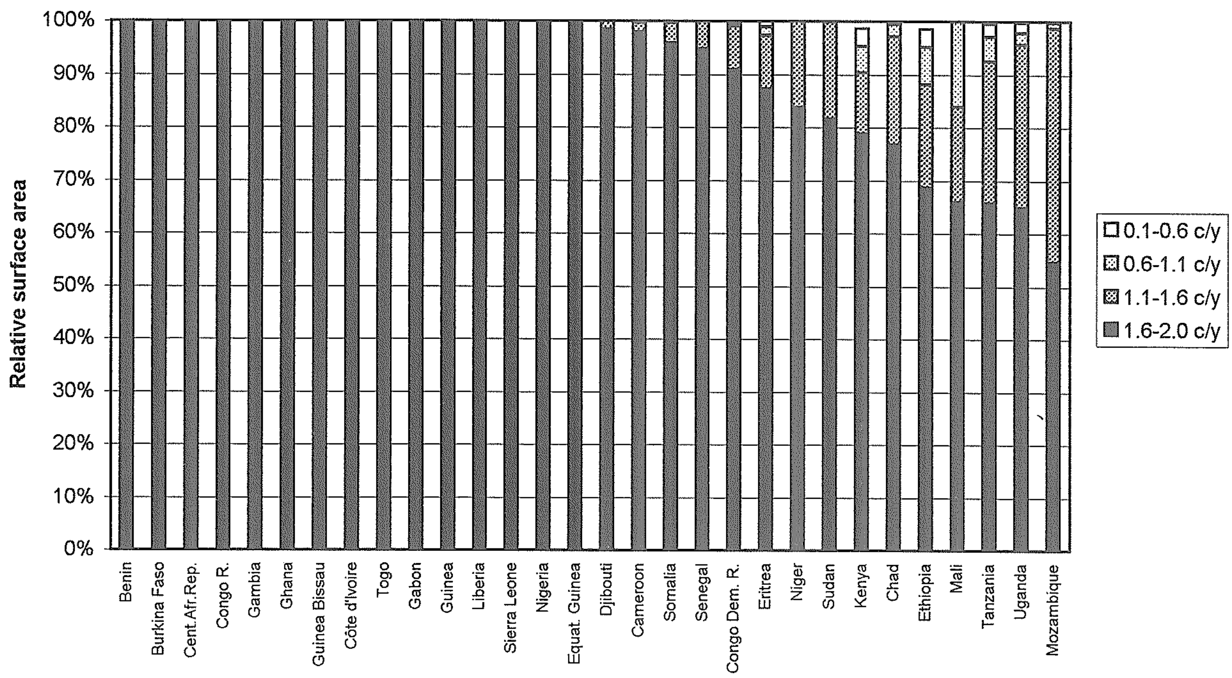


Figure 3.27 Relative surface area with potential yield (crops/y) of African catfish - Commercial farming

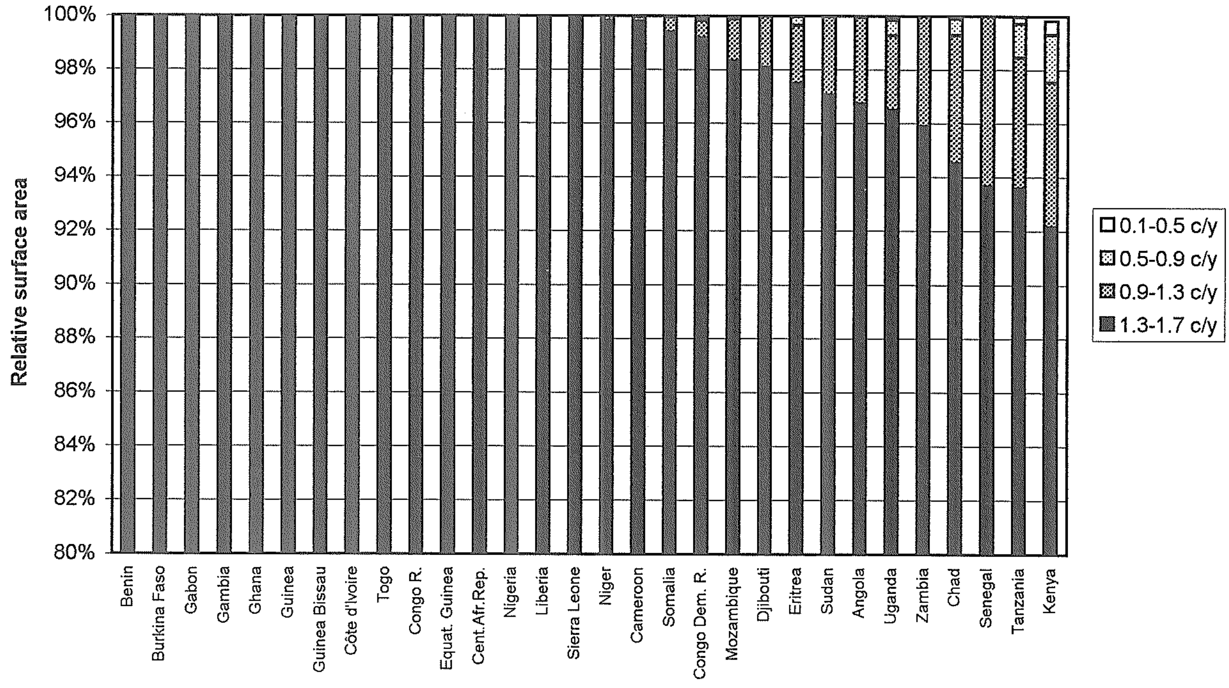
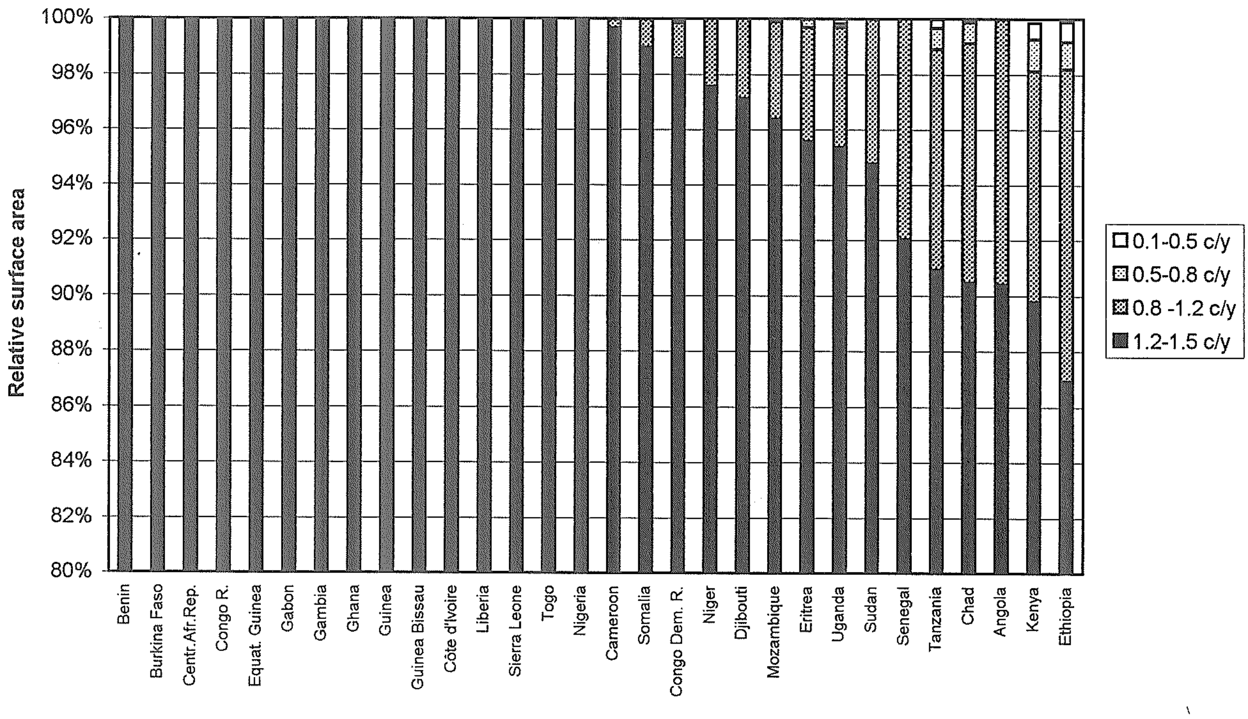


Figure 3.28 Relative surface area with potential yield (crops/y) of Common carp - Commercial farming



3.4 Combination estimates of the potential for small-scale and commercial farming system models with the fish growth models.

Continental overview

Despite the constraints imposed by meeting the requirements of the farming system models along with those of favourable for fish yields, over 15% of Africa has land areas scored as VS-1stQ for the three fish species and for both types of culture systems (**Table 3.11**). The largest surface area scored in the VS-1stQ combinations was found for Common carp in the small-scale model. Nile tilapia stands out as being markedly more restrictive than the other two species in the VS-1stQ; however, the opposite occurs in the VS-2ndQ and VS-3rdQ combinations (**Table 3.11**).

With regard to the S-1stQ and S-2ndQ combinations, Nile tilapia potential again extends over a smaller area in comparison to the other two species (**Table 3.11**).

Much of the relatively high yield potential is lost and assigned to other combinations as in the case of land areas scored as MS-3rdQ, where Nile tilapia has a higher potential compared with the other two species.

Table 3.11 Suitability of farming system models combined with fish yields (crops/y) for fish farming development and operation as a percentage of the surface area in continental Africa.

	VS-1stQ	VS-2ndQ	VS-3rdQ	S-1stQ	S-2ndQ	S-3rdQ	MS-1stQ	MS-2ndQ	MS-3rdQ
Small-scale									
Tilapia	15.5	3.5	2.9	11.9	2.5	4.8	8.3	3.5	3.5
Catfish	18.5	3.2	0.8	13.1	3.8	3.4	8.8	5.5	2.5
Carp	21.2	1.0	0.4	15.4	3.9	1.1	12.1	3.8	1.0
Commercial									
Tilapia	15.4	4.4	2.0	10.4	5.7	5.8	11.4	3.5	2.5
Catfish	19.7	1.7	1.4	13.9	6.5	2.6	13.5	3.5	1.0
Carp	19.0	2.5	1.1	13.3	7.3	2.3	13.1	4.0	0.8

The influence of the two types of farming system models on fish yield output is clearly shown in the spatial pattern of the combined results (**Figures 3.29 to 3.34**). The major difference between the two culture systems is that the commercial results show patchy distributions attributed to the urban market size and proximity submodel, a feature that is not present in the small-scale model results.

Very suitable sites with 1stQ yield ranges for small-scale farming of the three fish species are located across Africa between 14° - 20° S and 17° - 40° E. Very suitable locations with 1stQ yield ranges for commercial farming are also located within this geographical range. However, the importance of the urban market size and proximity submodel does identify other areas not identified in the small-scale model as having higher or lower potential such as the Democratic Republic of the Congo and South Africa respectively.

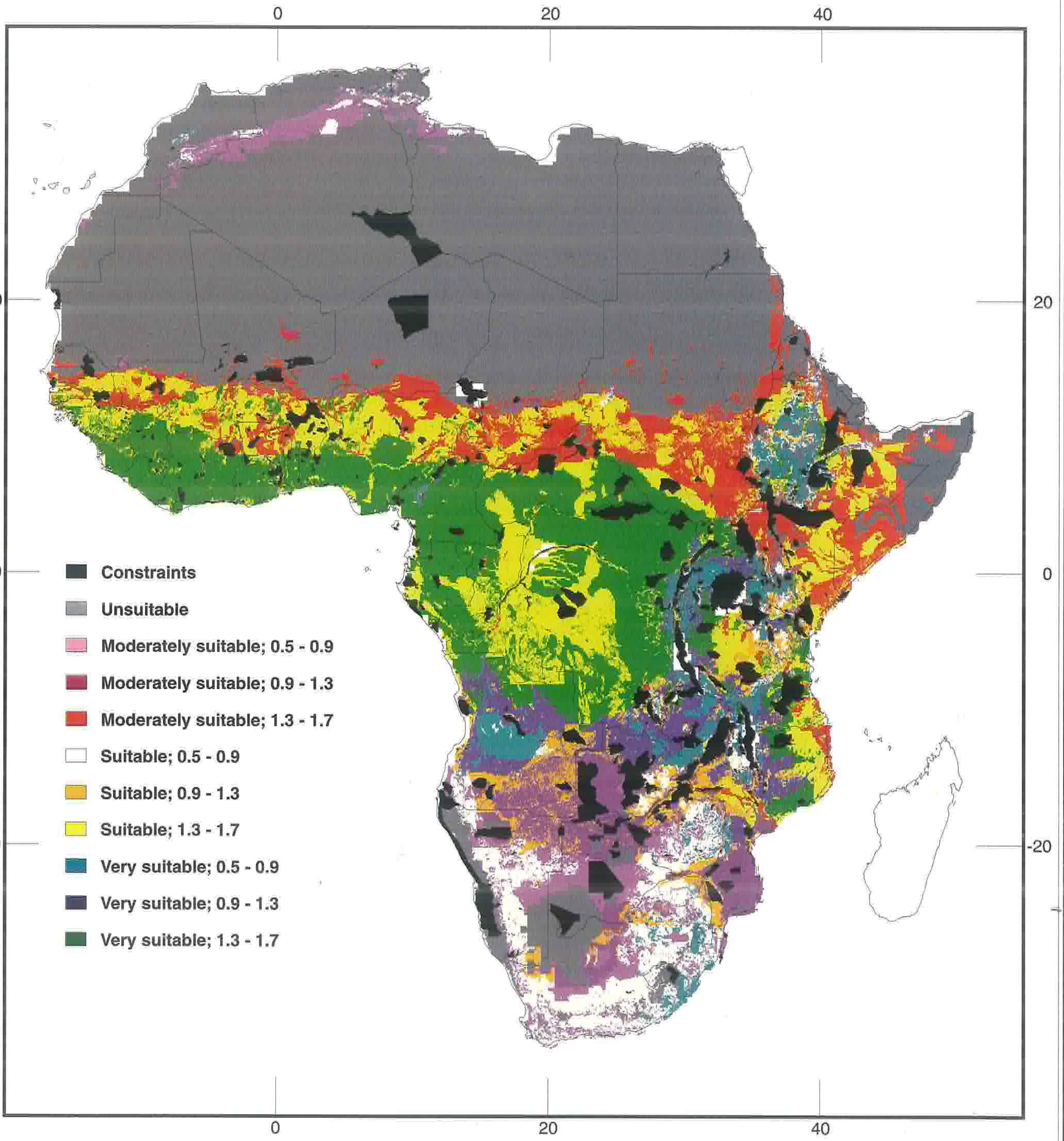


Figure 3.29
Suitability for small-scale farming and potential yield (crops/y) of Nile tilapia

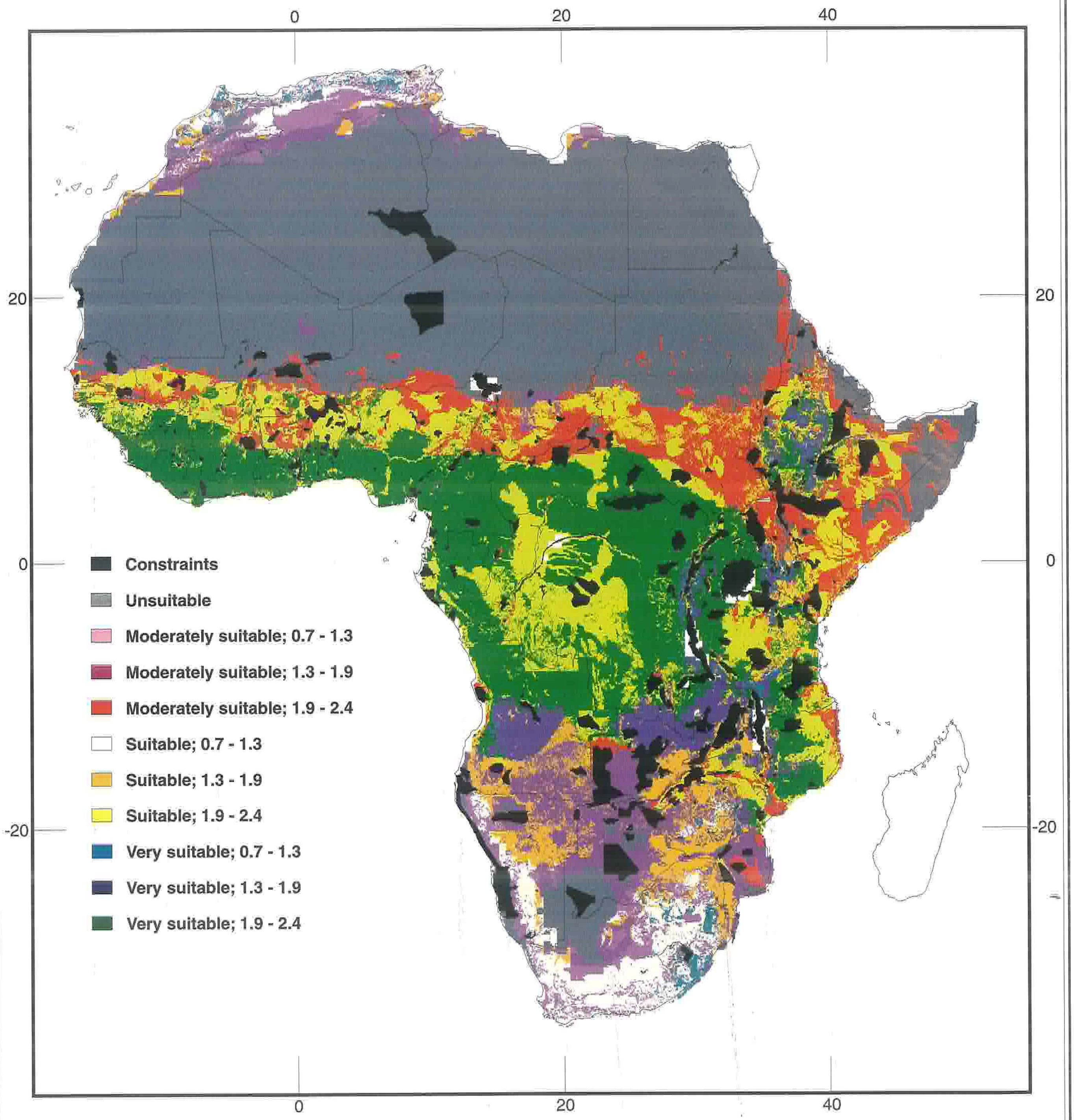


Figure 3.30
Suitability for small-scale farming and potential yield (crops/y) of African catfish

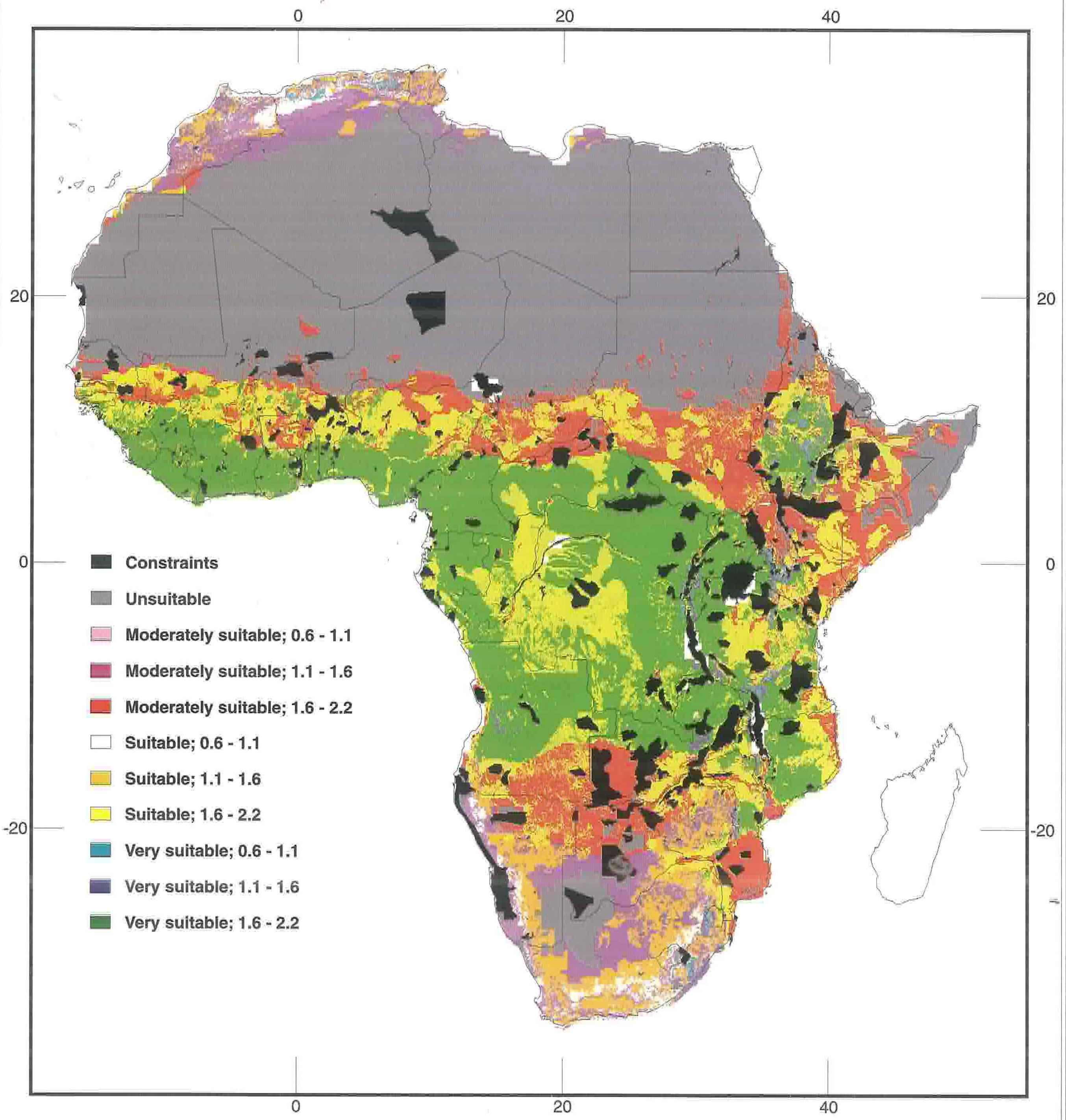


Figure 3.31
Suitability for small-scale farming and potential yield (crops/y) of Common carp

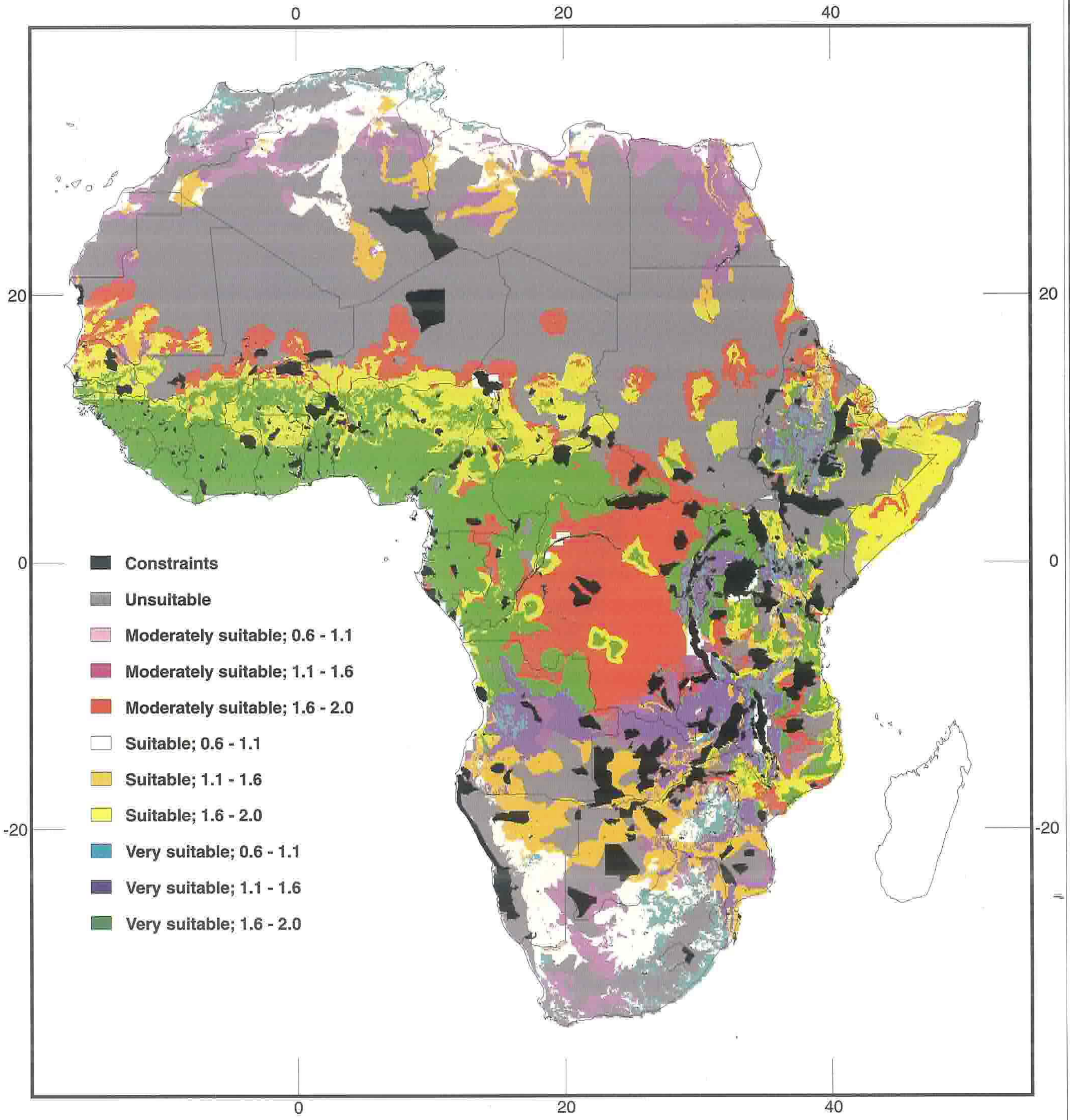


Figure 3.32
Suitability for commercial farming and potential yield (crops/y) of Nile tilapia

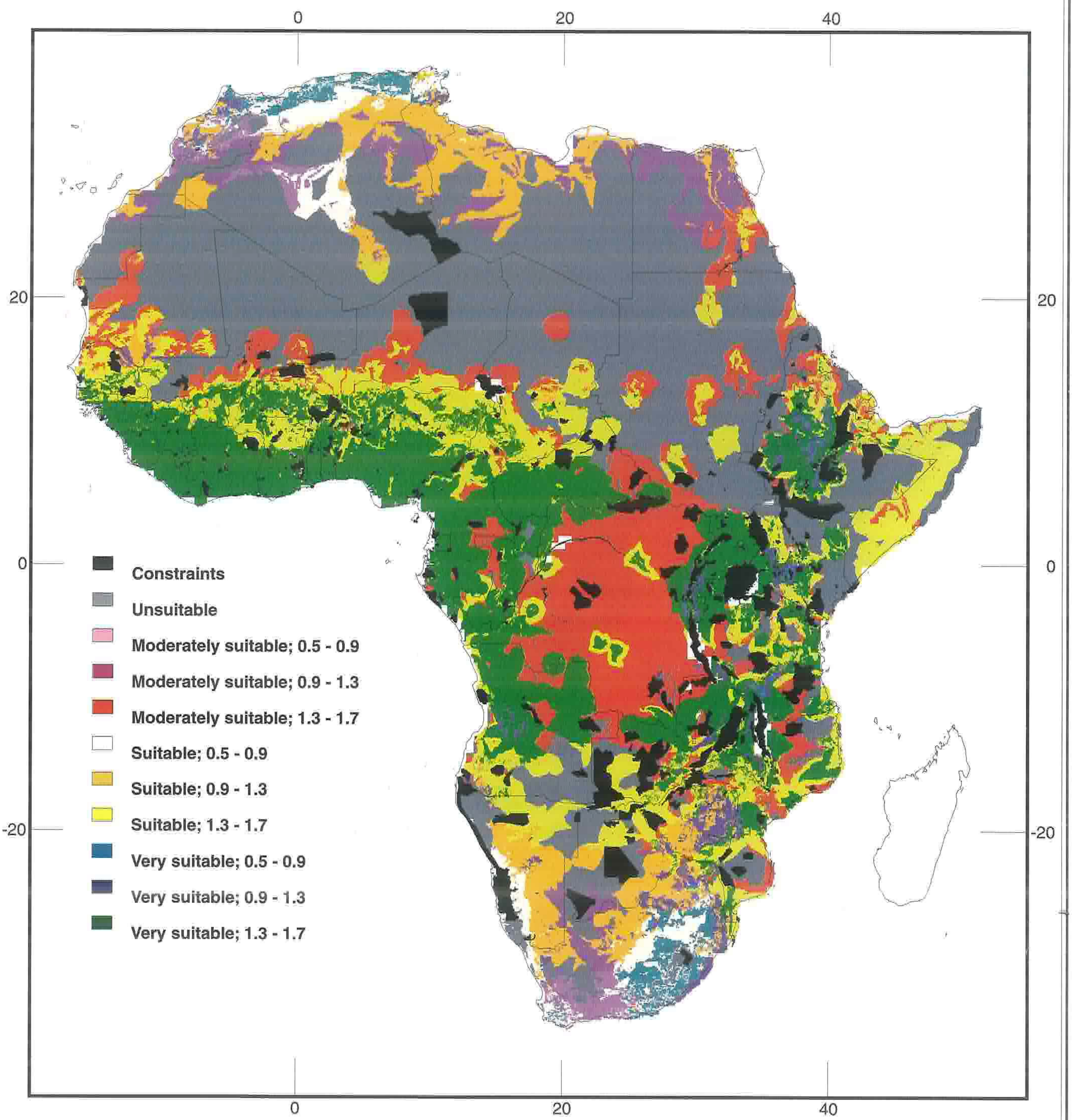


Figure 3.33
Suitability for commercial farming and potential yield (crops/y) of African catfish

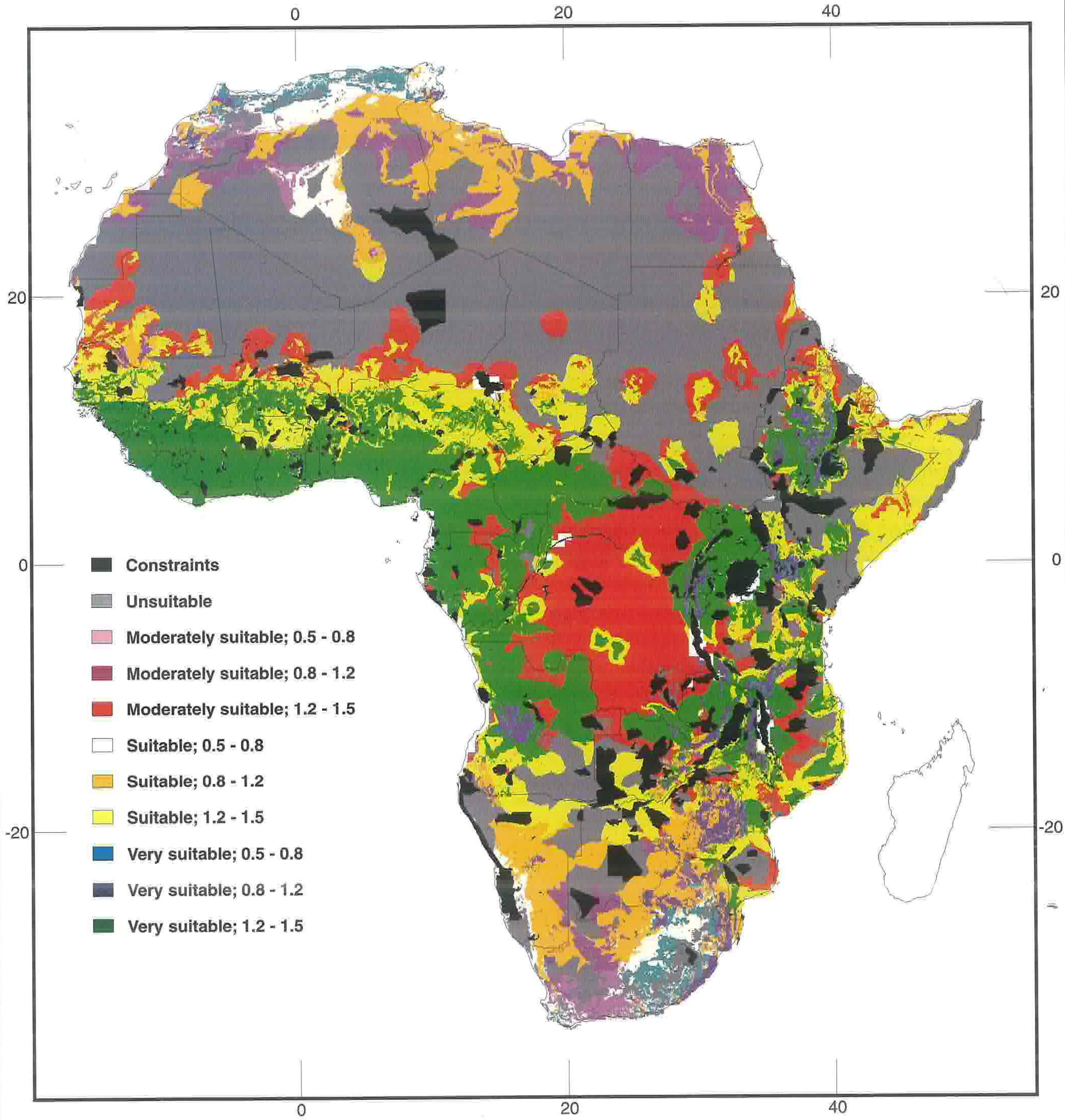


Figure 3.34
Suitability for commercial farming and potential yield (crops/y) of Common carp

Country-level overview

The maps previously presented (**Figures 3.29** to **3.34**) indicate all combinations of model outcomes from VS to US and crops/y outcomes for the 1st, 2nd, 3rdQ and 4thQ ranges. However, in order to draw attention to those areas of Africa where inland fish farming is most favourable, as well as for simplicity and clarity, only the highest ranking combinations are discussed below at a country-level. These are restricted to areas that scored VS or S for the farming system models and areas that are apt for fish crops in the 1stQ and 2ndQ ranges of crops/y.

Small-scale farming

Nile tilapia

Potential areas for small-scale farming of Nile tilapia have a smaller spatial distribution when compared to the other two species (**Figure 3.29** to **3.34**). Only 11 countries were scored as VS-1stQ in 50% or more of their surface area; however, the ranks of these countries are quite similar to the other species. Moreover, there are 12 countries that have at least 25% of their area that provide S-1stQ possibilities and another six with at least 10% of their area being S-2ndQ (**Figure 3.35**).

African catfish

14 countries have 50% or more of their land area scored as VS-1stQ and an additional seven countries possess this score in more than 25% of their area (**Figure 3.30**). There are 15 countries that exceed S-1stQ possibilities over 25% of their national areas and eight more that scored S-2ndQ in at least 10% of their area (**Figure 3.36**).

Common carp

The results for this species are quite similar to those of African catfish in terms of spatial distribution and the rank order of the countries by area (**Figures 3.31** and **3.37**); however, a few more countries which offer VS-1stQ and S-1stQ possibilities are favoured for Common carp.

Commercial farming

The commercial farming results are similar to those for small-scale farming, except that the spatial distribution of the potential sites for commercial farming is greater for the VS-1stQ, VS-2ndQ and S-2ndQ ranges. Sixteen countries have more than 50% of their area that is VS-1stQ for Nile tilapia (**Figure 3.38**), whereas there are 19 and 18 countries for African catfish and Common carp respectively in the same category (**Figures 3.39 to 3.40**). In all there are 11 countries that meet or exceed S-1stQ requirements for 25% or more of their national areas for African catfish, nine for Common carp and eight for Nile tilapia.

Table 3.12 provides a summary of the combined outputs as number of countries per percentage land area for the different suitability levels. **Table 3.13** lists the top ten countries which were found most favourable for inland fish farming in these land quality-fish yield combinations. From the latter list, it is evident that the ranks of the countries are quite similar when comparing fish farming potential among the three species and between the two farming systems. Liberia, Sierra Leone, Côte d'Ivoire, and Equatorial Guinea, were found to be most favourable for the three fish species and for both culture systems.

Table 3.12 Summary of combined evaluation as number of countries by percentage land area for VS -1st Q, 2nd Q and S-1st Q, S-2nd Q crops/y range.

	VS-1st Q	Vs-2nd Q	S-1st Q	S-2nd Q
AREA	50% or more	25% or more	25% or more	10% or more
Small-scale				
Tilapia	11	3	12	6
Catfish	14	3	15	8
Carp	15	0	17	7
Commercial				
Tilapia	16	6	8	8
Catfish	19	2	11	9
Carp	18	4	9	10

Table 3.13 Top ten countries with potential from the small-scale and commercial models combined with the species yields models.

SMALL-SCALE			COMMERCIAL		
TILAPIA	CATFISH	CARP	TILAPIA	CATFISH	CARP
Liberia	Liberia	Liberia	Liberia	Liberia	Liberia
Sierra Leone	Sierra Leone	Sierra Leone	Sierra Leone	Sierra Leone	Sierra Leone
Côte d'Ivoire	Côte d'Ivoire	Côte d'Ivoire	E. Guinea	E. Guinea	E. Guinea
E. Guinea	E. Guinea	E. Guinea	Côte d'Ivoire	Côte d'Ivoire	Côte d'Ivoire
Cameroon	Cameroon	Uganda	Guinea	Uganda	Uganda
Gabon	Uganda	Cameroon	Gabon	Guinea	Guinea
Guinea	Gabon	Burundi	Togo	Gabon	Gabon
Cent.Afr.Rep.	Guinea	Rwanda	Benin	Togo	Togo
Togo	Cent.Afr.Rep.	Gabon	Congo, Rep.	Burundi	Burundi
Congo, Dem. Rep. of	Togo	Congo, Dem. Rep. of	Guinea Bissau	Rwanda	Benin

Figure 3.35 Relative surface area with suitability for small-scale farming and potential yield (crops/y) of Nile tilapia

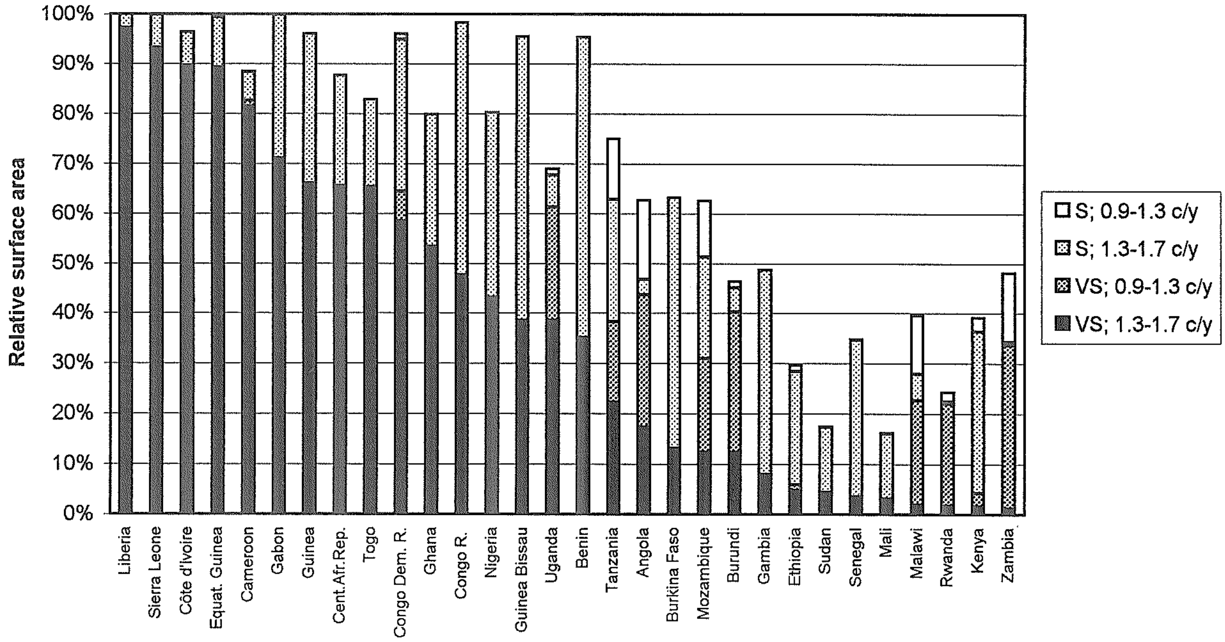


Figure 3.36 Relative surface area with suitability for small-scale farming and potential yield (crops/y) of African catfish

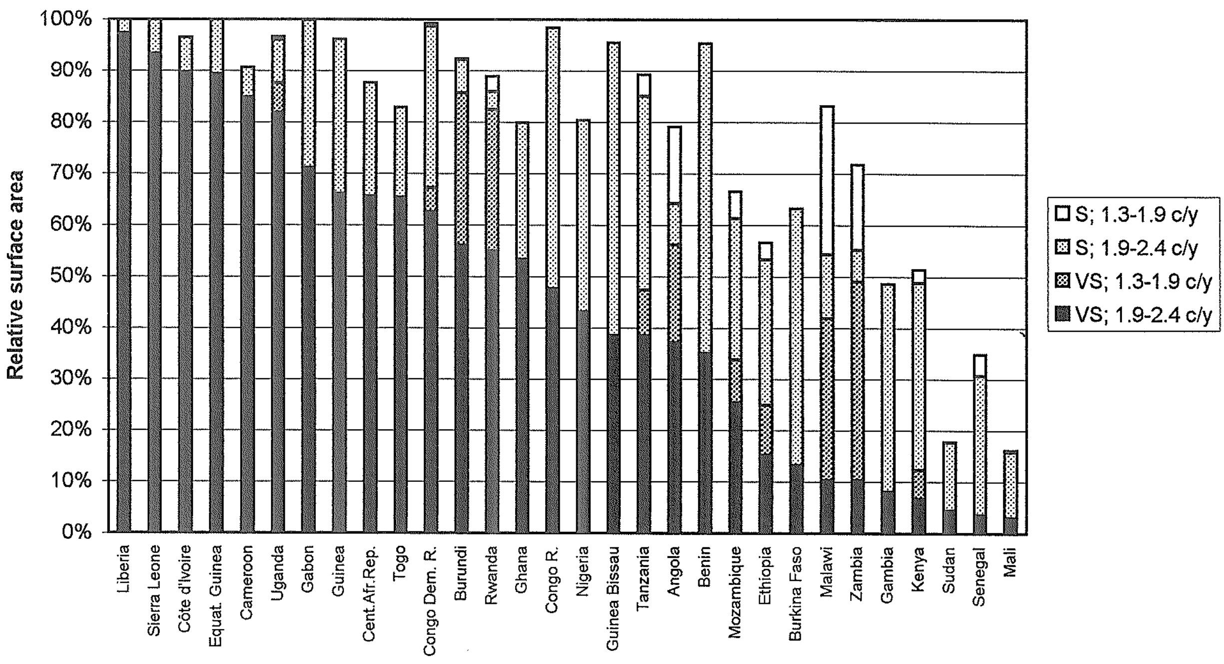


Figure 3.37 Relative surface area with suitability for small-scale farming and potential yield (crops/y) of Common carp

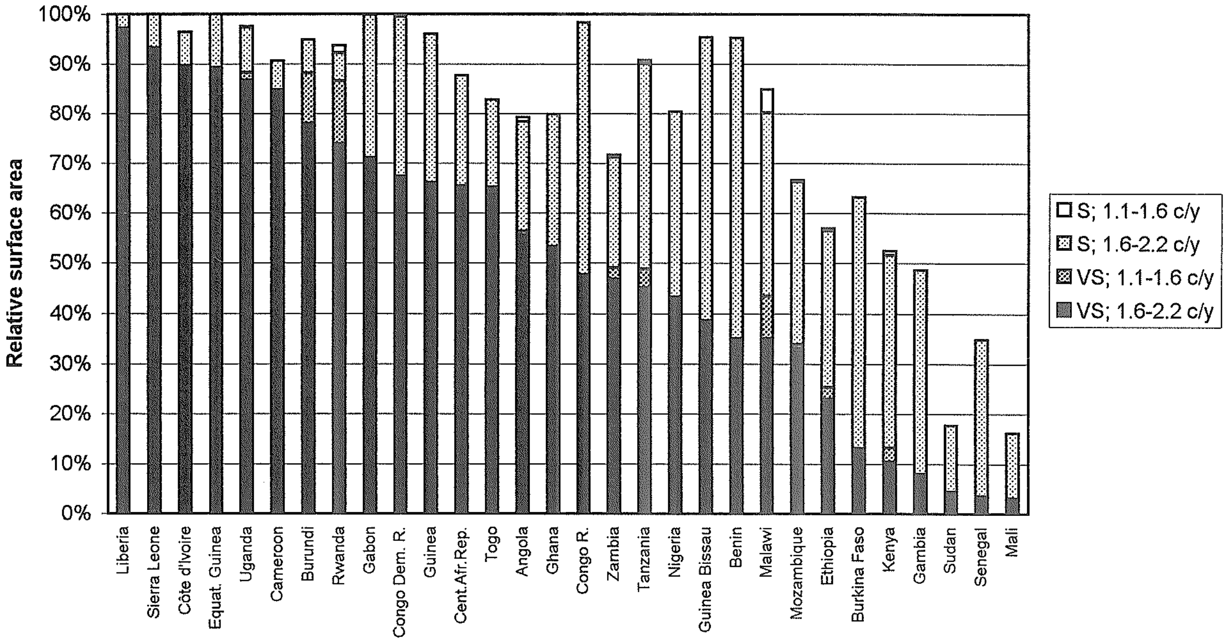


Figure 3.38 Relative surface area with suitability for commercial farming and potential yield (crops/y) of Nile tilapia

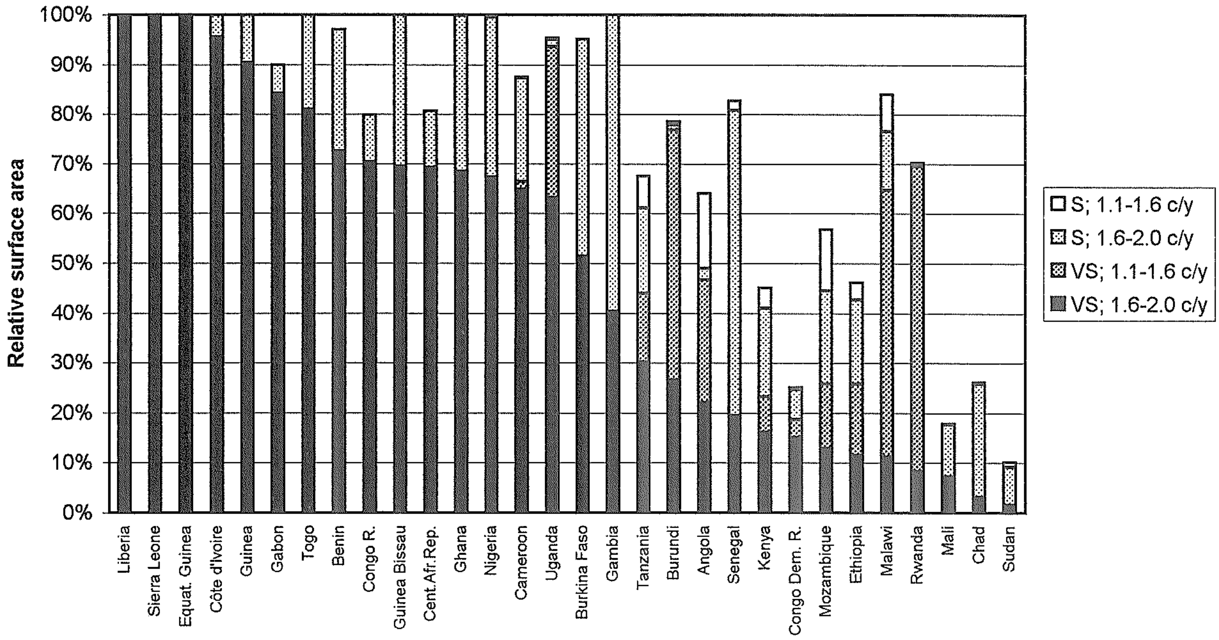


Figure 3.39 Relative surface area with suitability for commercial farming and potential yield (crops/y) of African catfish

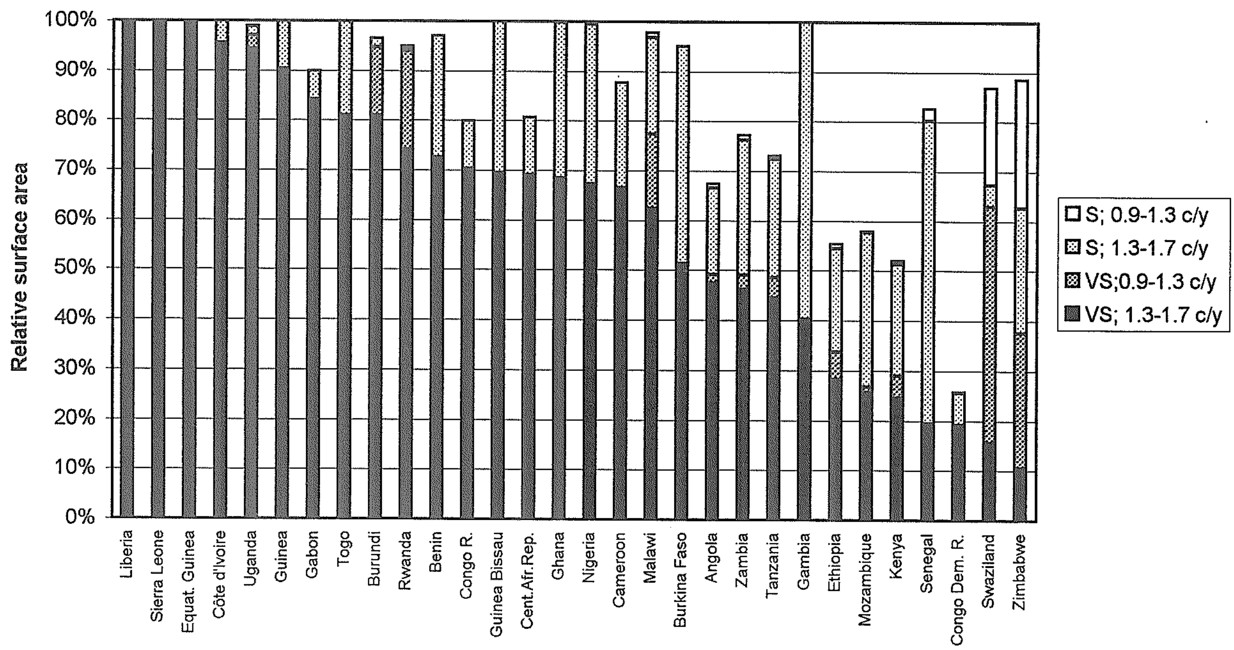
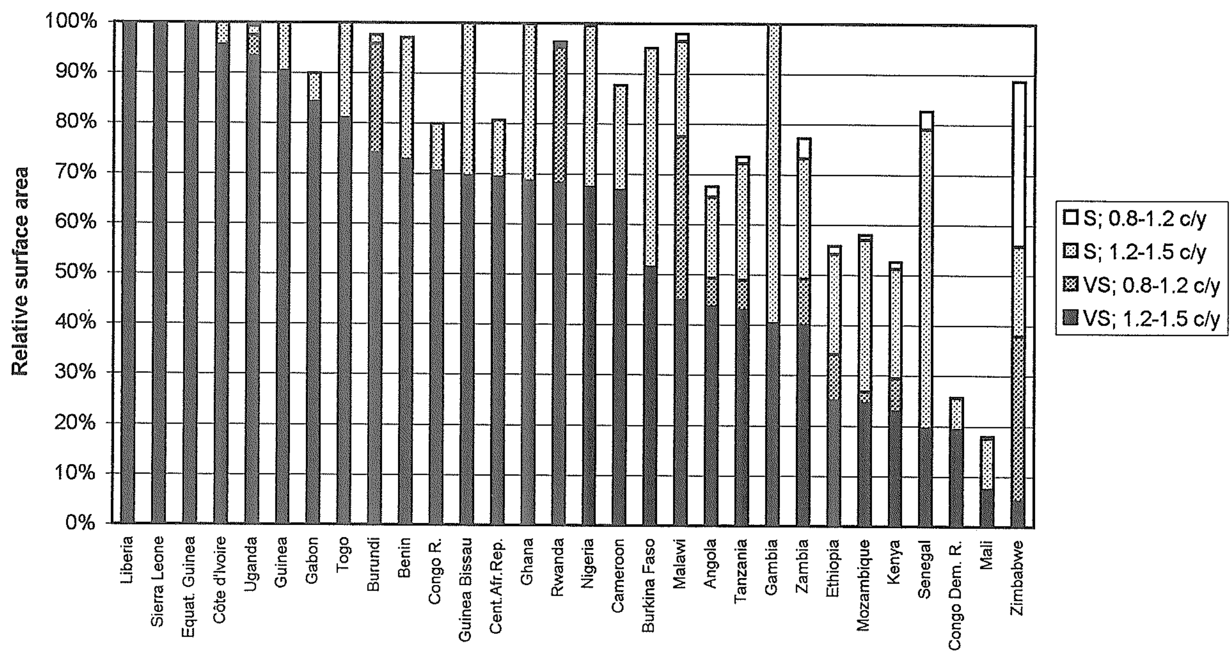


Figure 3.40 Relative surface area with suitability for commercial farming and potential yield (crops/y) of Common carp



3.5 Coincidence among fish species

Continental overview

The fish yield outputs (crops/y) presented above for all three fish species were aggregated into four equal length quarters according to their respective crops/y yield ranges. This evaluation was made separately because one may want estimates of fish farming potential according to the species used. However, it is difficult to evaluate the coincidence among fish yields for the three species due to the differences in crops/y yield ranges. To evaluate such coincidence, the results of the combined evaluation (**Figures 3.29 to 3.34**) were combined to identify sites where fish farming is most favourable for the three species by culture system. Thus, **Figures 3.29** to **3.31** were combined to create a small-scale farming scenario (**Figure 3.41**) and **Figures 3.32** to **3.34** were combined to obtain the commercial scenario (**Figure 3.42**).

Overall, the bulk of the areas scored as VS-1stQ for the three fish species and for both types of culture systems were located in Central and NW Africa between 12° -10° S and 17° - 35° E (**Figures 3.41** and **3.42**). Other areas outside this geographical range containing this suitability score, but with smaller spatial areas, were located in Ethiopia, Kenya, Tanzania and Mozambique.

The main difference between the two types of farming systems was found in Central Africa (e.g. the Democratic Republic of the Congo), where there is a considerable decrease in areas scored as VS-1stQ and S-1stQ for the commercial model, but much of this potential is gained in the north, at about 12-14°N, where small-scale farming is less suitable.

The results (**Table 3.14**) show that 37 % of the African surface contains areas with relatively high potential for small-scale farming of Nile tilapia, African catfish and Common carp, and 43% of the African surface has potential for commercial farming for these three species.

Areas with the highest correspondence for each farming system and with the highest suitability score (VS-1stQ) were identified in about 15% of continental Africa (**Table 3.14**). Similarly, over 10% of the African surface was scored as S-1stQ .

Table 3.14 Suitability of coincidence between models combined with fish yields for farming development and operation as a percentage of the surface area in continental Africa.

SCORE	VS-1stQ	VS-2ndQ	VS-3rdQ	S-1stQ	S-2ndQ	S-3rdQ	MS-1stQ	MS-2ndQ	MS-3rdQ	SUM
Small-scale	15.5	0.01	0.1	11.8	0.1	0.5	8.1	0.3	0.2	36.5
Commercial	15.4	0.2	0.5	10.3	2.1	1.3	11.4	1.5	0.4	43.2

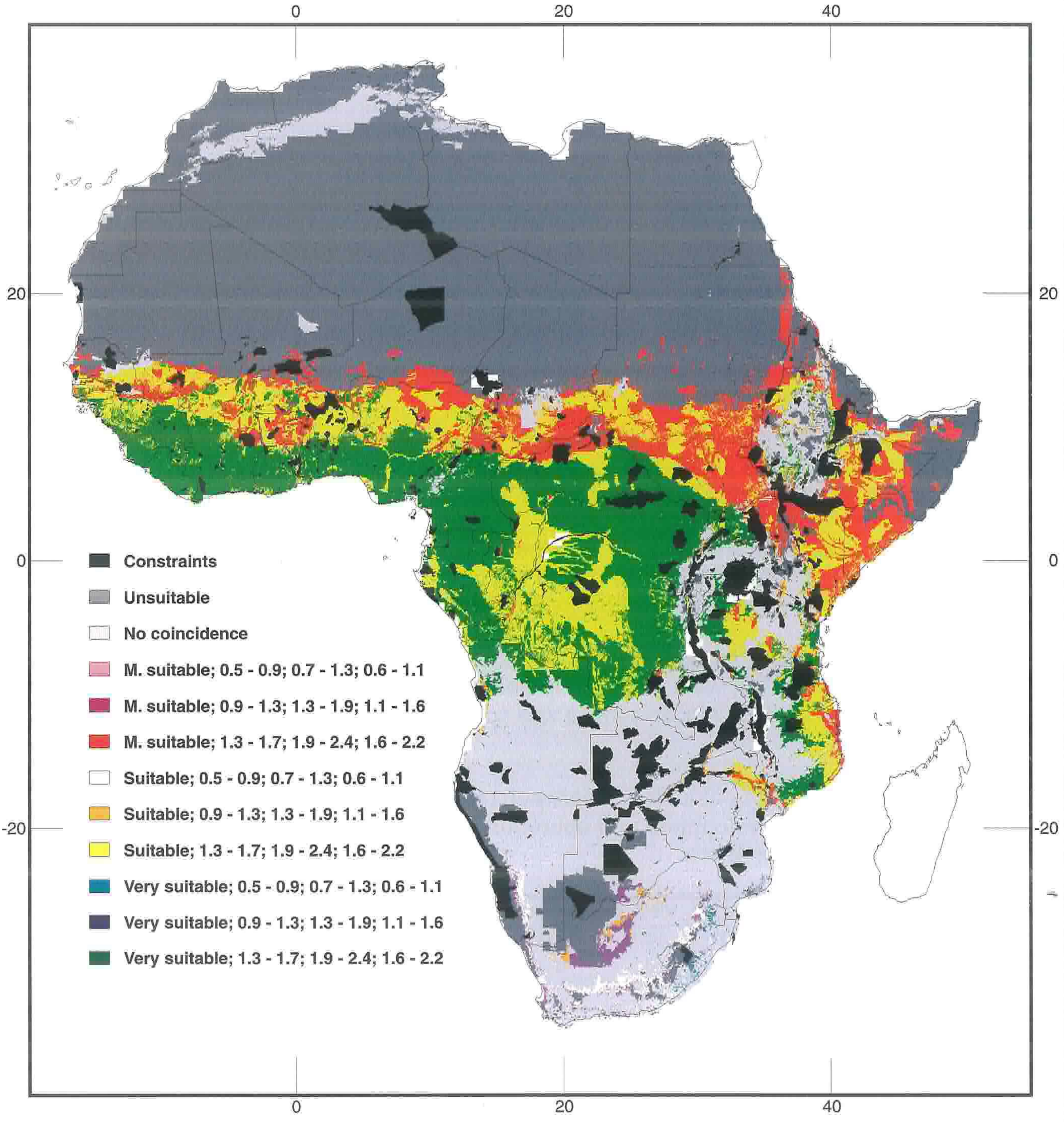


Figure 3.41
Suitability for small-scale farming and potential yield (crops/y) of Nile tilapia, African catfish and Common carp

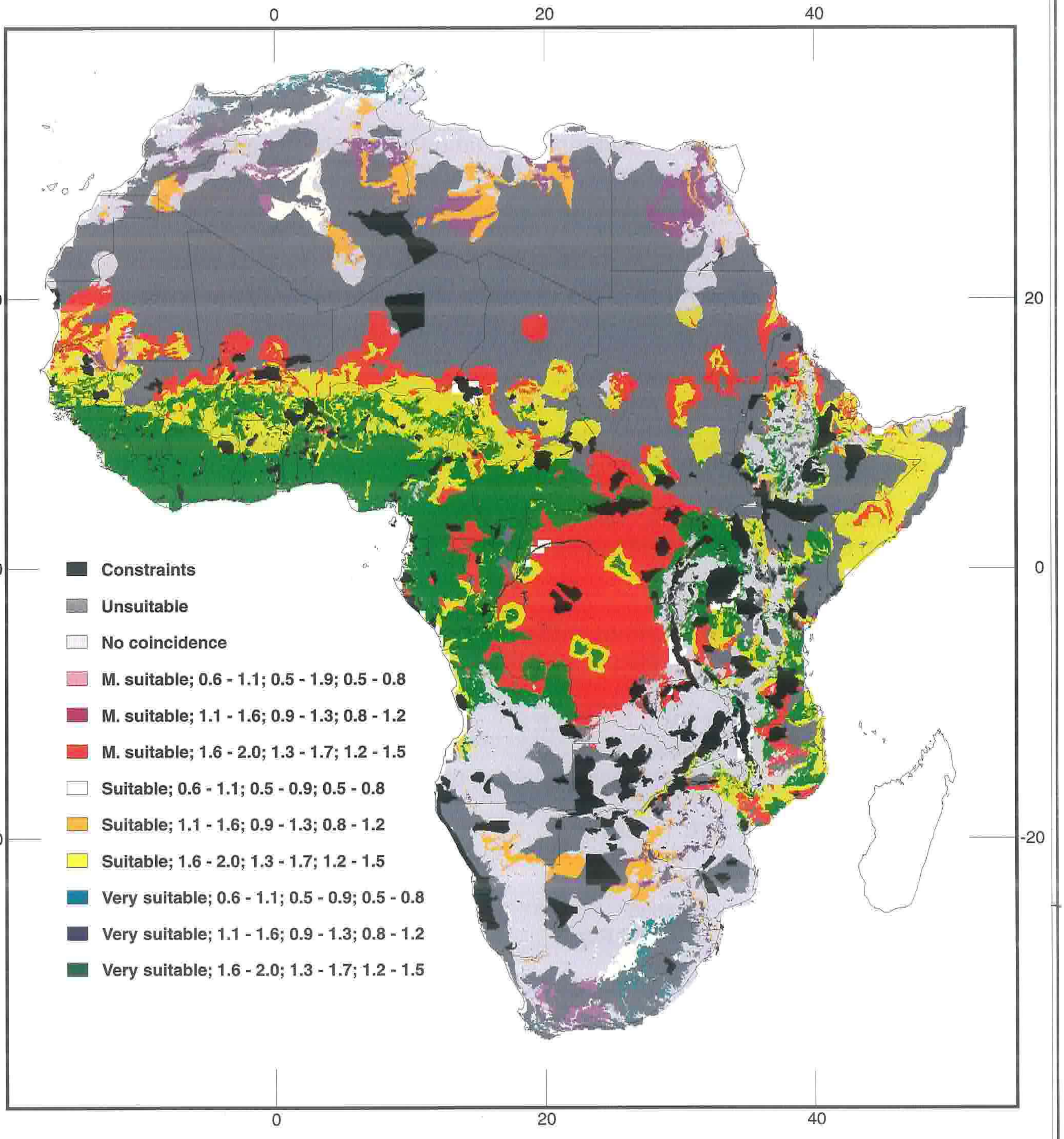


Figure 3.42
Suitability for commercial farming and potential yield (crops/y) of Nile tilapia, African catfish and Common carp

Country-level overview

Small-scale and commercial farming

Potential areas for small-scale fish farming have a smaller spatial distribution (**Figure 3.41**) when compared to commercial farming (**Figure 3.42**). Only 11 countries possess 50% or more of their national area scored as VS-1stQ for small-scale farming compared to 16 for commercial farming (**Figure 3.43** and **3.44**). However, the opposite occurs for those areas scored as S-1stQ since small-scale farming has 4 more countries in this suitability category (**Table 3.15**).

Table 3.15 Summary of coincidence evaluation as number of countries by percentage land area for VS-1stQ, VS-2ndQ and S-1stQ, S-2ndQ crops/y range.

SCORE	VS-1stQ	VS-2ndQ	S-1stQ	S-2ndQ	SUM
AREA	**50% or more**	**25% or more**	**25% or more**	**10% or more**	
Small-scale	11	0	12	0	23
Commercial	16	0	8	2	26

Table 3.16 provides a list of the top ten countries (in rank order) which were found to be most favourable for inland fish farming of the three fish species for each type of farming system. The list shows that Liberia and Sierra Leone were ranked as the top two countries for both types of culture systems. Two countries (Côte d'Ivoire and Equatorial Guinea) were also high on the top ten list for both small-scale and commercial farming systems.

Table 3.16 Top ten countries with potential for small-scale and commercial farming of Nile tilapia, African catfish and Common carp.

SMALL-SCALE	COMMERCIAL
Liberia	Liberia
Sierra Leone	Sierra Leone
Côte d'Ivoire	E. Guinea
E. Guinea	Côte d'Ivoire
Cameroon	Guinea
Gabon	Gabon
Guinea	Togo
Cent.Afr.Rep.	Benin
Togo	Congo, Rep.
Congo, Dem. Rep. of	Guinea Bissau

Figure 3.43 Relative surface area with suitability for small-scale farming and potential yield (crops/y) of Nile tilapia, African catfish and Common carp

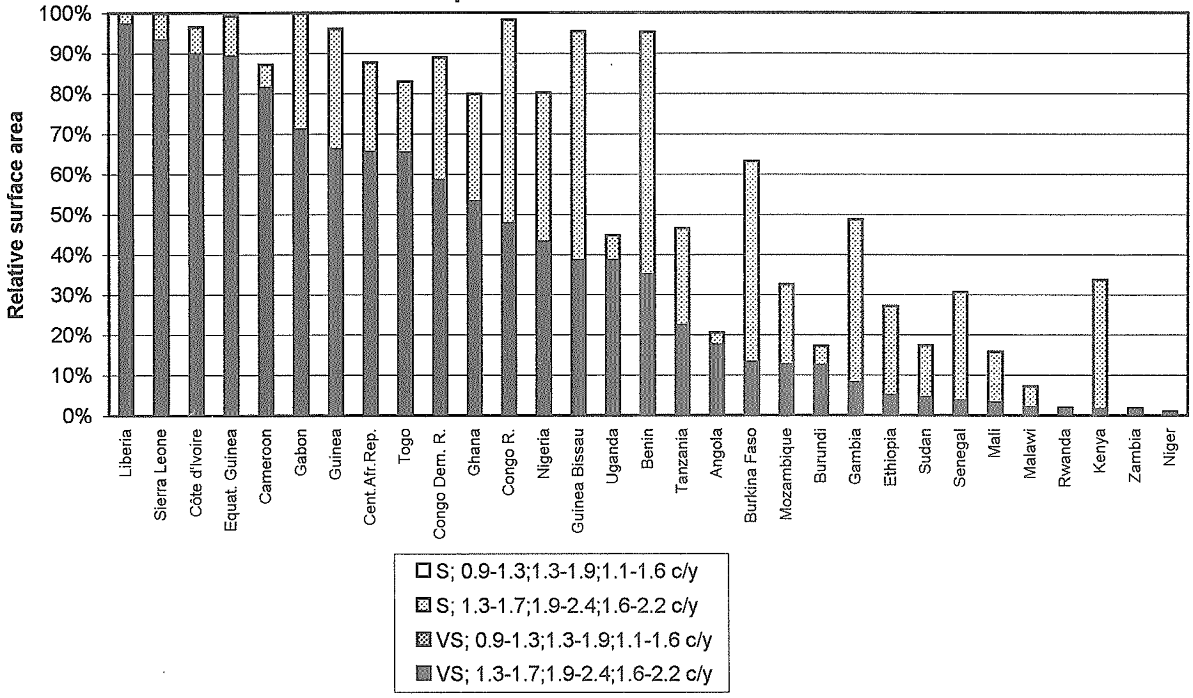
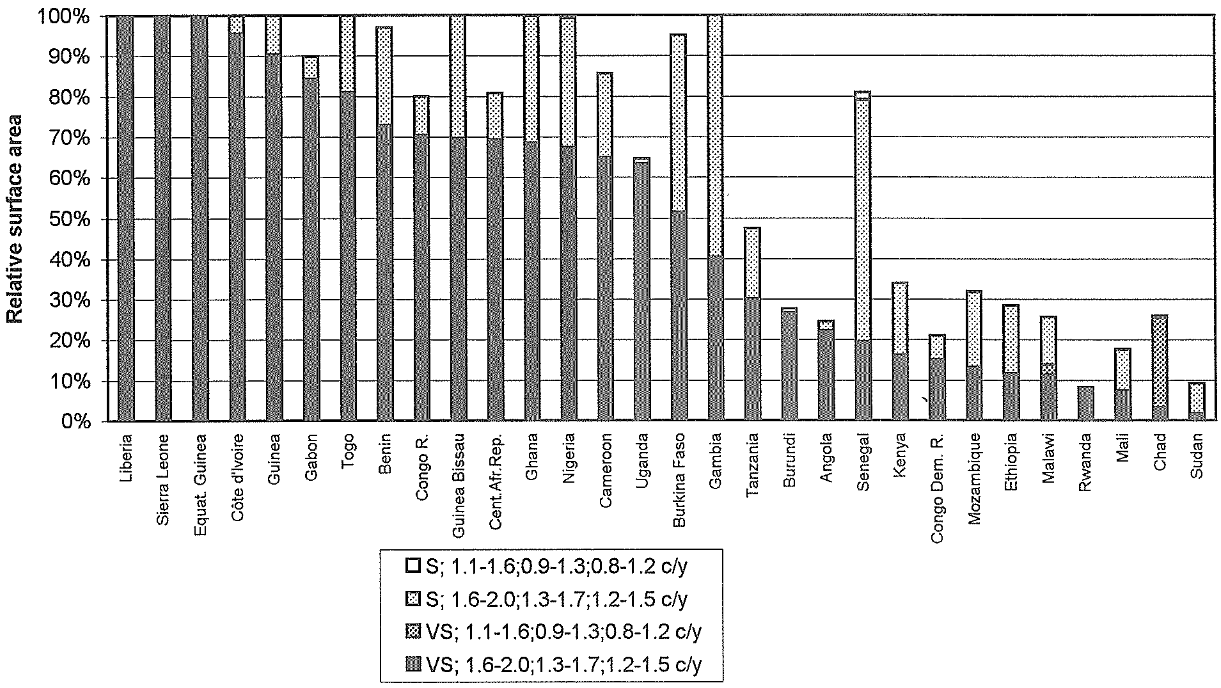


Figure 3.44 Relative surface area with suitability for commercial farming and potential yield (crops/y) of Nile tilapia, African catfish and Common carp



3.6 Verification

For clarity, verification results are presented separately by general and water temperature categories. In addition, general verification results are presented from another perspective: verification by existing farm locations and by the number of farms at a county-level.

Results are presented for the three fish species and for both types of farming systems. However, because most of the fish farms for which information was available for verification are reported to raise Nile tilapia, the farming potential of this species is the focus of the discussion below.

3.6.1 General verification

Verification by existing fish farm locations

ZIMBABWE

Verification work required locations of the fish farms and attribute data. The locations were obtained by visiting farm sites with a GPS receiver. The objective of the work was to locate and characterise a number of farm sites and operations among areas that differed from one another in terms of water requirement, terrain, availability of inputs, farm-gate sales, proximity to roads and markets, water temperature and fish weights at harvest. Characterisation of the farms was based upon the description of the factors (e.g., water requirement) and thresholds established in this study.

A total of 9 commercial fish farms were visited across Zimbabwe. Farm selection was based on an inventory of commercial fish farms (57 in total) carried out by Balarin, Chisawa and Evans (1997). Contrary to information from the latter inventory, field verification work by Zimudzi (1997) found that some farmers had never practised fish farming on any scale except to stock a few ponds. Due to time and resource limitations no small-scale fish farms were visited. Moreover, although 9 farms were visited, only 6 were operational and therefore only the results for these are presented below.

Most farms visited either exclusively or predominantly raised Nile tilapia (*Oreochromis niloticus*) (**Text box 3.1**). Although some farms raised *O. mossambicus,* it is not a popular species for culture due to excessive recruitment and slower growth rate. In two instances, *Clarias gariepinus* was stocked to control the breeding of both *O.mossambicus* and frogs.

Text Box 3.1 Commercial farms raising Nile tilapia and other species among those surveyed.

No. of Farms	Species mix
1	*O. niloticus* alone
2	*O. niloticus* and *C. gariepinus*
2	*O. niloticus* and *O. mossambicus*
1	*O. niloticus, O. mossambicus* and *C. gariepinus*

The weights at harvest of Nile tilapia varied considerably among the six commercial fish farms from a minimum weight of 50 g to a maximum of 750 g (**Text Box 3.2**). The evaluation for commercial farming of Nile tilapia showed that most farms were found in areas scored as MS among the land quality factors (**Table 3.17a**).

Text Box 3.2 Weights at harvest of Nile tilapia from 6 commercial farms in Zimbabwe.

Farms ID	Weights (g)
1	125
2	No data
3	375
4	No data
5	50 - 750
6	50 - 200

Table 3.17a Comparison of existing commercial fish farm locations in Zimbabwe to the predicted farming system and fish growth suitability score. (number of farms out of 6 possible)

Farming system (suitability score)	VS	S	MS	US
Water	-	-	6	-
Soils	3	2	1	-
Inputs	2	-	4	-
Farm-gate	-	1	4	1
Urban	5	1	-	-
Commercial model	2	3	1	-
Fish growth (suitability score)	**1stQ**	**2ndQ**	**3rdQ**	**4thQ**
Commercial				
Nile tilapia	-	2	4	-
African catfish	2	4	-	-
Common carp	2	4	-	-

Abbreviations: Water = water requirement for shallow ponds; Soils = soil an terrain suitability for fish ponds; Inputs = Livestock wastes and agricultural by-products; Farm-gate = Farm-gate sales; Urban = Urban market size and proximity.

Notes: The symbol " - " equals to No fish farms. Data for African catfish and Common carp are only presented for reference.

All except one of the farms scored VS for urban market size and proximity, but water requirement was found to be the most limiting factor for all the farms (**Table 3.17a**). Despite this, the outcome of the commercial model showed that 3 of the 6 farms were in areas scored as S. Moreover, 2 farms were in grid cells predicted to yield crops of Nile tilapia in the 2ndQ range and 4 in the 3rdQ range (**Table 3.17b**). The combined evaluation showed that 4 of the farms are located in areas that scored S, one in the 2ndQ range and three in the 3rd Q. In addition, one farm was located in an area scored as VS, with yield ranges in the 3rd Q. None of the farms were located in areas where potential for farming of the three species coincided.

Table 3.17b Comparison of existing commercial fish farm locations in Zimbabwe to the predicted model combination suitability score. (number of farms out of 6 possible)

Model combination (suitability score)	VS-1stQ	VS-2ndQ	VS-3rdQ	S-1stQ	S-2ndQ	S-3rdQ	MS-1stQ	MS-2ndQ
Commercial								
Nile tilapia	-	-	1	-	1	3	-	1
African catfish	1	1	-	1	3	-	-	-
Common carp	1	-	-	1	3	-	1	-

Database verification

To evaluate the accuracy of the database developed in this study, information obtained by Zimudzi (1997) was scored according to the thresholds first established in the methods section of this study. This approach enabled a comparison among the scores obtained from the six farms visited with those defined in the database.

Lack of field data did not allow the development of a quantitative estimate of the accuracy of the database. However, from indicative analyses (**Table 3.18**) it was found that soils and

slopes had the highest accuracy (i.e., 4 farms that scored VS on the field were located in 4 grid cell sites also scored as VS). Water requirement predictions were also found to be accurate, water is in most cases insufficient due to low-rainfall conditions. Lowest accuracy was found for farm-gate sales because higher suitability was found on the field, and this was also found to be the case for inputs. Conversely, scores for urban size and proximity to markets were found to be lower in the field. For example, one of the farmers has to travel 175 km one way to an urban market.

Table 3.18 Evaluation of the accuracy of the database in Zimbabwe. (number of farms out of 6 possible)

	WATER		SOILS		INPUTS		FARM-GATE		URBAN	
SUITABILITY	DAT	FLD	DAT	FLD	DAT	FLD	DAT	FLD	DAT	FLD
VS	-	-	4	5	2	4	-	4	5	3
S	-	3	1	1	-	-	1	-	1	-
MS	6	3	1	-	4	-	4	-	-	2
US	-	-	-	-	-	2	1	2	-	1

Terminology: DAT = Database grid cell; FLD = Field survey.

Abbreviations: Water = water requirement for shallow ponds; Soils = soil an terrain suitability for fish ponds; Inputs = Livestock wastes and agricultural by-products; Farm-gate = Farm-gate sales; Urban = Urban market size and proximity.

Notes: The symbol " - " equals to No fish farms. Data for African catfish and Common carp are only presented for reference.

KENYA

All of the 31 small-scale farms for which information was available raised Nile tilapia. Moreover, according to Marquet, Achieng and Obuya (1996) African catfish is also very acceptable in this area, but only a few farmers can raise this species because very few fry survive and adequate information on managing fry ponds is not available.

The outcome of the comparison shows that the majority of farms were located in areas scored as VS among the factors selected for evaluating the quality of the land (**Table 3.19a**).

Table 3.19a Comparison of existing commercial fish farm locations in Kenya to the predicted farming system and fish growth suitability score. (number of farms out of 31 possible)

Farming system (suitability score)	VS	S	MS	US
Water	-	31	-	-
Soils	23	8	-	-
Inputs	25	6	-	-
Farm-gate	7	-	-	24
Urban	31	-	-	-
Small-scale model	31	-	-	-
Fish growth (suitability score)	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
Small-scale				
Nile tilapia	-	15	16	-
African catfish	23	8	-	-
Common carp	31	-	-	-

All farms were located within easy reach of urban markets. Twenty four farms were scored US for farm-gate sales because they were located in high population density areas where the land could be too expensive for small-scale farming, however, a high population density also implied a potential market source (see **section 2.3.5** above). Moreover, of the 24 farms, 17 were located in areas having 301 - 450 i/km^2 meaning that the population density thresholds were slightly higher than the VS threshold of 150 - 300 i/km^2, (see **Text Box 2.9** in section 2.3.5 above). Likewise, in spatial terms, the farms were very close or adjacent to the VS areas. In conclusion, the 24 farms classified as US for farm-gate sales could be re-classified as MS by a slight increase of the limit at which land would become to expensive (i.e. 300 i/km^2).

All of the farms were in grid cell sites scored as VS by the small-scale model (**Table 3.19a**) and 15 farms were in cells predicted to yield crops in the 2ndQ range; and an additional 16 predicted yields in the 3rdQ range. The combined evaluation (**Table 3.19b**) showed that 15 farms were located in areas scored as VS-2ndQ and 16 additional farms possess a score of VS-3rdQ. None of the farms were located in areas where potential for farming of the three species coincided.

Table 3.19b Comparison of existing commercial fish farm locations in Kenya to the predicted model combination suitability score. (number of farms out of 31 possible)

Model combination (suitability score)	VS-1stQ	VS-2ndQ	VS-3rdQ
Small-scale			
Nile tilapia	-	15	16
African catfish	23	8	-
Common carp	31	-	-

Notes: The symbol " - " equals to No fish farms. Data for African catfish and Common carp are only presented for reference.

Verification by number of fish farms at a county-level

UGANDA

Data on fish farming in Uganda (Candia, 1997) were only available for Arua district by the number of fish farms at a county-level (**Text Box 3.3**). All of the 202 farms are reported to raise Tilapia alone and most of the farms were using small-scale methods for culture.

Digital data for county boundaries was not available for Arua district, so these data were digitized from a paper map at a 1:1,500,000 scale (Department of Lands and Surveys, 1986). Once the data were digitized, the database was transformed to the base grid (i.e., grid cell size of 3 minutes and Lat/Long. projection).

Text Box 3.3. Number of fish farms according to intensity of farming among 7 counties in Arua.

County	Small-scale	Commercial	Total
Aringa	2	0	2
Ayivu	37	3	40
Koboko	5	1	6
Madi-Okollo	1	0	1
Maracha	83	10	93
Terego	7	4	11
Vurra	44	5	49
Total	179	23	202

The objective was to examine the areas covered by each fish farming suitability class for Nile tilapia for each county in Arua, and then to compare this with the number of fish farms by district (Text Box 3.3).

Protected areas were identified in 4 of the 7 counties in Arua district, with the largest surface area in Aringa comprising about 15% of the county (**Text Box 3.4**).

The verification results show that among the land quality factors, the least limiting factor is the urban market; all seven counties scored VS in 100% of their area (**Table 3.20**). In contrast, the most limiting factor is the inputs, as five counties have 35 to 100% of their surface area scored as US.

Text Box 3.4. Constraints as percentage of the surface area among 7 counties in Arua.

County	Constraints area (%)
Aringa	15
Ayivu	7
Koboko	5
Madi-Okollo	8
Maracha	0
Terego	0
Vurra	0

The commercial model shows that very suitable sites occur in all counties in 100% of their area. Good, but lower potential was found for small-scale farming (i.e., four counties with 100% at the VS level).

The spatial distribution of fish farming opportunities for Nile tilapia are extensive in that almost all the counties possess 1^{st}Q yields in 100% of their surface area for both small-scale and commercial farming (**Table 3.20**). Similarly, the outcome of the combined evaluation is also very positive. All counties except Vurra for the small-scale model combination had most, if not all of their land area scored as VS-1^{st}Q for both culture systems. Interestingly, the potential for the culture of the three species is also high as indicated by the coincidence evaluation.

To verify the predictions, it was assumed that the greater the number of fish farms the higher the potential for fish farming. However, it was difficult to corroborate this assumption in order to pin-point the county with the highest number of fish farms (i.e., Maracha) because all the predictions showed similar potential for all counties. This difficulty is attributable to two sources:

a) the use of choropleth data (i.e., data that cover a large area), and
b) the lack of data on all farm characteristics such as availability of inputs.

Despite this difficulty, the results do confirm the fact that Arua is one of the districts of Uganda with considerable aquaculture potential as concluded by Candia (1997).

Table 3.20 Suitability of fish farming as a percentage of the surface area among Arua counties.

COUNTY	ARINGA				AYIVU				KOBOKO				MADI-OKOLLO				MARACHA				TEREGO				VURRA			
Farming system	VS	S	MS	US	VS	S	MS	US	VS	S	MS	US	VS	S	MS	US	VS	S	MS	US	VS	S	MS	US	VS	S	MS	US
Water	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-
Soils	70	30	-	-	92	8	-	-	100	-	-	-	41	54	5	-	100	-	-	-	59	41	-	-	38	58	4	-
Inputs	-	-	100	-	-	31	8	62	-	-	65	35	-	-	48	52	-	6	31	63	-	-	100	-	-	-	-	100
Farm-gate	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-
Urban	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-
Small-scale model	100	-	-	-	92	8	-	-	100	-	-	-	66	34	-	-	100	-	-	-	100	-	-	-	39	62	-	-
Commercial model	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-
Fish growth	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q	1^{st}Q	2^{nd}Q	3^{rd}Q	4^{th}Q
Small-scale																												
Nile tilapia	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	94	6	-	-	100	-	-	-	89	12	-	-
African catfish	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-
Common carp	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-
Commercial																												
Nile tilapia	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	96	4	-	-
African catfish	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-
Common carp	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-	100	-	-	-
Model combination	VS-1^{st}Q				VS-1^{st}Q		S-1^{st}Q		VS-1^{st}Q				VS-1^{st}Q		S-1^{st}Q		VS-1^{st}Q		VS-2^{nd}Q		VS-1^{st}Q				VS-1^{st}Q	VS-2^{nd}Q	S-1^{st}Q	S-2^{nd}Q
Small-scale																												
Nile tilapia	100				92		8		100				66		34		94		6		100				35	4	54	8
African catfish	100				92		8		100				66		34		100		-		100				39	-	62	-
Common carp	100				92		8		100				66		34		100		-		100				39	-	62	-
Commercial																												
Nile tilapia	100				100		-		100				100		-		100		-		100				96	4		
African catfish	100				100		-		100				100		-		100		-		100				100	-		
Common carp	100				100		-		100				100		-		100		-		100				100	-		
Coincidence	VS-1^{st}Q				VS-1^{st}Q		S-1^{st}Q		VS-1^{st}Q				VS-1^{st}Q		S-1^{st}Q		VS-1^{st}Q		None		VS-1^{st}Q				VS-1^{st}	S-1^{st}Q		None
Small-scale	100				92		8		100				66		34		94		6		100				35	54		12
Commercial	100				100		-		100				100		-		100		-		100				96	-		4

Notes: The symbol "-" equals to No fish farms. Data for African catfish and Common carp are only presented for reference.

3.6.2 Water temperature verification

The water temperature predicted in this study for a grid cell characterises its entire area primarily based on air temperature (see **Appendix 8.1** for details of air temperature). Monthly maps and statistical results of the water temperature predictions at a continental-level are presented in **Appendix 8.8**. However, for verification purposes, the database was queried for water temperature predictions for 3 countries where a general verification was conducted as described above; additionally, water temperature data for Malawi was also included (**Table 3.21**).

Table 3.21 Predicted water temperatures at a country-level.
[°C]

	ZIMBABWE	KENYA	UGANDA	MALAWI
Annual monthly range	10.2-31.9	4.7-32.1	5.1-29.1	8.6-31.1
Annual mean range	16-27.7	7.3-30.9	7.0-27.8	14.1-27.6
Annual mean	22.8	25.7	23.9	23.7

In order to compare predicted and actual water temperature values, the database was queried for those grid cells where existing fish farms were located. Farm data on water temperature were not available for Uganda, but data from Malawi were available (**Table 3.22**).

The comparison shows that predictions for minimum water temperatures were found to be in close agreement with the actual values. Predicted maximum temperatures were lower than actual values (Table 3.22), particularly for Kenya. This may be due to the fact that the comparison for this country was done between predicted water temperature (based on mean air temperatures calculated over a large number of years) and actual water temperature for the month of July 1996 alone. Significant variations can occur from year to year in the annual pattern of both air and water temperatures (see also **Appendix 8.8**). All in all, the comparison shows that there is a tendency towards both lower values and a narrower range for predicted temperatures. This tendency was also found in the Latin America study by Kapetsky and Nath (1997) and in part may account for poor predictions of fish yields in the grid cells where active fish farms exist. Despite this, and as opposed to the Latin America study, the present one did not find any fish farms located in grid cells predicted as US for fish farming which, in turn, implies that there was an increase in the accuracy of the water temperature predictions.

Table 3.22 Predicted vs. actual water temperature evaluation.
[°C]

	ZIMBABWE (6 Farms)			KENYA (31 Farms)			MALAWI (17 Farms)		
	PRE	ACT	DIFF	PRE	ACT	DIFF	PRE	ACT	DIFF
Minimum	13.5	11	2.5	19.1	20	-0.9	14.1	14.9	-0.8
Maximum	29.8	31	-1.2	22.7	31	-8.3	27.6	31.1	-3.5
Range	16.3	20		3.6	11		13.5	16.2	

Terminology: **PRE** = Predicted water temperatures; **ACT** = Actual water temperatures among the fish farms surveyed; DIFF = Difference between predicted and actual water temperature predictions.

Note: Actual data for Kenya was only available for July 1996, and therefore the predicted value is only presented for this month.

4.1 Potential for inland fish farming in Africa

From a continental viewpoint the results are generally positive. The final fish farming potential estimates for the three species together show that about 37 and 43% of the African surface contains areas with at least some potential for small-scale and commercial farming respectively. Moreover, the most significant finding of the study was that 15% of the same areas has the highest suitability score. This implies that for small-scale fish farming, from 1.3 to 1.7 c/y of Nile tilapia, 1.9 to 2.4 c/y of African catfish and 1.6 to 2.2 c/y of Common carp can be achieved in these areas. Similar ranges for commercial farming are from 1.6 to 2.0 c/y of Nile tilapia, 1.3 to 1.7 c/y of African catfish and 1.2 to 1.5 c/y of Common carp.

From a country viewpoint, the results are also generally positive. For small-scale farming of the three species, 11 countries scored VS-1stQ in 50% or more of their national area and an additional 12 scored VS-2ndQ in 25% or more of their area. The corresponding results for commercial farming were that 16 countries scored VS-1stQ in 50% or more of their national area and 8 have VS-2ndQ in 25% or more of their area.

According to the previous fish farming potential estimates by Kapetsky (1994), about 31% of Africa encompasses potential for small-scale farming of Nile tilapia and about 13% for commercial farming of the same species from which 1 to 2 c/y can be obtained. In comparison, the present study found more sites having this potential. That is, about 33% of Africa scores very suitable to suitable for small-scale farming of Nile tilapia where 0.9 to 1.7 c/y can be obtained; for commercial farming, about 36% of Africa scores very suitable to suitable with 1.1 to 2.0 c/y.

4.2 Interpretation of results

Several factors, common to any GIS-based study, had a general effect on the results of this study. These include data quality, surrogate factors, and thresholds and scoring.

Results in general

Data quality

The outcome of GIS modelling is strongly dependent on the quality of the raw data (primary data) because any errors from existing data records will likely be transferred into a GIS database; therefore, it is essential to have full knowledge of the raw data available. Moreover, due to the large, varied and complex data sets used in this study, it was considered crucial to verify the accuracy of the primary spatial datasets for Africa and the models, so great care was taken to have the most accurate and recent data to achieve the best results.

Although it was impractical to check the accuracy of the majority of the data, a number of verifications were carried out during this study. For example, on a country-level, some of the raw data for inputs were partially verified by comparison with data from different information sources (e.g., numerical data on livestock from the Ministry of Agriculture, Development and Marketing (1997), and digital data on crops by Van Velthuizen, Verelst and Santacroce (1995). Furthermore, on a site-level, some raw data verification was achieved during field work.

Surrogate factors

Although a great amount of data were obtained primarily from the USGS, there were instances when required data were not available in any form. Even if the data were

available, the resolution was often inadequate for the application on hand (e.g., data were too coarse). Therefore, in many cases, surrogate data proved to be very useful. The most important surrogate data in this study were the predictions of fish growth based on water temperature, in turn predicted from air temperature and wind velocity data. Second to fish growth, livestock data proved to be suitable to infer the availability of manure as inputs, and thirdly, population density data proved useful as surrogate for farm-gate sales and for urban market potential.

Thresholds and scoring
The results were dependent upon the selection of thresholds and scores selected for the criteria, small-scale and commercial models, and fish yield models. The thresholds and scoring of such criteria established by the first author were based on decisions that were primarily derived from the literature; however, criteria will tend to vary among decision-makers. Hence, the primary goal of this study was the development of analytical procedures and assumptions for classifying and integrating the criteria.

In order to establish a consistent classification that would enable spatial comparison among factors, and to minimise subjectivity in the scoring process, four suitability classes were employed throughout the study, i.e., from very suitable to unsuitable, and from 1^{st}Q to 4^{th}Q yield ranges.

The 1-4 score range was useful because some of the data were already classified to a range of about four values. However, as the number of spatial manipulations increase, it is common that the number of threshold values also increase, making it more difficult to distinguish suitability classes. To solve this problem, and in agreement with the methodology developed by Aguilar-Manjarrez (1996) and Kapetsky and Nath (1997), the selection of thresholds was always based upon an examination of the frequency plots of the grid cells for each criteria, model and fish yield range.

Farming system models

Selection of weights
Results based on the first author's weighting were strengthened by comparing them with the results of questionnaire responses from a group of experts. More importantly, the overall results from the Kendall coefficient of concordance ranking test demonstrated that the rank position of the scores, and therefore the weights, were in close agreement with the experts. In all, greatest benefit from the MCE in this study was gained by the feedback obtained from the group of experts through their comments and during their interviews.

Constraints
The present study incorporated the most complete and up-to-date dataset for protected areas, about 6% of continental Africa. The grid cell size used in this study allowed the inclusion of a majority of the constraints. Results suggest that only 0.04% of Africa that appears to have fish farming potential is reserved for areas classified as constraints (i.e. there are areas with farming potential that coincide with constraint areas) like protected areas and inland water bodies smaller than 5 km x 5 km.

In order to make accurate estimations of fish farming potential and for ease of interpretation, the constraint areas were masked out from all the maps in this study. This spatial manipulation was carried out throughout this study in order to make separate evaluations of the estimates from each of the factors involved in the evaluation.

All aspects of the primary spatial datasets for Africa were standardized to allow spatial comparisons among factors. However, the areas occupied by large inland water bodies did not coincide with some of the factors. This was inevitable, because the livestock and the potential evapotranspiration data obtained had large water bodies which had already been

masked out (i.e., no data) and which did not coincide with the area of the water bodies constraints used in the study (i.e., DCW data). Although the differences in areas are in general small, lakes Victoria, Chad, Malawi and Tanganyika as well as parts of Congo River have areas shown in white (i.e., no data) which could affect (to a minor extent) our estimates of fish farming potential.

Soil and terrain suitability for ponds
Slopes were evaluated independently from the soils evaluation in order to select more precise slope thresholds. This separate evaluation proved to be useful because it enabled a better understanding of the siting criteria required for pond construction. From the soils evaluation, it was found that soils scored as VS are distributed throughout Ethiopia, about 30% and an additional 46% rated S. However, and contrary to expectations, some areas in Ethiopia, that were VS and S for soils, were found US for slopes. This anomaly was also shown on the maps of the earlier Africa study (Kapetsky, 1994). According to F. Nachtergaele (FAO, pers. comm.) this irregularity can be attributed to the resolution used for both studies which did not allow the development of specific site predictions. Another way of expressing the same idea is that given the scales of the maps, predictions could only be made for a whole area (the mapping unit) and not for a specific point within it. Moreover, the fact that slope was evaluated independently sometimes leads to apparent contradictions as relatively good soils may occur in unfavourable terrain (as in the case for Andosols and Nitisols in parts of Ethiopia).

Inputs
The inputs submodel results were affected by two important factors: firstly, the 4'48" resolution available for the livestock data (used to calculate the total amount of manure available) proved to be too coarse to allow more detailed identification of potential manure sites, and secondly, even though the crops data were available at a very fine resolution (i.e. 30-arc-seconds), it was not possible to differentiate among crops types in order to select those which could be suitable as fish feed and/or fertilisers. Despite this, because the evaluation was entirely dependent upon the data available, the analytical methodology developed in this study proved to be an improvement of inputs predictions over that of the earlier Africa study (Kapetsky, 1994) which did not consider the potential availability of manure inputs.

Urban market size and proximity
In spite of a relatively small road density in Africa (around 4%), the results of this study suggest that about 50% of continental Africa is within reasonable proximity of large urban centres that could be important for fish farming development, but that not all of these sites are favourable for fish farming. For instance, some areas in north Africa especially in Algeria, were identified as being very suitable, because Algeria has roads classified as very suitable (**Appendix 8.7**, **Figure 8.14**) meaning that the results of the submodel are logical. In order to enhance the evaluation in order to pin down unfavourable sites, it would be necessary to incorporate other factors. For example, if data were available and comparable Africa-wide, a fish price and acceptability factor could be incorporated into the cities classification to enhance the urban market size and proximity submodel. On the other hand, addition of more detailed information of this nature may be more appropriate in GIS analyses conducted for individual countries, rather than at a continental scale.

Small-scale and commercial models
The most significant difference between the small-scale and commercial models is attributable to the inclusion of the urban market size and proximity submodel in the commercial model. Because this submodel was given the highest weight in the commercial model, additional areas with potential for fish farming not identified in the small-scale model were found by the commercial model. However, some of these areas (as discussed above) should have been identified as unsuitable for areas such as parts of Algeria where water availability is likely to be a serious constraint for fish farming development (i.e., the water

requirement submodel was assigned a logical weight, but the urban market size and proximity submodel needs to be refined).

Yield potential for species

Verification exercises conducted during development of the fish growth model (**Appendix 8.8**) suggest that relatively accurate estimates of yields can be obtained for all the three fish species. However, these exercises were conducted with more detailed and accurate data on model inputs (e.g., water temperature and feeding rates) compared to data used in the actual estimation of yields across the African continent. The results section indicates that predicted water temperatures, particularly maximum temperatures, were lower than actual values for sites where such data were available (i.e., Kenya, Malawi and Zimbabwe). These differences may in part be due to unavailability of some types of input data (e.g., solar radiation) for the water temperature model. The effect of lower water temperatures is primarily manifested as a decrease in potential fish yields predicted by the growth model, and may explain why yields in the grid cells where active fish farms exist tend to be scored lower than the actual potential. However, the lack of quantitative information on fish yields from the farms surveyed precludes estimation of the extent of the possible discrepancy. Development of a database with this information from countries in Africa should be actively pursued in the future.

Field verification work

For the purposes of verification, it was most important to analyze areas where fish farming is practised but where farming potential has not been forecasted as first noted by Kapetsky, (1994) and explored in detail in other studies (Ross and Aguilar-Manjarrez (1995); Aguilar-Manjarrez ,1996). In particular, for this study, it was crucial to verify if the predictions of small-scale and commercial suitability combined with the yield potential corresponded to the locations of existing fish farms.

In general, there was a lack of quantitative information on farm characteristics and water temperature for the four countries for which data was available for verification of this studies results. For example, for Kenya, no data on fish farm characteristics were available and water temperature data were only available for July (see **Table 2.9** in **section 2.8** above). Despite this, the outcome of the verifications that were carried out for the four countries showed that the results were positive because none of the existing farms evaluated were located in areas scored as US.

Insights gained from field work in Zimbabwe

According to Zimudzi (1997) it appears that after initial enthusiasm to embark on fish farming enterprises in the 1980's, the majority of Zimbabwean fish farmers have stopped fish farming. Reasons for this trend are summarized in **Text Box 4.1**.

Zimudzi (1997) found that most of the farmers practised fish farming only as part of their overall activities and not as the primary focus. She concludes that fish farming in Zimbabwe has had a checkered history - there have been lots of failures as well as notable successes. The failures can perhaps be attributed to the fact that it was inevitable as the enterprise was still new, and farmers were still in a learning curve. To be successful some of the most important factors affecting fish farming (**Text Box 4.1**) have to be resolved (e.g. high input costs and marketing).

Text Box 4.1 Factors affecting growth of fish farming in Zimbabwe.

1. Environmental:
   - Drought conditions,
   - Poor growth rates of Nile tilapia due to low water temperatures.
2. Biotechnological:
   - Problems with stocking and survival rates especially in systems with no distinct production cycles.
3. Financial and economic:
   - Low profitability caused by high inputs (e.g. electricity and fish feeds),
   - Competition with imported marine fish from South Africa and Namibia,
   - Distant markets.
4. Social and human:
   - Theft.
5. Administrative and legal:
   - Bureaucracy and lack of dialogue,
   - Poor information exchange,
   - Lack of back-up service for the farmers

Source: Data extracted from Zimudzi (1997).

4.3 Study refinements

The present study is both more refined and sophisticated than the strategic assessment of warm-water fish farming potential by Kapetsky (1994). Nevertheless, additional refinements can be made, some of which could be carried with the existing data.

Farming system models

Scores and weights

Although a careful definition of the submodels was carried out for score assignment (see **Table 2.9** in **Section 2.4.2** above), an enhancement of this study would be to make separate evaluations of the submodels according to the environmental or socio-economic interpretation. In the present study, it was the combined interpretation that was used to give a score to each one of the submodels, and this score assignment proved to be difficult in some cases. For example, because the urban market size and proximity submodel was ranked first in the commercial model, this submodel tended to be socio-economically orientated. In order to make a separate evaluation, submodels would have to be reclassified or re-interpreted, but overall submodel classification depends on how they are integrated to model a particular query. Therefore, reclassifications and trade-offs will vary.

It is evident from this study that different results can be produced at the weighting stage, due to different individuals considering different factors to be more or less important to their own objective. Nevertheless, a strong general consensus was obtained and because it included the expert opinion from various decision-makers, this combined technique gave very useful results. However, as noted by Kapetsky (1994) uncertain data quality in a large database can have a negative influence on the weights assigned by putting more reliability on the results than they deserve. Therefore, to enhance the selection and adjustments of weights, information about the quality of the data should be included in the questionnaire provided to the decision-makers.

Likewise, the maps for each of the submodels had not been completed when the experts were brought in for weight assignments. It is likely that the inclusion of these maps in the questionnaire may have influenced their weighting priorities. Moreover, even though a group consensus for weights was achieved in this study, the greatest benefit from the MCE technique can be realised by bringing experts together to discuss the different scenarios created for the farming system models. This can be accomplished based on iterative weight selection and assignment on the computer screen in order to make final weight adjustments.

In terms of improving model outputs, weightings could be derived from local people. Moreover, it would be an interesting exercise to compare weightings derived from technical experts with those produced by socio-economists and by local planners and local farmer groups (M.C.M. Beveridge, pers.comm.).

Constraints

Nile tilapia, African catfish and Common carp were selected as "index" species for the modelling purposes of this study to evaluate the absolute and relative performance of such species across Africa. However, there is growing concern about the impacts of species introduced for aquaculture purposes on indigenous fish communities and fisheries yields. In Malawi, for example, Common carp and other introduced species are excluded from aquaculture in the Lake Malawi basin area. In other words, there are already conservation areas of sorts excluded from the constraint areas of the present study (M.C.M. Beveridge, pers.comm.). Therefore, if spatial data on introduction of fish species were available Africa-wide then this data would be incorporated into the constraints submodel of the present study.

Water requirement

The water requirement estimation benefited from data available for potential evapotranspiration based on the Penman-Monteith method which is the most widely accepted formula, yielding errors below 10%. However, such data were only available at a 30 arc-minute grid resolution, therefore, the most significant improvement to this submodel would be the increase of resolution of this data (e.g. to 3-arc-minutes).

Data on groundwater availability would enhance the present water requirement estimation to assess fish farming potential in drier areas. For example, Zimbabwe is a country with relatively low rainfall, but where groundwater is perhaps the most important source of water for fish ponds (Kapetsky, 1994).

Interpolation of cities

Major cities are commonly represented spatially as points, therefore, the land areas are small and their size is dependent upon the spatial resolution used. Thus, in some cases, real urban areas may have been underestimated. To solve this problem, an interpolation procedure would have to be carried out for each of the cities according to its population density, the basic assumption being that the higher the population density, the larger the spatial area occupied by the city. The interpolation procedure would improve the constraints submodel by masking out the real urban areas from any fish farming development, and the urban market size and proximity submodel by allowing more accurate calculations of market proximities.

Livestock wastes

An increase in the resolution of the livestock data used to estimate the total amount of manure available would be the most significant improvement to the inputs submodel. Moreover, if data for fish pond areas were available for the whole of Africa, the manure estimation would be greatly enhanced. For example, animal manure application rates for fish pond fertilisation (e.g. Auburn University, 1997) could be used, along with the number of pond areas, to make a rough estimate of the amount of manure needed (e.g., by the multiplication of these two factors). Also, it would be possible to estimate the amount of manure needed as opposed to that actually available by calculating the percentage ratio between these factors (i.e., manure needed/manure available x 100). A low percentage would indicate that the amount of manure available is ample, and therefore, in these areas the amount of manure needed would in fact be available, even if most of it was being used intensively for other production activities like agriculture.

Agricultural by-products

It was not possible to differentiate cropland classes in order to assist in identifying suitable crops for fish culture. However, recent updates of the 1 km land cover data from the USGS, from which the cropland classes were obtained, do give some indication that these types of problems will be resolved in the near future. In the long term, cropland classes from the land cover map could be differentiated with the help of two FAO projects: AFRICOVER (FAO, 1997) will create a digital georeferenced database on land cover and a geographic reference (geodesy, toponomy, roads, hydrography) for the whole of Africa, and AGDAT (FAO Agrometeorology Group, Environment and Natural Resources Service (*In prep.*)) will provide digital agricultural data at a sub-national level.

Multi-objective land allocation (MOLA) decision-making technique.

To assess final fish farming potential, the interaction with other production activities competing for resources must be considered as some of the identified areas that have potential for fish farming in this study are reserved for other uses.

The MOLA technique developed by Eastman (1993) has been created to evaluate the interaction among production activities. This technique also involves the use of weights and could be used in this study to establish the relative strength or priority of each activity with respect to fish farming development. This technique could help identify wider management

options and help resolve conflicts of land allocation and land use. Likewise, by using MOLA, a compromise among activities could be established in order to make a better use of the natural resources available. Two good examples of applications of the MOLA technique for aquaculture are: 1) Aguilar-Manjarrez (1995a,b; 1996), when assessing conflicts in Sinaloa, Mexico between shrimp farming development and other production activities like agriculture, and 2) a more sophisticated one, outlined by Looijen, Pelesikoti and Staljanssens (1996) when evaluating conflicts between mangrove forest conservation and the development of shrimp culture in mangroves in Thailand.

Dynamic aspect of the models

Inter-annual variations in temperature affecting fish growth and production (**Appendix 8.8, Figures 8.15** and **8.17**), and variations in precipitation and evaporation affecting water availability (**Appendix 8.3**, **Figures 8.1** to **8.3**), are clear indications that the application of the models developed in this study are subject to many changes, so the dynamic aspect of the models should be further developed. Kapetsky and Nath (1997) mention that these types of weather data could be used to look at best and worst cases for the operation of ponds and for the production of fish.

Field verification

Clearly, verification results show that a large number of factors affect the development and operation of fish farms. This has to be taken into account while assessing results of the current study because only five general factors (in weighted combination) were used in the farming systems models developed. Nevertheless, as more data becomes available, it should be possible to incorporate more factors that are important for the development of fish farming. For example, the development of a well classified, high resolution land cover map, should allow the extraction of relevant data for fish farming such as crop types and urban areas.

Other refinements that would require new data or new approaches include:

- A complete set of climate data to allow inclusion of Madagascar.
- Once the 1 km land cover classes are further defined by the USGS, these data will allow the present study to use the MOLA decision-making technique to make better estimates of land actually available for aquaculture.
- Since the GIS evaluation in this study was primarily "land-based" (i.e., based upon the data available), it is vital that "water-based" data are incorporated into the GIS system (e.g., using remote sensing data). The primary reason for this would be to further improve water temperature estimations.
- Extend the study to include cold-water species such as rainbow and brown trout.
- Improve the fish growth model to investigate polyculture opportunities.
- Increase the number of fish farms to be verified in the field for both types of culture systems and for the three fish species.
- At a national-level, the present study could be extended to include cage culture and commercial aquaculture geared towards export markets. In Zimbabwe, about 1500 t of tilapias will be produced from cage aquaculture in 1998 and there are plans to increase this substantially over the next few years, making it one of the more important sources of farmed fish in the country (M.C.M. Beveridge, pers.comm.). Investment decisions by multinationals with commercial fish farming interests are made on the basis of political stability as much as by factors such as water quality and soils - domestic markets are unimportant; proximity to airports, however, would be (M.C.M. Beveridge, pers.comm.).

5. CONCLUSIONS

Use only of data that are comparable Africa-wide
As a follow-up to the work of Kapetsky (1994), this study only used data that are comparable for the whole of Africa. This approach limited the number of factors that could have been used for the evaluation, but it enabled comparisons among countries. More importantly, this methodology enables development work to be planned and executed by evaluating the needs and similarities among countries or regionally. To this end, the primary objectives of this study - to stimulate improved planning for fish farming development at national levels, and at the same time to provide a tool to plan comprehensively for technical assistance by FAO and other national and international organisations - were achieved.

The present study identified potential areas for fish farming development, and it is at this stage that the assessment can allow planners to select countries or regions in which to conduct more detailed studies by bringing more factors into the analysis and taking advantage of data at resolutions that are higher than are appropriate at a continental scale. For example, addressing cage culture, and socio-economic criteria are good options for priority setting. However, such exercises are perhaps better addressed at a national-level, rather than in a continental study such as the present one, because socio-economic conditions vary greatly both between countries and within individual ones and it is unlikely that simplified weightings that would apply to all of Africa can be easily derived.

Fish farming potential
The results of this study are generally positive for the development of inland fish farming in Africa. There are apparently vast areas in Africa that have potential for both small-scale and commercial farming of Nile tilapia, African catfish and Common carp without serious constraints, either from the quality of the land or from constraints of temperature on fish growth. The most significant finding was that the final fish farming potential estimates for the three fish species together show that about 15% of the African surface contains areas with the highest suitability score for both small-scale and commercial farming.

The culture system and the yield models appear to work well separately as well as together to give reasonable estimates for fish farming potential. Therefore, refinements and not reconstruction of the models are needed to improve predictions of this study.

In correspondence to the earlier fish farming studies (Kapetsky, 1994; Kapetsky and Nath, 1997), primarily because of the continental scale used, the resolution and the assumptions employed, the estimates of fish farming potential generated in this study are essentially indicative of aquaculture potential. Not all of the area that has been identified as having potential can be allocated to fish farming as some land areas may already be used for other uses such as buildings and roads.

The estimates of area with potential (or lack of potential) for fish farming development were influenced by many factors. Some of these factors originate from the inaccuracy of the data, their spatial and temporal availability, the analytical approach and the underlying assumptions adopted. However, the increasing availability of data and the greater capabilities of computer technology continue to expand the potential role of GIS, and many of the problems affecting this study's results will be minimised or eliminated as more data becomes available, and more experience is gained with aquaculture-oriented GIS.

Thresholds
Although strong efforts were made to use objective thresholds, because the majority of the thresholds were identified through literature research (e.g., slope classes for fish ponds) and guidance from expert staff at FAO, there is some subjectivity in the results.

Nonetheless, this feature is to some extent inevitable as "scoring" involved interpretation of data. Interestingly, this feature actually allows flexibility in GIS modelling, while at the same time introducing subjectivity, and the balance between the two is an important consideration in practical decision-making.

Weights

Although more field studies need to be carried out to further reduce the subjectivity of weights (or relative importance of submodels in the small-scale and commercial models), the group of experts generally agreed in choosing the appropriate weights. Moreover, the rank order of the weights and even the weights themselves of this study were quite similar to the Latin America study (Kapetsky and Nath, 1997) implying that the weight selections were based on sound decisions. For example, the urban market size and proximity submodel in this study was ranked first in importance for commercial farming and given a weight of 46% which is very similar to the value of 49% used in the Latin America study.

Verification

Overall, verification results proved to be in close agreement with the GIS predictions. There was a good correspondence between the predictions of small-scale and commercial suitability combined with the yield potential, to the locations of existing fish farms. Because none of the existing farms were located in areas scored as unsuitable, these results suggest that reasonable confidence can be placed on the predictions of the suitability of the grid cell "sites" for fish farming.

Future applications

Food security

A related use of the present results would be to update the study by Kapetsky (1995) on the potential contribution of fish farming to overall fish supply and to food security in Africa.

Evaluation and management of inland fisheries

Some of the primary data or submodels will be used directly or will be re-assessed and developed as inputs to spatial models for the evaluation and management of inland fisheries. This work is underway by the Inland Water Resources and Aquaculture Service (FIRI) at FAO led by Dr. J.M. Kapetsky. In short, the kinds of models that will be created as outlined by J.M. Kapetsky (pers.comm.) are:

1. Fishery potential under wild or natural conditions.
2. Fishery potential under various kinds of enhancements in order to estimate the likely increases in benefits compared with unenhanced fisheries.
3. Losses of potential yield due to general environmental degradation, so that mitigation or rehabilitation is properly scaled and financed.

Significant refinements to the data developed in the present study will be made by using "a catchment approach" to spatially delineate factors that directly or indirectly affect fishery potential. The primary data from the present study that will be used are: inland water bodies, soils, precipitation, temperature, roads, population density and land cover.

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7. REFERENCES

Aguilar-Manjarrez, J. 1996. Development and evaluation of GIS-based models for planning and management of coastal aquaculture. A case study in Sinaloa, México. *PhD Thesis*. Institute of Aquaculture, University of Stirling, Scotland, UK. 375 pp.

Aguilar-Manjarrez, J. 1992. Construction of a GIS for Tabasco State Mexico. Establishment of technical and social decision models for aquaculture development. *M.Sc. Thesis*. Institute of Aquaculture, University of Stirling, Scotland, UK. 125 pp.

Aguilar-Manjarrez, J., and Ross, L.G. 1995a. Geographical Information Systems (GIS), environmental models for aquaculture development in Sinaloa state, Mexico. *Aquaculture International,* **3** (2):103-115.

Aguilar-Manjarrez, J., and Ross, L.G. 1995b. GIS enhances aquaculture development. *GIS World,* **8** (3): 52-56.

Aguilar-Manjarrez, J., and Ross, L.G. 1993. Aquaculture development and Geographical Information Systems. *Mapping Awareness and GIS Europe,* **7** (4) 49-52.

Auburn University. 1997. Organic fertilizers for fish ponds. International Center for Aquaculture and Aquatic Environments (ICAAE). *Water harvesting and aquaculture manuals*. No. FF3, 10 pp.

Balarin, J.D., Chisawa, A., and Evans, R. 1997. Commercial fish farming poised to take off in Zimbabwe. *The FAO Aquaculture News Letter*. April 1997,**15**: 18-19.

Banai, R. 1993. Fuzziness in Geographic Information Systems: contributions from the analytical hierarchy process. *International Journal of Geographical Information Systems*, **7**: 315-329.

Belward, A.S., and Loveland, T.R. 1995. The IGBP-DIS 1-km Land Cover project: Remote Sensing in Action. *In*: *Proceedings of the 21st Annual Conference of Remote Society*. Southampton, United Kingdom.

Bok, A.H., and Jongbloed, H. 1984. Growth and production of sharptooth catfish, *Clarias gariepinus* (Pisces: Clariidae), in organically fertilized ponds in the Cape Province, South Africa. *Aquaculture*, **36**: 141-155.

Bolte, J.P., Nath, S.S., and Ernst, D.H. 1995. POND: A decision support system for pond aquaculture. Twelfth Annual Administrative Report, PD/A CRSP, Corvallis, OR. pp. 48-67.

Born, A.F. Verdegem, M.C.J., and Huisman, E.A. 1994. Macro-economic factors influencing world aquaculture development. *Aquaculture and Fisheries Management*, **25**: 519-536

Brooks, A.C., and Maluwa, A.O. 1997. Fish farming in Malawi: A case study of the Central and Northern Regions Fish Farming Project. Technical Supplement: On-station Pond Trials. Government of Malawi and European Commission. 37 pp.

Candia, G.R.B. 1997. A brief report about aquaculture situation in West Nile (Arua) region of Uganda. Nile Fishtec and Business Consult Services. Arua, Uganda. FAO Field Document, Report No. ER53/1.12. Rome, FAO. 20 pp.

Carver, S.J. 1991. Integrating multi-criteria evaluation with Geographic Information Systems. *International Journal of Geographical Information Systems*, **5**: 321-339.

Coche, A.G. (ed.) 1994. Aquaculture development and research in sub-Saharan Africa. National reviews. *CIFA Technical Paper*. No. 23, Suppl. Rome, FAO. 397 pp.

Coche, A.G., and Laughlin, T. 1985. Soil and freshwater fish culture. *FAO Training Series,* No.6, 6174 pp.

Coche, A.G., and Van der Wal, H. 1981. Water for freshwater fish culture. *FAO Training Series* No. 4, 111 pp.

Coche, A, G., Muir, J.F., and Laughlin,T. 1996. Management for freshwater fish culture. Ponds and water practices. *FAO Training Series* (21/1): 233 pp.

Coche, A.G., Haight, B., and M. Vincke. 1994. Aquaculture development and research in sub-Saharan Africa. Synthesis of national reviews and indicative action plan for research. *CIFA Technical Paper.* No. 23. Rome, FAO. 151 pp.

De Kimpe, P., and Micha, J.-C. 1974. First guidelines for the culture of *Clarias lazera* in Central Africa. *Aquaculture,* **4**: 227-248.

Department of Lands and Surveys. 1986. Uganda administrative boundaries. Topographic map, scale 1:1,500,000. Transverse Mercator projection. Uganda P.O. Box 1, Entebbe.

Diana, J.S., Lin, C.K., and Yi, Y. 1995. Stocking density and supplemental feeding. Thirteenth Annual Technical Report, PD/A CRSP, Corvallis, OR. pp. 117-125.

Dickson, M.W., and Brooks, A.C. 1997. Fish farming in Malawi: A case study of the Central and Northern Regions Fish Farming Project. Government of Malawi and European Commission. 70 pp.

Doorenbos, J., Kassam, A.H., Bentvelsen, C.L.M., Branscheid, V., Plusjé, J.M.G.A., Smith, M., Uittenbogaard, G.O., and Van Der Wal, H.K. 1986. Yield response to water. *FAO Irrigation and Drainage Paper.* No. 33, 193 pp.

Doorenbos, J., Pruitt, W.O., Aboukhaled, A., Damagnez, J., Dastane, N.G., Van Den Berg, C., Rijtema, P.E., Ahsford, O.M., Frere, M., and FAO Field Staff. 1992. Crop Water Requirements. *FAO Irrigation and Drainage Paper,* N. 24. Rome, FAO. 144 pp.

Eastman, J.R. 1993. IDRISI version 4.1. Update Manual. Clark Laboratories for Cartographic Technology and Geographic Analysis. Clark University, Worcester, MA, USA. 120 pp.

Eastman, J.R., Kyem. P.A.K., Toledano, J., and Jin, W. 1993. GIS and Decision Making. United Nations Institute for Training and Research. *Explorations in Geographic Information Systems Technology.* The Clarks labs for Cartographic Technology and Geographic Analysis. Clark University, Worcester MA, USA. Vol. 4. pp 112.

Encyclopaedia Britannica. 1993. Africa. The New Encyclopaedia Britannica. Vol. 13. pp 37 -72.

Engle, C.R. 1997. Optimal Resource Allocation by Fish Farmers in Rwanda. *Journal of Applied Aquaculture,* 7(1): 1-17.

Engle, C.R., Brewster, M., and Hitayezu, F. 1993. An economic analysis of fish production in a subsistence agricultural economy: the case of Rwanda. *Journal of Aquaculture in the Tropics,* **8**: 151-165.

ESRI. 1992a. ESRI Digital Chart of the World for use with ARC/INFO, Version 1. ESRI, Redlands, CA, USA.

ESRI. 1992b. ESRI Arc World 1:3M. User's Guide. ESRI, Redlands, CA, USA.

FAO. 1997. AFRICOVER. Land cover classification. Rome, FAO. 76 pp.

FAO, 1996a. FOOD FOR ALL. Book issued on the occasion of the World Food Summit in Rome, 13-17 November, 1996. Rome, FAO. 64 pp.

FAO, 1996b. Poverty and Food Security in Africa. Documentation issued on the occasion of the World Food Summit in Rome, 13-17 November, 1996. Rome, FAO. 2 pp.

FAO, 1996c. Fisheries and Food security. Documentation issued on the occasion of the World Food Summit in Rome, 13-17 November, 1996. Rome, FAO. 2 pp.

FAO. 1995. Digital Soil Map of the World and derived soil properties. Version 3.5. CD-ROM. Rome, FAO.

FAO Agrometeorology Group, Environment and Natural Resources Service (*In prep.*). AGDAT. *FAO Agrometeorology Series*, *Working Paper* N. 14.

FAO Fisheries Department. 1996a. Fisheries and aquaculture in Sub-Saharan Africa: situation and outlook in 1996. *FAO Fisheries Circular* No. 922, 44 pp.

FAO Fisheries Department. 1996b. Fisheries and aquaculture in Near East and North Africa: situation and outlook in 1996. *FAO Fisheries Circular* No. 919, 37 pp.

FAO Water resources, Development and Management Service (AGLW). 1996. Estimating water requirements for small ponds in Latin America. *Internal FAO report*. Rome, FAO. 28 pp.

FAO-UNESCO. 1977. FAO-UNESCO Soil Map of the World. Vol. VI Africa. UNESCO, Paris. 299 pp.

FAO-UNESCO. 1974. FAO-UNESCO Soil Map of the World. Vol. I Legend. UNESCO, Paris, 59 pp.

Fertilizers and Agriculture, 1997. FAO World Food Summit Confirms Role of Fertilizers. *Fertilizers and Agriculture*, March 1997. Rome, FAO. 8 pp.

Fritz, J.J. Meredith, D.D., and Middleton, A.C. 1980. Non-steady-state bulk temperature determination for stabilization of ponds. *Water Research*, **14**: 413-420.

Gommes, R., and Petrassi, F. 1994. Rainfall Variability and Drought in Sub-Saharan Africa since 1960. *Agrometeorology Series Working Paper*, No. 9. Rome, FAO. 100 pp.

Greenwood, J. A., and Hartley, H. O. 1962. Guide to Tables in Mathematical Statistics. Oxford University Press, London.

Hajek, B.F., and Boyd, C.E. 1990. Rating soil and water information for aquaculture. *Aquaculture engineering,* **13**: 115-128.

Harrison, E. 1994. Aquaculture in Africa: Socio-economic dimensions. *In*: Muir, J.F., and Roberts, R.J. (eds.), *Recent advances in Aquaculture.* Blackwell Science, Oxford. pp. 240-299.

Haylor, G.S., 1993. Aspects of the biology and culture of the African catfish *Clarias gariepinus* (Burchell 1822) with particular reference to developing African countries. *In*: Muir, J.F. and Roberts, R.J. (eds.), *Recent advances in Aquaculture* IV, Blackwell Scientific Publications, London. pp. 233-294.

Hepher, B., 1988. Nutrition of pond fishes, Cambridge University Press. 388 pp.

Hopkins, K.D., 1992. Reporting fish growth: A review of the basics. *Journal of the World Aquaculture Society*, **23**: 173-179.

Human Development Report, 1996. UNDP.

Hutchinson, M.F. 1991. The application of thin plate splines to continent-wide data assimilation. *In*: Jasper, J.D. (ed.), Data Assimilation Systems. BMRC Res. Rep. No. 27, Bureau of Meteorology, Melbourne, 104-113.

Hutchinson, M.F., and Gessler, P.E. 1994. Splines - more than just a smooth interpolation. *Geoderma*, **62**: 45-67.

Hutchinson, M.F., Nix, H.A., McMahon, J.P., and Ord, K.D. (*In prep.*). The development of a topographic and climate data base for Africa.

ICLARM and GTZ. 1991. The context of small-scale integrated agriculture-aquaculture systems in Africa: a case study of Malawi. *ICLARM Stud. Rev.* 18, 302 pp.

Janssen, R. and Rietveld, P. 1990. Multicriteria analysis and Geographical Information Systems. An application to agricultural land use in the Netherlands. In: *Geographical Information Systems for Urban and Regional Planning*, edited by Scholten, H.J. and Stillwell, J.C.H. (Dordrecht: Kluwer Academic Publishers), pp. 129-139.

Kapetsky, J.M. 1995. A first look at the potential contribution of warm water fish farming to food security in Africa. pp. 547-592, *In*: Symoens, J-J., and Micha, J-C. (eds.) *Proceedings of the Seminar on the Management of Integrated Freshwater Agro-Piscicultural Ecosystems in Tropical Areas*. Brussels, 16-19 May 1994. Technical Centre for Rural Coorporation (CTA), Wageningen, the Netherlands.

Kapetsky, J.M. 1994. A strategic assessment of warm-water fish farming potential in Africa. *CIFA Technical Paper*, N. 27. Rome, FAO. 67 pp.

Kapetsky, J.M., and Nath, S.S. 1997. A strategic assessment of the potential for freshwater fish farming in Latin America. *COPESCAL Technical Paper* N. 10. Rome, FAO. 128 pp.

Kendall, M.G. 1984a. *Rank correlation methods*. Griffith, London, U.K.

Kendall, M.G. 1984b. The advanced theory of statistics. Vol 1 (4^{th} Ed.). Griffith, London, U.K.

Lamb, H.H. 1982. Climate, History and the Modern World. Methuen, London and New York. 387 pp.

Leemans, R., and Cramer, W. 1991. The IIASA Database for Mean Monthly Values of Temperature, Precipitation, and Cloudiness on a global Terrestrial Grid. IIASA Research Report, Laxenburg, Austria.

Little, D., and Muir, J.F. 1987. *A guide to integrated warm water aquaculture*. Institute of Aquaculture publications. University of Stirling, Scotland. 238 pp.

Looijen, J., Pelesikoti, N., and Staljanssens, M. 1996. ICOMIS: a spatial multi-objective decision-support system for coastal resource management. Department of land resources and urban sciences. *ITC Journal*, **3**: 202-216.

Malczewski, J. 1996. A GIS-based approach to multiple criteria group decision-making. *International Journal of Geographical Information Systems*, **10** (8): 955-971.

Marquet, J.P., Achieng, P., and Obuya, S. 1996. Technical report of general fish culture aspects and reformulation of the follow-up project. Technical cooperation Programme. Support to small-scale rural aquaculture in Western Kenya. Rome, FAO. 22 pp.

Meaden, G.J., and Kapetsky, J.M. 1991. Geographical Information Systems and Remote Sensing in Inland Fisheries and Aquaculture. FAO *Fisheries Technical Paper*, No. **318**. 262 pp.

Meyer-Burgdorff, K.-H., Osman, M.F., and Gunther, K.D. 1989. Energy metabolism in *Oreochromis niloticus*. *Aquaculture*, **79**: 283-291.

Ministry of Agriculture, Livestock Development and Marketing. 1997. Latest livestock data (1995) for Kenya at a District level. FAO Representative in Nairobi, Kenya. 2 pp.

Molnar, J.J., Rubagumya, A., and Adjavon, V. 1991. Sustainability of aquaculture as a farm enterprise in Rwanda. *Journal of Applied Aquaculture,* **1**(2): 37-62.

Monteith, J.L. 1965. Evaporation and the environment. *In*: The State and Movement of Water in Living Organisms. XIXth Symposium. Soc. for xp. Biol., Swansea Cambridge University Press. pp. 205-234.

Moteith, J.L. 1981. Evaporation and surface temperature. Quarterly *J. Royal Meteo. Soc.* **107**: 1-27.

Muir, J.F., and Kapetsky, 1988. Site selection decisions and project cost: The case of brackish water pond systems. Aquaculture engineering. Technologies for the Future. Institution of Chemical Engineers Symposium Series No. 111. EFCE Publication Series No.66 pp 45-63.

Muir, J.F., and Beveridge, M.C.M. 1987. Water resources and aquaculture development. *Archives of Hydrobiology,* **28**: 321-324.

Nash, C.E. 1995. *Aquaculture Sector Planning and Management*. Fishing New Books, Farnham, U.K. 310 pp.

Nath, S.S. 1996. Development of a decision support system for pond aquaculture. *PhD Dissertation*, Oregon State University, Corvallis, OR. 273 pp.

Nicholson, S.E. 1981. The historical climatology of Africa. *In*: Wigley *et al.*, 1981: 249-270.

Nicholson, S.E., Kim, J., and Hoopingarner, J. 1988. Atlas of African rainfall and its interannual variability. Florida State University. Department of Meteorology. No. 15, 237 pp.

Ofori, J., Asamoah, M., and Prein, M. 1996. Rapid appraisal of low-input aquaculture systems. In: Research for the future development of aquaculture in Ghana. ICLARM/IAB/GTZ. ICLARM Conf. Proc. 42, pp. 37-41.

Olson, J.S., and Watts, J.A. 1982. Major World Ecosystem Complex Map. Oak Ridge, TN: Oak Ridge National Laboratory.

Pedini, M and Shehadeh, Z. 1997. Aquaculture in Sub-Saharan Africa: Situation and outlook. *FAO Aquaculture Newsletter (FAN)*, April 1997, No. 15: 3-6.

Pereira, J.M.C. and Duckstein, L. 1993. A multiple criteria decision-making approach to GIS-based land suitability evaluation. *International Journal of Geographical Information Systems* 7(5): 407-424.

Phillips, M.J., Beveridge, M.C.M., and Clarke. 1991. Impact of aquaculture on water resources. *In*: Brune, D.E. and Tomasso, J.R. (eds). *Advances in World Aquaculture,* **3**, 568-591.

Reynolds, J.E. (ed.). 1993. Marketing and consumption of fish in eastern and southern Africa: selected country studies. *FAO Fisheries Technical Paper*. No. 332. Rome, FAO. 194 pp.

Ross, L.G., and Aguilar-Manjarrez, J. 1995. GIS enhances aquaculture development. *In*: Environmental modelling and management of complex datasets for aquaculture: progress in using GIS by Lindsay G. Ross. *Aquaculture News*, Institute of Aquaculture, University of Stirling, Scotland, UK November 1995, **20**: 21-24.

Ross, L.G., and Aguilar-Manjarrez, J. 1993. Aquaculture development and Geographical Information Systems in the Institute. *Aquaculture News*, Institute of Aquaculture, University of Stirling, Scotland, UK July 1993, **16**: 14-15.

Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures, *Journal of Mathematics. Physiology* **15**: 234-281.

Siegel, S. 1965. *Nonparametric Statistics for the Behavioural Sciences*. McGraw Hill Book Company Inc., USA. pp. 229-239.

Sys, C.1980. Land Evaluation . ITC for Postgraduate Soil Scientists .Ghent , Belgium.

Szumiec, M. 1979a. Hydrometerology in pond fish culture. *In*: T.V.R. Pillay (ed.), Advances in Aquaculture, FAO, Fishing News Books Ltd., England. pp. 117-120.

Szumiec, J. 1979b. Some experiments on intensive farming of common carp in Poland. In: In: T.V.R. Pillay (ed.), Advances in Aquaculture, FAO, Fishing News Books Ltd., England. pp. 157-161.

Szumiec, M., and Szumiec, J., 1985. Studies on intensification of carp farming. 2. Effect of temperature on carp growth. *Acta Hydrobiol.*, **27**: 147-158.

Tacon, A.G.J. 1991. Kenya. Development of Tilapia feeds. A report prepared for the project small-scale fish farming in the Lake Basin. FAO Field Document, Project KEN/86/027. Rome, FAO. 31 pp.

Tacon, A.G.J. 1989. Nutrici0n y alimentaci0n de peces y camar0nes cultivados. Manual de capacitaci0n. *AQUILAII Documento de Campo*, (4): 572 pp.

Tacon, A.G.J., Maciocci, G., and Vinatea. J.E. 1987. National agriculture feed surveys (NAFS) for aquaculture planning and development in Latin America and the Caribbean. 1. Guidelines (GCP/RLA/075/ITA). Field document 1/E. Brasilia, Brazil. Rome, FAO. 11 pp.

Teichert-Coddington, D.R., Green, B.W., Claros, N., and Rodriguez, M.I. 1991. Optimization of feeding in combination with organic fertilization. Eighth Annual Administrative Report, PD/A CRSP, Corvallis, OR. pp. 30-32.

Tobler, W., Deichmann, U., Gottsegen, J., and Maloy, K. 1995. The global demography project. National Center for geographic Information and Analysis. Technical Report 95-6. 75 pp. + diskette.

Turner, B.L.II, Hyden, G., and Kates, R.W. 1993. *Population growth and agricultural change in Africa.* Gainsville, FL: University Press.

Ursin, E. 1967. A mathematical model of some aspects of fish growth, respiration, and mortality.J.Fish.Res.Bd.Can., **24**:2355-2453.

Van Velthuizen, H. Verelst, L., and Santacroce, P. 1995. Crop production system zones of the IGADD sub-region. *Agrometeorology Working Paper Series* No. 10. Rome, FAO. 89 pp + 1 diskette + maps.

Verheust, L., Rurangwa, E., and Veverica, K. 1991. Production and growth of supplementally fed *Oreochromis niloticus* males stocked at three densities in fertilized ponds. Ninth Annual Administrative Report, PD/A CRSP, Corvallis, OR. pp. 34-35.

Vincke, M. 1985. Developing productive systems under village conditions. Paper presented at the Commonwealth Consultative Workshop on Village Level Aquaculture Development in Africa, Sierra Leone, 14-20 February 1985. 23 pp.

Webb, B.W. and Nobilis, F. 1997. Long-term perspective on the nature of the air-water temperature relationship - A case study. *Hydrological Processes,* **11** (2): 137-147.

Yoo, K.H., and Boyd, C.E. 1994. Hydrology and water supply for pond aquaculture. New York, NY: Chapman and Hall. 483 pp.

Zimudzi, F. 1997. Locations and characteristics of fish farms in Zimbabwe for verification work of a strategic re-assessment of fish farming potential in Africa. FIRI PLANSYS No. 670.004. Rome, FAO. 19 pp.

8. APPENDIX

GIS analyses for the assessment of fish farming potential in Africa

by

José Aguilar-Manjarrez

8.1 OVERVIEW

This appendix provides full and detailed descriptions of the database and the methodology used in this study. Compared with the first fish farming GIS study done for Africa, the methodology developed here is considerably more sophisticated. This study has been based on the development of a recent study for Latin America. In comparison to the latter, the present one has made adjustments and improvements. The most significant advance has been the development of the fish growth models.

INTERNET addresses are provided in this appendix for the interest of readers who wish to obtain the original data that were used in this study or for additional details.

8.1.1 Hardware and software

Hardware

Almost the entire GIS analyses was carried out using a Sun Spark Station 10.

Other GIS analyses and ASCII data manipulations using QBASIC and VISUAL-BASIC programs were run on a Pentium PC, MS P/133, 1.2 GB, 17 inch Video Super VGA. The PC was set up to run under DOS with no network connection to obtain maximum memory (e.g. for running QBASIC programs) or with network capabilities for data file transfers.

Data transfers between the Sun Spark Station 10 and the Pentium PC were carried out under Microsoft Windows for work groups version 3.11 and XTGOLD software.

Digital data for verification of fish farming potential in Uganda were created by digitizing a paper map using a Calcomp 9100 SMART A0 digitizer.

Software

A Geographic Information System (ARC, Version 7.0.3, ESRI, Redlands, CA, USA) which has both raster and vector capabilities was used. This system is able to efficiently store geographically referenced information in a database which includes both digital maps and their attribute files. Different criteria were kept in separate directories in the database and were called when required. Criteria were combined using logical conditions and/or mathematical operations according to the models developed.

Other GIS software (i.e. IDRISI for Windows version 1, ERDAS version 1 and IDA version 4.2) were used to take advantage of some of their capabilities (e.g. MCE from IDRISI) or as a tool to convert to or from different data formats (e.g. UNIX - ERDAS - IDRISI file conversions or vice versa).

8.1.2 Database

Base grid

A grid was used as a template to standardise grid extensions. Since most of the study was based on the air temperature data, the cell size and geographic projection of one of these data were chosen as the base grid. A copy of the Grid file for maximum temperature for the month of January was made, renamed as AFMASK and reclassified to contain only values of 1 for the African continent and -999 for the NO DATA values (e.g. the Ocean).

A description of AFMASK is illustrated below:

Arc: describe afmask

Description of Grid /disk5/faogis7/pepe57/general/afmask

Cell Size =	0.050	Data Type:	Integer
Number of Rows =	1450	Number of values =	2
Number of Columns =	1380	Attribute Data (bytes) =	8

BOUNDARY		STATISTICS	
Xmin =	-17.475	Minimum Value =	-999.000
Xmax =	51.525	Maximum Value =	1.000
Ymin =	-34.975	Mean =	-497.075
Ymax =	37.525	Standard Deviation =	499.996

COORDINATE SYSTEM DESCRIPTION

Projection	GEOGRAPHIC		
Units	DD	Spheroid	CLARKE1866

The spatial extensions of AFMASK ensure coverage of the entire African continent except for Madagascar. Data originally stored in vector or ASCII format or having a different resolution or projection were converted to the base grid.

Based on the number of rows and columns defined above, the base grid had a total of 2,001,000 pixels (i.e. 1450 * 1380 = 2,001,000). The number of pixels for the African continent including the inland water bodies was 1,004,351 (i.e. Madagascar not included).

Database directory

The present database was almost entirely developed under the directory: /sun2disk5/faogis7/pepe57/ of SUN2. Due to lack of space in the latter directory, part of the appendix was developed under the following directories: /sun1disk3/faogis3/waba/ and /sun1disk3/faogis3/epsanex of SUN1.

FILE	CONTENT
Documentation	
pepe57/zzzreadme.txt	Detailed description of the directory.
pepe57/abstract.txt	Abstract of the study.
pepe57/demo.aml	Demo that displays main maps of study.
Pepe57/digit/digit.doc	Detailed description of digitizing procedures.
Grid and coverage files	
pepe57/general	General grids and coverages for main maps.
pepe57/tiff/annex/general	General grids, coverages and map compositions for appendix.
pepe57/constraint	Constraints (Protected areas, inland water bodies and urban areas).
/sun1disk3/faogis3/waba	Monthly water requirement grids (i.e. precipitation, potential evapotranspiration and water balance).
pepe57/waterreq	Annual water requirement grid.
pepe57/nsoils	Soil and terrain suitability for ponds.
pepe57/inputs	Livestock wastes.
pepe57/landc	Agricultural by-products.
pepe57/farmgate	Farm-gate sales.
pepe57/market	Urban market size and proximity.
pepe57/tiff/annex/airtmp	Mean monthly air temperature.
pepe57/tiff/annex/wind	Mean annual wind velocity.
pepe57/tiff/annex/watmp	Mean monthly water temperature.
pepe57/fishsim	Fish growth.
pepe57/models	Programmes developed to integrate data (i.e. farming system models).
pepe57/tiff/main	Final grids for the main section of the study.
pepe57/digit	Digitized data for verification.
pepe57/verify	Verification of database and of the models produced.
Map compositions	
pepe57/tiff/csystem	Eight map compositions (i.e. one for each farming system submodels).
pepe57/tiff/fishsim	Six map compositions (i.e. by fish specie and farming system).
pepe57/tiff/combine	Six map compositions (i.e. by fish specie and farming system).
pepe57/tiff/coincide	Two map compositions (i.e. small-scale and commercial).
pepe57/tiff/annex/waba	Three map compositions (i.e. precipitation, potential evapotranspiration and water balance).
pepe57/tiff/annex/general	Five map compositions (soils, slopes, manure, crops and cost).

pepe57/tiff/annex/airtmp	One map composition for monthly air temperature grids.
pepe57/tiff/annex/wind	One map composition for mean annual wind velocity grid.
pepe57/tiff/annex/watmp	One map composition for monthly water temperature grids.
Postscript files (eps)	
pepe57/tiff/eps	Final eps files of all main maps. 23 maps and 23 eps files, including the front cover map of the report.
/sun1disk3/faogis3/epsanex	Final eps files for all maps in the appendix, 11 maps and 66 eps files.
Statistics	
pepe57/statist	Statistical data of study results at a continental and country level.

8.1.3 Database criteria description

As with any GIS-base study, the analysis was strongly dependent upon the quality and accuracy of the data used, so in order to account for this, a detailed description of the data used is provided below:

CONSTRAINTS

Protected areas

Delineation of protected areas in digital format (vector) were available from the WCMC. Those areas were classifies as: conservation; wildlife and additional forest. These areas were classified into a single class with a value of zero.

INTERNET address: http://unep.unep.org/unep/partners/global/wcmc/home.htm

Water bodies

They were derived from the DCW (ESRI, 1992a) at 1 million scale and rasterized. The grid includes perennial lakes and rivers which can be detected at 0.050 degree resolution. These areas were classified into a single class with a value of zero.

INTERNET address: DCW can be downloaded from the Digital Chart of the World data Server of the *Pennsylvania State University Libraries*. Also see the following site for DCW in ARC/INFO format: http://www.esri.com/base/data/online/browse.html

Major cities

Locations of major cities were provided by ArcWorld at 1:3000,000 scale, rasterized, and classified into a single class with a value of zero.

INTERNET address: http://www.esri.com/base/support/faq/pcarc/5datacon/7_1547.html. The DCW site (above) also contains information for Arc/World.

FARMING SYSTEM MODELS

FACTORS (PHYSICAL AND ENVIRONMENTAL RESOURCES)

Water requirement

Precipitation

The source data were twelve ASCII files containing gridded values of mean monthly precipitation. The source data and the procedure to import these files into GRID is similar to the one described for the air temperature data (below). The standard errors of the rainfall grids range between 5 and 15%, depending on the data density and the spatial variability of the actual mean monthly rainfall. These files were obtained in standard ARC/INFO ASCII INTEGER GRID format in millimetres.

INTERNET address: http://cres.anu.edu.au/software/africatxt.html

Potential evapotranspiration
Twelve GRID files containing monthly potential evapotranspiration values for the whole world in ARC/INFO export format were obtained from IIASA (i.e. IIASA-LUC project and W.Cramer).

The PET data were calculated using the Penman-Monteith equation (Monteith, 1965; 1981; Doorenbos *et al.*, 1992) based on the IIASA-LUC project input data. In more detail, the input data were derived from two sources:

a) Leemans and Cramer (1991), and

b) Variable Wind Speed: derived from LUC project based on ECMWF database (over 10 years daily wind data) were averaged to monthly data.

INTERNET address: http://www.iiasa.ac.at/

Soil and terrain suitability for fish ponds

Soils
Soils data for Africa were obtained from the DSMW CD-ROM (Version 3.5, FAO, 1995). This database is based on the FAO-UNESCO Soil Map of the World, original scale 1:5,000,000. The CD-ROM contains two types of files: DSMW map sheets and Derived Soil Properties files with images derived from the Soil Map of the World.

The DSMW consists of the following map sheets: Africa, North America, Central America, Europe, Central and Northeast Asia, Far East, Southeast Asia, and Oceania. The maps are available in three formats: one vector format (ARC/INFO Export), and two raster formats called ERDAS and IDRISI (or flat raster) formats. All the maps are in geographic projection, with spherical datum. The coordinates are expressed in decimal degrees. The scale of the original map (and the vector formatted data) is 1:500, 000.

The Derived Soil Properties files consist of interpretation programmes and related data files. The programs are written in QuickBasic version 4.5 and can be read using a DOS or OS/2 operating system. Included are programmes that interpret the maps in terms of agronomic and environmental parameters such as: pH, organic carbon content, C/N ratio, clay mineralogy, soil depth, soil and terrain suitability for a specific crop production, soil moisture storage capacity, and soil drainage class. The output is given in the form of maps and data files which can be stored for later retrieval. Special country analyses can be made for specific soil inventories, problem soils and fertility capability classification for every country in the world. Also included are maps of classification units of the World Soil reference Base Units and topsoil distribution, which can facilitate the teaching of soil science. Finally, there is a soil database developed, specifically for environmental studies on a global scale, which includes soil moisture storage capacity, soil drainage class and effective soil depth.

INTERNET address: http://internal.fao.org/ag/agl/agls/t1.htm

Slope
Slope was derived from a DEM. A new globally consistent 1km resolution (1:1 million map scale) DEM dataset called GTOPO30 was used. This database is the product of more than three years of international collaborative efforts involving UNEP, USGS, NASA, GSI and INEGI. Data from different sources and resolutions were brought together to create this product using new algorithms and a software developed by scientists from the EROS-Data Center.

INTERNET address: http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html

LAND USES AND INFRASTRUCTURE

Livestock wastes and agricultural by-products

Livestock wastes

Livestock population was used as a surrogate for manure. Livestock populations for cattle, goats, sheep and pigs in the form of animal/km^2 were obtained from U.S. Army CERL and CRSSA, Cook College, Rutgers University.

The GlobalArc™ CD-ROM Database is for use with ARC/INFO 6.0 or higher and ARC-VIEW™ 2 software. It is a global-scale environmental database, converted from all of the raster data contained in the Global GRASS CD-ROM datasets 1-5, the largest single-format, global environmental database available. This CD-ROM contains 84 themes and a total of 147 layers. CRSSA was responsible for converting the datasets to ARC/INFO format.

INTERNET address: http://deathstar.rutgers.edu/global/info.html

Agricultural by-products

Data on crops were derived from an African land cover data-set. This database is one portion of a global land cover characteristics database that is being developed at a continent-by-continent basis. All continents in the global database share the same map projection and are based on 1-km AVHRR data spanning April 1992 through March 1993.

The raster image of the Africa land cover contains class number values for each pixel that correspond to the appropriate land cover classification scheme legend. On the basis of such a classification scheme legend, a core set of derived thematic maps was produced through the aggregation of seasonal land cover regions which are included in each continental database.

The original African land cover data set contains 195 classes, from which five sets are derived: (1) Olson Global Ecosystems Legend, consisting of 94 classes; (2) IGBP Land Cover Classification, 17 classes; (3) U.S. Geological Survey Land Use/Land Cover System, 27 classes; (4) Simple Biosphere Model, 19 classes; and (5) Biosphere-Atmosphere Transfer Scheme, 20 classes.

The Africa database is available in two different map projections: the Interrupted Goode Homolosine and the Lambert Azimuthal Equal Area, the later projection was the one obtained for this study. The USGS, the University of Nebraska-Lincoln, and the European Commission's DG Joint Research Centre are generating this global land cover database, and the USGS-EROS Data Center is carrying out its distribution.

INTERNET address: Documentation: http://edcwww.cr.usgs.gov/landdaac/glcc/globdoc.html; Data: http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html.

Farm-gate sales

Population density

This layer was provided by NCGIA from the University of California at Santa Barbara. It is a grid produced by NCGIA as a result of town interpolations. The algorithm used to generate the surface also takes into account the total population of the countries and the number of people living in the 2nd level administrative districts. The GRID expresses population density in individuals/km^2.

INTERNET address: http://www.geog.buffalo.edu/ncgia/index.html

Urban market size and proximity

Major cities

Locations of major cities were provided by ArcWorld (1:3,000,000). ArcWorld's major cities are represented by points, consequently even large towns do not have an area, however, since the objective of this study was to analyse the proximity to the potential market(s), the undefined extension of the towns were not a limitation as the fish market(s) could be located in any part of the town. Points are assumed to be located at the centre of towns.

INTERNET address: See major cities constraints above.

Roads

The road network was derived from ArcWorld (ESRI, 1992b) and rasterized.

INTERNET address: See major cities constraints above (roads are also included in such INTERNET site).

FISH GROWTH

Air temperature

The source data were 24 ASCII files containing gridded values of mean monthly daily minimum and maximum temperatures. Air temperature grids were created from the source, point and line data using the spatial analysis and interpolation techniques ANUDEM, ANUSPLIN and ANUCLIM developed by CRES at the Australian National University. Grids were obtained by first fitting topographically dependent climate surfaces to point climate data using procedures in the ANUSPLIN package (Hutchinson, 1991; Hutchinson and Gessler, 1994).

In addition to data already obtained by CRES from miscellaneous sources, monthly climate data were acquired from research agencies including CIMMYT, FAO, East Anglia Climate Research Unit, CSIRO Division of Forestry, Texas A & M University and from the national meteorological services of Djibouti, Gambia, Ghana, Kenya, Malawi, Morocco, Namibia, Rwanda, Seychelles, Sudan, Tanzania, Uganda and the Democratic Republic of the Congo. Data were collected over all available years of record to maximize spatial coverage. Most data were collected between 1920 and 1980, so the fitted temperature grids can be interpreted as estimates of standard means for the period of 1920 to 1980.

The number of accurately geocoded stations for which mean monthly air temperature data were obtained were 1,504 for daily minimum temperatures and 1,499 for daily maximum temperatures. Data were subjected to comprehensive error detection and corrections procedures based on ANUDEM and ANUSPLIN. Complete descriptions of these data are being prepared (Hutchinson, *et al.*, *In prep.*).

The error of the temperature grids depended mainly on the accuracy of the underlying climate surfaces. The standard errors of the temperature were about 0.5 °C. Grid files were obtained in standard ARC/INFO format in units of tenths of degrees Celsius. Grids covered the entire African continent except for some off-shore islands, where climate interpolation was not supported by climate data (i.e. Madagascar). These files were processed and the output was converted to a grid (the procedure is described in **Appendix 8.8**).

INTERNET address: http://cres.anu.edu.au/software/africatxt.html

Wind velocity

Mean annual wind velocity was provided by UNEP/DEIA/GRID-Geneva. This file originally in IDRISI format was converted to GRID. These African data originate from manuscripts that were received by ESRI from FAO, as part of the work performed under a UNEP contract. The source maps were prepared directly from original hand-drawn maps, provided by FAO on stable basemap copied at a 1:5,000,000 scale. Isolines plotted on the FAO/AGS basemaps were then manually digitized by ESRI. The final products were rasterized at UNEP/GRID-Geneva.

INTERNET address: http://www.grid.unep.org/gnvd0039.htm

Fish growth

Predictions of fish growth were based on water temperature, in turn predicted from air temperature and wind velocity data.

INTERNET addresses:

Biosystems Analysis Group:	http://biosys.bre.orst.edu/
Latin America:	http://biosys.bre.orst.edu/aqua_gis/prelim.htm
Aquaculture Decision Support Software:	http://biosys.bre.orst.edu/pond/pond.htm

8.2.1 Protected areas

Datum from protected areas was obtained from WCMC. The GRID file was downloaded with FTP in compressed format using UNIX 'compress' command and was called af_reg.e00.Z.

a) Uncompressing file:
gissw2-faogis>> uncompress -v af_reg.e00.Z

b) Importing the grid files:
Arc: import grid af_reg.e00.Z afreg

c) Adjusting grid extensions and cell size:
Grid: setwindow afmask
Grid: setmask afmask
Grid: setcell afmask
Grid: afreggrd = afreg1

8.2.2 Water bodies

The DCW tiles (about 100) for perennial inland water bodies for Africa were joined by K. Lethcoe of USGS. This datum was raterized at 3-arc-minutes.

Arc: gridpoly afwater afwacons_s1

8.2.3 Major cities

Grid: citycons_s1 = merge(uncity, mscity, scity, vscity),

where: citycons_s1 = new grid with all the citycons_s1; merge = GRID command to merge GRID data; uncity = unsuitable citycons_s1; mscity = moderately suitable citycons_s1; scity = suitable citycons_s1 and vscity = very suitable citycons_s1.

Note: This data were also used in the urban market size and proximity submodel.

Re-classification of constraint grids
To mask out constraint areas from the all the maps, a single value of zero was assigned to the constraint grids and a value of one to the remaining African land area. The AML **mask.aml** automates these steps and combines the three grids to make an overall constraint grid:

promask1 = afreg1 (afreg1, 'value gt 0')
promask1b = con(isnull (promask1) == 1, 0, promask1)
promask1c = setnull(promask1b == 1,1)
wamask1 = afwacons_s1 (afwacons_s1, 'value gt 0')
wamask1b = con(isnull (wamask1) == 1, 0, wamask1)
wamask1c = setnull(wmask1b == 1,1)
citymask1 = citycons_s1 (citycons_s1, 'value gt 0')
citymask1b = con(isnull (citymask1) == 1, 0, citymask1)
citymask1c = setnull(citymask1b == 1,1)

constraint = promask1c * wamask1c * citymask1c

Using this approach, when the constraints grid (constraint) is multiplied with the grids, the constraints are masked out from those grids and the suitable areas within those suitability grids retain their suitability score.

8.3 WATER REQUIREMENT

8.3.1 Mean monthly precipitation

Copying and converting ASCII files into ARC/INFO GRID
Twelve ASCII files containing gridded mean monthly values of precipitation were copied and converted from the CRES compact disk into ARC/INFO grid format. Example syntax for the month of January was:

Arc: asciigrid /cdrom/961206_0935/afrain01.grd afrain01.gr

Table 8.1 shows the statistics on the monthly precipitation values in Africa and **Figure 8.1** shows the monthly distribution of precipitation values.

Table 8.1 Mean monthly precipitation values for Africa.
[mm]

MONTH	MIN.	MAX.	MEAN	SD
1. **January**	0	486	48.056	73.136
2. **February**	0	401	47.564	66.972
3. **March**	0	398	57.475	72.679
4. **April**	0	499	53.308	66.07
5. **May**	0	474	44.729	61.934
6. **June**	0	493	41.214	69.177
7. **July**	0	781	54.581	86.32
8. **August**	0	830	69.078	101.786
9. **September**	0	592	61.35	90.05
10. **October**	0	478	53.426	74.443
11. **November**	0	385	49.307	67.227
12. **December**	0	414	49.578	72.712
Annual	**0**	**6231**	**629.666**	**902.506**

Note: **SD** = Standard Deviation

8.3.2 Monthly potential evapotranspiration

Downloading potential evapotranspiration grid files via ftp
Monthly potential evapotranspiration grid files in ARC/INFO export format were downloaded via ftp.

Preparing files for UNIX
Two steps were necessary to prepare the files into a UNIX format.

a) Renaming files: gissw2-faogis>> rename etm1.e00 etm1.e00.Z

b) Uncompressing files: gissw2-faogis>> uncompress -v etm1.e00.Z

Importing the grid files
An example syntax is illustrated below for the month of January:

Arc: import grid etm1.e00 etm1

The Grid AML **gridimport.aml** automates the procedures for all the months.

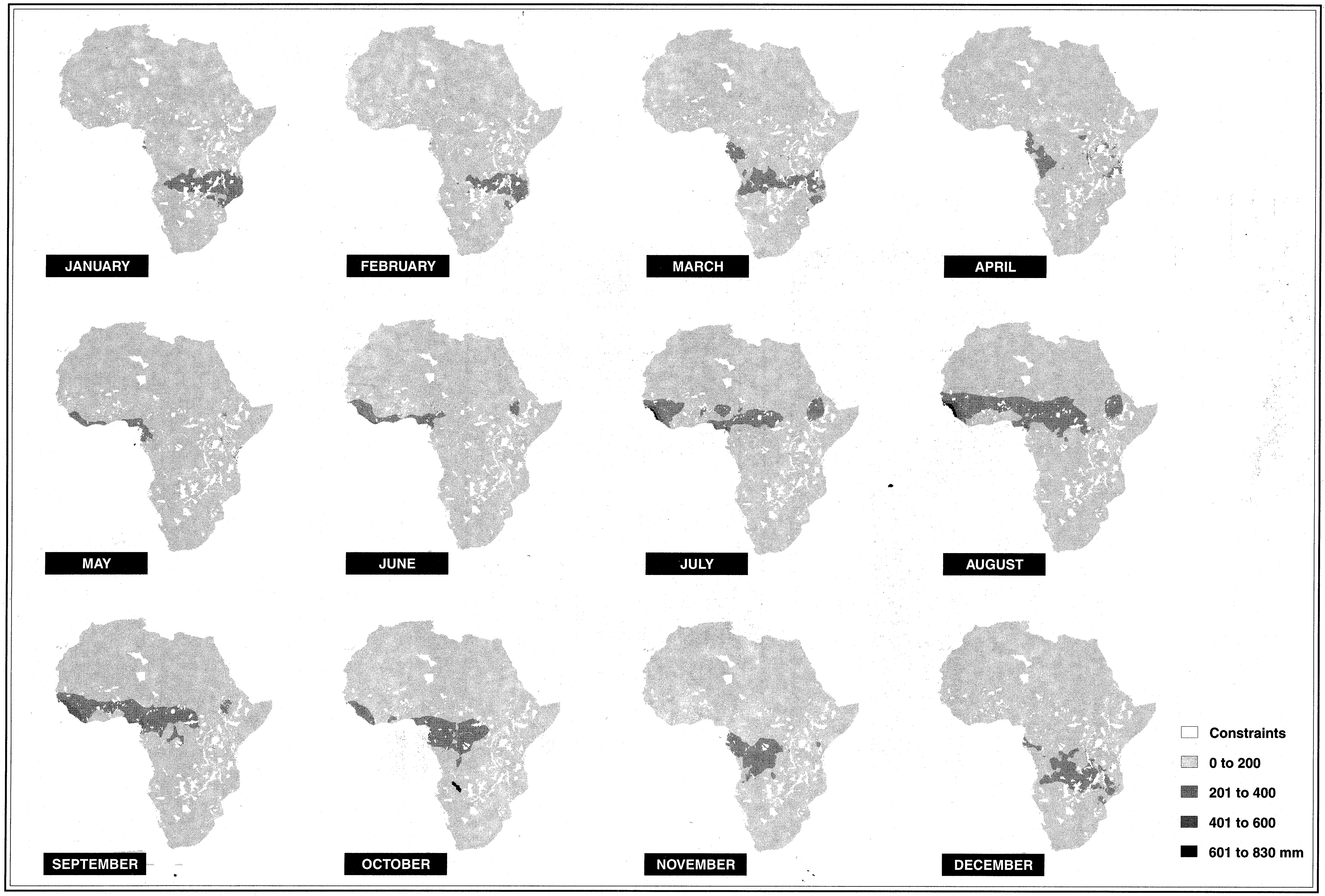


Figure 8.1 **Mean monthly precipitation**

Adjusting grid extensions and cell size
The Grid modules SETWINDOW and SETCELL were used to extract and adjust the grid extensions of the monthly grid files to the base grid.

Grid: setwindow afmask
Grid: setmask afmask
Grid: setcell afmask
Grid: etm1gr = etm1

Moreover, because etm1 contained cells which were not a part of the temperature and precipitation grid files (e.g. Arabia) a mask had to be used to remove these areas from the evaluation.

Grid: etm1new = etm1gr * afmaskv,

where: afmask = a temperature grid file containing only one value "1".

A Grid AML **etsetwindow.aml** automates the procedures described above for all the months.

Table 8.2 shows the statistics on the monthly potential evapotranspiration values for Africa and **Figure 8.2** shows the resulting monthly distribution of evaporation values.

Table 8.2 Monthly potential evapotranspiration values for Africa.
[mm]

	MONTH	MIN.	MAX.	MEAN	SD
1.	January	73	266	161.178	42.185
2.	February	78	258	156.722	40.816
3.	March	91	303	183.062	49.995
4.	April	85	306	179.733	51.857
5.	May	83	317	186.211	61.089
6.	June	76	323	176.403	66.28
7.	July	64	362	178.484	73.397
8.	August	62	362	178.248	69.351
9.	September	77	319	178.266	57.849
10.	October	90	336	182.948	49.762
11.	November	82	281	166.151	41.488
12.	December	75	279	159.266	40.953
	Annual	**936**	**3712**	**2086.672**	**645.022**

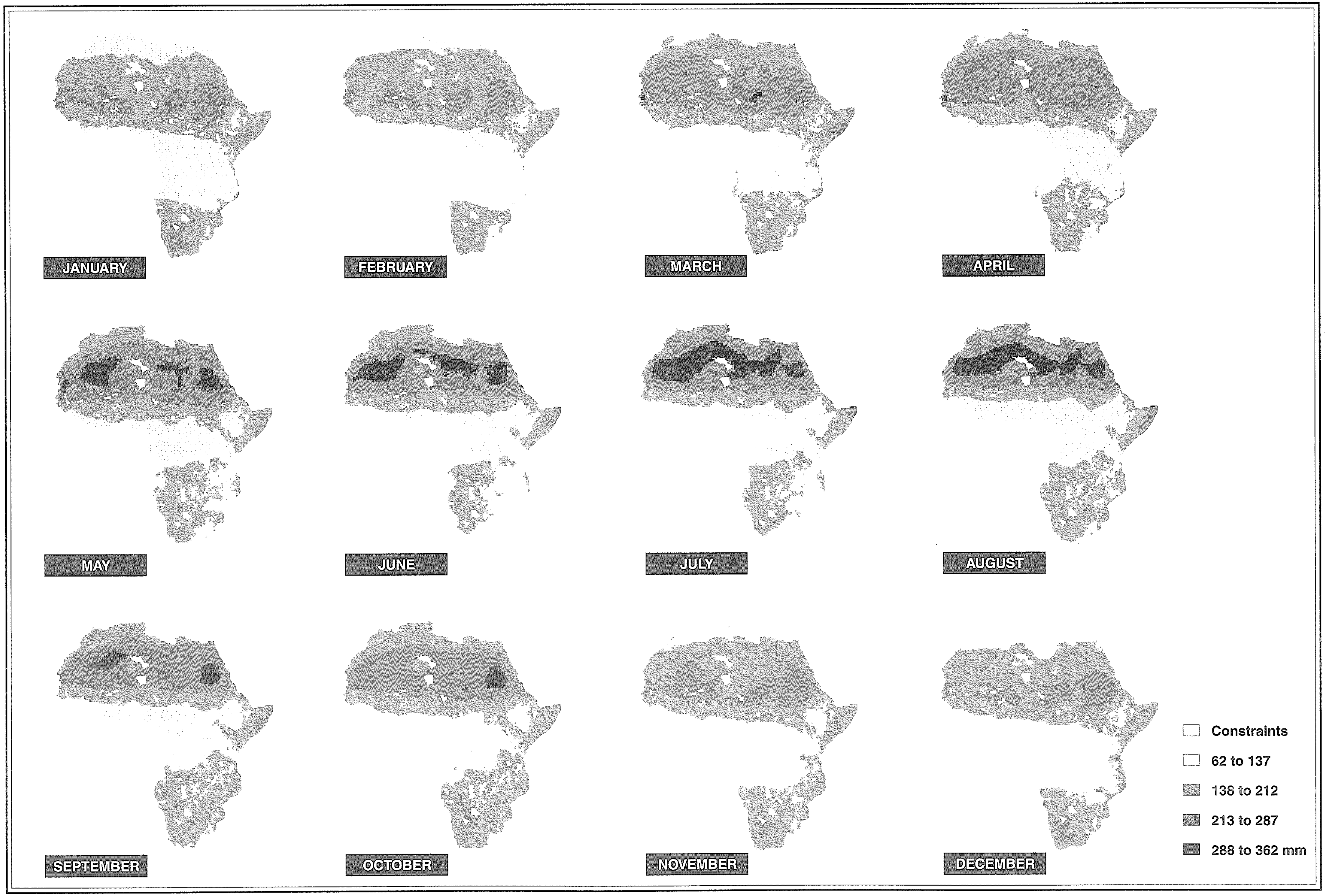


Figure 8.2 **Monthly potential evapotranspiration**

8.3.3 Water requirement for shallow ponds

a) Calculating water requirement

Table 8.3 shows the statistical water requirement values obtained by the difference between mean monthly precipitation and monthly potential evapotranspiration. The following formula was used:

$$WR = P - E,$$

where: WB = Water requirement; P = mean monthly precipitation; E = monthly potential evapotranspiration.

Example of syntax used in GIS analysis for the month of January was:

Grid: wabape = afrain01gr - etm1new

where: wabape = water derived from the difference between precipitation and evaporation; afrain01gr = mean monthly precipitation; etm1new = monthly potential evapotranspiration.

Table 8.3 Monthly water requirement values in Africa.
P - E [mm]

MONTH	MIN	MAX	MEAN	SD
1. **January**	-266	365	-113.251	103.299
2. **February**	-258	291	-109.292	99.081
3. **March**	-303	272	-125.80	115.773
4. **April**	-306	388	-126.735	110.086
5. **May**	-317	342	-141.610	110.110
6. **June**	-323	414	-135.053	116.052
7. **July**	-362	711	-123.676	136.253
8. **August**	-362	762	-108.911	150.124
9. **September**	-319	502	-116.781	134.869
10. **October**	-336	369	-129.608	116.003
11. **November**	-281	286	-117.140	101.622
12. **December**	-279	294	-109.94	102.762

b) Calculating water requirement for shallow ponds

Based on the Latin America study (i.e. except for the evaporation coefficient) the following formula was used in order to estimate the volume of water which has to be provided to the ponds during the dry seasons:

$$WR = (P * 1.1) - (E * 1.3) - 80 ,$$

This formula also gives the deficit between precipitation and evaporation during that season.

where: WR = Water requirement; P= mean monthly precipitation; E = monthly potential evapotranspiration

Correction factors:

- precipitation was multiplied by 1.1 to include the amount of rain that drains into the pond from the pond dikes;
- evaporation was multiplied by 1.3 to compensate for the higher evaporation from free surfaces such as small open ponds;
- 80 = seepage from ponds [mm].

Example syntax of the above formula was:

Grid: waba = (afrain01gr * 1.1) - (etm1new * 1.3) - 80

where: afrain01gr = precipitation grid for the month of January; etm1= evapotranspiration grid for the month of January.

The Grid AML **waba.aml** automates the procedures for all the months.

The above formula was applied to the available P and E dataset and the results are shown in **Table 8.4** and **Figure 8.3.**

Table 8.4 Monthly water requirement values for shallow ponds in Africa.
(P * 1.1) - (E * 1.3) - 80
[mm]

MONTH	MIN.	MAX.	MEAN	SD
1. January	-425.8	297.3	-236.812	120.582
2. February	-415.4	218.1	-231.565	116.113
3. March	-473.9	194	-254.992	136.594
4. April	-477.8	324.6	-255.355	130.707
5. May	-492.1	274.6	-273.014	132.187
6. June	-499.9	359.6	-263.839	139.111
7. July	-550.6	688.1	-251.741	162.258
8. August	-550.6	744.6	-235.452	176.697
9. September	-494.7	456.2	-244.112	158.459
10. October	-516.8	307.5	-259.158	136.667
11. November	-445.3	215.6	-242.084	119.273
12. December	-442.7	219.4	-232.787	119.879

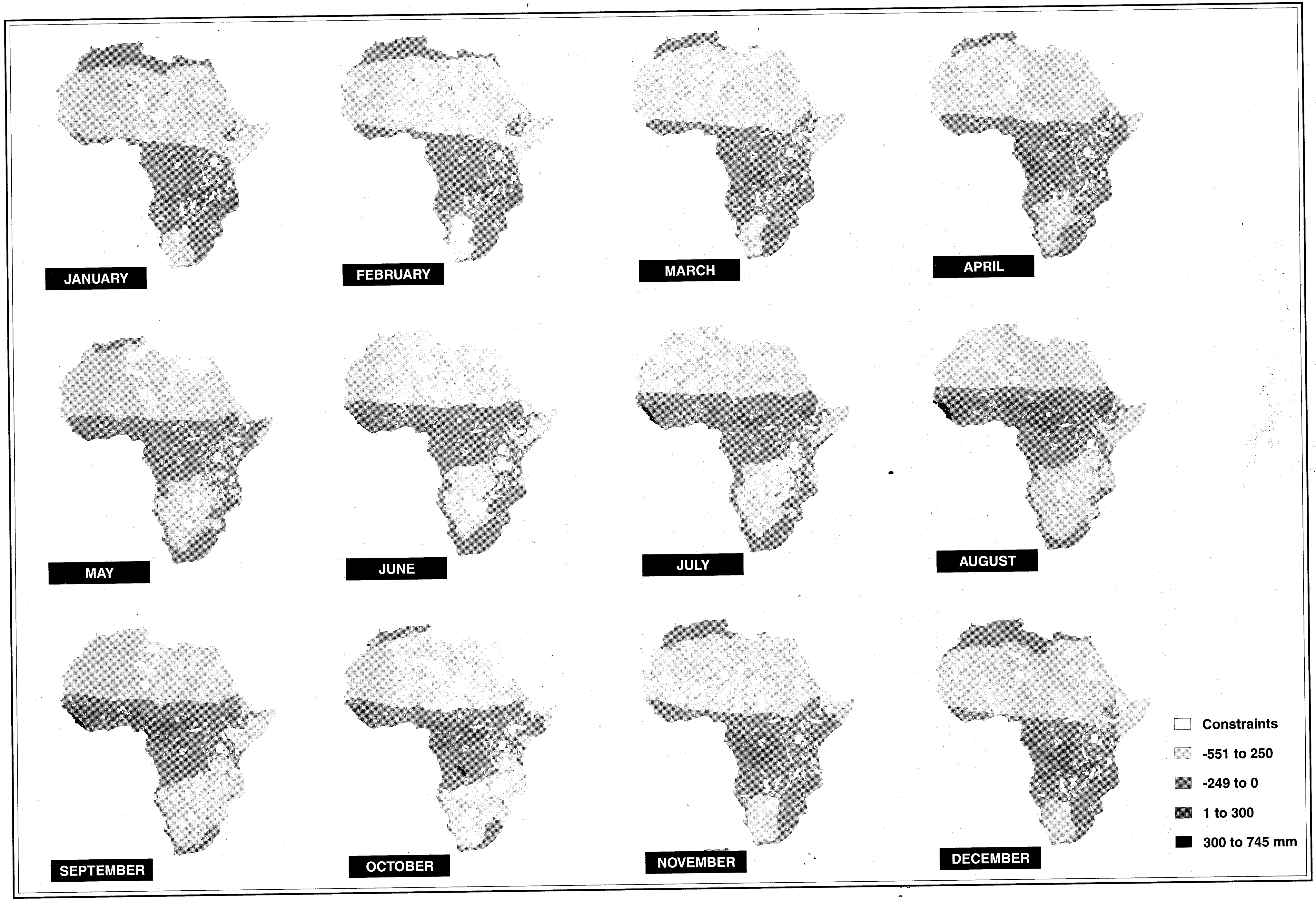


Figure 8.3 **Monthly water requirement for shallow ponds**

Seasonal negative minima (creating sample points)
To evaluate the existence of two negative minima (i.e. or areas in which the lowest minima occurs) a set of sample points was defined. These points were chosen to be at about $5^{\circ} \times 5^{\circ}$ distance (i.e. latitude) and they were used to sample the 12 monthly [(P * 1.1) - (E * 1.3) - 80] values.

a) The Grid SAMPLE module was used to create an ASCII file listing each cell location along with the 12 monthly water requirement values.

The following syntax's was used:

Grid: Waba.txt = sample(waba1, waba2, waba3, waba4, waba5, waba6, waba7, waba8, waba9, waba10, waba11, waba12)

An extract of Waba.txt is illustrated below:

```
-999 -14.975 24.875 MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING
-999 -14.925 24.875 MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING
-999 -14.875 24.875 MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING
1 -14.825 24.875 MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING
1 -14.775 24.875 MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING MISSING
1 -14.725 24.875 -263.7 -254.4 -301.2 -291.9 -302.3 -310.1 -336.1 -349.1 -321.5 -305.5 -271.9 -248.9
```

First column are the mask values not recorded in the sample point extraction; MISSING correspond to NO DATA values or -999 in this study.

Note: The ASCII file above was 212 Mb and took about 20 minutes to create.

b) Sample points were extracted from Waba.txt using a text editor in ARC/INFO, these points were copied into a separate file and imported to a spreadsheet for analyses.

Tables 8.5 shows the statistical results of the sample points and **Figures 8.4** to **8.9** illustrate some examples of their distribution. It was found that seasonal minima occurred four times: latitude 0° N and S, longitude 10° (**Figures 8.6** and **8.7**); latitude 5° S longitude 15° (**Figure 8.8**) and latitude 10° S, longitude 20° (**Figure 8.9**).

Net annual water requirement for shallow ponds
Even though two seasonal negative minima occurred four times, the total annual amount of water, which needs to be provided to the ponds during the dry seasons was found by the sum of the monthly values of [(P * 1.1) - (E * 1.3) - 80] :

Adding the water requirement grid files:

Grid: netann = waba1 + waba2 + waba3 + waba4 + waba5 + waba6 + waba7 + waba8 + waba9 + waba10 + waba11 + waba12

where: netann = sum of the monthly water requirement grids (positive and negative values); waba1 to waba12 = water requirement grids.

Table 8.5 Water requirement sample points.

[(P * 1.1) - (E * 1.3) - 80]

ID-num	X-coord	Y-coord	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Net annual
1	4.5	37	1374.9	1325.4	1312.2	1278.1	1267.1	1239.6	1219.8	1227.5	1268.2	1306.7	1350.7	1380.4	15550.6
2	10	37	-107.1	-124	-173.7	-207	-205.8	-294.1	-351	-349.7	-280.1	-222.1	-163.3	-115.6	-2593.5
3	-5	35	-71.4	-88.3	-112.3	-160.9	-204.4	-253.6	-308.8	-314.4	-256.3	-190.3	-116.8	-96.2	-2173.7
4	0	35	-137.4	-141.6	-186.1	-207.5	-227.2	-264.8	-324.6	-323.9	-265.6	-223.8	-154.7	-133.9	-2591.1
5	5	35	-179.2	-179.2	-223.1	-253.8	-279	-312.5	-367.9	-362.7	-307.6	-262.1	-201.6	-185.5	-3114.2
6	10	35	-161.7	-161.7	-208.8	-227.2	-270.2	-298.9	-361.4	-350.1	-281.3	-260	-215.6	-176.5	-2973.4
7	-5	30	-229.5	-236	-277.6	-298.4	-325.7	-346.5	-371.4	-367.7	-333	-293.7	-246.1	-225.8	-3551.4
8	0	30	-240.7	-248.1	-305.7	-326.5	-369	-394.8	-433.6	-429.7	-383.3	-329.5	-269.3	-226.1	-3956.3
9	5	30	-243.3	-257	-322.2	-353.4	-410.2	-444	-503.8	-480.4	-424.5	-362.5	-284.7	-242.2	-4328.2
10	10	30	-244.4	-253.5	-315.9	-343	-397.2	-434.9	-473.9	-445.3	-406.3	-354.5	-286	-242.2	-4197.1
11	15	30	-239.8	-246.9	-297.9	-311.8	-365.1	-380.3	-414.1	-399.8	-360.1	-321.2	-285.7	-237.8	-3860.5
12	20	30	-220.6	-244.9	-302.5	-316.8	-367.5	-367.3	-377.7	-390.7	-355.8	-335.6	-293.2	-231.5	-3804.1
13	25	30	-239.6	-252.2	-301.4	-319.6	-364.9	-394.6	-428.4	-434.9	-372.5	-326.1	-288.6	-251.1	-3973.9
14	30	30	-239.8	-243.9	-288.4	-310.3	-343.9	-366	-385.5	-392	-362.1	-341.3	-281.8	-244.7	-3799.7
15	-10	25	-294.5	-302.3	-368.6	-384.2	-416.7	-444	-510.3	-503.8	-424.4	-370.7	-310.5	-289.7	-4619.7
16	-5	25	-321.8	-333.5	-395.9	-424.5	-460.9	-463.5	-511.6	-499.9	-451.8	-406.3	-340	-310.1	-4919.8
17	0	25	-352.7	-327	-418	-432.3	-477.8	-470	-536.3	-528.5	-480.4	-425.8	-355.6	-306.2	-5110.6
18	5	25	-270	-277.8	-356.9	-367.5	-400.2	-387	-440.1	-435.1	-403	-364.7	-311.6	-272.6	-4286.5
19	10	25	-255.5	-263.3	-328.3	-346.5	-386.8	-398.5	-437.5	-444	-388.1	-347.8	-297.1	-258.1	-4151.5
20	20	25	-269.8	-277.6	-353	-379	-450.5	-462.2	-454.4	-449.2	-411.5	-371.2	-320.5	-267.2	-4466.1
21	25	25	-272.4	-273.7	-341.7	-373.1	-443.1	-444	-464.8	-461.5	-402.4	-376.4	-321.8	-286.7	-4461.6
22	30	25	-289.3	-293.2	-350.4	-375.1	-427.1	-434.9	-441.4	-444	-421.9	-402.4	-329.6	-301	-4510.3
23	-16	20	-336.1	-324.6	-382.9	-392	-405	-402.4	-357.1	-353.4	-366.2	-390.2	-345.6	-324.6	-4380.1
24	-15	20	-340	-329.8	-394.6	-407.6	-432.3	-433.8	-396.3	-369.8	-371.1	-390.6	-347.1	-323.5	-4536.5
25	-10	20	-338.7	-336.1	-402.4	-412.8	-450.5	-451.8	-466.1	-421.9	-392.7	-387.4	-344.1	-325.7	-4730.2
26	-5	20	-351.7	351.7	-420.6	-434.9	-464.8	-463.5	-468.7	-431.6	-413.4	-408.9	-366	-330.9	-4203.3
27	0	20	-342.6	-338.7	-419.3	-432.3	-444.4	-427.7	-417.9	-387.4	-398.1	-424.5	-362.1	-323.1	-4718.1
28	5	20	-314	-314	-380.3	-389.4	-407.6	-384.2	-384.5	-349.9	-381	-390.7	-336.1	-311.4	-4343.1
29	10	20	-314	-314	-376.4	-381.6	-420.6	-421.9	-433.8	-413.7	-421.9	-390.7	-343.9	-317.9	-4550.4
30	15	20	-306.2	-316.6	-373.8	-394.6	-432.3	-433.6	-441.8	-421.1	-432.3	-405	-346.5	-314	-4617.8
31	20	20	-288	-290.6	-353	-376.4	-421.9	-427.1	-432.3	-413.1	-412.8	-385.5	-325.7	-294.5	-4420.9
32	25	20	-314	-307.5	-371.4	-391.1	-419.7	-418	-394.4	-369.2	-403.7	-405	-338.7	-316.6	-4449.3
33	30	20	-350.4	-343.9	-410.2	-431	-471.3	-468.7	-437	-440.2	-477.8	-490.8	-398.5	-358.2	-5078
34	-15	15	-405	-393.3	-458.3	-455.7	-440.3	-307.7	-186.8	-71	-131.8	-311	-379.2	-381.8	-3921.9
35	-10	15	-359.5	-351.7	-411.5	-387.6	-364.9	-266.8	-132	-51.7	-160.6	-304.2	-346.9	-342.6	-3480
36	-5	15	-362.1	-359.5	-419.3	-402.6	-370.6	-308.5	-197.6	-119.1	-231.7	-348.3	-373.8	-343.9	-3837

Table 8.5 Continuation

ID-num	X-coord	Y-coord	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Net annual
37	0	15	-368.6	-363.4	-420.6	-405	-374	-321.3	-238.7	-157.1	-271.7	-365.4	-386.8	-373.8	-4046.4
38	5	15	-359.5	-354.3	-403.7	-389.8	-377.9	-309.6	-226.9	-143	-263.9	-375.4	-366	-363.4	-3933.4
39	10	15	-310.1	-310.1	-354.3	-346.5	-346	-308.3	-219.2	-149.2	-266.8	-346.9	-328.5	-314	-3599.9
40	15	15	-336.1	-336.1	-395.9	-385.5	-375.7	-341.4	-285.6	-201.4	-312.6	-383.1	-360.8	-343.9	-4058.1
41	20	15	-414.1	-403.7	-462.2	-437.5	-422.7	-362.7	-272.8	-172.6	-327.6	-445.5	-425.8	-421.9	-4569.1
42	25	15	-362.1	-349.1	-402.4	-398.5	-390.6	-344.8	-239	-168.5	-316.6	-394.6	-360.8	-355.6	-4082.6
43	30	15	-368.6	-366	-414.1	-414.3	-418.2	-358.6	-264.3	-224.9	-333.8	-423.2	-395.9	-372.5	-4354.4
44	35	15	-392	-385.5	-450.5	-428.8	-401.3	-339.4	-232.8	-199.6	-287.9	-382.5	-401.1	-394.6	-4296
45	40	15	-261.5	-247.2	-313.5	-338.5	-341.6	-362.1	-308.8	-306.6	-348.2	-346.1	-315.4	-277.6	-3767.1
46	-14	10	-289.3	-278.9	-310.3	-275.2	-148.7	174.3	640.2	737.6	372.8	96.4	-157	-263.6	298.3
47	-10	10	-300.3	-274.6	-270.1	-179.7	-98.1	32	80.2	158.9	158.4	-21.4	-193.5	-277.5	-1185.7
48	-5	10	-334.1	-305.5	-284.1	-203	-154.9	-80.8	-14	104.4	17.9	-162.6	-265	-313.4	-1995.1
49	0	10	-361	-332.1	-315.9	-239.4	-175.1	-101.8	-57.5	18.2	28.9	-181.5	-309.7	-353.6	-2380.5
50	5	10	-349.5	-339.3	-332.6	-256.2	-156.6	-86.7	-24	38.7	49	-167.1	-316.5	-354.3	-2295.1
51	10	10	-337.4	-329.6	-336.9	-258.1	-178.9	-93.4	11.2	88.7	-41.6	-241.5	-327	-346	-2390.5
52	15	10	-356.9	-355.6	-388.5	-320.1	-236.3	-130.3	-40	44.7	-69	-281.7	-342.6	-355.6	-2831.9
53	20	10	-364.7	-358.2	-362.4	-301.8	-225	-124.4	-15.9	65.1	-37	-219.5	-319.4	-343.9	-2607.1
54	25	10	-345.2	-332.2	-359	-314.5	-215.7	-131.7	-29.6	13.8	-71.6	-230.8	-324.6	-336.1	-2677.2
55	30	10	-373.8	-367.3	-390.9	-326.5	-232.1	-136.9	-86.8	-71.5	-105.1	-215.9	-336.5	-360.8	-3004.1
56	35	10	-346.5	-331.3	-330.4	-276.7	-111.5	26.7	43.7	67.6	8.4	-149.6	-252.4	-316.8	-1968.8
57	40	10	-237.7	-216.5	-204.7	-182.2	-214.4	-190.7	-43.8	-18.9	-141	-233.4	-237.3	-241.3	-2161.9
58	45	10	-313.7	-290.4	-314.6	-252.6	-251.1	-304.9	-327.5	-313.7	-269.5	-304.1	-311.9	-308.6	-3562.6
59	50	10	-336.1	-320.5	-365.3	-321	-305.1	-384.8	-405.4	-412.9	-362.2	-344.6	-331.9	-338.9	-4228.7
60	-9	5	-203.9	-154	-114.1	-62	93	328.6	116.7	33.7	265.4	148.3	-37.1	-129.4	347.2
61	10	5	-221.4	-181	-77.1	-20.1	25.5	86.7	180.7	243	286	151	-110.2	-215.1	148
62	15	5	-235.8	-207.7	-162.7	-100.9	-64.9	-22.4	-45.2	-0.5	33.1	29.8	-155	-232.9	-1165.1
63	20	5	-257.8	-232.6	-174.8	-123.9	-62.7	-50.3	0.6	20	1	-8.3	-158.6	-262.3	-1309.7
64	25	5	-263.2	-240.2	-175.6	-88.4	-39.5	-16.5	-12.9	20.2	27.6	4.5	-164.5	-251.5	-1200
65	30	5	-335.6	-305.1	-258.3	-126.9	-83.2	-65.5	-36.9	-28.7	-89.1	-119.7	-234.9	-308.7	-1992.6
66	35	5	-295.4	-270.5	-230.4	-176.6	-204.7	-228.3	-199.8	-218.8	-241.5	-240.4	-211.9	-267.1	-2785.4
67	40	5	-266	-241.8	-230.4	-65.6	-96	-210.6	-207.6	-221.7	-211.6	-112.5	-173.6	-238.4	-2275.8
68	45	5	-347.8	-338	-357	-245	-248.6	-341.2	-334.8	-360.8	-357	-232.1	-261.5	-325.2	-3749
69	6.5	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0
70	10	0.03	-16.4	-30	66.7	101.1	17.2	-184.8	-198.9	-194.7	-107.1	190.6	209.9	15.4	-131
71	15	0.03	-102.5	-84.9	-45	-15.5	-15.6	-123.9	-174.1	-156.2	-12.9	41.6	-5.8	-65.8	-760.6
72	20	0.03	-86.3	-91.4	-49.2	-24.3	-39.3	-62.4	-63.3	-26.9	7.9	18.5	29.6	-51.9	-439
73	25	0.03	-132.1	-111	-55	-32.9	-48.4	-90.9	-83	-42.2	-26.9	7.1	-5.1	-88.7	-716.2
74	30	0.03	-165.1	-139.1	-100	-41.4	-83.4	-136.1	-149.1	-97.2	-69.8	-55.9	-54	-120.8	-1211.9

Table 8.5 Continuation

ID-num	X-coord	Y-coord	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Net annual
75	35	0.03	-192.1	-152.9	-106.2	6.5	-37.4	-99.8	-111.5	-85.7	-118.1	-136.2	-110.1	-144.3	-1287.8
76	40	0.03	-290.7	-283.6	-282.2	-206.2	-257.7	-262.3	-266	-280.8	-291.8	-276.4	-203.9	-234.9	-3136.5
77	10	-0.03	-16.4	-31.1	65.6	98.9	13.9	-184.8	-198.9	-195.8	-110.4	185.1	209.9	15.4	-148.6
78	15	-0.03	-100.3	-83.8	-45	-13.3	-14.5	-126.1	-175.2	-157.3	-14	41.6	-5.8	-64.7	-758.4
79	20	-0.03	-84.1	-90.3	-49.2	-23.2	-39.3	-63.5	-64.4	-29.1	7.9	18.5	30.7	-50.8	-436.8
80	25	-0.03	-131	-111	-53.9	-32.9	-49.5	-92	-84.1	-42.2	-26.9	6	-4	-87.6	-709.1
81	30	-0.03	-168.4	-141.3	-103.3	-44.7	-86.7	-138.3	-152.4	-101.6	-74.2	-62.5	-57.3	-123	-1253.7
82	35	-0.03	-196.5	-157.3	-112.8	-7.8	-55	-114.1	-126.9	-106.6	-133.5	-149.4	-117.8	-145.4	-1296.2
83	40	-0.03	-290.7	-283.6	-282.2	-207.3	-256.6	-262.3	-266	-280.8	-291.8	-276.4	-202.8	-234.9	-3135.4
84	15	-5	-86.3	-112.7	-42.2	46.7	-72	-199.8	-194.4	-202.4	-177.9	-86	70.9	-3.9	-1060
85	20	-5	-61.2	-82.6	-55.8	-38.1	-138.3	-228.8	-226	-180.6	-72	-15.6	19.4	-19	-1098.6
86	25	-5	-37	-38.6	-43.1	-46.9	-182.6	-228.9	-229.9	-172.1	-130.3	-74.8	0.2	7.4	-1176.6
87	30	-5	-67.2	-64.4	-56.4	-48.7	-192.6	-236.6	-250.3	-257	-236.6	-195.8	-63.4	-27.6	-1696.6
88	35	-5	-100	-105.7	-115.3	-157.4	-227.3	-243.8	-254.2	-263.3	-270	-280.6	-215.2	-107.9	-2340.7
89	15	-10	-125.5	-118.8	-26.2	-14.9	-234.3	-254.2	-236	-232.5	-200.8	-93	-35.7	-82.9	-1654.8
90	20	-10	-11.1	-40.9	25.9	-88.7	-267.8	-278.9	-284.1	-266.6	-201.9	-119.3	0.6	-4.1	-1536.9
91	25	-10	-3.7	-7.4	-14.9	-170.8	-282.1	-277.6	-286.7	-284.7	-249.7	-169.5	-35.4	25.1	-1757.4
92	30	-10	69	44	66.3	-126.5	-250.7	-254.4	-265.9	-275	-271.9	-230.4	-38.4	86.1	-1447.8
93	35	-10	53.5	31.7	87.4	4.7	-173.2	-202.6	-217.8	-228.4	-244	-253.2	-173.2	-21.2	-1336.3
94	15	-15	-91.7	-47.3	-42.8	-167.7	-270.4	-255.5	-263.3	-289.3	-300.3	-249.1	-156	-100.8	-2234.2
95	20	-15	-22.5	-28.4	-75.9	-226.1	-298.8	-281.5	-295.8	-316.6	-318.7	-268.6	-141.6	-81.7	-2356.2
96	25	-15	-5.7	-14.9	-113.4	-244.2	-281.9	-268.5	-281.5	-303.6	-315.7	-292.5	-132.1	-0.6	-2254.6
97	30	-15	-8.3	-27.6	-144.2	-246.8	-273.6	-259.4	-269.8	-295.8	-315.5	-319.2	-209.8	-26	-2396
98	35	-15	13.5	-18	-106.6	-204	-238.7	-219.7	-232.1	-257	-276.9	-287.2	-188	-57.9	-2072.6
99	40	-15	7.5	-17.8	-65	-176.2	-253.7	-236.2	-243.4	-270.5	-299.6	-319.6	-254	-87.1	-2215.6
100	15	-20	-193.4	-163.3	-195.2	-225.8	-257.2	-242.5	-247.7	-256.8	-265.9	-272.5	-242.4	-224.3	-2787
101	20	-20	-197.4	-172.8	-231.2	-276	-312.2	-290.6	-302.3	-329.6	-349.3	-341.5	-277.4	-254.8	-3335.1
102	25	-20	-161.3	-176.9	-234.8	-268.9	-296.6	-269.8	-281.5	-310.1	-339.1	-331.7	-258.4	-204.8	-3133.9
103	30	-20	-117.8	-128.3	-189.8	-232.4	-242.4	-225.1	-239.9	-264.6	-283.6	-273.6	-173.8	-111.7	-2483
104	15	-25	-227.3	-208.2	-225.5	-219.5	-215.4	-202.4	-202.4	-201.1	-203.5	-213.9	-211.3	-217.8	-2548.3
105	20	-25	-307.3	-260.9	-292	-305	-300.7	-276.3	-289.3	-315.3	-334.1	-349.8	-339.1	-343.8	-3713.6
106	25	-25	-236.5	-233.3	-236.6	-248.4	-266.8	-252.6	-270	-302.7	-314.9	-318.2	-272.6	-255.4	-3208
107	30	-25	-122.9	-142.7	-172.7	-209.9	-232.2	-230.5	-228.5	-258.2	-265.5	-230.6	-145	-134.4	-2373.1
108	20	-30	-354.6	-323.1	-313	-278	-245.8	-225.3	-229.6	-250	-274.7	-315.2	-327.7	-350.5	-3487.5
109	25	-30	-298.9	-254.1	-242.9	-244.9	-240	-223.1	-232.2	-265.1	-276.5	-295.8	-301.7	-316.8	-3192
110	30	-30	-120.5	-119.3	-126.4	-191.7	-202.4	-201.5	-212.8	-219.6	-210	-174.8	-133.3	-123.1	-2035.4
111	20	-35	-240.2	-219.4	-210.1	-176.2	-154	-144.9	-148.2	-149.3	-159.1	-175.3	-196.9	-233.1	-2206.7

Figure 8.4 Sample points at latitude 10 N.

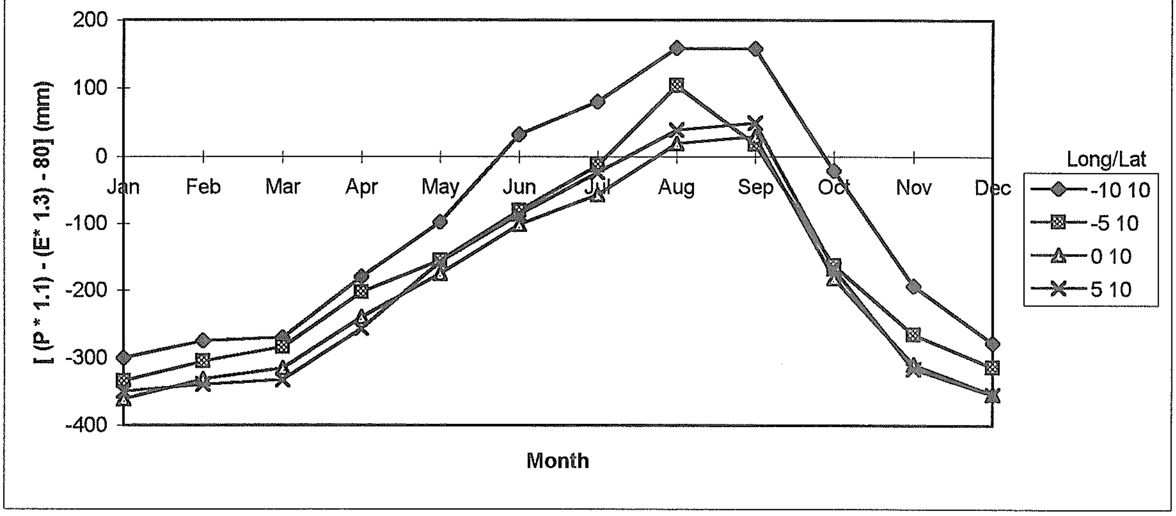


Figure 8.5 Sample points at latitude 5 N.

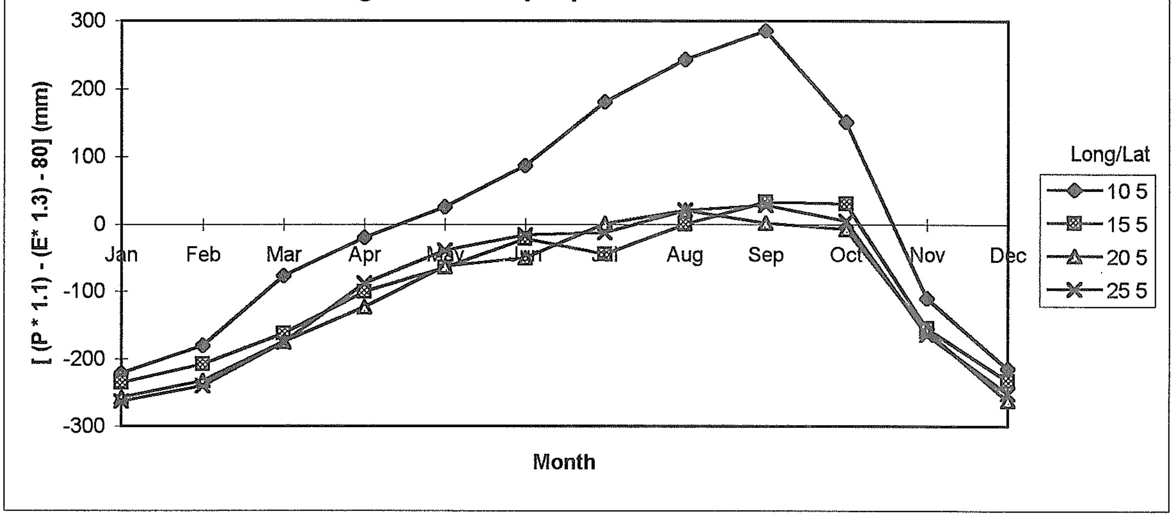
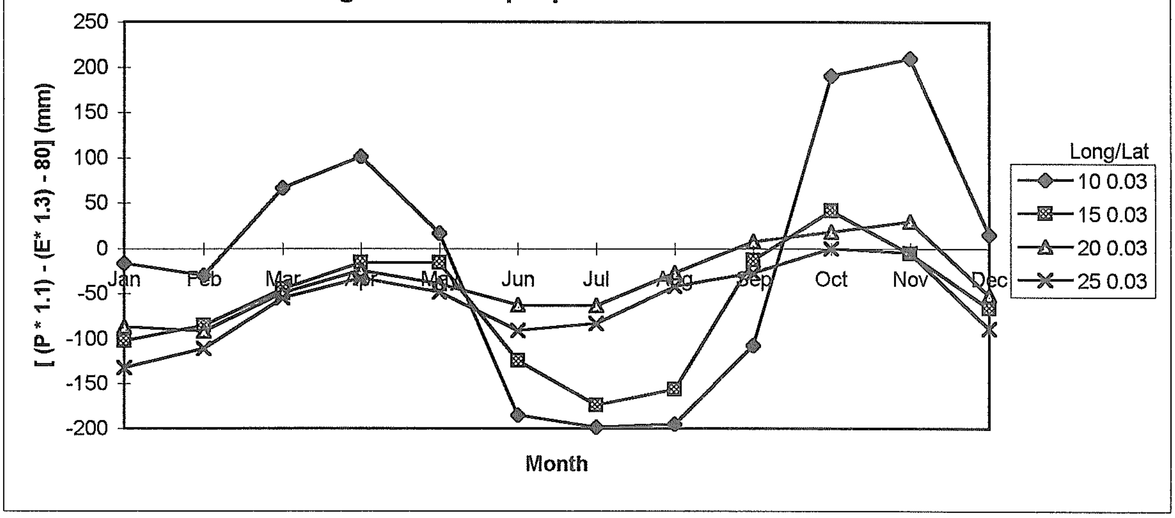


Figure 8.6 Sample points at latitude 0.03 N.



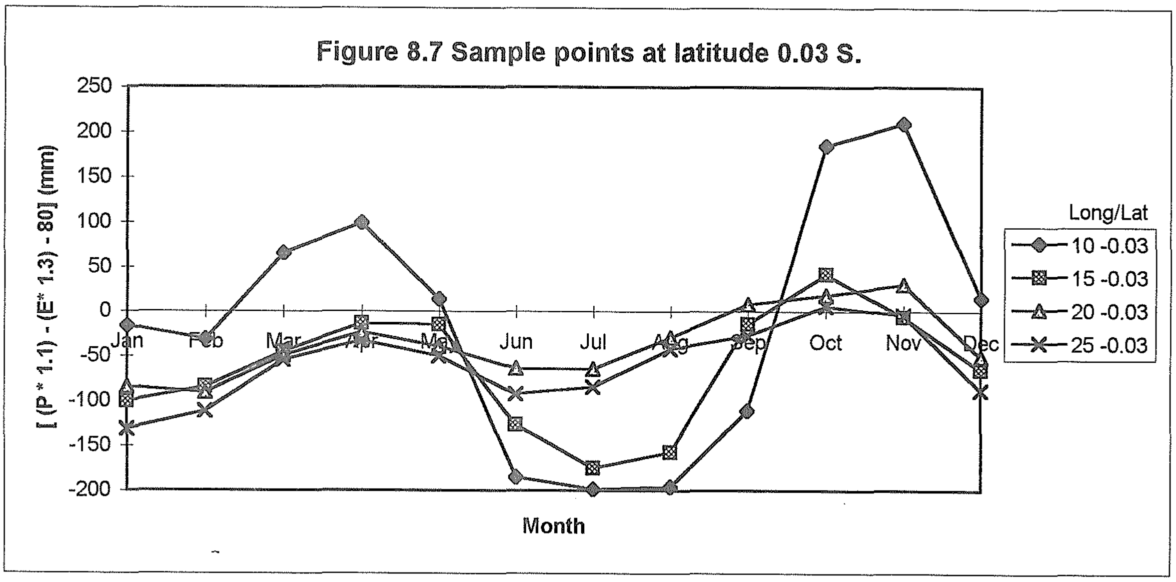


Figure 8.7 Sample points at latitude 0.03 S.
[(P * 1.1) - (E* 1.3) - 80] (mm)
250
200
150
100
50
0
-50
-100
-150
-200
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Long/Lat
10 -0.03
15 -0.03
20 -0.03
25 -0.03

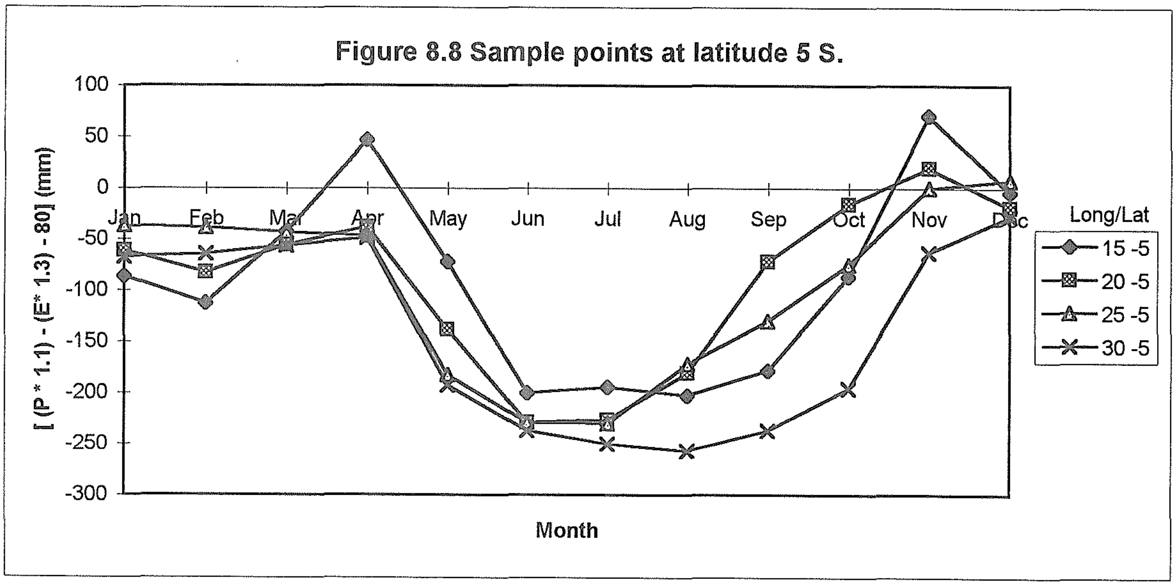


Figure 8.8 Sample points at latitude 5 S.
[(P * 1.1) - (E* 1.3) - 80] (mm)
100
50
0
-50
-100
-150
-200
-250
-300
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Long/Lat
15 -5
20 -5
25 -5
30 -5

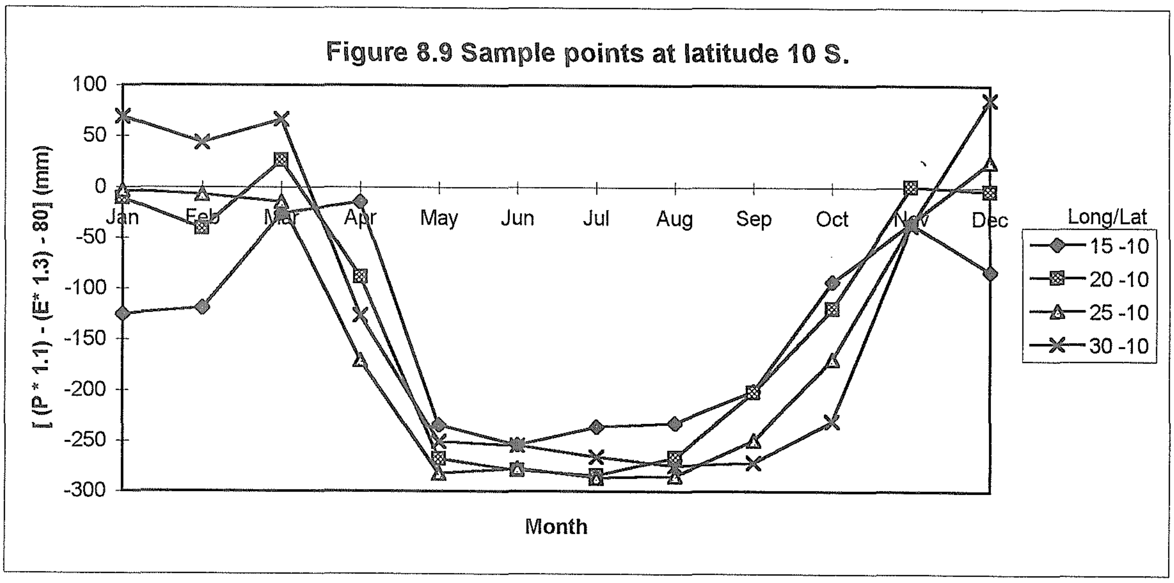


Figure 8.9 Sample points at latitude 10 S.
[(P * 1.1) - (E* 1.3) - 80] (mm)
100
50
0
-50
-100
-150
-200
-250
-300
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Long/Lat
15 -10
20 -10
25 -10
30 -10

8.4 SOIL AND TERRAIN SUITABILITY FOR FISH PONDS

8.4.1 Soils

Soil parameter selection, thresholds and data extraction
The appropriate soil parameter selection as well as the thresholds evaluation and data extraction, were carried out by F. Nachtergaele (FAO-AGLS Division).

Five maps were produced: Four referred to the percentage of area covered by soils according to their suitability for fish ponds (i.e. very suitable, suitable, moderately suitable and unsuitable). The fifth map resulted in the combination of these four maps to arrive at an overall soil suitability.

Geographic projection
The maps prepared by F. Nachtergaele were in IDRISI format in plane projection. The following document file was provided for these maps:

```
file title  : Very suitable land for fishponds
data type   : integer
file type   : binary
columns     : 4320
rows        : 2160
ref. system : plane
ref. units  : m
unit dist.  : 1.0000000
min. X      : 0.0000000
max. X      : 1.0000000
min. Y      : 0.0000000
max. Y      : 1.0000000
pos'n error : unknown
resolution  : unknown
min. value  : 0
max. value  : 255
value units : unspecified
value error : unknown
flag value  : none
flag def'n  : none
legend cats : 0
```

To convert from a plane reference system to a Lat/Long projection the following changes had to be made to the document file provided:

```
rows        : 1764
ref. system : lat./long
ref. units  : deg
unit dist.  : 0.0833333
min. X      : -180
max. X      : 180
min. Y      : -57
max. Y      : 90
```

Exporting to ERDAS
Using the IDRISI export command, IDRISI files were converted into ERDAS format.

Converting files from ERDAS to GRID
When importing the ERDAS files into ARC/INFO using the imagegrid command, it was found that the new geographic projection was not maintained. To solve this problem, the ERDAS software was used. Using ERDAS, the ERDAS files were imported as IMAGE files, and then exported as ARC/INFO GRID files.

Defining the study area (SETMASK), its extent (SETWINDOW) and cell size (SETCELL)
Grid: setwindow afmask
Grid: setmask afmask
Grid: setcell afmask
Grid: soils1 = soils

Notes: soils1 = grid representing percentage of area covered by unsuitable soils. The same procedure was used for the other 4 soil grids.

Figures 8.10 shows the resulting spatial distribution of the very suitable soils grid.

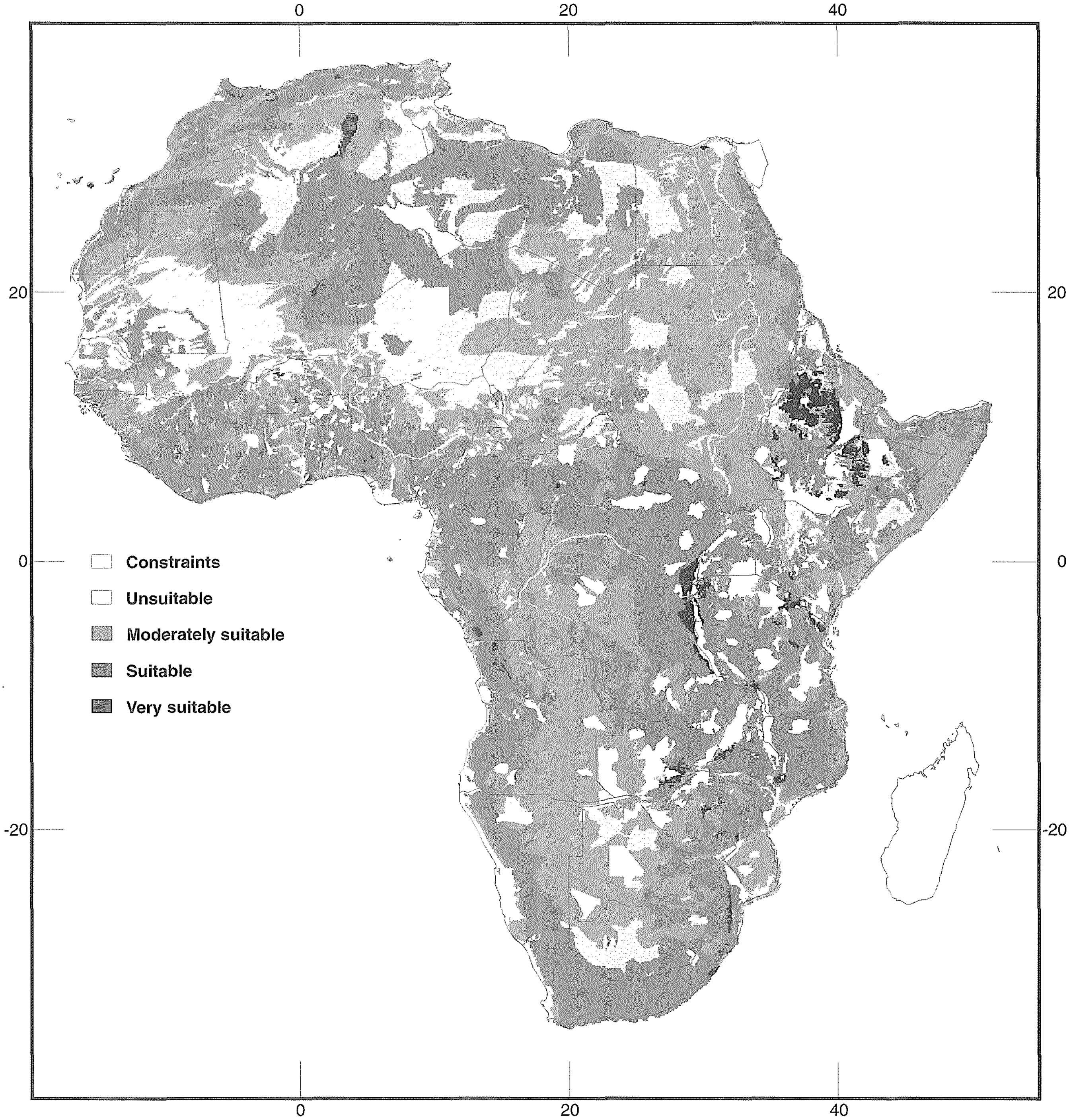


Figure 8.10
Soil suitability for ponds

8.4.2 Slopes

Converting the GTOPO30 imagine file into GRID
The DEM (GTOPO30) was obtained in IDRISI format in Lat/Long projection, so it was possible to export it with IDRISI software as an ERDAS file and then the GRID imagegrid command was used to convert such ERDAS file into a GRID.

Grid: imagegrid dem.gis demgrd
where: dem = ERDAS image file; demgrd = grid file.

Defining the study area (SETMASK), its extent (SETWINDOW) and cell size (SETCELL)
Grid: setwindow afmask
Grid: setmask afmask
Grid: setcell afmask
Grid: demgrd = afmask

Creating the slopes
a) Projecting data to an equal area projection
The DEM was projected into an equal area projection (Polar quartic projection), so that the ground units and zunits would be the same, which are in meters. No z_factor was used for this method. The SLOPES command and the use of the zunits and the z_factor are explained in the ARC/INFO manual.

Arc: project grid demgrd demgrd_pq,
where: demgrd = grid file; demgrd_pq = grid in an equal area projection.

b) Using the SLOPES command.
To create the slopes from the DEM the SLOPES command was used:

Grid: afslope = slopes (demgrd_pq, percentrise),
where: pndlsope = slope image; slopes = slopes command; demgrd_pq = grid in an equal area projection; percentrise = keyword to output the percent rise, also referred to as the percent slope.

c) Assigning thresholds
The slope grid (aflsope) was re-classified according to the thresholds defined by Hajek and Booyd (1990):

Grid: pndslope = reclass(afslope, remap_afslope),

where: pndlsope = re-classified slope grid with 4 suitability thresholds for fish ponds; reclass = grid command; remap_afslope = look up table to reclassify afslope.

Figure 8.11 shows the spatial distribution of the slope grid after re-classification.

8.4.3 Soils and slopes

Creating the soils and terrain suitability grid:
Grid: soilslope = 1.5 * soils5 + pndlsope

where: soilslope = soil and terrain suitability grid; 1.5 = coefficient assigned to give a higher weighting to soils5; soils5 = overall soil suitability grid; pndslope = re-classified slope grid with 4 suitability thresholds for fish ponds.

Grid: soilslope_sl = slice(soilslope, table, remap_soilslope)

where: soilslope_sl = final suitability image; remap_soilsope = look up table to reclassify soilslope.

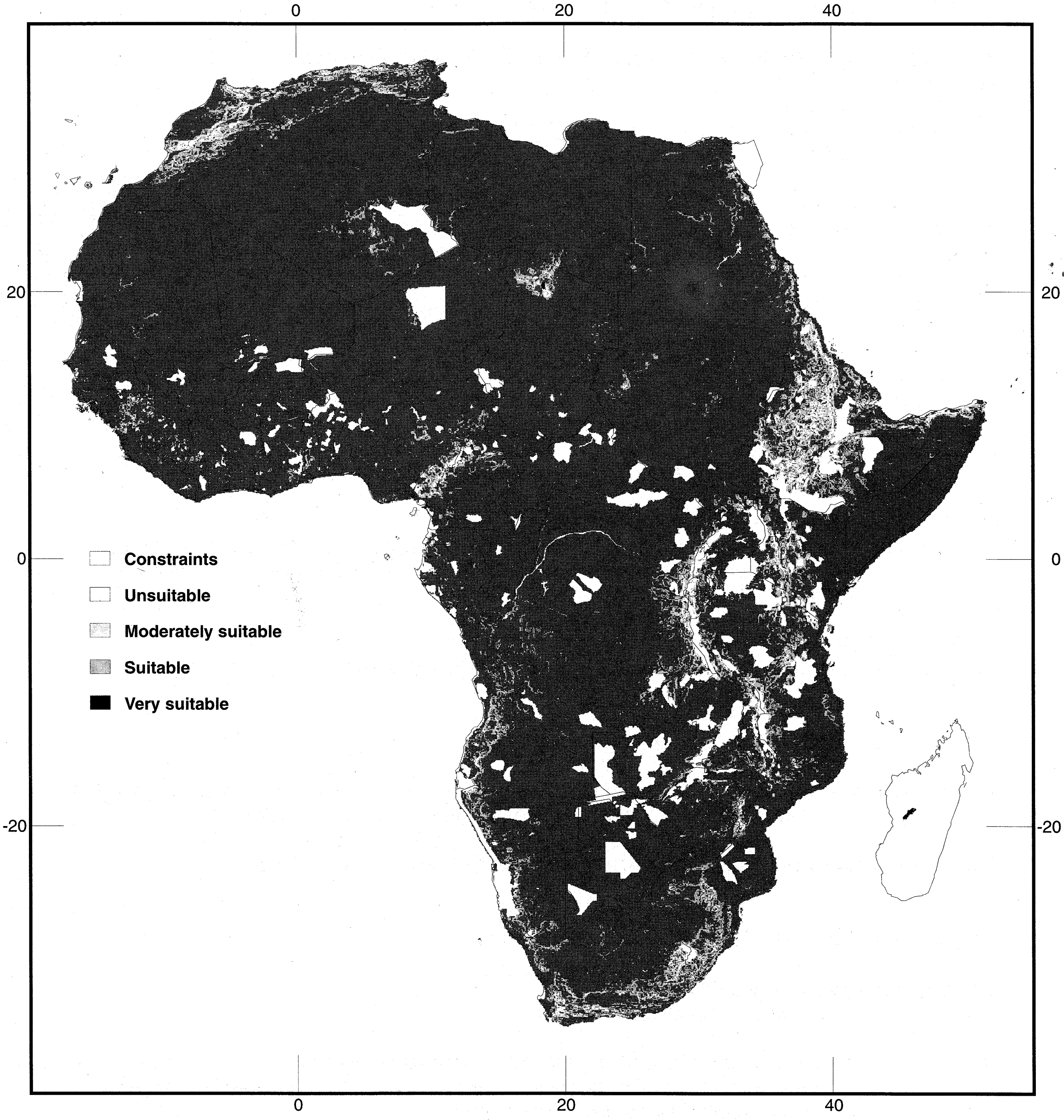


Figure 8.11
Slope suitability for ponds

8.5 LIVESTOCK WASTES AND AGRICULTURAL BY-PRODUCTS

8.5.1 Livestock wastes

Defining the study area (SETMASK), its extent (SETWINDOW) and cell size (SETCELL)
Example for cattle:

Grid: setwindow a fmask
Grid: setmask afmask
Grid: setcell afmask
Grid: cattle = afcattle

The same procedure was applied for the other 3 livestock types.

Data conversion from animals/km^2 to livestock numbers
The cell values in the original data are not the actual number of cattle, but rather the categories (because the data were originally created using GRASS software, which is limited to integer cell values 0-255).

Livestock data are listed as animal/km^2 x 1000. For example, category #147 (located in Kenya) is 16900 cattle/km^2 x 1000 or 16.9 cattle/km^2. The later option was used for this study.

a) Data for cattle, sheep, goats and pigs were projected to Flat Polar Quartic projection. Example of data conversion for cattle:

Arc: project grid cattle cattle_p,

where: project = Arc projection command; cattle = original data; cattle_pq = data in flat polar quartic projection.

Conversion of projection takes place according to the parameters specified in the file **llpolq.prj** illustrated below:

```
INPUT
PROJECTION GEOGRAPHIC
UNITS DD
PARAMETERS
OUTPUT
PROJECTION FLAT POLAR QUARTIC
UNITS METERS
PARAMETERS
00 00 00
end
```

b) Data frequency extraction

Arc: frequency cattle_pq.vat cattle_frq

Enter the 1st item: value

Enter the 2nd item: count

Enter the 3rd item: end

Arc: tables

Enter command: sel cattle_frq

Enter command: unload cattle_frq value count

where: tables & frequency = Arc commands for data extraction; cattle_pq = cattle data in flat polar quartic; cattle_frq = file name given containing the frequency data for cattle.

c) Data manipulation in EXCEL

To calculate the area occupied by each livestock category, the number of cells (COUNT) was multiplied by the square of the cell size in kilometres (5.930642* 5.930642). Then, this calculated area was multiplied by the livestock category.

Example: For category # 147 there are: 16.9 cattle/km^2 occupying 15,167 cells (count).

Therefore:

15,167 * (5.930642 * 5.930642) = 533,462 km^2

16.9 (cattle/km^2) * 533,462 (km^2) = 9,015,500 cattle

d) Livestock numbers from EXCEL to SUN

Calculations of livestock numbers were prepared as lookup tables in EXCEL in order to reclassify the original grid data. Once the data were prepared they were copied from EXCEL to SUN through the computer network.

Original livestock data were re-classified:

Grid: lncatlle = reclass (cattle, remap_lncattle)

where: lncattle = cattle grid containing livestock numbers; reclass = GRID command; cattle = original cattle grid; remap_lncattle = lookup table to reclassify original cattle data to livestock numbers.

Calculating the amount of manure available

a) To calculate the amount of manure available from each livestock type the following formula was used:

Amount of manure available [tons] = livestock number [1000] x livestock weight [tons] x solid manure /1,000 kg of livestock:

Grid: macattle = lpcattle * 0.21 * 60
Grid :masheep = lpsheep * 0.030 * 70
Grid :magoats = lpgoats * 0.030 * 70
Grid :mapigs = lppigs * 0.063 * 60

b) Calculating the total amount of manure available:
totmavai = macattle + masheep + magoats + mapigs,

where: totmavai = total manure available; macattle = manure available from cattle; masheep = manure available from sheep; magoats = manure available from pigs.

c) Reclassifying into four suitability classes:
The total amount of manure available grid contained 49 values which were subdivided into 4 suitability classes.

Grid: pndmanure = reclass (totmavai , remap_totmavai),

where: pndmanure = re-classified grid image; totmavai = total manure available; remap_totmavai = lookup table used to reclassify totmavai.

The resulting image using this reclassification is presented in **Figure 8.12**.

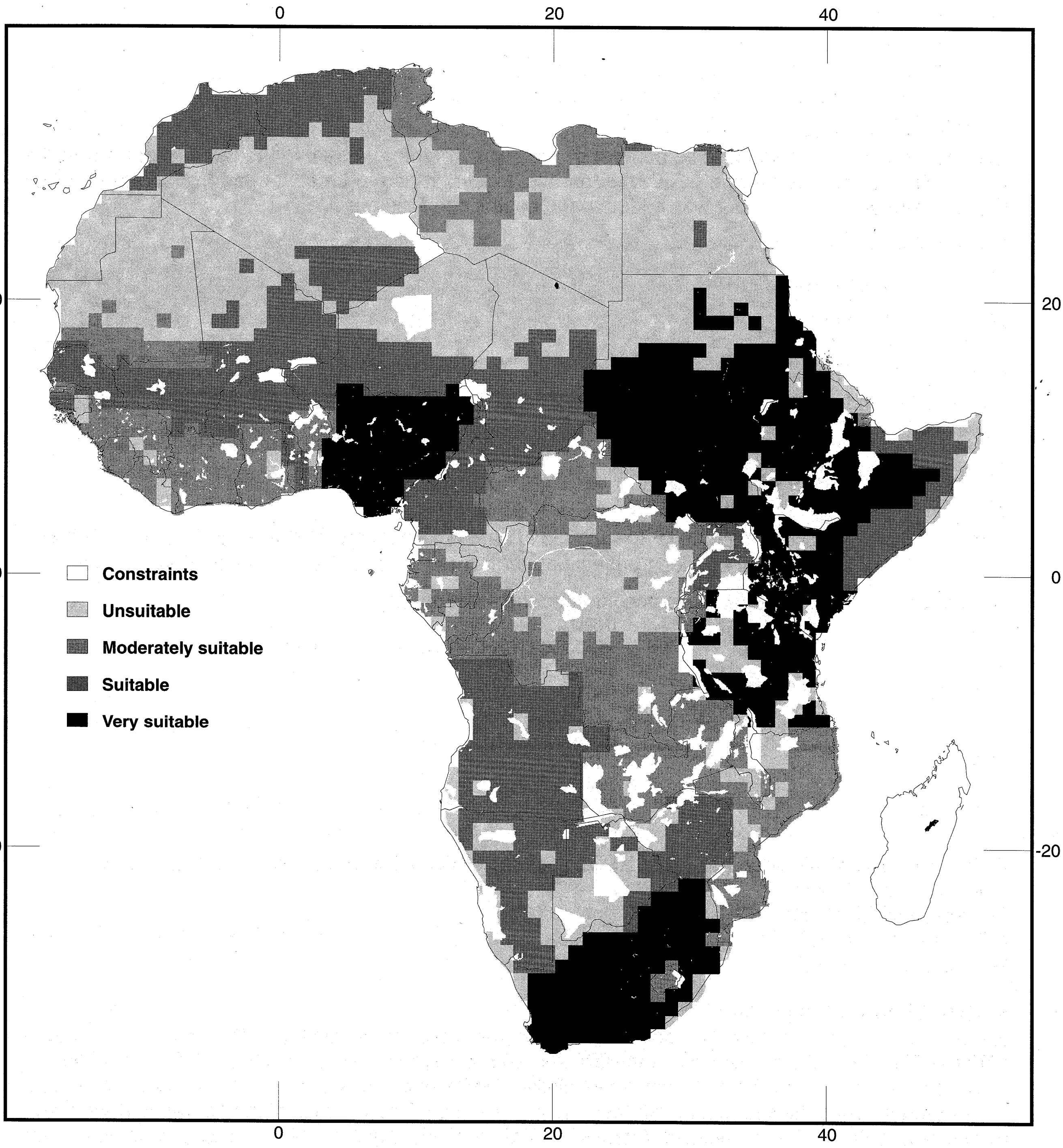


Figure 8.12
Total manure available

8.5.2 Agricultural by-products

a) Converting the land cover image file into grid
The land cover image (lndcvr.img) was obtained in IDA format in Lambert Azimuthal Equal Area projection at 1 km resolution. Using a PC, the IDA version 4.2 software was used to convert the land cover image in IDA format to a GRID file using the procedure described below:

Using IDA select from the menu:
- Process,
- Convert,
- ASCII,
- Name of the input file (e.g. g:\aflcida\lndcvr.img\), and
- Name of the output file (e.g. d:\pepe\landcov\lndcvr.txt\)

The output file, lndcvr.txt was a space delimited ASCII file containing, in each line, the pixel values of one row of the original image. The number of lines was, therefore, equal to the number of rows of the image. To convert this file to a GRID, the text file, lndcvr.txt had to be converted from DOS (i.e. PC) to UNIX format, then a header was added at the beginning of the file:

```
ncols  8350
nrows  9276
xllcenter  -4457834.848
yllcenter  -4795411.919
cellsize 1000
nodata_value: -999
```

The new file, lndcvru.txt was converted to a GRID file using the ASCIIGRID command: Arc: asciigrid lndcvru.txt lndcvr, where: lndcvr = grid file.

b) Change of projection
Arc: project grid lndcvr lndcvrll lamll.prj

where: project = Arc command; lndcvr = grid file in Lambert Azimuthal Equal Area projection; lndcvrll = grid file in Lat./long projection; **lamll.prj** = file containing projection parameters.

Conversion of projection took place according to the file **lamll.prj**:

```
INPUT
PROJECTION LAMBERT_AZIMUTH
UNITS METERS
PARAMETERS
OUTPUT
PROJECTION GEOGRAPHIC
UNITS DD
PARAMETERS
00 00 00
end
```

c) Defining the study area (SETMASK), its extent (SETWINDOW) and cell size (SETCELL)
Grid: setmask afmask
Grid: setwindow afmask
Grid: setcell afmask
Grid: acrops = lndcvrll

d) Extracting the crops data
Efforts were made to re-classify cropland areas by crop types, but it was found that this is not possible because the data source does not differentiate cropland types. As a result, from the 195 classes provided by the original data, all cropland classes were re-classified into a single value of 4 and considered as potential sources of fish feed inputs. All other areas were assigned a value of zero (i.e. no crops): Grid: crops = reclass (acrops, remap_lndcvr), **Figure 8.13** shows the spatial crop distribution.

e) Combining manure and crops
Grid: byprod = 1.5 * manure + crops

The resulting byprod grid contained 8 values which were subdivided into 4 equal-interval classes:

Grid: byprod_sl = slice(byprod, remap_inputs), where: remap_inputs = reclassification file.

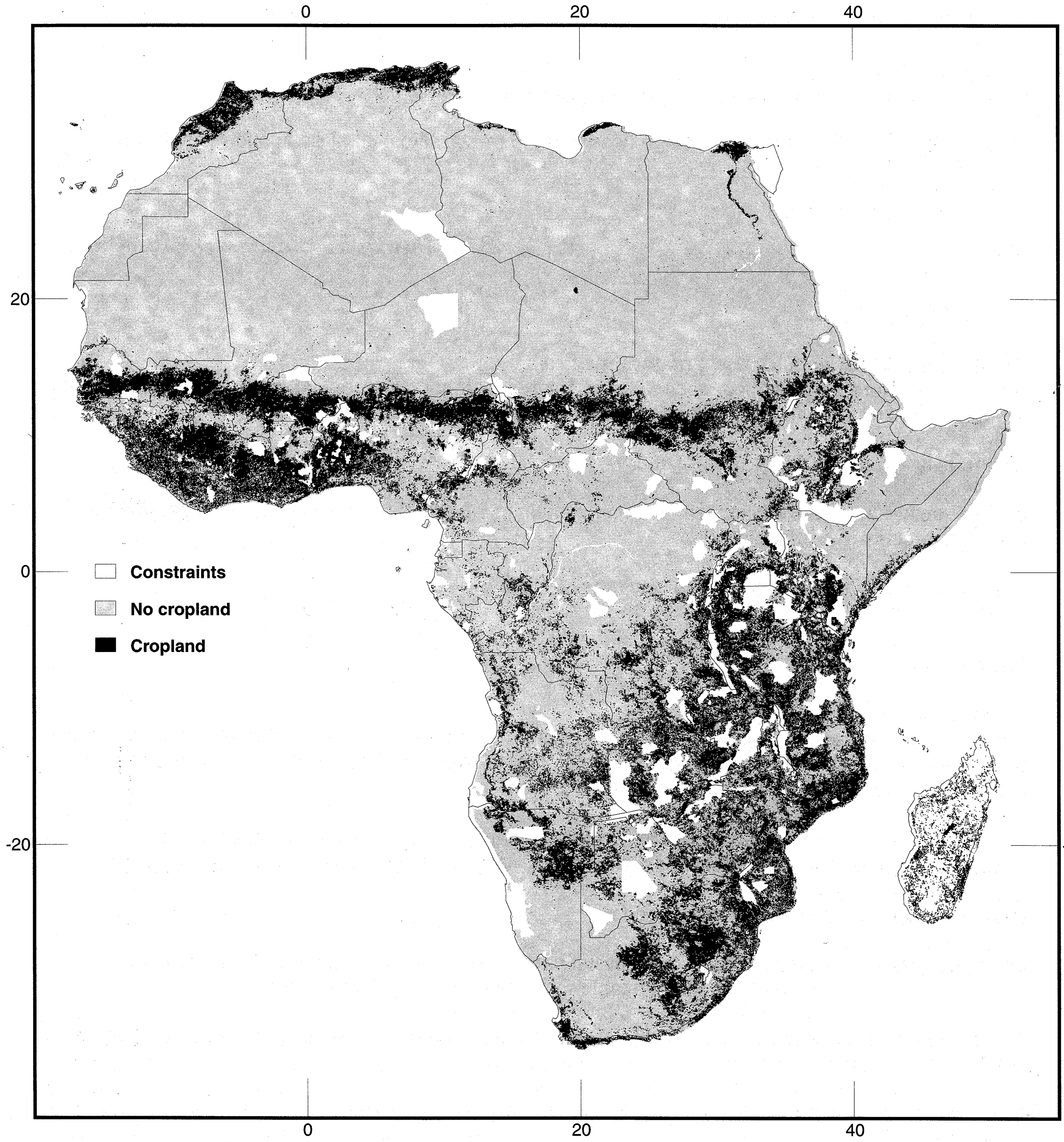


Figure 8.13
Cropland areas

8.6 FARM-GATE SALES

8.6.1 Population density

Defining the study area (SETMASK), its extent (SETWINDOW) and cell size (SETCELL)
Grid: setwindow afmask
Grid: setmask afmask
Grid: setcell afmask
Grid: popaf_dens = popworld_dens

Re-classification
Grid: farmgate = reclass (popaf_dens, remap_popden),

where: farmgate = final suitability image based on the re-classification of population density data.

8.7 URBAN MARKET SIZE AND PROXIMITY

8.7.1 Major cities

Creating a grid for each of the 4 major cities
Major cities were re-classified according to their accompanying population density classification system. An example syntax is given for cities classified as very suitable:

Grid: uncity = reclass(cities, remap_uncity),

where: uncity = unsuitable cities; cities = grid containing all cities; remap_uncity = lookup table used to reclassify unsuitable cities.

The same operation was repeated for the other 3 cities.

8.7.2 Roads

Creating the cost grid
The cost grid represents the time cost and it is assumed that the time required to travel from one cell to another in absence of main roads is 5 times longer than the time needed on the main road. To create such a grid the following procedures were used:

a) Roads were re-classified according to their accompanying road type classification system. An example syntax is provided for roads classified as very suitable:

Grid: roads1 = reclass(roads, remap_roads1),

where: roads1 = very suitable roads (i.e. lowest cost) ; roads = grid containing all road types; remap_roads1 = look up table to re-classify very suitable roads.

The same operation was repeated for the other 3 road types. Areas where there was an absence of roads were assigned a value of 5.

b) Grids for the 4 roads types and a grid that represents the absence of roads were combined to create a COST grid:

rdsgrd_cost = merge (roads1, roads2, roads3, roads4, roads5),

where: roads1 = very suitable roads; roads2 = suitable roads; roads3 = moderately suitable roads; roads4 = unsuitable roads; roads5 = absence of roads.

Figure 8.14 shows the resulting cost grid:

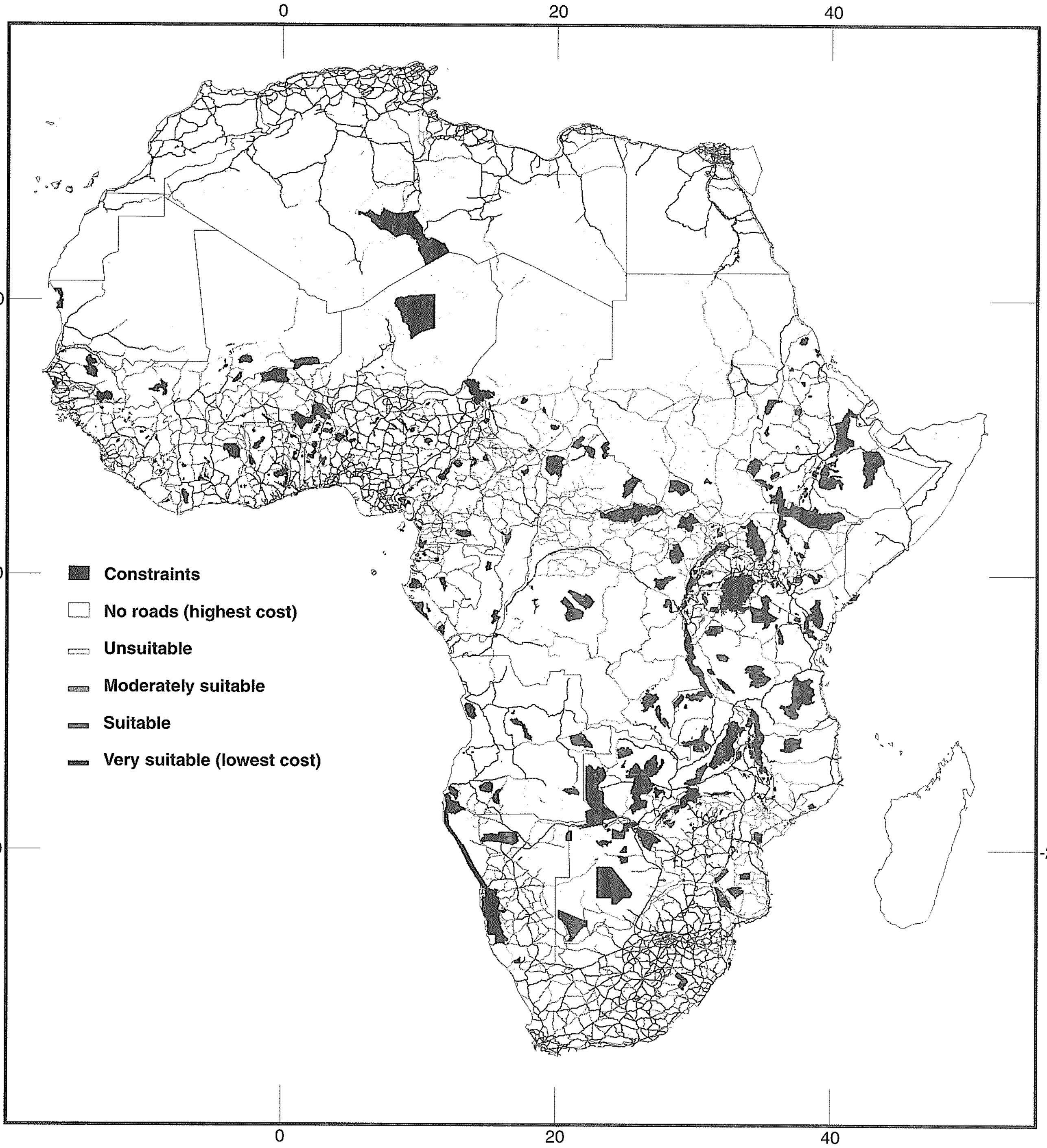


Figure 8.14
Cost grid

8.7.3 Major cities and roads

Using the COSTDISTANCE command

This GRID command calculates the least accumulative cost distance from each cell to the towns. In other words, it finds for each cell the best (and most convenient) route to go to the town. It is not necessarily the closest town, but it is the easiest to reach. The cost-distance analysis is explained in the ARC/INFO manual.

dist1_temp = costdistance(uncity, rdsgrd_cost, backl1),

where: dist1_temp = distance to unsuitable cities; rdsgrd_cost = cost grid and backl1 = grid containing the direction of the paths on a cell by cell basis.

This grid allows reconstruction of the various paths to the towns. Directions are indicated with numbers from 0 to 8 indicating the next neighbouring cell along the least accumulative cost path from any cell of the grids to reach the town. If the path is to pass into the right neighbour, the cell will be assigned the value 1, 2 for the lower right diagonal cell and so on, continuing clockwise. The value 0 is reserved for the cells representing the towns.

Changing the values of the grid backl1 into the corresponding degrees (the North is indicated by 360 (which is equivalent to 0))

dire1_deg = con(backl1 == 1, 90, backl1 == 2, 135, backl1 == 3, 180, backl1 == 4, 225, backl1 == 5, 270, backl1 == 6, 315, backl1 == 7, 360, backl1 == 8, 45, backl1)

Creating a grid containing latitude values

The following GRID AML, automates the creation of the latitude grid for Africa:

```
setcell afmask
setwindow afmask
docell
afrlatgrd = 37.5 - ( $$rowmap x 0.05 )
end
```

where: afmask is the based grid; aflatgrd is the resulting latitude grid.

Calculating the real distances from the towns along the paths

Since the grids are in geographic co-ordinates (Latitude/Longitude in decimal degrees), the dist1_temp grid cannot be used to calculate the distances.

Real distances can be derived from geographic distances considering that the distance between 2 points varies with the cosine of the latitude, if the direction is East-West and it is constant if the direction is North-South. Diagonal paths have a length in between the two (E-W and N-S) which vary with the sin of the direction. The formula is the following:

length1_rd1 = 111 * abs(sqrt(sqr(0.050) * (sqr(sin(dire1_deg / deg)) * cos(afrlatgrd div deg) + sqr(cos(dire1_deg / deg))))),

where: 111 is the length of 1 degree at the Equator expressed in km; 0.050 is the cell size in decimal degrees; deg is a variable built in GRID to convert from radians to degrees; afrlatgrd is a grid containing the latitude value of each cell.

Assigning weights to the road grid

Real distance grid (length1_rd1) is multiplied by the cost grid (rdsgrd_cost). This grid is used to give a weight to the road grid in such a way that areas without roads have a weight (cost) 5 times higher than the others.

length1_rd2 = length1_rd1 * rdsgrd_cost

The grid length1_rd2 provides weighted distances calculated from one cell to the other
To obtain the least accumulative cost paths in real distances a new cost-distance has to be re-calculated. The result must be divided by the cell size (0.050) to keep the already calculated distances.

dist1_fin = costdistance(uncity, length1_rd2) / 0.050

Calculating distances in hours
Distances in hours (travelling time) is obtained by dividing the least accumulative cost paths (dist1_fin) by 90 considering an average speed of 90 km/h on the road. Since the road grid weighted as 4 areas without roads, it is assumed an average speed of 90 / 5 = 18 km/h outside the main roads (using graded roads or tracks).

dist1_hour = dist1_fin / 90

Limiting the suitable areas for commercial fish farming to 6 hours travelling time
dist1_h6 = con(dist1_hour le 6, dist1_hour, 9999)

The value 9999 was assigned to areas further away than 6 hours.

The 9999 value is extended to the whole African grid (covering unsuitable areas previously indicated with NODATA)
dist1_h6a = con(isnull(dist1_h6) == 1, 9999, dist1_h6)

The same operations (steps 4.3 to 4.9) are repeated for the other 3 classes of towns
The GRID AML **mktgrd.aml** automates the procedures for all the towns.

The least accumulative cost path grids calculated separately for the 4 classes of towns are multiplied by the town weight and added together
cost_fin6 = min(dist1_h6a, dist2_h6a * 2, dist3_h6a * 3, dist4_h6a * 4)

Finally, the area indicated with 9999 is unsuitable
mktgrd = con(cost_fin6 ge 9999, 9999, cost_fin6)

8.8.1 Air temperature

Copying and converting ASCII files into ARC/INFO grid
Twenty four ASCII files containing mean monthly gridded values of daily minimum and daily maximum temperatures were copied and converted from the CRES Compact disk into ARC/INFO grid format. The following example illustrates how one of the files (AFMINT01) was copied and converted into a grid:

Arc: asciigrid /cdrom/961206_0935/afmint01.grd afmint01.gr

Note: The GRID AFMINT01 corresponds to the month of January.

Dividing the GRID files by a factor of ten
Original ASCII files were obtained in units of tenths of degrees Celsius so the gridded ASCII files had to be individually divided by a factor of ten to obtain their original vales. The following example illustrates how one of the files was divided by ten:

Grid: afmint01ten = afmint01.grd / 10

Note: A Grid AML **tentemp.aml** automates the procedure for the 24 GRID files by repeating the command above for each one of the GRID files.

Table 8.6 shows the statistics on the 24 mean monthly air temperature values for Africa:

Table 8.6 Statistics of the 24 mean monthly air temperature values for Africa.
[°C]

MONTH	MEAN MONTHLY DAILY MINIMUM AIR TEMPERATURE				MEAN MONTHLY DAILY MAXIMUM AIR TEMPERATURE			
	MIN.	MAX.	MEAN	SD	MIN.	MAX.	MEAN	SD
1. January	-15	24	13.292	5.697	-1	38	27.319	5.701
2. February	-14	24	14.399	5.25	0	39	28.805	5.297
3. March	-12	25	16.017	4.679	-1	40	30.282	5.025
4. April	-9	27	17.137	4.534	-2	42	31.505	5.201
5. May	-9	28	17.657	5.547	-3	44	32.007	5.950
6. June	-11	29	17.612	6.788	-4	46	31.864	6.906
7. July	-11	31	17.630	6.941	-5	47	31.323	6.963
8. August	-11	31	18.005	6.103	-4	46	31.368	5.991
9. September	-12	29	18.226	4.692	-2	43	31.787	4.744
10. October	-11	27	17.558	3.638	-1	40	31.292	3.959
11. November	-10	25	15.631	3.984	-2	38	29.304	4.232
12. December	-13	24	13.684	5.223	-2	37	27.461	5.296

Note: SD = Standard Deviation.

Merging the No Data numerical value to the GRID files
Based on the ASCII files received from CRES the No Data values in the GRID images created were assigned a value of -999 within the African continent but the No Data values corresponding to the Ocean (i.e. commonly called "c" values) had no numerical value assigned to them and therefore it was necessary to assign them the No Data value of -999 in order to create the header information necessary for the creation of the final GRID files.

Three steps were necessary to include the -999 value in the GRID files:

a) The GRID command ISNULL was used with the base grid image AFMASK to create a GRID named TEMP. ISNULL returns a numerical value of "1" for those values that have NO DATA, and "0" if they have data, on a cell by cell basis within the analysis window. The syntax used is presented below:

    Grid: TEMP = isnull(afmask)

Result of TEMP: African continent = 0 ; Ocean = 1

b) The GRID file TEMP was multiplied by the value of -999 to create a GRID file named NODATA.

    Grid: NODATA = Temp * -999

Result of NODATA: African continent = 0 ; Ocean = -999

c) The GRID command MERGE was used to multiply the input grids (AFMINT01TEN and NODATA) into a single grid (AFMINT01NEW).

Grid: AFMINT01F= merge (AFMINT01TEN, NODATA)

Result of NODATA: African continent = air temperatures values ; Ocean = -999

Note: A Grid AML **merge.aml** automates the procedure for the 24 GRID files by repeating step "c" above for each one of the GRID files.

Creating two ASCII files using SAMPLE
The Grid SAMPLE module was used to create two ASCII files from the 24 GRID files above. SAMPLE lists the values of a group of cells from one or more grids. For each selected cell, information on cell locations in Longitude and Latitude and the relevant temperature values from each of the input grids is written to an ASCII file.

The Grid AML **gridtemp.aml** was used to produce two ASCII files.

MIN.TXT = minimum temperature data
MAX.TXT = maximum temperature data

The Grid AML gridtemp is illustrated below:

```
MIN.TXT = sample( afmask, afmint01f, afmint02f, afmint03f, afmint04f, afmint05f, afmint06f,
            afmint07f, afmint08f, afmint09f, afmint10f, afmint11f, afmint12f)
MAX.TXT = sample( afmask, afmaxt01f, afmaxt02f, afmaxt03f, afmaxt04f, afmaxt05f, afmaxt06f,
            afmaxt07f, afmaxt08f, afmaxt09f, afmaxt10f, afmaxt11f, afmaxt12f)
```

An extract of MIN.TXT file is reported below:

```
-999 -14.975 24.875 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999
-999 -14.925 24.875 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999
-999 -14.875 24.875 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999 -999
1 -14.825 24.875 22 23 24 24 25 26 28 29 29 28 25 22
1 -14.775 24.875 22 23 24 24 25 26 28 29 29 28 25 22
1 -14.725 24.875 22 22 24 24 25 26 29 29 29 28 25 22
```

Replacing MISSING with -999
A very small number of data values were reported as MISSING in both of the text files, so these data were replaced with -999 using a text editor (i.e. find and replace option).

The ASCII files were converted into DOS format using the module UNIX2DOS in ARC/INFO:
Arc: unix2dos min.txt afmin.dos
Arc: unix2dos max.txt afmax.dos

Creating two comma-delimited ASCII files
The QBASIC program **COMMAS.BAS** illustrated below was used to modify the two ASCII files to create two comma-delimited ASCII files:

MINAF.TXT = minimum temperature data
MAXAF.TXT = maximum temperature data

The QBASIC program COMMAS.BAS is illustrated below:

```
CLOSE
min$ = "D:\unldatin\min.dos"
max$ = "D:\unldatin\max.dos"
minf$ = "D:\unldatin\minaf.txt"
maxf$ = "D:\unldatin\maxaf.txt"
 FOR y = 1 TO 2
   IF y = 1 THEN
   OPEN min$ FOR INPUT AS #1
   OPEN minf$ FOR OUTPUT AS #2
   ELSE
   OPEN max$ FOR INPUT AS #1
   OPEN maxf$ FOR OUTPUT AS #2
   END IF
   DO
   LINE INPUT #1, a$
   b$ = MID$(a$, (INSTR(1, a$, " ") + 1))
   c$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, c$, " ") + 1))
   d$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, d$, " ") + 1))
   e$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, e$, " ") + 1))
   f$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, f$, " ") + 1))
   g$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, g$, " ") + 1))
   h$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, h$, " ") + 1))
   i$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, i$, " ") + 1))
   l$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, l$, " ") + 1))
   m$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, m$, " ") + 1))
   n$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, n$, " ") + 1))
   o$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, o$, " ") + 1))
   p$ = LEFT$(b$, (INSTR(1, b$, " ")))
   b$ = MID$(b$, (INSTR(1, p$, " ") + 1))
   q$ = LEFT$(b$, (INSTR(1, b$, " ")))
   r$ = MID$(b$, (INSTR(1, q$, " ") + 1))
   a1$ = RTRIM$(c$) + "," + RTRIM$(d$) + "," + RTRIM$(e$) + ","
   a2$ = RTRIM$(f$) + "," + RTRIM$(g$) + "," + RTRIM$(h$) + ","
   a3$ = RTRIM$(i$) + "," + RTRIM$(l$) + "," + RTRIM$(m$) + ","
   a4$ = RTRIM$(n$) + "," + RTRIM$(o$) + "," + RTRIM$(p$) + ","
   a5$ = RTRIM$(q$) + "," + RTRIM$(r$)
   PRINT #2, a1$ + a2$ + a3$ + a4$ + a5$
   LOOP UNTIL (EOF(1))
   CLOSE
   NEXT
```

COMMAS.BAS created two output files (MINAF.TXT and MAXAF.TXT). An extract of MINAF.TXT is reported below:

```
-14.975, 24.875, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999
-14.925, 24.875, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999
-14.875, 24.875, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999, -999
-14.825, 24.875, 22, 23, 24, 24, 25, 26, 28, 29, 29, 28, 25, 22
-14.775, 24.875, 22, 23, 24, 24, 25, 26, 28, 29, 29, 28, 25, 22
-14.725, 24.875, 22, 22, 24, 24, 25, 26, 29, 29, 29, 28, 25, 22
```

The mask values are not recorded in the output.

Calculating mean monthly air temperature

The program DATAIO.EXE was used to calculate the mean monthly air temperature. DATAIO.EXE takes the input files AFMIN.TXT and AFMAX.TXT to create TEMPMEAN.TXT (note: file names are user-defined; programs that can accept any name).

An extract of TEMPMEAN.TXT is reported below:

```
-14.975000, 24.875000, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0
-14.925000, 24.875000, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0
-14.875000, 24.875000, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0
-14.825000, 24.875000, 17.0, 18.0, 19.0, 19.5, 20.5, 21.5, 23.0, 24.0, 24.0, 23.0, 20.5, 17.5
-14.775000, 24.875000, 17.0, 18.0, 19.0, 19.5, 20.5, 21.5, 23.0, 23.5, 24.0, 23.0, 20.5, 17.5
-14.725000, 24.875000, 17.0, 17.5, 19.0, 19.0, 20.0, 21.5, 23.5, 23.5, 23.5, 22.5, 20.5, 17.5
```

Note: TEMPMEAN.TXT was 214 Mb and took the PC 6 hours to process.

Changing the ASCII file TEMPMEAN.TXT to the format required by ARC/INFO

The QBASIC program AIRTEMP.BAS was used to change the ASCII file TEMPMEAN.TXT to the format required by the ARC command ASCIIGRID. The first part of the program checks the size of the GRID and the order of the cells. A cell out of sequence causes a program interruption and an error message. The second part checks the number of variables included in the input file and creates an equal number of output files. It also determines the number of rows and columns of the GRIDS and produces the header (see ARC/INFO ASCIIGRID syntax) indicating the items listed below:

number of columns
number of rows
cellsize
x co-ordinates of the first cell
y co-ordinates of the first cell
value of NODATA

All parameters are determined by the program itself except for the cell size and NODATA value. Default values are:

cellsize = 0.05
NODATA value = -999

If those values need to be changed, new values must be replaced in the program (which can be edited using any available text editor) in the box indicated below:

```
REM ************ PARAMETERS UPDATED BY THE USER ****************
infile$ = "D:\unldatin\TEMPMEAN.TXT"
cell$ = "0.05"
nodata$ = "-999"
REM ********************************************************************************
```

Input file name and location can also be modified.

The QBASIC program AIRTEMP.BAS is illustrated below:

```
DIM b$(50)
COMMON xcoord AS DOUBLE
COMMON ycoord AS DOUBLE
COMMON cc AS LONG

REM ************ PARAMETERS UPDATED BY THE USER ****************
infile$ = "D:\ unldatin \tempmean.txt"
cell$ = "0.05"
nodata$ = "-999"
REM ************************************************************************************
CLOSE
OPEN infile$ FOR INPUT AS #1
LINE INPUT #1, a$
xll$ = LEFT$(a$, INSTR(1, a$, ",") - 1)
commas = 0
zz = LEN(a$)
FOR z = 1 TO zz
 IF MID$(a$, z, 1) = "," THEN
  commas = commas + 1
 END IF
NEXT
row = 1
coln = 1
DO
 firstc = INSTR(1, a$, ",")
 xcoord = VAL(LEFT$(a$, firstc - 1))
 ycoord = VAL(MID$(a$, firstc + 1, INSTR(firstc + 1, a$, ",") - 1))
 LINE INPUT #1, a$
 firsts = INSTR(1, a$, ",")
 IF VAL(MID$(a$, firsts + 1, INSTR(firsts + 1, a$, ",") - 1)) = ycoord THEN
  IF VAL(LEFT$(a$, firsts - 1)) > xcoord THEN
   IF row = 1 THEN
    coln = coln + 1
   END IF
  ELSE
   PRINT "Error in the X coordinates.  Check the input file"
   STOP
  END IF
 ELSE
  IF VAL(MID$(a$, firsts + 1, INSTR(firsts + 1, a$, ",") - 1)) < ycoord THEN
   PRINT "I am checking row " + STR$(row)
   row = row + 1
  ELSE
   PRINT "Error in the Y coordnates.  Check the input file"
   STOP
  END IF
 END IF
LOOP UNTIL (EOF(1))
yll$ = STR$(ycoord)
commas = commas - 1
FOR x = 1 TO commas
 outfile$ = "D:\pepe\airtmp" + LTRIM$(STR$(x)) + ".txt"
 yy = x + 1
 OPEN outfile$ FOR OUTPUT AS #yy
 PRINT #yy, "ncols " + STR$(coln)
 PRINT #yy, "nrows " + STR$(row)
 PRINT #yy, "xllcorner " + xll$
 PRINT #yy, "yllcorner " + yll$
 PRINT #yy, "cellsize " + cell$
 PRINT #yy, "nodata_value " + nodata$
NEXT
CLOSE #1
OPEN infile$ FOR INPUT AS #1
cc = 1
DO WHILE NOT EOF(1)
 LINE INPUT #1, a$
 firstc = INSTR(1, a$, ",")
```

```
  prevc = INSTR(firstc + 1, a$, ",")
  FOR x = 1 TO commas - 1
    nextc = INSTR(prevc + 1, a$, ",")
    b$(x) = MID$(a$, prevc + 1, nextc - (prevc + 1))
    prevc = nextc
  NEXT
  b$(commas) = MID$(a$, nextc + 1)
  FOR x = 1 TO commas
    yy = x + 1
    PRINT #yy, LTRIM$(b$(x))
  NEXT
  PRINT "I am processing line " + STR$(cc)
  cc = cc + 1
LOOP
CLOSE
```

Note: Each monthly water temperature files was 14 Mb. It took the PC 5 hours to create these files. An extract of one of the files AIRTMP1.TXT for the month of January is reported below:

```
ncols  1380
nrows  1450
xllcorner -17.475000
yllcorner -34.974998
cellsize 0.05
nodata_value -999
-999.0
-999.0
-999.0
-999.0
-999.0
-999.0
```

Converting the output files of AIRTEMP.BAS to ARC/INFO GRIDS

After generating mean monthly air temperature files with TEMP.BAS, the 12 output files were converted to UNIX format (DOS2UNIX command in ARC). Once this was done, the ASCIIGRID command was used to convert the ASCII files to GRIDS. The AML **airgrids.aml** was used to automate the manipulation procedure for the 12 files as illustrated below:

```
&setvar 1 1
&do &while %1% < 13
  dos2unix airtmp%1%.txt airtmp%1%u.txt
  asciigrid airtmp%1%u.txt airtmp%1% float
  &setvar 1 [calc %1% + 1]
&end
&return
```

Table 8.7 shows the statistics on the 12 mean monthly air temperature values for Africa and **Figure 8.15** show the resulting monthly distribution of air temperature values.

Table 8.7 Mean monthly air temperature values in Africa. [°C]

MONTH	MIN.	MAX.	MEAN	SD
1. **January**	-8	29.5	20.305	5.471
2. **February**	-6.5	31.5	21.601	5.007
3. **March**	-5	32.5	23.148	4.6
4. **April**	-5.5	33.5	24.32	4.592
5. **May**	-6	35	24.831	5.507
6. **June**	-7.5	36.5	24.737	6.61
7. **July**	-8	38.5	24.475	6.685
8. **August**	-7.5	37.5	24.685	5.746
9. **September**	-7	35	25.005	4.449
10. **October**	-6	32	24.424	3.567
11. **November**	-6	30	22.466	3.874
12. **December**	-7	29.5	20.572	5.029

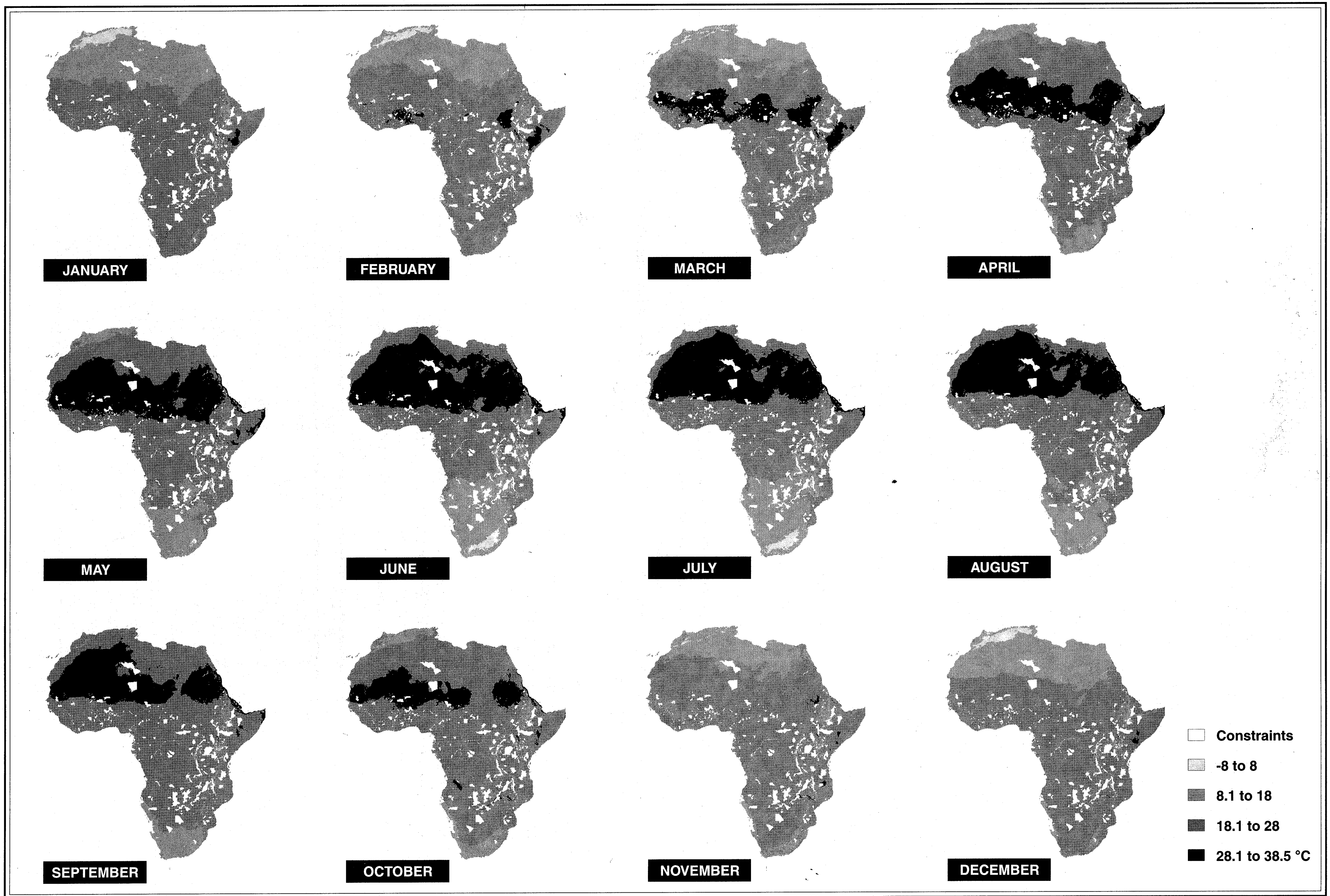


Figure 8.15 **Mean monthly air temperature**

8.8.2 Wind velocity

Copying and converting the IDRISI file into ARC/INFO grid
Original data **AFDBCH04.IMG** was received through FTP in IDRISI format. A document file was created for this image file in IDRISI for Windows version 1.

Using file export in IDRISI, AFDBCH04.IMG was exported as an ERDAS file as WINDAF.GIS

The IMAGEGRID module in ARC/INFO was used to convert WINDAF.GIS into a grid WINDAFGR:

Arc: imagegrid windaf.gis windafgr

Adjusting grid extensions and cell size
The Grid modules SETWINDOW and SETCELL were used to adjust the grid extensions and cell size of windafgr to the base grid:

Grid: setwindow afmask
Grid: setcell afmask
Grid: windnew = windafgr

Table 8.8 shows the statistics on the mean annual wind velocity grid for Africa and **Figure 8.16** illustrates the distribution.

Table 8.8 Mean annual wind velocity values in Africa.

CLASSS NUMBER	WIND SPEED RANGE (meters / second)
1	0.0 - 0.5
2	0.5 - 1.0
3	1.0 - 1.5
4	1.5 - 2.0
5	2.0 - 2.5
6	2.5 - 3.0
7	3.0 - 3.5
8	3.5 - 4.0
9	4.0 - 4.5
10	4.5 - 5.0
11	5.0 - 5.5
12	5.5 - 6.0
13	> 6.0

Creating an ASCII file using SAMPLE
The following command was used to produce one ASCII file.

WINDAF.TXT = sample(afmask, windnew), where: WINDAF.TXT = ASCII file for mean annual wind velocity.

An extract of WINDAF.TXT file is reported below:
-999 -14.975 24.875 -999
-999 -14.925 24.875 -999
-999 -14.875 24.875 -999
1 -14.825 24.875 8
1 -14.775 24.875 8
1 -14.725 24.875 8

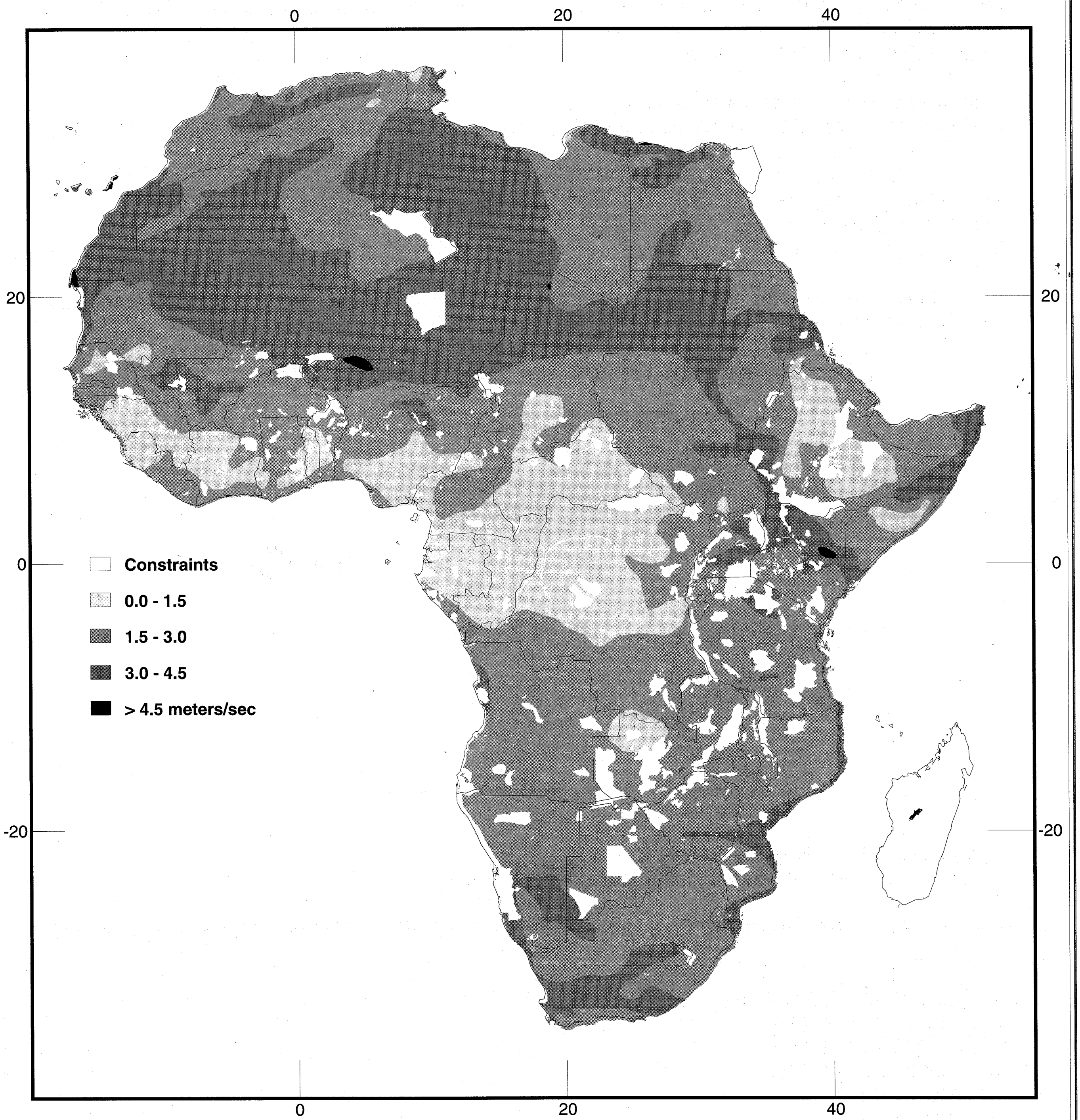


Figure 8.16
Mean annual wind velocity

The ASCII file was converted into DOS format using the module UNIX2DOS in ARC/INFO:
Arc: unix2dos windaf.txt windaf.dos

Creating a comma-delimited ASCII file
A VISUAL-BASIC program **COMWIND.BAS** was created to modify the ASCII file windaf.dos to create a comma-delimited ASCII file **WINDCOM.TXT**. The first part of the program deletes the first column or mask value column. The second part places commas between the Longitude and Latitude and the mean annual wind speed values.

WIN.BAS was executed by opening the WIND icon in program manager. A small window is open where the user can enter the input and output file locations. Example syntax:

input file: D:\unldatin\afmin.txt
outputfile: D:\unldatin\windcom.txt

The VISUAL-BASIC program WIND.BAS is illustrated below:

```
' This procedure has been written for Visual Basic 4 Professional Edition
  ' But, it can be run for any Visual Basic version.
  ' <> required parameters

  sSource = <Input File>
  sResult = <OutPut File>

  Open sSource For Input As #1
  Open sResult For Output As #2

  Do Until (EOF(1))
    sOutPut = "": iFirst = 1
    Line Input #1, sStrTmp
    sStrTmp = Trim$(sStrTmp)
    Do While sStrTmp <> ""
      iWhere = InStr(sStrTmp, " ")
      If 0 < iWhere Then
        sWord = Left$(sStrTmp, iWhere - 1)
        If iFirst <> 1 Then
          sOutPut = sOutPut & IIf(sWord = "0", "-999", sWord) + ","
        End If
        sStrTmp = LTrim$(Mid$(sStrTmp, iWhere + 1))
      Else
        If iFirst <> 1 Then sOutPut = sOutPut & IIf(sStrTmp = "0", "-999", sStrTmp)
        sStrTmp = ""
      End If
      iFirst = 0
    Loop
    Print #2, sOutPut
  Loop
  Close
```

An extract of WINDCOM.TXT file is reported below:

-14.975, 24.875, -999
-14.925, 24.875, -999
-14.875, 24.875, -999
-14.825, 24.875, 8
-14.775, 24.875, 8
-14.725, 24.875, 8

8.8.3 Water temperature

Calculating mean monthly water temperature

The program WATEMP.EXE was used to calculate the mean monthly water temperature. WATEMP.EXE reads monthly air temperature files created using DATAIO.EXE and mean annual wind speed file, calculates water temperature, and writes monthly water temperature to the output. All input and output files are comma delimited.

WATEM.EXE is packaged as a windows application. It was executed using File/Run from the Windows program manager.

Example syntax: watemp.exe tempmean.txt comwind.txt watemp.txt,

where: watemp.exe = executable program; tempmean.txt = mean monthly air temperature;
comwind.txt = mean annual wind velocity; watemp.txt = monthly water temperature.

An extract of WATEMP.TXT file is reported below:

```
-14.975000, 24.875000, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0
-14.925000, 24.875000, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0
-14.875000, 24.875000, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0, -999.0
-14.825000, 24.875000, 17.6, 18.2, 19.8, 20.9, 22.0, 22.9, 24.0, 24.7, 24.3, 22.9, 20.2, 17.5
-14.775000, 24.875000, 17.6, 18.2, 19.8, 20.9, 22.0, 22.9, 24.0, 24.4, 24.3, 22.9, 20.2, 17.5
-14.725000, 24.875000, 17.5, 17.9, 19.7, 20.6, 21.6, 22.9, 24.3, 24.4, 23.9, 22.5, 20.2, 17.5
```

Note: WATEMP.TXT was 214 Mb and took the PC 12 hours to create.

Changing the ASCII file TEMPMEAN.TXT to the format required by ARC/INFO

The QBASIC program **AIRTEMP.BAS** (above) was copied, renamed (**WATEMP.BAS**) and used to change the output of WATEMP.EXE to the format required by the ARC command ASCIIGRID.

Converting the output files of AIRTEMP.BAS to ARC/INFO GRIDS

After generating mean monthly water temperature files with WATEM.BAS, the 12 output files were converted to UNIX format and then the ASCIIGRID command was used to convert ASCII files to GRIDS. The AML **airgrids.aml (step 1.10)** was copied, and renamed (**watergrids.aml**) to automate this procedure for the 12 months:

```
&setvar 1 1
&do &while %1% < 13
 dos2unix watmp%1%.txt watmp%1%u.txt
 asciigrid watmp%1%u.txt watmp%1% float
 &setvar 1 [calc %1% + 1]
&end
&return
```

Table 8.9 shows the statistics on the 12 monthly water temperature values for Africa:

Table 8.9 Mean monthly water temperature in Africa.
[°C]

MONTH	MIN.	MAX.	MEAN	SD
1. **January**	-6.2	33	23.071	6.343
2. **February**	-3.1	33.3	23.623	5.427
3. **March**	1.1	34.2	25.149	4.508
4. **April**	2.2	35	26.068	4.227
5. **May**	0.6	36.1	26.268	5.205
6. **June**	-2.2	36.4	25.977	6.399
7. **July**	-2.2	38.4	25.895	6.507
8. **August**	-0.2	37.6	26.342	5.34
9. **September**	1.4	35	26.749	3.756
10. **October**	2.6	32.6	26.232	3.121
11. **November**	-0.7	32.1	24.456	4.227
12. **December**	-4.9	31.7	22.723	5.748

Reclassifying water temperature values to zero for temperatures below 0 °C

Because the water temperature model (watemp.exe) has been adequately tested only for conditions where the water temperature exceeds 0 °C, the water temperature below 0 °C should be replaced with mean monthly air temperature. However, by isolating both the water temperature and the air temperature pixels < 0 °C it was found that the corresponding air temperature values for these water temperatures were also found to be < 0 °C. Moreover, by counting the number of pixels < 0 °C for each image it was found that on average each image had 0.002 percent of pixels < 0 °C (highest number of pixels < 0 °C was found in January with 0.007 percent).

The following sequence of GRID commands illustrates the procedure used to isolate and evaluate both the water and air temperature pixels which had values < 0 °C for the month of January:

```
watrmp1new = con (watmp1 > 0, 0, watmp1)
watmp1int = int (watmp1new)
buildvat watmp1int
setwatmp1 = setnull (watmp1 > 0, watmp1)
setmask setwatmp1
airmask1 = airtmp1
```

The AML **watemp_zero.aml** automates the procedure for months 1, 2, 6, 7, 8, 11 and 12. The rest of the months (3, 4, 5, 9 and 10) did not have values < 0 °C so they remained the same.

Because it was not possible to replace the water temperature vales < 0 °C for air temperature it was decided to reclassify these values to zero:

```
zwatmp1 = con ( watmp1 < 0, 0, watmp1),
```

where: zwatemp1 = reclassified water temperature values < 0 °C to zero for the month of January;
con = keyword for a condition statement in GRID; watmp1 = original water temperature grid.

The AML **reclass_zwatmp.aml** automates this procedure for all the moths (i.e. 1, 2, 6, 7, 8, 11 and 12).

Comparing mean monthly air and water temperature values

Results of the temperature ranges are presented in **Table 8.10**. Numbers in bold are those months for which the water temperature values < 0°C had to be substituted by a zero. The influence of annual wind velocity is also shown in this table by comparing the air temperature with the water temperature values.

Table 8.10 Mean monthly air and water temperature ranges. [°C]

MONTH	MINIMUM		MAXIMUM	
	Air	Water	Air	Water
1. January	**-8**	**0**	29.5	33
2. February	**-6.5**	**0**	31.5	33.3
3. March	-5	1.1	32.5	34.2
4. April	-5.5	2.2	33.5	35
5. May	-6	0.6	35	36.1
6. June	**-7.5**	**0**	36.5	36.4
7. July	**-8**	**0**	38.5	38.4
8. August	**-7.5**	**0**	37.5	37.6
9. September	-7	1.4	35	35
10. October	-6	2.6	32	32.6
11. November	**-6**	**0**	30	32.1
12. December	**-7**	**0**	29.5	31.7

Figure 8.17 shows the final mean monthly distribution of water temperature values.

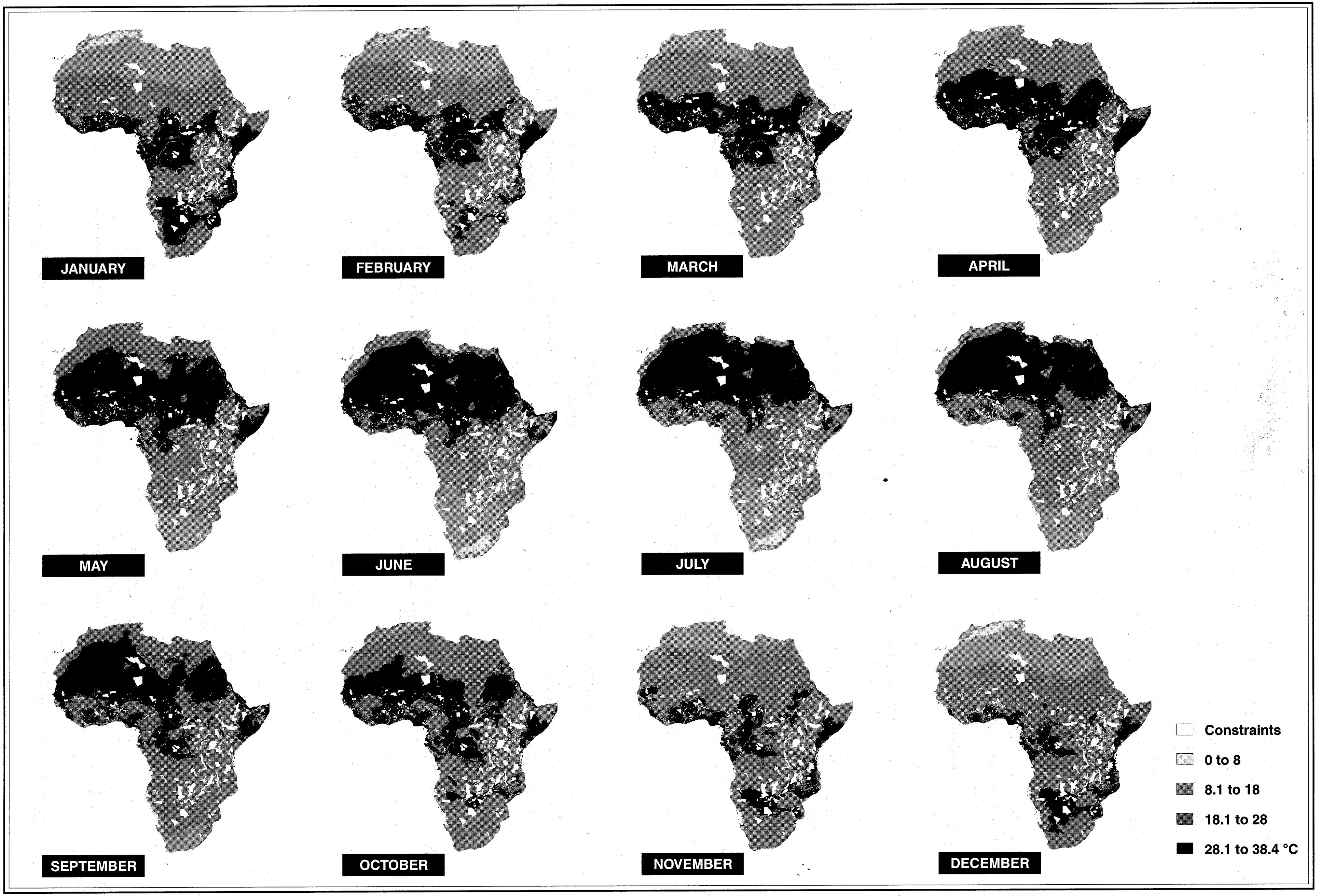


Figure 8.17 **Mean monthly water temperature**

8.8.4 Fish growth programmes

The physical suitability of the considered species was evaluated by two programs called FISHSIM.EXE (i.e. Common carp and African catfish) and TILAPIA.EXE (i.e. Nile tilapia) which both require, for input, the mean monthly temperature file (WATEMP.TXT). These programs match the water temperature of each cell location with the fish requirement database (NT-PARAM, PARAMS.DB, TILAPIA.DB and SPECIES.DB).

The "NT-PARAMS.DB" file contains the simulation parameters for Nile tilapia:

```
;Species,outfile,NatFeed,ArtFeed,feedLevel,fertCSC,feedCSC,Prot,Energy,InitWt,TargWt,SD, AnnMort
Tilapia,til-sub.txt, 1, 0, 0, 400, 3500, 25, 3.0, 25, 150, 10000, 0.8
Tilapia,til-com.txt, 1, 1, 75, 1000, 3500, 25, 3.0, 50, 300, 30000, 0.8
```

The first line is the header indicating the internal names of the parameters. The next two lines are for the commercial and subsistence runs for Nile tilapia. The relevant commercial and subsistence output files are til-com.txt and til-sub.txt.

The "PARAMS.DB" file contains the simulation parameters for Common carp and African catfish:

```
;Species,outfile,NatFeed,ArtFeed,feedLevel,fertCSC,feedCSC,Prot,Energy,InitWt,TargWt,SD, AnnMort
Carp,carp-sub.txt, 1, 0, 0, 300, 4000, 25, 2.8, 20, 250, 5000, 0.8
Carp,carp-com.txt, 1, 1, 75, 750, 3500, 25, 3.0, 50, 600, 20000, 0.8
Catfish,cat-sub.txt, 1, 0, 0, 300, 6000, 30, 3.2, 20, 250, 5000, 0.8
Catfish,cat-com.txt, 1, 1, 75, 750, 4000, 25, 3.0, 50, 600, 20000, 0.8
```

The first line is a header indicating the internal names of the parameters. The next two lines are for the commercial and subsistence runs for Common carp, the same for African catfish. The relevant commercial and subsistence output files are carp-com.txt, carp-sub.txt, cat-com.txt and cat-sub.txt.

The "TILAPIA.DB" file has the bioenergetic parameters for Nile tilapia:

```
Version = 1
;name, etc.......
Nile tilapia, 0.613243, 0.764879, 0.686799, 1.02518, 0.552739, 0.850645, 0.013882, 0.0166826
26, 0.0910785, 2.6, 0.902036
12.4413, 36.2529, 31.6559
1, 2, 1.5, 1, 0.05, 1, 1, 1, 1, 1, 1, 1, 1, 1
```

The "SPECIES.DB" file has the bioenergetic parameters for Common carp and African catfish:

```
Version = 1
;name, etc.......
Common carp, 0.552182, 0.863553, 0.670403, 1.12562, 0.542543, 0.718516, 0.0143931, 0.00228105
31, 0.0780699, 3.1, 0.857784
10.2565, 35.9885, 29.931
2, 10, 0.5, 0.5, 0.1, 1, 1, 1, 1, 1, 2, 8, 0.25, 0.5
African catfish, 0.604677, 0.790724, 0.673948, 1.09118, 0.479202, 0.808136, 0.0131722, 0.00974941
40, 0.105066, 3.6, 0.910912
10.9975, 36.1834, 29.3961
2, 10, 0.5, 0.5, 0.1, 1, 1, 1, 1, 1, 2, 8, 0.25, 0.5
```

From the run menu in Windows 95 the following commands were typed:

a) For Nile tilapia: tilapia.exe nt-params.db watemp.txt

b) For Common carp and African catfish: fishsim.exe params.db watemp.txt,

where: "watemp.txt" is the name of the relevant water temperature file.

Note: Data and programs are all contained within the same directory. SPECIES.DB and TILAPIA.DB are not typed in the dialog box of the run menu (section above), but they are used by their corresponding program during their execution.

At this stage, the programs automatically executed the scenarios indicated above, and created the corresponding output files:

Each output file contained the following data:

Longitude of the cell
Latitude of the cell
Number of crops per year
Yield in Kg/ha/year
Predicted feed requirements in Kg/ha/year

Note: It took the PC about 19 hours to run the FISHSIM.EXE programme and 12 for TILAPIA.EXE.

Changing the ASCII files (til-sub.txt, til-com.txt, cat-sub.txt, cat-com.txt, carp-sub.txt and carp-com.txt) to the format required by ARC/INFO
The QBASIC program **AIRTEMP.BAS (step 1.9)** was copied, renamed for each of the 6 txt files (carpcom.bas, carpsub.bas, catcom.bas, catsub.bas, tilcom.bas and tilsub.bas) and used to change the outputs of FISHSIM.EXE and TILAPIA.EXE to the format required by the ARC command ASCIIGRID.

Converting the output files of AIRTEMP.BAS to ARC/INFO GRIDS
The 12 output files were converted to UNIX format and then the ASCIIGRID command was used to convert ASCII files to GRIDS. The AML **airgrids.aml (step 1.10)** was copied, and renamed (**fishgrids.aml**) to automate this procedure:

```
&setvar 1 1
&do &while %1% < 13
 dos2unix watmp%1%.txt watmp%1%u.txt
 asciigrid watmp%1%u.txt watmp%1% float
 &setvar 1 [calc %1% + 1]
&end
&return
```

Reclassifying into four suitability classes
The fish yield grids were reclassified into 4 equal-interval classes (quarters) assigning number 1 to the lowest range and 4 to the highest. Values assigned with a zero representing no crops retained the zero value. Example for small-scale fish yield of Common carp:

Grid: re_cpsub1 = slice (cpsub1, table, remap_psub1),

where: re_cpsub1 = reclassified grid; slice = GRID command to reclassify real numbers; cpsub1 = original grid; table = part of slice GRID command; re_cpsub1 = lookup table for reclassification.

```
remap_cpsub1:  0     0   : 0
               0     0.6 : 1
               0.6   1.1 : 2
               1.1   1.6 : 3
               1.6   2.2 : 4
```

8.8.5 Fish growth models (by Shree S. Nath)

This appendix briefly summarizes refinements that have been made to the fish growth simulation model used to assess inland aquaculture potential in Latin America (Kapetsky and Nath, 1997). Additional details regarding the original model can be found elsewhere (Nath, 1996). The refined model has been incorporated into POND Version 4.0, the decision support system developed at the Department of Bioresource Engineering, Oregon State University.

Model structure

The fish bioenergetics model used by Kapetsky and Nath (1997) considered the effects of fish size, food availability, photoperiod, and temperature on growth performance. This model was refined in the current study to address the effects of (i) high fish biomass, and (ii) feed type (moisture, protein and energy contents) and feeding levels on fish growth.

High biomass effects on fish growth in fed ponds

It is known that fish growth may often be reduced in fed ponds that have a high fish biomass (Hepher, 1988). The actual mechanisms by which these effects occur include deterioration of water quality and behavioral changes, neither of which can be adequately addressed without adding substantial complexity to the structure of the bioenergetics model. The alternate approach used in the current study involves the definition of a species-dependent parameter, the critical fish biomass (CFB_{feed}) which is the standing crop below which growth is not adversely affected in fed ponds. To account for high fish biomass (FB) effects, daily fish growth rate (g d^{-1}) calculated in the bioenergetics model (Kapetsky and Nath, 1997) is multiplied with a biomass scaler (B; 0-1) given by:

$$B = \begin{cases} 1.0, & \text{if } FB < CFB_{feed} \\ CFB_{feed}/FB, & \text{if } FB \geq CFB_{feed} \end{cases} \quad (1)$$

Effects of feed type and feeding levels on fish performance

A fundamental assumption of the earlier version of the fish bioenergetics model (Nath, 1996; Kapetsky and Nath, 1997) was that the composition of fish and their diet is identical. This assumption has its roots in Ursin's (1967) growth model, which is the basis of our work in the area of fish bioenergetics. However, to adequately account for the effects of supplemental feeds of different quality (primarily moisture, protein and energy contents) on fish performance, it is necessary to remove the above assumption. Further, the bioenergetics model used by Kapetsky and Nath (1997) assumed that the digestibility coefficient is constant. In reality, this parameter varies with fish feeding levels (Meyer-Burgdorff, Osman and Gunther, 1989). In this section, we discuss changes made to the bioenergetics model (Kapetsky and Nath, 1997) to account for the effects of the above variables.

Moisture Content: In the present version of the bioenergetics model, the ratio of the dry matter content of fish (DM_{fish}; g dry matter per g fish) to that of feed (DM_{feed}; g dry matter per g feed) is used to adjust the daily ration (R; g feed per day) for differences in moisture content between fish and the feed material supplied. The expression used is:

$$R = \frac{W f_s}{q} \times \frac{DM_{fish}}{DM_{feed}} \quad (2)$$

where W = fish mass (g), f_s = fraction of the diet that comprises artificial feed, and q = feed quality coefficient.

Protein content: According to Hepher (1988), dietary protein (d_p expressed on a % dry matter basis) does not affect fish growth if it is above a critical level (P_{crit}) that is species dependent. As dietary protein level reduces from P_{crit}, growth drops off at an increasing rate. The following protein scaler (P_s; 0-1) used in the current study captures this effect:

$$P_s = 1.0 - \exp[p_1 d_p] \quad (3)$$

where p_1 is a parameter that controls the rate at which P_s changes as d_p decreases.

Energy content: A similar approach to the one for protein is used in the bioenergetics model to account for situations where dietary gross energy drops below a critical level (E_{crit}; kcal g^{-1}) that is again species dependent. The corresponding equation is as follows:

$$E_s = 1.0 - \exp[\,p_2\ d_e\,] \qquad (4)$$

where E_s = energy scaler (0-1), and p_2 is a parameter that controls the rate at which E_s changes as the gross dietary energy d_e (kcal g^{-1}) decreases.

It is difficult to evaluate growth response to diets that are sub-optimal in both protein and energy contents. For simplicity, we assume that when both protein and energy are below the respective critical levels required by the species, the scaler that is most limiting reduces the anabolic term in the bioenergetics model (see Kapetsky and Nath, 1997 for additional details regarding estimation of the anabolic term.).

Feeding levels and digestibility: It is well established that the digestibility (b) of food decreases as the amount consumed by fish increases (Hepher, 1988; Meyer-Burgdorff, Osman and Gunther, 1989). In the present bioenergetics model, we assume that digestibility decreases linearly with increasing levels of feeding (from maintenance to full satiation). The slope (e) of this relationship is estimated as follows (**Figure 8.18**):

$$e = \frac{(b_{max} - b_{min})}{(1.0 - f_{maint})} \qquad (5)$$

where b_{max} = maximum digestibility coefficient (assumed to occur at a maintenance ration), b_{min} = minimum digestibility coefficient (at satiation), and f_{maint} = feeding level parameter in the bioenergetics model (Kapetsky and Nath, 1997) corresponding to a maintenance ration. Once the slope *e* from Equation 5 is estimated, the actual digestibility coefficient is obtained as follows:

$$b = b_{max} - e\,(f - f_{maint}) \qquad (6)$$

where f = feeding level parameter (0-1) for the actual feeding rate.

Model calibration and validation

In order to use the revised bioenergetics model (i.e., including equations 2-6), it was necessary to estimate six new parameters (i.e., P_{crit}, E_{crit}, p_1, p_2, b_{max} and b_{min}), in addition to the previous one in the fish bioenergetics model (Kapetsky and Nath, 1997). Among the six parameters, P_{crit} and E_{crit} were adapted from bioenergetic studies with different species as synthesized by Hepher (1988). The other four new parameters were added to an automatic model calibrator (Nath, 1996), which estimates appropriate values by the use of an adaptive, non-linear search algorithm in conjunction with experimental data from pond trials.

A listing of the 15 parameters estimated for the three fish species in this study is provided in **Table 8.11**. Data sources and model performance for each of the species are discussed below.

Nile tilapia
A large number of datasets appropriate for model calibration and validation was collected for this species. Consequently, calibration of the energetics model for this species was accomplished across several sites and different production systems, ranging from a small-scale fertilized system in Ghana to intensely fed ponds in Thailand (**Table 8.12**). Parameters estimated for this species (**Table 8.11**) resulted in fairly good predictions of Nile tilapia growth at all the sites (**Table 8.12**). Model predictions are compared to observed data for two of the sites (Rwanda and Honduras) in **Figure 8.19**.

Model fits were not as accurate as those obtained with the previous version of the energetics model (Nath, 1996), presumably because the current study focused on generating a set of Nile tilapia growth parameters that would result in reasonable predictions at different geographical locations. This is in contrast to our previous study (Kapetsky and Nath, 1997) where model calibration for Nile tilapia was confined to only one site (El Carao, Honduras).

African catfish
Calibration for this species was accomplished by the use of growth data from sites in South Africa and the Central African Republic (CAR) (**Table 8.12**). Although growth predictions for both sites are quite good (**Figure 8.20**), there appears to be a slight tendency towards over-prediction of final fish weights (**Table 8.12**). This is particularly noticeable for the CAR simulation run, and appears to be due, in part, to a sharp reduction in observed fish weights from the expected growth profile (De Kimpe and Micha, 1974). Such departures are not uncommon in pond experiments and have been attributed to biases in sampling methods (Hopkins, 1992). It is difficult to account for such biases during calibration of the energetics model used herein without extensive knowledge and familiarity with actual experimental protocols.

Independent validation was not conducted for African catfish because only two datasets that were complete in terms of fish growth, temperature and feeding/fertilization data could be identified. These were both used for model calibration in order to generate a set of parameters that would reflect growth performance of this species at geographically different locations.

Common carp
The energetics model for this species was calibrated with data from Poland primarily because only one complete growth dataset for this species could be identified for African conditions. This dataset was reserved for model validation. Model performance was excellent for the two sites in Poland and South Africa (**Figure 8.21**; **Table 8.12**). It is expected that good predictions would be obtained at other locations as well because the above two locations are very diverse particularly in terms of ambient water temperatures.

Summary

A previously developed energetics model (Nath, 1996) was refined to include the effects of high fish biomass, feed types and feeding levels on growth performance of pond fish. Calibration and validation for three target fish species (Nile tilapia, African catfish and Common carp) was also successfully accomplished. In contrast to calibration procedures used previously that involved fitting the model to growth data for one location, we estimated parameters for the refined model across different sites. This approach is expected to result in better projections of fish growth for all three fish species, under different geographical conditions in the African continent.

Table 8.11 Best-fit growth parameters estimated for Nile tilapia, African catfish and Common carp.

PARAMETER	Nile tilapia	African catfish	Common carp
Anabolism Parameters			
Efficiency of assimilation at maintenance ration (b_{max})	0.6132	0.6047	0.5522
Efficiency of assimilation at satiation (b_{min})	0.7648	0.7907	0.8636
Anabolism exponent (m)	0.6868	0.6739	0.6704
Food consumption coefficient (h)	1.0252	1.0912	1.1256
Optimum protein level (P_{crit})	26.0	40	31.0
Optimum energy level (E_{crit})	0.0911	0.1051	3.1
Controlling parameter for protein (p_1)	2.6	3.6	0.07807
Controlling parameter for energy (p_2)	0.9020	0.9109	0.8578
Catabolism Parameters			
Feeding catabolism coefficient (a)			
Catabolism exponent (n)	0.5527	0.4792	0.5425
Minimum catabolism coefficient (k_{min})	0.8506	0.8081	0.7185
Temperature parameter (s)	0.0139	0.0132	0.0144
	0.0167	0.0097	0.0023
Temperature Scalers			
Minimum (T_{min})			
Maximum (T_{max})	12.4	11.0	10.3
Optimum (T_{opt})	36.3	36.2	36.0
	31.7	29.4	29.9

Source: Verheust, Rurangwa and Veverica (1991).

Table 8.12 Summary of model calibration and validation results for the three species chosen for analysis.

Fish Species	Site	Data Source	Production System	Stocking Density (fish m^{-2})	Final Fish Weights (g) Observed	Final Fish Weights (g) Predicted	Percent Relative Error[a]
Calibration							
Nile tilapia	Mampong, Ghana	1	Semi-intensive (fertilized)	3.0	152.5	176.7	+15.9
	Butare, Rwanda	2	Semi-intensive (fertilized & fed)	1.0 3.0	269.4 206.6	285.1 214.1	+5.8 +3.6
	El Carao, Honduras	3	Semi-intensive[b] (fertilized & fed)	1.0[b] 1.0[c]	276.4 258.4	304.8 278.3	+10.3 +7.7
	AIT, Thailand	4	Intensive (fertilized & fed)	3.0	447.3	455.6	+1.9
African catfish	East London, S. Africa	5	Semi-intensive (fertilized)	0.06	782.5	801.8	+2.5
Common carp	Bangui, Central African Republic	6	Semi-intensive (fed)	2.0	540.0	584.3	+8.2
	Golysz, Poland	7-9	Semi-intensive (fed)	1.0[d] 0.4[e]	400.0 920.0	400.2 884.4	+0.05 -3.9
Validation							
Nile tilapia	Butare, Rwanda	2	Semi-intensive (fertilized & fed)	2.0	220.7	251.8	+14.1
	El Carao, Honduras	3	Semi-intensive (fertilized) Semi-intensive (fertilized & fed)	1.0[f] 1.0[g]	206.4 256.5	200.2 284.4	-3.0 +10.9
Common carp	East London, S. Africa	5	Semi-intensive (fertilized)	0.15	516.8	541.1	+4.7

Notes: [a] Calculated as [(P - O)/O] * 100, where P and O are the final predicted and observed weights (g) respectively.
[b] Treatment involved fertilization with chicken manure for one month followed by feeding for four months.
[c] Treatment involved fertilization with chicken manure for three months followed by feeding for two months.
[d] Growth data are for 1-2 year old carp.
[e] Growth data are for 2-3 year old carp.
[f] Treatment involved fertilization with chicken manure for five months.
[g] Treatment involved fertilization with chicken manure for two months followed by feeding for three months.

Data Sources: 1. Ofori, Asamoah and Prein (1996) and M. Prein (ICLARM, pers. commn.); 2. Verheust, Rurangwa and Veverica (1991) and L. Verheust (ALCOM, pers. commn.); 3. Teichert-Coddington *et al.* (1991); 4. Diana, Lin and Yi (1995); 5. Bok and Jongbloed (1984); 6. De Kimpe and Micha (1974); 7. Szumiec (1979a); 8. Szumiec (1979b); 9. Szumiec and Szumiec (1985).

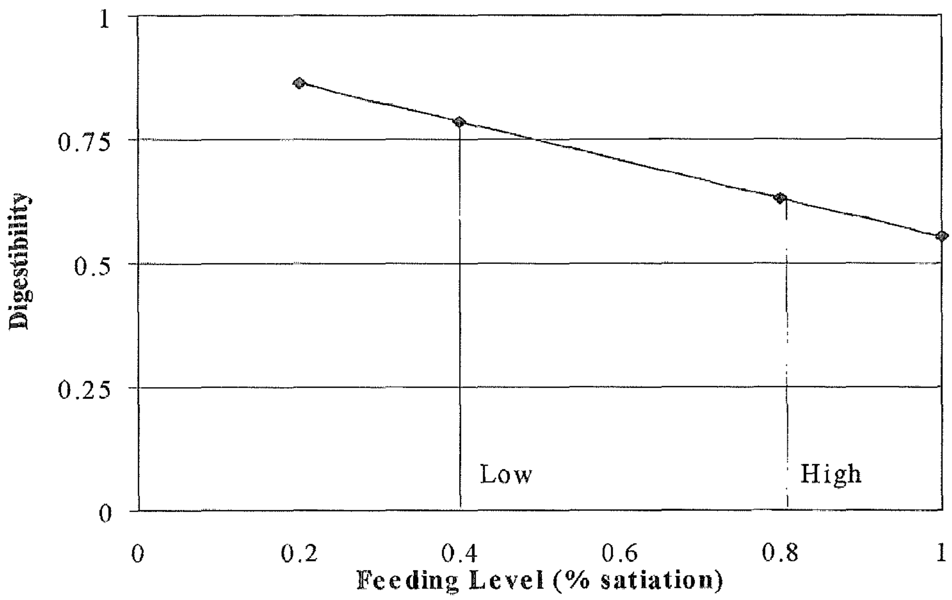


Figure 8.18 Relationship between digestibility and ration size ranging from a hypothetical maintenance ration to a maximum amount at full satiation. Digestibility values for a low (40% satiation) and a high (80% satiation) ration are also indicated

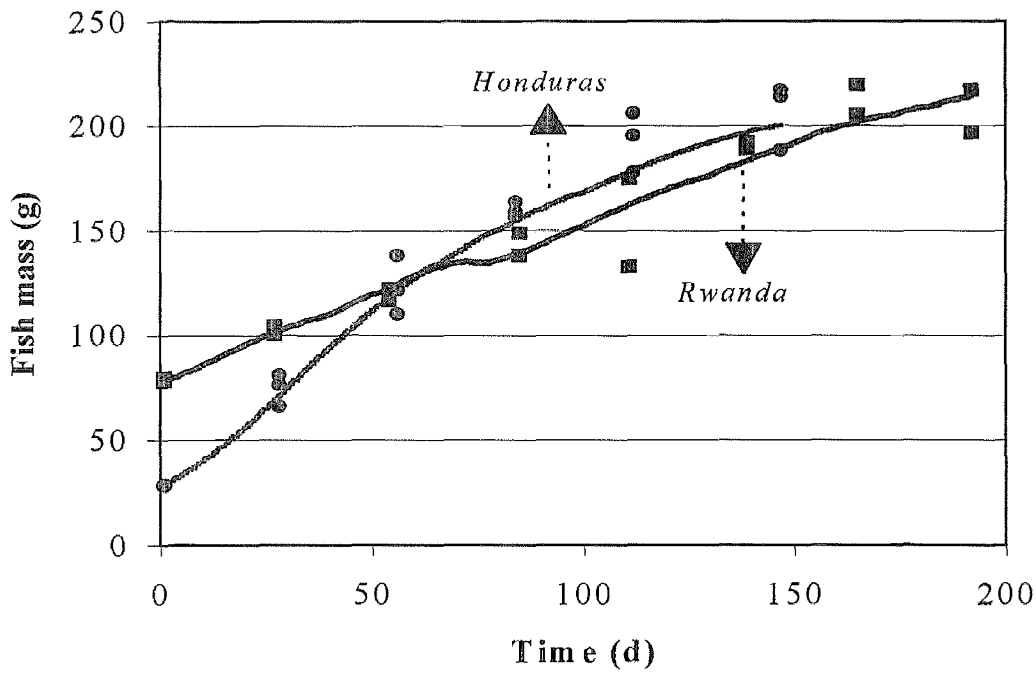


Figure 8.19 Calibration and validation results for Nile tilapia. Observed data for the former are for the two replicates of the treatment in Butare, Rwanda, wherein the stocking density was 3 fish m^{-2} (Verheust, Rurangwa and Veverica, 1991; see also Table 8.12). Observed data for model validation are for the three replicates of the chicken manure only treatment in El Carao, Honduras (Teichert-Coddington *et al.*, 1991; see also Table 8.12)

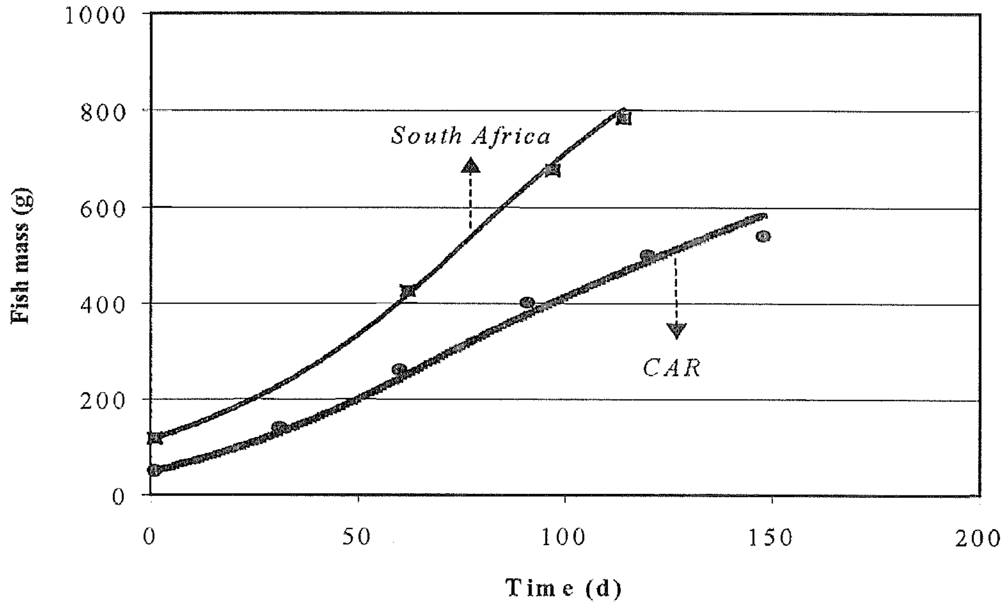


Figure 8.20 Calibration results for African catfish (see also Table 8.12). Observed data are from East London, South Africa and Bangui, Central African Republic (CAR)

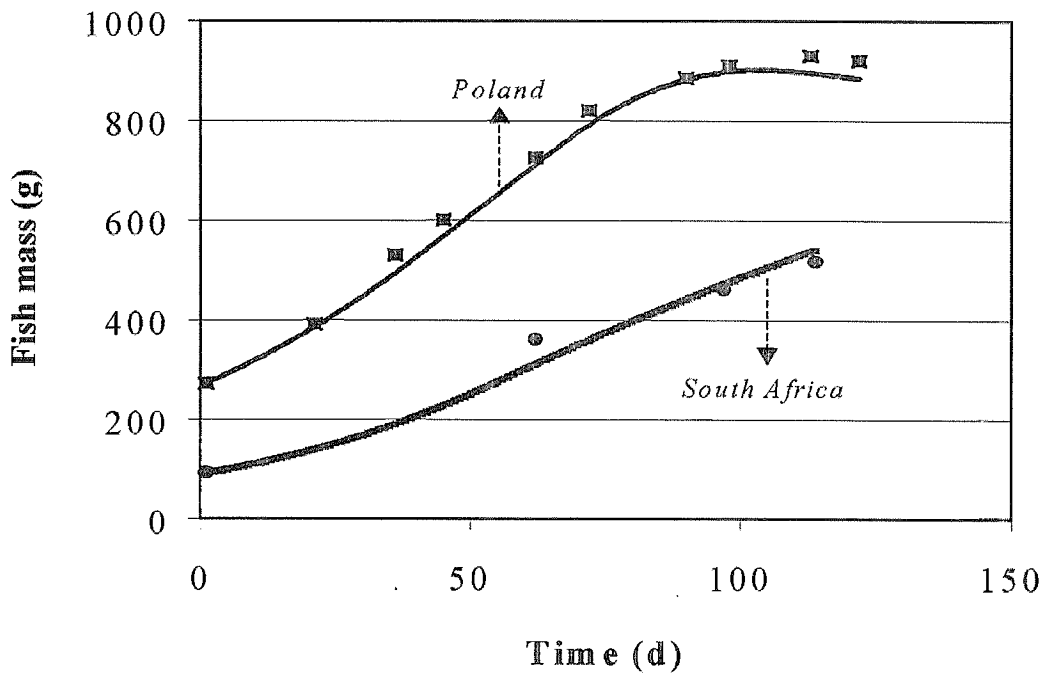


Figure 8.21 Calibration and validation results for common carp. Observed data for the former are for 2-3 year old fish in Golysz, Poland, whereas those for model validation are from East London, South Africa (see alsoTable 8.12)

8.9 MODELS

8.9.1 Farming system models

Two models, based on multiple criteria analysis, were developed for the fish farming potential assessment:

a. Small-scale fish farming
b. Commercial fish farming

Inputs for the small-scale fish farming model were:

- Water requirement
- Soil and terrain suitability for ponds
- Inputs
- Farm-gate sales for aquaculture

Inputs for the commercial fish farming model were:

- Water requirement
- Soil and terrain suitability for ponds
- Inputs
- Farm-gate sales for aquaculture
- Urban market size and proximity

Standardisation and thresholds

Input criteria were evaluated in terms of suitability by assigning scores to the pixel values. A standard classification was applied to the layers used by the two models:

4 = Very suitable
3 = Suitable
2 = Moderately suitable
1 = Unsuitable

Small-scale model fish farming model

The formula was the following:

small = (waterlos_sl * 0.30) + (soilslope_sl * 0.13) + (byprod_sl * 0.04) + (farmgate_sl * 0.07) + (mkgrd_sl * 0.46)

Commercial model fish farming model

This grid was produced using the following formula:

comer = (waterlos_sl * 0.56) + (soilslope_sl * 0.26) + (byprod_sl * 0.12) + (farmgate_sl * 0.06)

where: waterlos_sl = water requirement; soilslope_sl = soil and terrain suitability for ponds; byprod_sl = potential for inputs; farmgate_sl = farm-gate sales; mktgrd_sl = urban market size and proximity.

8.9.2 Small-scale and commercial farming system models combined with fish yields

Integrating the models

The small-scale fish farming grid (**small**) was combined with the fish yield outputs for Nile tilapia (tilcom1), African catfish (catcom1), and Common carp (cpcom1) and the commercial grid (**comer**) was combined with the fish yield outputs for Nile tilapia (tilsub1), African catfish (catsub1), and Common carp (cpsub1).

The following procedures were used for grid combinations:

a) The grids small and comer were each multiplied by a factor of ten:

Grid: 10small = small * 10

Grid: 10comm = comer * 10

b) The grids were added to the fish yields:

Grid: md_tilsub1 = (10small + tilsub1)

Grid: md_tilcom1 = (10comm + tilcom1)

Grid: md_catsub1 = (10small + catsub1)

Grid: md_catcom1 = (10comm + catcom1)

Grid: md_cpsub1 = (10smal + cpsub1)

Grid: md_cpcom1 = (10comm + cpcom1)

The VALUE of the output grids created was a two digit integer in which the first digit indicated the class of the commercial model and the second the class of yield in terms of crops/y for each fish species.

c) The grids were re-classified to exclude those areas of no coincidence. Example for small-scale farming of tilapia.

Grid: rm_tilsub1 = reclass(md_tilsub1, remap_tilsub1),

where: rem_tilsub1 = reclassified image and remap_tilsub1 = table which assign the values to re-classify).

8.9.3 Coincidence of farming system models and fish yield suitability for the three fish species

Small-scale fish farming

a) Grid: smallcoi = (md_catsub1) + (md_cpsub1 * 10,000) + (md_tilsub1 * 100)

The VALUE of the output grid created was a six digit integer in which the first two digits indicate the class of grid md_catsub1; the second two digits indicate the class of grid md_cpsub1, and the last two digits indicate the class for md_tilsub1.

b) The grids were re-classified to exclude those areas of no coincidence.

Grid: smallcoi_sl = reclass(smallcoi, remap_smallcoi)

Commercial farming

Same procedure as for small-scale farming was followed:

a) Grid: comercoi = (md_catcom1) + (md_cpcom1 * 10,000) + (md_tilcom1 * 100)

b) Grid: comercoi_sl = reclass(comercoi, remap_comercoi)

8.10 VERIFICATION

8.10.1 General verification

Verification by existing fish farm locations

a) Creating the point features
Lat/Long locations of existing fish farms for Zimbabwe and Kenya were added to a coverage. The Arc module GENERATE was used to add features to a coverage and the coordinates of each feature were entered from a file:

Zimbabwe:
Arc: generate z1farms
Generate: input z1farms.txt
Generate: points

Note: Coverage located in the directory: /pepe57/verify/zimbabf/

where: generate = Arc module to create coverages; z1farms = output cover for farm number one; z1farms.txt = file containing Lat/Long coordinates of farm number one; points = feature cover type.

The same procedure was applied to Kenya, and those coverage's are located in the directory: /pepe57/verify/kenyaf/.

b) Verification
To obtain the suitability score from each one of the farm sites, the point cover created with the generate command (above) was plotted over each of the resulting suitability grids. The suitability score was obtained from each grid cell site where a farm was located. Example of verification procedure for the water requirement suitability grid:

Grid: grids waterlos_sl
Grid: points z1farms
Grid: cellvalue waterlos_sl *

where: waterlos_sl = water requirement grid; z1farms = coverage containing Lat/Long location for farm number one; cellvalue = Grid command to query the grid value.

Verification by number of farms at a county-level

a) Digitizing
Arua counties were digitized from a paper map (Department of Lands and Surveys, 1986). A detailed description of the methodology (10 pages) is provided in the document called **digit.doc** located in the directory /sun2disk5/faogis7/pepe57/digit/ of SUN 2.

b) Verification
The grid file that contains all counties in Arua district was converted into an equal area projection, and then statistical data was extracted following the same procedure described in Appendix 8.11 for grid files.

8.10.2 Water temperature verification

Country grids and verification

Grids for Zimbabwe, Kenya and Malawi were extracted (i.e. by means of reclassifications) from the grid AFBOUNDARY which contains all the country areas. Each of the country grids (i.e containing only a value of one) were then multiplied to each one of the water temperature grids and then, the statistical water temperature data were extracted:

Grid: watmp1 * zimbabwe
INFO> SEL ZWATMP1.STA

where: watmp1 = water temperature grid for January; zimbabwe = zimbabwe grid (i.e. grid with a value of one); SEL ZWATMP1.STA = INFO syntax to extract statistical data; ZWATMP1.STA = water temperature grid for Zimbabwe for January.

8.11.1 Questionnaire

The concordance coefficient W is based upon the following hypothesis:

HO: The m sets of rankings are not associated;
H1: The m sets of rankings are associated and are derived using the following formula:

$$W = \frac{\sum_{j=1}^{n=1} 12\, Rj^2 - 3m^2\, n\, (n+1)}{m^2\, n\, (n^2 - 1)}$$

where: W...Kendall coefficient of concordance;
Rj....sum of the ranks assigned;
m....number of sets of rankings;
n.....number of individuals.

When the observed sets of rankings were in close agreement , *W* was large (close to one); conversely, when the agreement was poor *W* was close to zero. Therefore large values of *W* rejected HO. Furthermore, it was possible to compute: $X^2 = m\,(n-1)\,W$, and compare it with the value of ***chi:*** $\chi^2 = (n-1)$. If the X^2 was larger than ***chi***, rankings were associated and therefore there was an agreement.

High or significant values of *W* were interpreted as meaning that the decision-makers were essentially applying the same standard in ranking the factors under study. However, a significant value of *W* did not necessarily mean that the orderings observed were "correct". In fact, they may all be incorrect with respect to some external criterion (Siegel, 1965). It is possible that a variety of decision-makers can agree in ordering objects because they all employ the "wrong" criterion. In this case a high or significant *W* would simply show that all more or less agree in their use of a "wrong" criterion. To solve this problem Kendall (1984a) suggests that the best estimate of the "true" ranking when *W* is significant is provided by the order of the various sums of ranks, Rj.

A programme was created in MINITAB for Windows to automate the use of the formula above. However, a less simplified version of this formula was used because it was better suited for programming in MINITAB.

Simplified version of the Kendall coefficient of concordance formula:
If n items are ranked by *m* judges, and X_{ij} denotes the rank number given to the i^{th} item by the j^{th} judge, then Kendall's concordance is represented by:

$$S_w = \sum_{i=1}^{n} (X_i - 1/2\, m\, (n+1))^2,$$

where: $X_i = \sum X_{ij}$ is the total of the *m* ranks given to the i^{th} item and $m(n+1)$ is the mean of the X_i. The maximum of value of S_w is $m^2\,(n^3 - n)\,/\,12$, representing perfect agreement between judges.

$$\mathbf{W} = 12\, S_w \,/\, m^2\, (n^3 - n)$$

For details about this formula see: Greenwood and Hartley (1962).

MINITAB programme that automates the use of the Kendall Coefficient of concordance formula:

```
#  file: kendal.MTB
noecho          # turn screen output off
note
note
note        This Minitab Macro calculate Kendal coefficient
note            of concordance (W) statistic
note
note
note        Assume the data are stored in columns c1-c50
note
note
note    Enter the number of sets of rankings (m)
set 'terminal' c51;
nobs 1.
copy c51 k51
note
note    Enter the number of ranked objects (n)
set 'terminal' c51;
nobs 1.
copy c51 k52
note
note
note            Calculating the W statistic
note
note                Please Wait
note
#
#
let k53=k51+1
RSum c1-ck51 ck53                   # Calculate row sums
#
let k54=k53+1
#
let k55=0.5*k51*(k52+1)
let k56=sum((ck53-k55)**2)          #Calculates S_w=sum of (RowSums-0.5*m*(n+1))^2
note The S_w is
print k56
let k57=(k51*k51)*k52*((k52*k52)-1)  #m*m*n*(n*n-1)
let k58=(12*k56)/k57                #W statistic
                                    #(12*S_w)/(m*m*n*(n*n-1))
note The W-statistic is
print k58
#
let k59=k51*(k52-1)*k58             # Calculate test statistic and refer it to
                                    # a chi-square distribution with (n-1) df
note The equivalent chi-square test statistic is
print k59
#
let k61=k52-1                       # Calculate the degree of freedom
invcdf 0.95 k60;                    # At 5% significance level
chis k61  .                         # chi-square critical value
note At 5% Significance level, the chi-square critical value is:
print k60
```

8.11.2 GIS analysis

Converting grids to an equal-area projection

The result grids were converted to an equal-area projection (Flat Polar Quartic) to calculate the areas covered by each class in each country of Africa.

The grid AFBOUNDARY, which contains the country boundaries (i.e. areas) was converted to an equal area projection and was named COUNTRYGRD_PQ. The VALUE of the later grid is the country code. This grid was overlaid on the various themes in order to produce the statistics by country.

Arc: project grid afbounday countrgrd_pq

To convert grids to Flat Polar Quartic projection the parameters specified in the file **llpolq.prj** illustrated below were used:

```
INPUT
PROJECTION GEOGRAPHIC
UNITS DD
PARAMETERS
OUTPUT
PROJECTION FLAT POLAR QUARTIC
UNITS METERS
PARAMETERS
00 00 00
end
```

Combining grids

a) Combining COUNTRYGRD_PQ with the result grids.

The following is an example for the water loss grid:

Grid: cnwaterlos = combine(countrygrd_pq, waterlos_pq),

where: cnwaterlos = combined grid; combine = GRID command; countrygrd_pq = African country boundaries in flat polar quartic; waterlos_pq = water loss grid in flat polar quartic.

Adding the country names

a) The country name item (CNTRY_NAME) was added to the new grid:

Arc: additem cnwaterlos.vat waterlos.vat cntry_name 40 40 C

Where: 40 40 C indicate the number of words to be used in the country name item.

b) Adding the country names:

To add the country names according to the country values in COUNTRYGRD_PQ in the country item (CNTRY_ITEM) the AML **cnnames.aml** was used:

```
Arc: tables
Enter command: SEL CNWATERLOS.VAT
Enter command: &r cnnames.aml
```

Creating the text file

```
Arc: INFO
ENTER COMMAND  >SEL CNWATERLOS.VAT
ENTER COMMAND  >OUTPUT ../CNWATERLOS.TXT
ENTER COMMAND  > DISPLAY VALUE,',',COUNT,',',CNWATERLOS_PQ,',',COUNTRYGRD_PQ
,',',CNTRY_NAME  PRINT
```

Manipulating text files in EXCEL

a) The text files were imported into EXCEL

b) To calculate the areas of each class occurring in the countries, the number of cells (COUNT) was multiplied by the square of the cell size in kilometers (5.930642 * 5.930642).

c) Percentage areas were calculated from each class for each country.

d) Results were plotted using histograms.

File names
For clarity, Grid and file names were coded in such a way that names portray the essential information about the contents of the grids.

Models and statistics

Grids

Digits	Content	Meaning
Digits 1 - 3	md_	Model
	rm_	Reclassified grid
Digits 4 - 6	til	Tilapia
	cat	Catfish
	cp	Carp
Digits 7 - 9	sub	Small-scale fish farming
	com	Commercial fish farming
Digits 10	1	Crop/year

8.12 GRID OUTPUTS

8.12.1 Single or annual grids

The procedures used to create map compositions of single or annual grid files are illustrated below using the water requirement grid as an example:

Standardising the grid to a common colour range
For purposes of analysis and/or illustration, the single or annual grid files had to be reclassified to a common colour range. The following example is illustrated for mean annual wind velocity:

cwater = reclass (water, water.rem)

where: **cwater** = reclassified grid file; reclass = GRID function to reclassify (or change) integer values of the input cells using a remap table on a cell-by-cell basis within the analysis window; water = original water requirement grid; water.rem = remap table.

The remap table water.rem is shown below:

```
>0 : 1
-2,000 -1 : 2
-2,000 -3500 : 3
> -3500 : 4
```

Preparing the grid file for plotting
Preparing the keyshade.

To create the colour range legends in accordance to the remap table water.rem above the text file **water.txt** was created:

```
.1
>0
.2
-2.000 -1


> -3500 mm
```

AML to plot the grid
The AML **water.aml** illustrated below was used in ARCPLOT to generate a map composition **water_mc** for the water requirement grid:

```
killmap zwaterlos_mc
mape /sun2disk5/faogis7/pepe57/tiff/gratfin
shadeset pepe4
pagesize 8.3 11.7
gridnodatasymbol white
mapposition cen cen
mapscale automatic
map zwaterlos_mc
linesymbol 5
box 0.1 0.1 8.2 11.6
linesymbol 1
box 0.14 0.14 8.16 11.56
gridshades /sun2disk5/faogis7/pepe57/tiff/main/zwaterlos # remap_num
linecolor black
arcs /sun2disk5/faogis7/pepe57/general/afcntall
mape /sun2disk5/faogis7/pepe57/tiff/gratfin
arcs /sun2disk5/faogis7/pepe57/tiff/gratfin
textset font
textsymbol 1
textsize 2.0
annotext /sun2disk5/faogis7/pepe57/tiff/gratfin
textset font
textsymbol 1
textsize 0.13
```

```
keyposition 0.85 5.9
shadeset pepe4
keybox 0.15 0.1
keyseparation .13 .14
keyshade suitable.txt
move 1.2 1.2
textset font
textsymbol 1
textsize 0.15
text 'Figure 3.2 Net annual water requiremebnt for ponds'.
shadeset colornames
maplimits 6 0.5 7.8 3
MAPLIMITS 0.0 0.0 8.3 11.7
```

Note: The AML **water.aml** was used for all criteria (e.g. soils, inputs, farm-gate sales, mean annual wind velocity,) and only some elements (i.e. reclassification AML's, remap tables and keyshades) needed to be changed for each criteria according to their range of values.

In cases where the input grid values were real the " SLICE" GRID function was used (e.g. net annual water requirement) and in cases where the input values were integers the "RECLASS" GRID function was used (e.g. mean annual wind velocity).

8.12.2 Monthly grids

The procedures used to create map compositions of monthly grids for precipitation, potential evapotranspiration, water requirement, air temperature, water temperature, are illustrated below using the precipitation grids as an example:

Standardising grids to a common colour range

Most of the grids created had a large number of values, so it was necessary to reduce this number to facilitate interpretation and analyses. The following example illustrates how one of the GRID files for precipitation was reclassified:

crain1 = reclass (rain1, rain1.rem)

where: **crain1**= reclassified precipitation grid for the month of January; reclass = grid function to reclassify the values of the input cells by specified ranges; rain1.rem = remap table.

Note: The remap tables used were ASCII files specifying which values were changed, and to what output value.

A GRID AML **rerain** automates this procedure for all monthly precipitation grids by repeating the command above for each one of the GRID files.

The remap table rain.rem is shown below:

```
  0  200 : 1
201  400 : 2
401  600 : 3
601  830 : 4
```

Note: First two columns correspond to the original value ranges and the third column corresponds to the shadeset rainbow colour range.

Preparing grids for plotting

a) Generating a stack from the 12 monthly precipitation GRID files.

To group (or stack) the 12 monthly grids, the GRID command MAKESTACK was used:

Grid: makestack **rainstack** list crain1 crain2 crain3 crain4 crain5 crain6 crain7 crain8 crain9 crain10 crain11, crain12

where: makestack = GRID command; rainstack = name of the output stack; list = keyword indicating that the grids to be used to generate the stack will follow on the input command line; crain1 to crain12 = names of input grids that make up the stack.

b) Preparing the keyshade

To create the colour range legends in accordance to the remap table **rerain** above the text file **rain.txt** was created. Note that the constraints were assigned a value of 27.

```
.27
Constraints
.1
0 - 200
.2
201 - 400
.3
401 - 600
.4
601 - 830 mm
```

AML to plot the monthly grid files

The AML **rain.aml** illustrated below was used in ARCPLOT to generate a single map composition **rain_mc** for the 12 mean monthly precipitation grid files:

```
killmap rain_mc
shadeset grey5
pagesize 11.7 8.3
maplimits 0.8 0.8 11.0 8.0
gridnodatasymbol white
map position ll ll
map rain_mc
linesymbol 5
box 0.1 0.1 11.6 8.2
linesymbol 1
box 0.14 0.14 11.56 8.16
shadeset grey5
stackshade /sun1disk3/faogis3/waba/rainstack
move 5.0 .3
textset font
textsymbol 1
textsize 0.15
text 'Figure 8.1 Mean monthly precipitation'
move 1 5
textset font
textsymbol 1
textsize 0.14
keyposition 10.3 1.6
shadeset grey5
keybox 0.15 0.1
keyseparation .13 .14
keyshade rain.txt
```

Note: The AML **rain.aml** was used for all criteria (i.e. precipitation, potential evapotranspiration, water requirement, air temperature and water temperature,), and only some elements (i.e. reclassification AML's, remap tables, stacks and keyshades) needed to be changed for each criteria according to their range of values.

In cases where the input grid values were real the " SLICE" GRID function was used (i.e. air temperature, water temperature and water requirement) and in cases where the input values were integers the "RECLASS" GRID function was used (i.e. precipitation and potential evapotranspiration).

8.12.3 Shadesets and postscript files

Shadesets

Three palettes (shadesets) were created to represent the result grids. The first shadeset named **pepe4.shd (Table 8.13)** was used to represent the colour range for those grids used in the farming system models and the fish growth model which contained 5 or 6 values. The shadeset **pepe44.shd** was used for the combined models and coincidence grids. The third shadeset, **grey5.shd** was used to illustrate all maps in the appendix. Shadesets were created using the SHADEEDIT command in ARCPLOT.

Table 8.13 Shadesets created for the present study.

	ID	RED	GREEN	BLUE
pepe4	27	0	0	0
	0	130	130	130
	1	0	0	255
	2	255	0	0
	3	255	255	0
	4	0	190	0
pepe44	27	0	0	0
	11	220	220	220
	0	130	130	130
	22	238	130	238
	23	191	0	255
	24	255	0	0
	32	245	245	220
	33	255	179	0
	34	255	255	0
	42	0	255	167
	43	0	0	255
	44	0	190	0
grey5	27	245	245	245
	1	211	211	211
	2	130	130	130
	3	105	105	105
	4	0	0	0

Postscript files

All grid files which are presented in this study were converted to eps (i.e. postscript format). The following example illustrates how the water requirement grid was converted into and eps file:

```
gissw2-faogis>> setenv CANVASCOLOR WHITE
Arcplot: &r water.aml
Arcplot: display 1040
Arcplot: water.gra
Arcplot: plot water_mc box 0.5 0.5 7.7 10.7
Arc: postscript water.gra water.eps
```

where: setenv CANVASCOLOR WHITE = sets the background color to white; &r water.aml = automates the map composition of the grid; display 1040 = command used to save the map composition; water.gra = graphics file; plot water_mc box 0.5 0.5 7.7 10.7 = map composition which was reduced to suit the size required for publication; postscript = ARC command used to create the postscript file.

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The present study is an update of an earlier assessment of warm-water fish farming potential in Africa, CIFA Technical Paper No. 27 (1994). The study assesses locations and areal expanses that have potential for warm-water and temperate-water fish farming in continental Africa, based on previous estimates for Africa and for Latin America. However, new data have allowed a sevenfold increase in resolution over the previous Africa study and a twofold increase over that for Latin America (i.e. to 3 arc minutes, equivalent to 5 km x 5 km grids at the equator), making the present results more useful for evaluation of fish farming potential at the national level. Models for assessing both small-scale and commercial potential were developed by using a geographic information system (GIS) to evaluate each grid cell on the basis of several land-quality factors important for fish-farm development and operation. For small-scale fish farming, these factors included: water requirement of ponds as a result of evaporation and seepage, soil and terrain suitability for pond construction based on a variety of soil attributes and slopes, availability of livestock wastes and agricultural by-products as feed inputs based on manure and crop potential, and farmgate sales as a function of population density. For commercial farming, an urban market potential criterion was added based on population size of urban centres and travel time (proximity). Protected areas, large inland water bodies and major cities were identified as constraint areas and excluded from consideration for fish farming development. A bioenergetics model was incorporated into the GIS to predict, for the first time, fish yields across Africa. A gridded water temperature data set was used as input to the bioenergetics model to predict number of crops per year for three species: Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*) and common carp (*Cyprinus carpio*). These yield predictions were combined with the small-scale and commercial models derived from the land-quality evaluation for each grid cell to show the coincidence of each land-quality suitability class with a range of yield potentials. Finally, the land quality-fish yield potential combinations were put together to identify areas of fish farming potential for the three fish species.

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