The potential of Geographical Information System-based modelling for aquaculture development and management in South Western Bangladesh

A thesis submitted to the University of Stirling for the degree of Doctor of Philosophy

by

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Originality Statement

I declare that the work contained in this dissertation is my own, and where the work of others has been used it has been properly cited.

Md. Abdus Salam

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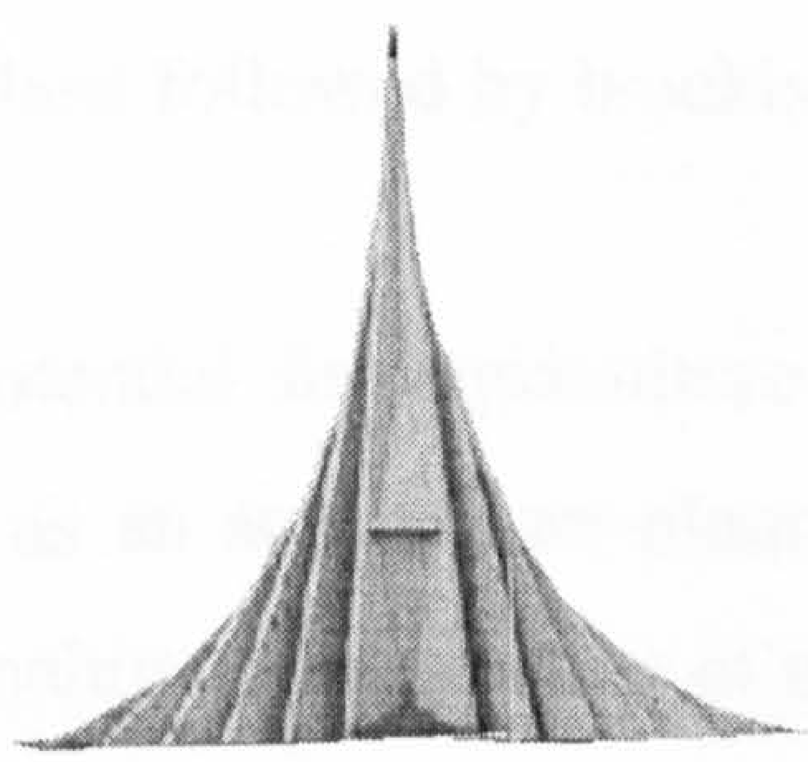
4th September 2000

Dedication

To my grand father T. U. M. Karim Dad, the source of all inspiration and support.

To my wife Bilkis Akhter and my daughter Aniqa Tasnim for their love and help.



To the memory of all the martyrs who had sacrificed their live for the sake of love of Bangladesh.

Abstract

This study describes the delineation of appropriate sites for aquaculture using remote sensing, GPS and GIS. A 1996 composite Landsat TM image covering the south-western part of Bangladesh was used to identify water bodies, the extent of brackish water and associated land use features in the image. The Remote Sensing image was complemented by digitised secondary data from a range of sources, including hard copy maps to produce a GIS database which included environmental layers such as water bodies, rivers, soils, land use, temperature, rainfall, salinity and pH. The database also included infrastructural issues, such as roads, railways, processing plants, towns and cities. A series of GIS models were developed in order to identify and prioritise the most suitable areas for freshwater prawn, tilapia and carp and brackish water shrimp and crab farming. A range of scenarios for land allocations were used to develop a series of resource use models linked to likely production outcomes.

Global warming and accelerated sea level rise is considered in the study area with different sea level rise scenarios of 50, 100, 150 and 200 cm. The consequence of land loses and displacement of the population from the area in different situations is discussed.

The economic characteristics of shrimp farming and alternative land uses in the Khulna region were also considered. Five land use options were studied based on economic output and job potential. Among these, brackish water shrimp and crab culture, moderately saline tolerant tilapia and prawn culture, fresh water carp culture and traditional rice production systems, and fresh water prawn culture performed best followed by brackish water shrimp and crab culture.

This study showed the extent of potential for aquaculture in the Khulna region and further demonstrates the usefulness of GIS as an aquaculture-planning tool. Model programming was also found to be very useful tool to enabling regenerating of multiple scenarios very quickly.

Overall, GIS modelling associated with remote sensing has great potential for informed decision-making in aquatic production systems and optimising management of natural resources in a region where they are already under considerable pressure. The implications for use of these systems in reducing land use conflict and sector planning for the region are discussed.

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Glossary

Aman rice	Local variety of rice grown in autumn.
Aus rice	Local variety of rice grown in summer.
B.aman rice	Broadcasted aman rice grown in autumn.
B.aus rice	Broadcasted aus rice grown in summer.
Baor	Ox-bow lake.
Beel	Natural water depression.
Behundi net	Behundi is a fixed bag net used to catch shrimp, bombay duck, promfret, large croaker and Spanish mackerel, one of these nets costs is 400-800 US dollar depending on size.
Bepari	A person who buys the catch and sell it to a shrimp culture project or middleman.
Boro rice	Local variety of rice gown in winter through irrigation.
Catla	Indian major carp, *Catla catla.*
Char land	Newly created land on the mouth of rivers or in the coastal areas
Dalal	Middleman.
Didhis	Man made big water body created by ancient ruler.
Funda or stake net	Funda is a 55 m long with 4-inch mesh net used to catch perch and Indian salmon in the shallow sea.
Gewa	*Excoecaria agallocha*, an Euphorbiaceae type of mangrove species which grows in the Sundarbans mangrove forest.
Gher	Shrimp culture project.
Golpata	*Nypa fruiticus,* palm tree grows in the Sundarbans mangrove forest and making a fringe in the riverbanks.
Goran	*Ceriops decandra, a* Rhizophoraceae type of mangrove species which grows in the Sundarbans mangrove forest.
Halda	River in the Chittagong region, major carp breeding place.
Hilsa	National fish of Bangladesh is a river shad or herring, *Hilsa ilisha*.
Hoar	Natural depressions, usually found North east corner of the country.
Jackfruit	*Artocarpus heterophyllus,* national fruit of Bangladesh grows up to 80kg.
Jhanna	*Rhizophora mucranata, a* Rhizophoraceae type of mangrove species which grows in the Sundarbans mangrove forest.
Katcha road	Dirt which is motorable only in the dry season.
Kewra	*Sonneratia apatala, a* Sonnetiaceae type of mangrove species which grows in the Sundarbans mangrove forest.
Mauza	Smallest land measurement unit
T.aman	Local transplanted aman rice grown in autumn.
Mrigal	Indian major carp, *Cirrhinus mrigala.*
Partex	Jute fibre board.
Robi crops	Mixed winter crops.
Rui	Indian major carp, *Labeo rohita.*
Sal forest	Inland forest grown in the hilly regions.
Sundari	*Heritiera fomes,* a Sterculiaceae type of mangrove species which only grows in the Sundarbans mangrove forest.
Thiodin	A typical pesticide used in the agriculture as well as in the aquaculture fields
BEPB	Bangladesh Export Promotion Bureau
BFDC	Bangladesh Fisheries Development Corporation
BIWTA	Bangladesh Inland Water Transport Authority

DOF	Directorate of Fisheries
EGIS	Environmental GIS
ESCAP	Economic and Social Commission for Asia and the Pacific, United Nations
MPO	Master Plan Organisation
UNEP	United Nations Environmental Program

Chapter 1

General Introduction

Population growth is creating great pressure on land, water, space and food production. More food protein needs to be produced and a contribution can be made to this by increasing fish production through extension of aquaculture and inland fisheries. The scope for inland aquaculture is indicated by the projected decline in world capture fisheries over the next few decades (Meaden and Kapetsky, 1991).

Bangladesh has a total water surface of 4.31 million hectares for inland fisheries, of which 70% is suitable for exploitation, with 2.61 million hectares of coastal waters and 1.66 million km^2 of marine water. The country offers a unique opportunity for the development of aquaculture. The coastline is an area of particularly high productivity and has a rich aquatic fauna including juvenile populations of a number of cultivable species of prawn, shrimp, fish, and crab. The presence of the extensive natural mangrove forest, like the Sundarbans inside Bangladesh, forms an ideal mangrove ecosystem, which supports a characteristic group of shrimp, prawns, edible crab and fish and also export food to the fisheries upon which many coastal communities depend (Ali, 1998; Ong, 1982; Rahman, 1998; Snedaker, 1978).

Aquaculture activities in Bangladesh are concentrated in two major sectors: 1) freshwater, mainly carp culture, and 2) brackish water, mainly shrimp culture (Chowdhury, 1987; Islam *et al.* 1998). The large delta created by the conveyance of the 'Ganges', the 'Jamuna' and the 'Brahmaputra' rivers (**Figure 1.1**) encompasses an area of 2.5 million hectares of coastal tidal land. Much of this area is suitable for brackish water aquaculture. Within this, Khulna division ($23^0$15' north, $88^0$30' west, $21^0$45' south and 90^0 east) has the best conditions for shrimp culture and it reportedly has 105, 000 hectares in operation (DOF, 1994-95). Because of the presence of the extensive polders, the cost of creating ponds in this area has been very low. It usually involves the construction of a wooden sluice gate in the main polders and upgrading the existing paddy embankments, so that a water depth of about 0.5-meter can be maintained (**Figure 1.2**). The principal operating costs associated with shrimp culture in Bangladesh are fry and labour. Farmers begin stocking their ponds as soon as fry become available, typically in February, and they continue adding fry to the ponds until May. In the Khulna area, harvesting begins in about May and continues through August (Rosenberry, 1990). **Figure 1.3** is a schematic diagram of shrimp culture procedure in Khulna region.

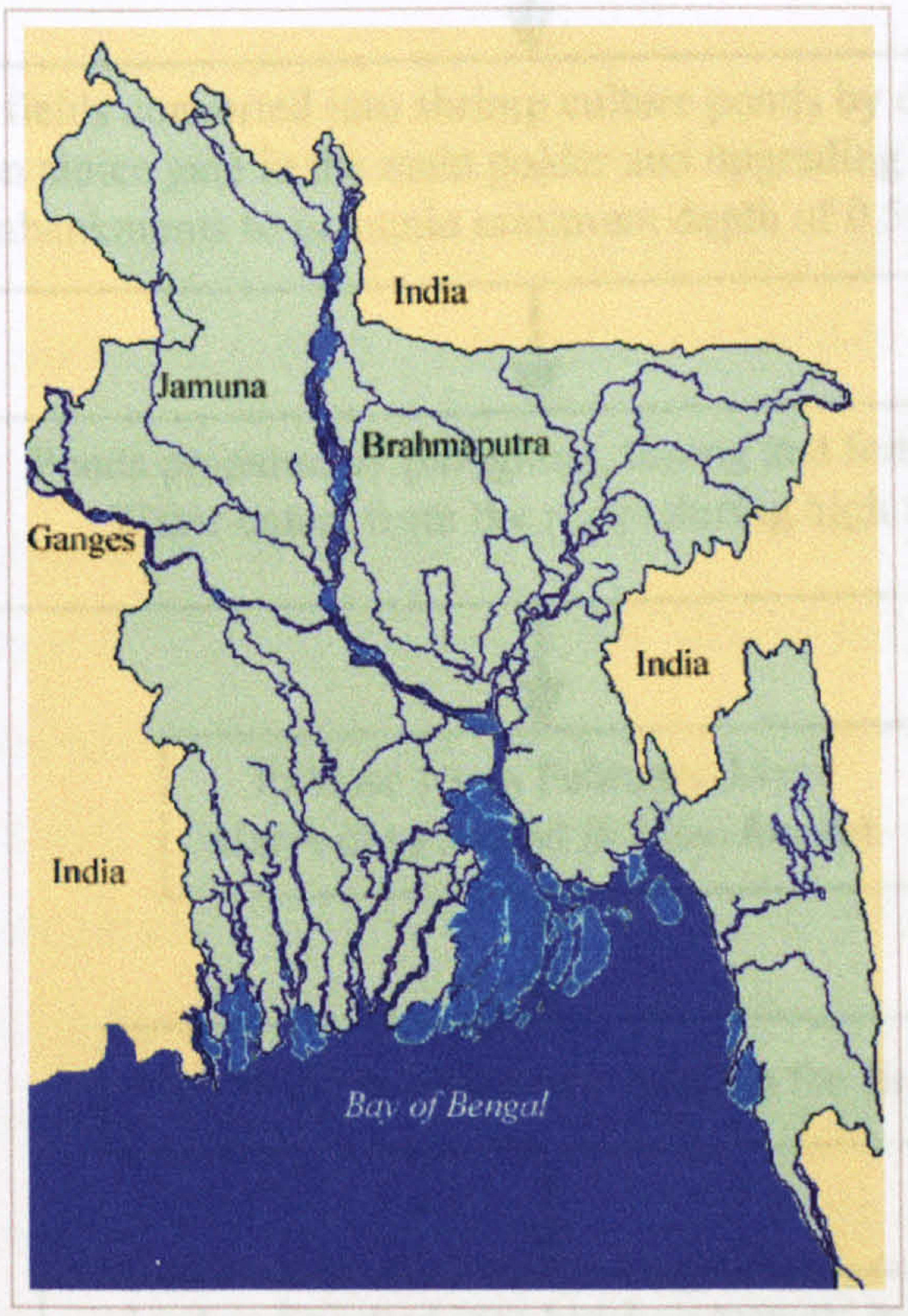

Figure 1.1. Map showing the major rivers, the Ganges, the Brahmaputra and the Jamuna emerging to the Bay of Bengal.

Figure 1.2. Shows the sluice gate built to hold and exchange the water in the shrimp projects in the Khulna region, Bangladesh.

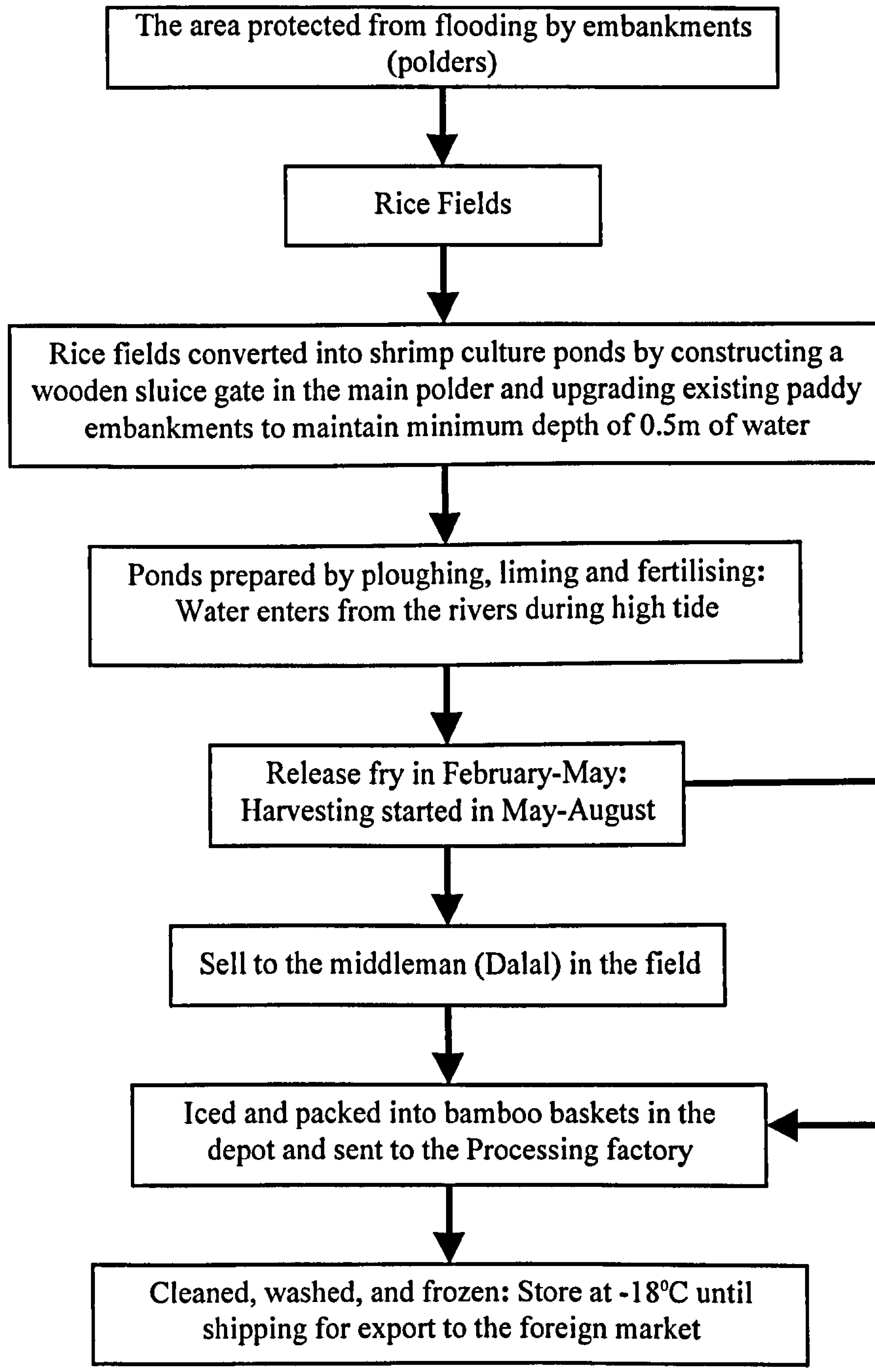

Figure 1.3. Illustrates schematic diagram of shrimp culture procedure in the Khulna region.

Coastal aquaculture, a traditional practice in Southeast Asia for over 500 years, was historically characterised by small-scale operations, minimal management and low yields. Accelerated development in the last three decades has created negative environmental impacts, such as extensive conversion of mangrove to ponds, changes in hydrological regimes in enclosed waters due to proliferation of aquaculture structures, and discharge of high levels of organic matter into coastal waters (Chua *et al.* 1989; Karim, 1998; Phillips *et al.* 1993). Moreover, significant strides in aquaculture development have occurred only in the last three decades. During this period production reached commercial scale through the improvement of fish farming technologies, such as the intensification of farm operations, refinement of hatchery technologies by controlled breeding, and general improvement in farm management (Kungvankij *et al.* 1986; Primavera, 1997).

Brackish water aquaculture is presently responsible for a relatively minor component of the total fish landings of the world, but is frequently cited as offering excellent potential for major expansion. Under the stimulus of very high international market value of Penaeid shrimp, the investment community, both private and public, has become substantially involved in brackish water shrimp aquaculture projects in tropical countries, especially during the past decades (Sato and Mimura, 1997). However, one major cause of low shrimp and fish productivity in a number of coastal aquaculture projects is the presence of pyrites, a very common iron sulphate mineral in tropical coastal soils and sediments, often associated with mangrove ecosystems. When exposed to air, pyrite in moist soils created problems. In many cases, the upper layer of the pyrite soils up to 20-30 cm tend to be suitable for dike construction, whereas deeper layers are very acidic (Cook *et al.* 1984; Uddin and Islam, 1998). Moreover, one major problem for a global expansion of *Macrobrachium rosenbergii* culture in the Asian region is the cost of seed production, which is due to dependence on imported *Artemia*, the only major live food used in prawn hatcheries (Alam *et al.* 1991). However, steps have been taken to replace *Artemia* by other live foods to boost shrimp and prawn production (Alam *et al.* 1995; Alam *et al.* 1996).

Mangroves are evergreen forests between the land and the sea occupying tracts along sheltered coasts, estuaries and deltas where they are influenced by tides salinity and rainfall. Mangroves form a unique environment and floral and faunal assemblages and are possibly the simplest and best-defined ecosystems among tropical forests (Nasker and Mandal, 1999; UNESCO, 1981). In addition, mangroves are best defined by their tree species, and few animals seem to be strictly linked to mangroves. The dominant biological feature of the mangrove ecosystem is a relatively low degree of species diversity, especially of plants, compared with neighbouring tropical communities (forests, savannahs or grasslands). Generally speaking, mangroves are trees and bushes growing below the high-water level of spring tides. Their root systems are thus regularly inundated with saline water, even though it may be diluted and flooding is limited to once or twice annually (Ali, 1998; UNESCO, 1982).

The mangrove ecosystem is commonly understood to be made up of a collection of woody plant species associated with characteristic flora and fauna and the typical anaerobic soils found in the intertidal zone of the subtropical and tropical coastline. One of its major characteristics is that it is an open system, interconnected up-stream with the land and downstream with the sea. Nutrients are primarily derived from upstream catchments or from tidal flooding while organic materials are transported towards the sea (Mirza, 1998). This organic material along with mangrove leaves produced a complex detrital-based food web and used by various brackish-water organisms (Wafar *et al.* 1997). These areas constitute a nursery ground for a variety of exploited species (Chaffy *et al.* 1985; Long *et al.* 1992; Robertson and Phillips, 1995).

Mangrove leaves are washed away by the incoming high and low tides and are broken down by bacteria, fungi and other living micro-organisms, thus entered into the food chain of coastal, estuarine and marine organisms. One third of the country's population is dependent directly or indirectly on the 5,773 km^2 of mangrove land as fishing, collecting palm leaves, honey, fish, and shrimp fry (Ali, 1998; Shahid and Pramanik, 1987).

The fresh water runoff of the tidal flushing regime constitutes a dominant mechanism in maintaining the salt balance, which has a direct influence on the settling of mangrove tree species, each of them responding to an optimum salinity level (0-15ppt). Erosion and accretion is another important factor controlling the extension and functioning of the mangrove ecosystem (Nicholls *et al.* 1995). They control not only the characteristics of the bottom sediment, but also the local mean water level, and the structure of the watercourses. Consequent influences on nutrient distribution, water regime and salt balance determine mangrove productivity as a whole (Hossain, 1984).

Mangroves play a very important role in the life of the people who live in or close to it, and also to the economy of the country as a whole. **Table 1.1** and **Figure 1.4** illustrates the environmental and economic values of mangrove forest. Countries, which have mangrove forests, are trying to conserve them for many purposes and also to utilise them on a sustained basis, but the results are a mixed success in some countries and a failure in others. No one can be sure what would happen to humans in coastal areas if mangroves were completely destroyed (Kabir, 1998).

Table 1.1. Shows the revenue earned in 1995-96 from different sources of the Sundarbans mangrove forest.

Sources	Amount M. Tones/M^3	Revenue in local currency (Taka)
Non forest sources		
Palm leaves	67,381	5748,493
Fish	4,090	6873,189
Dry fish	654	1137,988
Shrimps and Crabs	1,215	933,243
Lime/Molluscs	4,279	82,679
Honey and beeswax	200	589,462
Grasses and canes	4,011	70,408
No. of Shrimp fry	253,067,979	12762,472
Tax from fish catch	-	2394,973
Fine from different sources	-	4432,085
Tourism	-	448,558
Forest sources		
Sundari timber	13,557	116739,715
Bine timber	15	16,218
Kewra timber	19	27,715
Round timber	13,590	116753,148
Pulp wood (Gewa)	112,232	33656,775
Match wood	1,416	825,000
Total		303492,126

Source: Siddiki, 1998. 1 US $=50 Taka in 1999 market price

The mangrove can be considered as nature's own aquaculture system. An artificial culture system enjoys relatively easier harvest and selection of particular species, but the natural system is vastly more stable and less susceptible to diseases and epidemics. Unless artificial ponds can very significantly surpass the natural system, the establishment of aquaculture ponds may be a case of robbing Peter to pay Paul with the possible added cost of having to compensate Peter later (Ong, 1982).

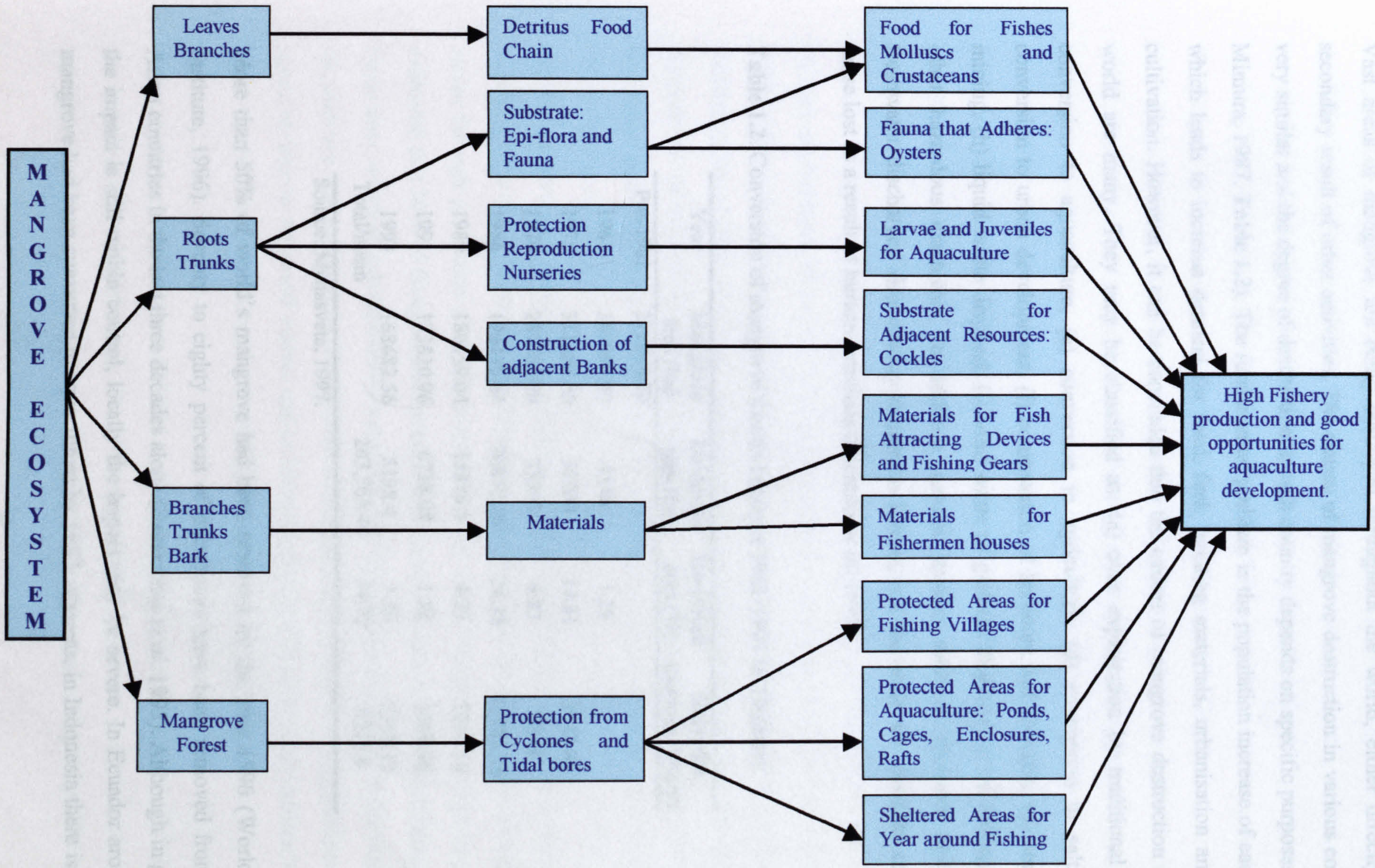

Figure 1.4: Some functional relationships of mangroves with artisanal fisheries, fishery resources and aquaculture (source: modified after Kapetsky,1985).

Vast areas of mangrove are being destroyed throughout the world, either directly, or as a secondary result of other activities. The causes of mangrove destruction in various countries are very similar and the degree of destruction in each country depends on specific purposes (Sato and Mimura, 1997, **Table 1.2**). The fundamental problem is the population increase of each country, which leads to increase demand for food, fuel, building materials, urbanisation and land for cultivation. However, it can be concluded that the causes of mangrove destruction around the world are many. They may be classified as: (a) over exploitation by traditional users, (b) conversion to aquaculture, (c) conversion to agriculture, (d) conversion to salt pans, (e) conversion to urban development, (f) construction of harbours and channels, (g) conversion to mining, (h) liquid waste disposal, (i) solid waste of garbage disposal, (j) oil spillage, and (k) other hazardous chemicals. In addition, natural stresses such as cyclones and excessive freshwater discharges also destroy mangrove forests, but the areas are minimal compared to those lost as a result of human activities (Nicholls *et al.* 1995).

Table 1.2. Conversion of mangrove forests between 1961-1993 in Thailand.

Year	Mangrove area (ha)	Destroyed area (ha)	Destroyed area (%)	Mean rate destroyed (ha/y)
Pre-1961	372448.00			
1961	367900.00	4548	1.23	
1975	311260.00	55200	14.81	3942.88
1979	287308.00	25392	6.82	6348
1986	196435.84	90872.16	24.38	12981.76
1989	180559.04	15876.8	4.27	5292.16
1991	173820.96	6738.08	1.82	3368.96
1993	168682.56	5138.4	1.39	2569.12
Total/mean		203,765.44	54.72	6225.6

Source: Menasveta, 1997.

More than 50% of world's mangrove had been removed by the year 1996 (World Resources Institute, 1996). Seventy to eighty percent of mangroves have been removed from Southeast Asian countries in the last three decades alone (Sasekumar *et al.* 1995). Although in global terms the impact is still within control, locally the impact may be severe. In Ecuador around 14% of mangrove had been converted to aquaculture by 1987, whereas, in Indonesia there is still around

4 million hectares of mangroves, with total aquaculture ponds accounting for less than 5% of this area. However, in certain areas, in particular, Java, Sulawesi and Sumatra, the impact has been severe, and development is continuing at a high rate. In addition, the Philippines converted as much as 50% of mangroves between 1951 and 1988 to construction of aquaculture ponds (Primavera, 1995). Moreover, recent estimates suggest that about 55% of mangrove forest areas in Thailand (totalling 203,765 ha) are in use for shrimp farming and other activities (Menasveta, 1997). However, coastal aquaculture is not the only reason for the disappearance of large swathes of mangrove forests.

The Malaysian Ministry of Agriculture estimated total 27,000 hectares of land in Peninsular Malaysia were suitable for brackish-water aquaculture, of which 20-25% was mangrove forests (Gedney *et al.* 1982). Furthermore, one of the major causes of deforestation in Matang mangrove forest in Malaysia was, that the mangrove forest could only provide 1,400 direct and 1,000 indirect employment, whereas, a fishing industry in the same area could provide 2,500 direct and 7,500 indirect employment and the return from fishing would be three times higher than the forestry (Ong, 1982). However, there is ample circumstantial evidence demonstrating the dependence of coastal fisheries on mangroves, supporting the contention that mangrove waterways support a variety of fauna including fish and prawns (Robertson and Duke, 1987).

Aquatic resources of Bangladesh contributed 73% to the production of fish and shrimp in the country (BBS, 1997). Recently, the fisheries sector has become an important foreign exchange earner through generation of export revenue (Karim, 1998; Nurizzaman, 1991). In 1990, it was estimated that 30% of Bangladesh's farm-raised shrimp was produced in the Chittagong / Cox's Bazar area, which was devastated by a cyclone, and 70% in Khulna region, which was unaffected (Rosenberry, 1991). However, Bangladesh is emerging as one of Asia's largest exporters of farm raised shrimp to the world market and in 1996-97, Bangladesh earned 279 million US dollar in much-needed foreign exchange by exporting shrimp and prawn (BEPB, 1997).

Bangladesh has a coastal area of 36,000 km^2 with a huge population supporting a variety of land use practices (Datta, 1998). Over 30% of the net cultivable areas are in the coastal region, where land use is very complex due to the effect of varying degrees of soil salinity. The major part of this coastal land is occupied by the world's largest continuous mangrove forest and shrimp culture activities. Rivers, wet marshes and coastal impounded waters also occupy a considerable amount of land. Agricultural land use in these areas is relatively poor, being much lower than the country's average cropping (Karim *et al.* 1990; Jahan *et al.* 1998, **Table 2.15**).

Khulna, Patuakhali and part of the Chittagong area are not suitable for winter crops (Rabi crops) without irrigation. However, short-term dry land winter crops are widely grown on the higher river banks in these regions and on generally silty soils of Bhola, Hatiya, Sandwip and southern part of Noakhali mainland. Transplanted rice (Aman) is the only stable crop in the area grown during August to December, when rain reduces the soil salinity. Moreover, a considerable amount of land is occupied by coastal aquaculture, where rice culture has been replaced by shrimp culture along the riverbanks of the regions (Deb, 1998; Rahman, 1994; Rahman *et al.* 1995).

Out of 14,000-km^2 land-mass in the area, 5,773 km^2 is occupied by the Sundarbans mangrove forest, and rivers, tidal canals and tributaries inside the forest. The remaining area is occupied by different permanent civil structures, such as, schools, colleges, hospitals and other residential buildings and huts in the town centre and in the villages respectively. There are 10,644 hectare of ponds, 5,488 hectare of ox-bow lakes and thousands of hectares of rivers in the region, are also considered permanent structures. So, assessment of suitable sites for aquaculture expansion, such as, shrimp, prawn, crabs or fish culture, needs to be well-planned (Haque *et al.* 1997).

With the advent of brackish water shrimp farming, the land use pattern has begun to change gradually, coastal aquaculture indiscriminately replacing other land-based practices (Mahmood *et al.* 1994; Rahman *et al.* 1995). In the Satkhira area, nearly 1,200,000 peasants have lost their land, which was their only source of food, to shrimp ponds. In addition, shrimp farmers often resort to coercion and violence to scare the peasants away. Local thugs and hardened criminals are called in regularly to prevent displaced peasants from to returning their land and the administration often sides with the shrimp farmers (Rosenberry, 1993).

Shrimp has become one of the most important export products in Bangladesh and the government has declared shrimp cultivation a primary industry and designed specific support programs to boost production (Karim, 1998; Sato and Mimur, 1997). Consequently, there has been a significant increase in the number of shrimp farms and production. However, if ecological and social impacts are taken into consideration, then it may be seen that many households have encountered a significant loss of opportunities. Among there are agriculture's for rearing poultry and livestock, growing fruit trees, kitchen gardening, fish culture in homestead ponds, availability of cow dung and firewood for fuel and access to fresh drinking water (CARE, 1994; Datta, 1995; Rahman *et al.* 1995; Rahman and Azad, 1994).

Marine, estuarine and inland waters have great fisheries potential in Bangladesh and the fisheries sector already plays an important role as providers of food, employment and as a foreign exchange earner. The sector accounts for more than 7% of the country's total export earnings (Mazid, 1998). However, major constraints continue to retard further fisheries development, in particular, insufficient investment, institutional weakness, lack of appropriate technologies, lack of quality seed supply, infrastructures, extension services and inadequately trained and experienced manpower (Rahman, 1994).

In Satkhira / Khulna area the practice of catching shrimp fry has been learned from the people on the other side of the Ichamati river in India, the border between India and Bangladesh (Rosenberry, 1992). Moreover, bamboo traps (Bundh) and set bag nets (Savar net) are unique trapping systems for the collection of shrimp and prawn, using bundh and nets posted in the migration routes of prawns and fishes which are now widely used in the tributaries of the Sundarbans (**Figure 1.5**). Mahapatra *et al.* (1993) noted that up to 26 kg of shrimp seed and 42 kg of fish seed could be collected from a bundh in a season. Total income from this is $101, with a net profit of $73 from a bundh during one operational period.

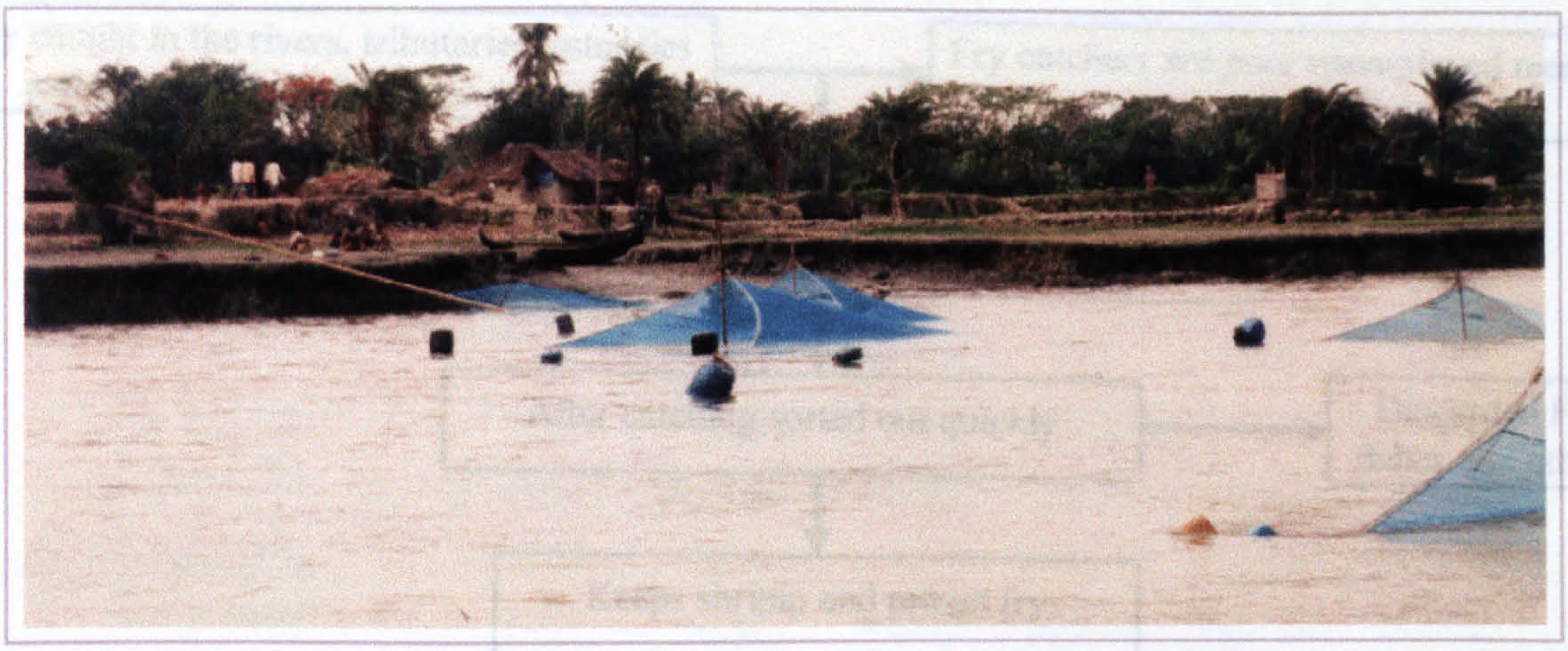

Figure 1.5. Illustrates fry catching by set bag net (Saver net) in Passur River at Mongla, Khulna, Bangladesh.

More than 40,000 men, women and children are associated with shrimp seed collection in the coastal belt of Cox's Bazar and Chittagong region, whereas, in Satkhira, Khulna and Bagerhat region, the number is more than 100,000. The fry catching season in these areas starts in mid-November and lasts until mid-July (Rosenberry, 1992). Once fry catching became established, it spurred another occupation: buying fry from the catchers and selling them to a farm or project (Gher). The overall trading pattern was described by Hossain (1995) and is shown in **Figure 1.6**.

During new moon or full moon, the prawn larvae are abundant in the rivers. Fry is collected twice in 24 hours, in a four to five hour period based on the semi-diurnal pattern of the tide. However, seed can be collected all the year round in the South-western part of the country due to higher salinity (Funegaard, 1986; Ubing, 1990). Immediately after a catch, the fry are sorted, discarding everything other than shrimp and prawn fry, such as fin-fishes, ichthyoplankton, zooplankton and crustacean fry and larvae (**Figure 1.7** and **Table 1.3**).

Though the shrimp culture industry of Bangladesh generates employment for thousands of rural poor, the marketing system is not well developed and high fry mortality occurs due to poor handling. The growing shrimp and prawn farming sectors, however, continue to demand increasing quantities of large juveniles. If the fry catchers were to rear the shrimp and prawn fry up to juvenile stage, this would minimise mortality and they would also benefit financially (Angell, 1994; CARE, 1994; Nielsen and Hall, 1993).

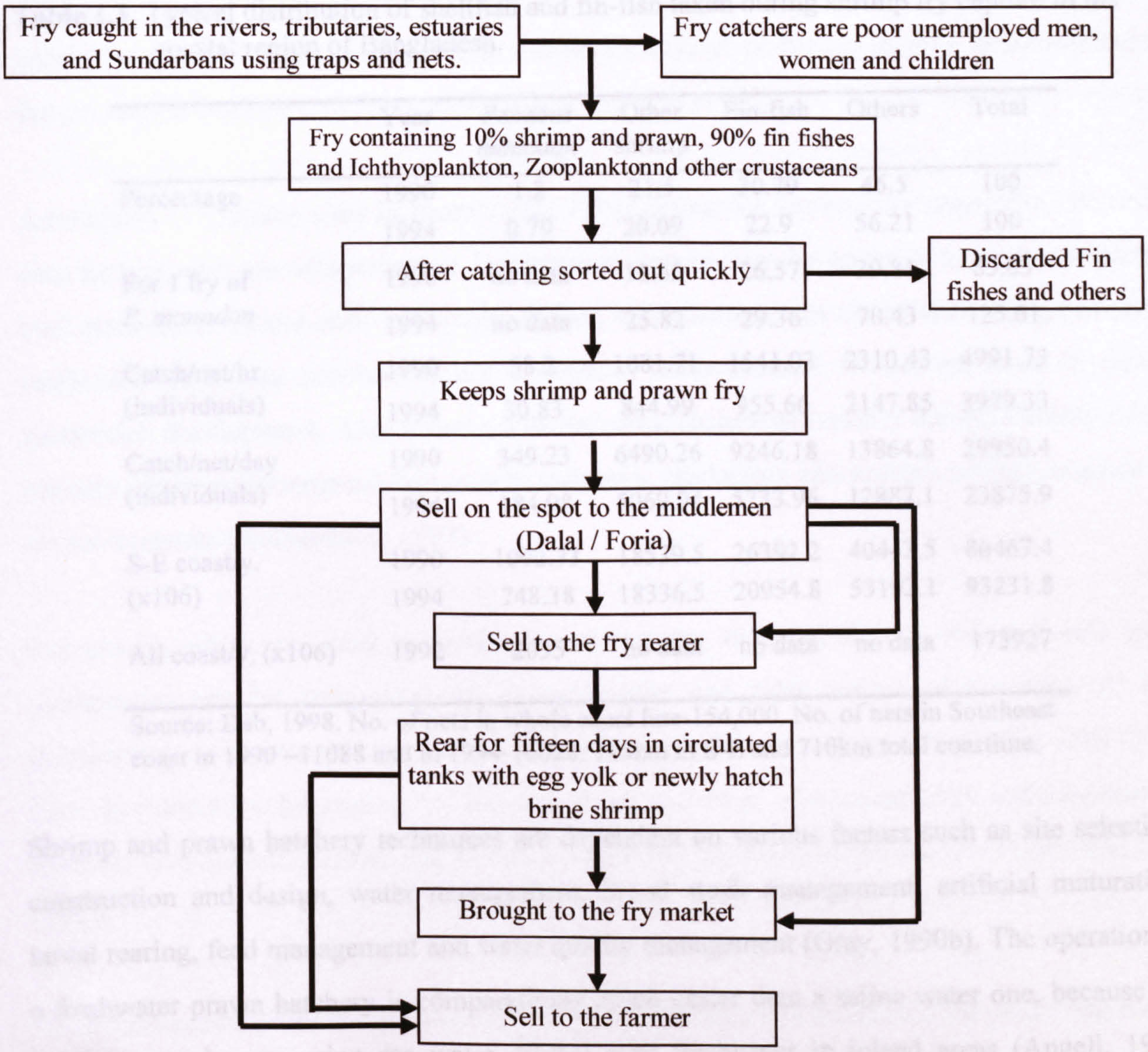

Figure 1.6. Schematic diagram of fry catching and marketing in Bangladesh (sources: Hossain,1995)

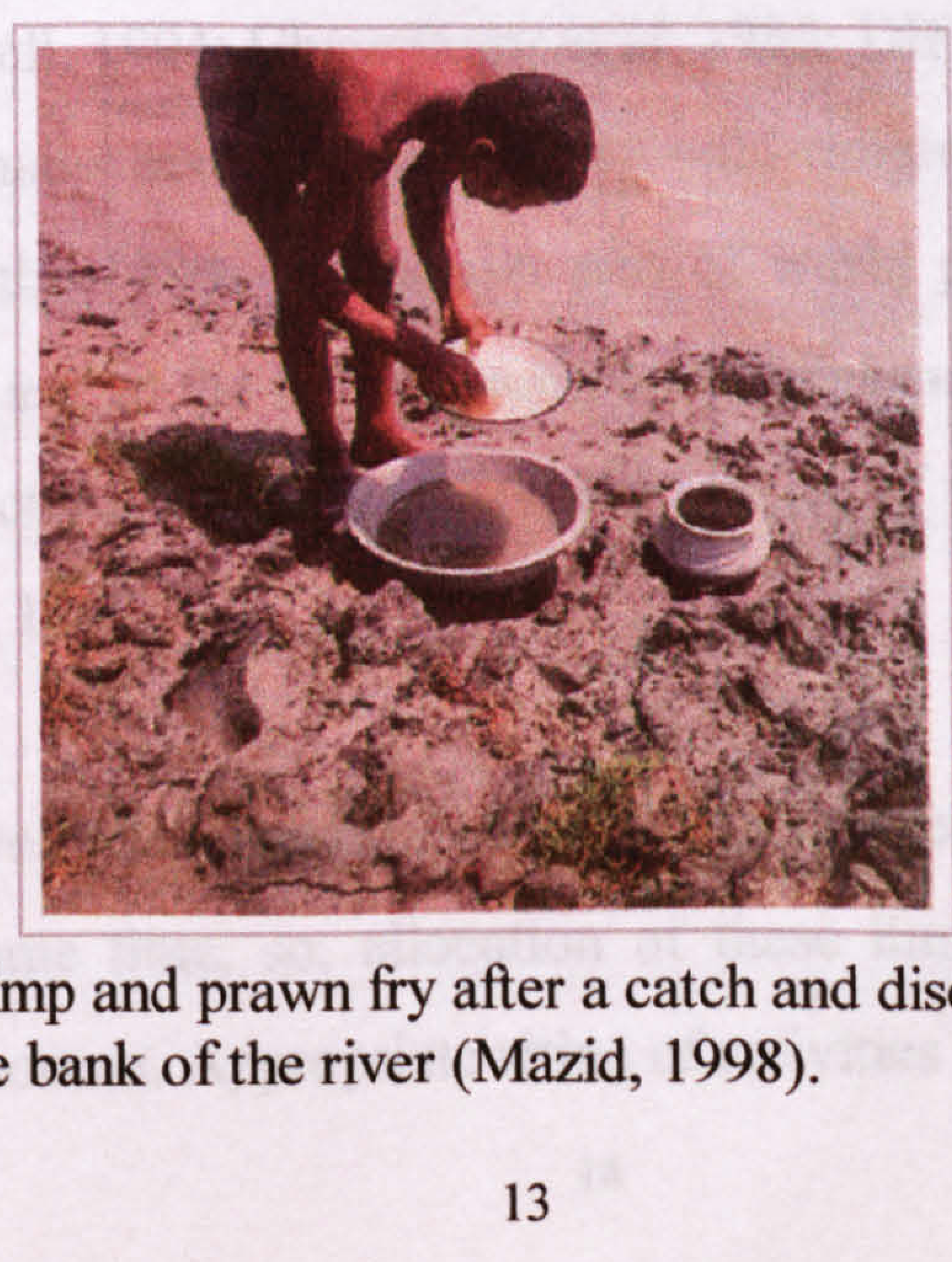

Figure 1.7. Sorting out shrimp and prawn fry after a catch and discard other than shrimp and prawn fry in the bank of the river (Mazid, 1998).

Table 1.3. Typical distribution of shellfish and fin-fish taken during shrimp fry capture in the coastal region of Bangladesh.

	Year	*Penaeus monodon*	Other shrimp	Fin-fish	Others	Total
Percentage	1990	1.2	21.5	30.79	46.5	100
	1994	0.79	20.09	22.9	56.21	100
For 1 fry of *P. monodon*	1990	no data	18.65	26.57	39.81	85.03
	1994	no data	25.82	29.36	70.43	125.61
Catch/net/hr (individuals)	1990	58.2	1081.71	1541.03	2310.43	4991.73
	1994	30.83	844.99	955.66	2147.85	3979.33
Catch/net/day (individuals)	1990	349.23	6490.26	9246.18	13864.8	29950.4
	1994	184.98	5069.94	5733.96	12887.1	23875.9
S-E coast/y. (x106)	1990	1092.33	18539.5	26392.2	40443.5	86467.4
	1994	748.38	18336.5	20954.8	53192.1	93231.8
All coast/y. (x106)	1992	2035	no data	no data	no data	173927

Source: Deb, 1998, No. of nets in whole coast line-154,000. No. of nets in Southeast coast in 1990 –11088 and in 1994-16020. 145km in S-E and 710km total coastline.

Shrimp and prawn hatchery techniques are dependent on various factors such as site selection, construction and design, water management, brood stock management, artificial maturation, larval rearing, feed management and water quality management (Gray, 1990b). The operation of a freshwater prawn hatchery is comparatively much easier than a saline water one, because the hatchery can be run using sea water diluted with freshwater in inland areas (Angell, 1994; Chowdhury *et al.* 1993; New *et al.* 1995). Moreover, recent development of economic prawn hatcheries using backyard techniques has opened new prospects for freshwater prawn culture in inland water bodies (Angell, 1994; Chowdhury *et al.* 1993; DIFTA and CARE, 1993). However, production of prawns remains mainly dependent on wild-caught juveniles, in Southeast Asia and Central America during the 1980s. The major part of world production of marine crustaceans relies on Penaeid shrimp and to the lesser extent, on *Macrobrachium* species. In 1994, the world shrimp and prawn production was 3,080,000 metric tones, of which 30% was from culture and 70% from capture (FAO, 1997).

Since aquaculture is developing rapidly in coastal areas, where there are many other activities also occurring at the same time, so, allocation of these limited land and water resources to various users is very important. Appropriate siting of activities acts as a precautionary measure to prevent land use conflicts among users, and environmental problems, thereby also maximising the production (Aguilar and Ross, 1995; Salam and Ross, 1999).

Assessment of suitable sites is fundamental for planning for aquaculture expansion. Potential sites for various types of aquaculture developments can be done by applying appropriate criteria, both environmental and socio-economic. Earlier, site selection was aimed at ensuring economic profit and increasing production, but at present, environmental factors are used to ensure sustainable development. Appropriate socio-economic factors will ensure the profitability of the industry, while environmental factors will maximise production and prevent adverse impacts on the environment (Jarayabhand, 1997).

The criteria which are most important for appropriate siting of shrimp, fish and crab pond construction can be categorised as: i) topography and tidal regime of the area, ii) soil characteristics, iii) water characteristics, iv) availability of the natural resources in the area, v) the flora and fauna of the region, vi) freedom from pollution, vii) accessibility and nearness to markets, viii) legal regulation and ix) socio-economic condition of the locality (Chou and Lee, 1997).

Freshwater prawn (*Macrobrachium rosenbergii*) juveniles are released into the ponds and reared from 6-12 months in Bangladesh. They attain an average length and weight of 210 mm and 142 g respectively. The rate of survival was about 82%, which is considered a most promising result for prawn culture in impounded waters. On the other hand, the improved methods of shrimp culture which are more capital oriented, could remove the reliance upon the expansion of lands for shrimp culture, while also creating lots of employment opportunities. Therefore, the introduction of improved shrimp culture techniques in the coastal areas would have two main implications. Firstly, it would facilitate the release of lands for use by other agricultural activities without affecting farm income. Secondly, support of institutional credit would enable the existing farms to expand (Ahmed, 1986).

Bangladesh might have been the most important shrimp farming country in the eastern hemisphere, if it were not has the viral diseases that plagued the shrimp culture (Rosenberry, 1993). By contrast, the integrated rice and prawn farming system is still experimental in Bangladesh and the prawn could be a suitable species for such integration in the south-eastern and south-western part of the country where tidal water exchanges regularly and post larvae are naturally available (Haroon, 1990; Hossain, 1995). In addition, aquaculture can integrate well with cattle, poultry and crop farming. Additionally, it is also a supplement of the fishing industry because it can contribute to the maintain level of a fishing population. Aquaculture in the coastal region, is not only the source of food and work for many women and children but also a source of income and for many it represents an alternative production activity when it is difficult to practice livestock rearing and agriculture (Burbridge, 1997; Rahman and Azad, 1994).

The high price of shrimp fry (*Penaeus monodon*), the profitability of hatchery operations and a low-cost hatchery design introduced by the South-east Asian Fisheries Development Centre attracted millions of dollars of investments in the mid 1980s (Angell, 1994; Deb, 1998). However, the export price of shrimp fell dramatically in 1989 and still further in 1998. This lowered fry demand, as most of the shrimp growers stopped operations or reduced stocking densities (Ling *et al.* 1999; Khulna Correspondent, 1998). The production of prawn will continue to increase in future, which may lead to further decline of prices in the international market. If the price in the international market become lower than the minimum sustainable production cost, then these shrimp culture industries with high costs will not survive (Hatch *et al.* 1996; Hirasawa, 1992).

Inshore fisheries, which are based upon traditional methods, gears and skills, are an important source of livelihood for many thousands of coastal dwellers in Bangladesh. These fishermen are socially, economically and educationally disadvantaged and, lacking their own financial resources, are heavily indebted to traders and middlemen. Constraints arise from over-population, low income and lack of alternative employment opportunities. Better management is also hindered by the lack of reliable biological data and conflicts arising from competing land uses in the coastal areas (Rahman, 1994). However, aquaculture, as well as coastal aquaculture, has created a lot of employment opportunities for the poor who are living in this area. In Bagerhat region, Bangladesh, women are engaged in income generating work, such as seasonal prawn peeling, snail meat selling, preparing and mending nets and traps, fish culture and agriculture (CARE, 1994).

The major objectives of fisheries development in Bangladesh are to improve the socio-economic condition of fishermen and increase production of food to fight proverty and malnutrition. Therefore, all government agencies, fisheries research and educational institutes that are supposed to provide support to the small scale fishermen, who use cheap technology do not provide government loans and subsidies and offer only inadequate extension services (Dwivedi, 1982). Sehara *et al.* (1992) suggested specific rules to overcome the problems of the small-scale fishermen, especially of artisanal sector. Examples include i) constitution of a public agency to purchase the fish at a minimum price, whenever there is surplus at the landing centres, and distributing those at interior places throughout the year, ii) provision of adequate finances at reasonable terms and conditions through co-operatives, and iii) extension of all facilities for developing prawn farming as well as integrated fish-crop-livestock farming.

In Southeast Asia, feed application is increasing through the expansion of intensive operations, although the quantity of organic matter discharged into coastal waters has yet to be determined. There has been an increasing use of antibiotics and growth promoting substances in aquaculture feeds for intensive farming, but its environmental impact, especially on public health, is yet to be assessed (Chua *et al.* 1989). In addition, the traditional use of fertilisers in limited quantities enhances aquaculture productivity, particularly where biodegradable organic wastes are employed. However, excessive doses can pollute the water as well as the whole environment (Karim, 1998; Phillips *et al.* 1993; Pillay, 1977).

Countries like India, Indonesia, the Philippines, Vietnam and Bangladesh are producing shrimp extensively although they utilise small quantities of feeds with low protein and fishmeal levels. The Asian shrimp feed market is highly competitive; most feed manufacturers are producing feeds with nutrients substantially in excess of requirements to assure their products are well received in the market. Hence shrimp feeds tend to contain a considerable volume of fishmeal, usually 30 to 35% (Corpron, 1994), whereas feeds such as trash fish, snail meat and formulated diets only used in semi-intensive and extensive systems, especially in the culture of carnivorous finfishes and shrimps. Unlike freshwater culture systems, eutrophication resulting from the discharge of nutrients and organic matter (faeces and uneaten feeds) in the pond or adjacent water bodies rarely occurs (Deb, 1998).

Use of pesticides in agriculture fields and in brackish water shrimp culture to eradicate unwanted species of fishes and crustaceans, industrial effluents, and development of residential areas have had impacts in the region (Apud, 1985; Deb, 1998; Khan and Hossain, 1996; Rosenburry, 1993). The majority of documented pesticide poisonings of aquatic organisms has been attributed to the impacts of agricultural runoff (Knox and Miyabara, 1984). Apart from pollution associated with culture activities, aquaculture development has a very significant impact on the environment. For instance, large-scale conversion of mangrove areas for brackish water fish and shrimp ponds in many Southeast Asian countries has not only rapidly depleted the valuable mangrove resources, but has also impaired the ecological balance in the estuarine ecosystem where mangroves are generally located. Obvious environmental impacts due to loss of mangrove swamps include coastal erosion, changes in shoreline configuration, salt water intrusion, reduction of freshwater sources and grazing land, increases sedimentation in the river beds, changes in water quality, destruction of planktonic species and loss of coastal habitat (Kabir, 1998; Khan, and Hossain, 1996; Niclolls *et al.* 1995; Phillips *et al.* 1993).

Bangladesh lies within a zone of cyclonic storms and devastating tidal bores which tend to occur in early summer (April – May) or late autumn (September – November). During the past three decades six catastrophic storms with winds reaching 240 km/h have devastated coastal areas (Choudhury *et al.* 1998; Rashid, 1991). Extensive damage is done not only to the large numbers of people and their property but to the environment and wildlife as well. Between 1797 and 1991, Bangladesh experienced 60 severe cyclones, which caused the death of 800,000 people and thousands of animals (Khalil, 1992; Nicholls *et al.* 1995). A devastating cyclone hit south Bengal at the mouth of the Ganges in 1737 and was one of the worst natural disasters in human history (Sensarma, 1994).

Cyclones not only destroy human life and the environment but also cause epidemiological diseases such as cholera and diarrhoea after they pass. In 1991, serious epidemiological diseases spread out from the fishing villages of Cox's bazar, Tekhnaf and Chittagong areas (Deb and Alam 1994). The high cyclonic frequency in the coastal areas of Bangladesh and protection from the damage afforded by the natural mangrove forest Sundarbans, led the Forest Department in 1966 to commence a massive mangrove afforestation program, which proved highly successful in stabilising coastal areas (Saenger and Siddiqi, 1993). However, the high and increasing population density is now forcing people to engage in agriculture and aquaculture in low lying coastal areas where they are more exposed to cyclone and tidal floods. Colonisation of these areas has also led to deforestation and other adverse impacts on the ecosystem (Bashirullah, 1989).

Global warming and sea level rise, could lead to an increase in cyclone intensity and an increase in storm surge heights, which will have disastrous effects on a deltaic country like Bangladesh, which lies not much above the mean sea level (Ali, 1996; Milliman *et al.* 1989). Long-term predictions have been made of sea-level rise, coastal erosion and land subsidence patterns due to a number of factors, including depletion of the ozone layer, large-scale fossil fuel burning and deforestation, ground-water pumping in coastal and deltaic areas and construction of large dams that obstruct the sediment load of rivers (Nicholls *et al.* 1995; Woods Hole Oceanographic Institution, 1986). **Table 1.4** shows the future sea-level rise situation in Asia.

Table 1.4. Land lost and existing population displaced for various sea levels rises (SLR) scenarios.

Country	SLR Scenario (cm)	Land loss		People Displaced	
		Km^2	%	Millions	%
Bangladesh	45	15,668	10.9	5.5	5.0
Bangladesh	100	29,846	20.7	14.8	13.5
India	100	5,763	0.4	7.1	0.8
Indonesia	60	34,000	1.9	2.0	1.1
Malaysia	100	7,000	2.1	>0.05	>0.3
Pakistan	200	1,700	0.2	n.a.	n.a.
Vietnam	90	>20,000	>6.1	n.a.	n.a.

Source: Nicholls *et al.* 1995.

It now seems certain that global warming will cause a rise in sea water level that will affect Bangladesh seriously, the coastal areas such as the Sundarbans in particular (Ali, 1996). By the year 2050, if the sea level rises one meter, Bangladesh could lose 12% of its land surface. This represents the living space of 9 million people and the mangrove areas will be reduced by 50% (FAO/UNDP, 1994). Moreover, by the year 2100, local sea levels at the Nile and Bangladesh deltas could be as much as 3.3 to 4.5 metres higher than at present level, respectively. As a result Egypt and Bangladesh would lose 26% and 34% of their currently habitable land respectively (Milliman *et al.* 1989). The additional loss of shoreline by erosion, loss of mangrove forests by 75 to 95% and decreased agriculture and fisheries would exacerbate environmental and economic impacts (Broadus, 1993).

Use of GIS, GPS and Remote Sensing in Aquaculture and Fisheries

Geographic information systems (GIS) are a computer-based tool for mapping and analysing things that exist and events that happen on earth. GIS technology integrates common database operations such as query and statistical analysis with the unique visualisation and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies. Moreover, GIS is a tool used by individuals and organisations, schools, governments, and businesses seeking innovative ways to solve their problems (ESRI, 1998).

GIS offers advantages over conventional approaches because of the speed and accuracy with which it handles large spatial datasets. Decision-makers can then have more informed decisions because multiple scenarios can be evaluated or spatial analyses conducted that would otherwise prove too unmanageable. Disadvantages of GIS include additional training for personnel, the costs of capital outlay, and the time required to initially assembling a GIS. A GIS database can be assembled from existing digital files, published maps, or using global positioning receivers. However, continuing software and hardware advancements have led to greater affordability and user friendliness of GIS (Isaak and Hubert, 1997; Pheng *et al.* 1992).

Two types of GIS have traditionally existed, namely vector based and raster based systems. The vector-based approach is more popular, but project specifics will dictate which approach is taken. Vector GIS uses the type of data found in Digital Line Graph (DLG) files and is best at depicting features with distinct boundaries or linear natures because they represent landforms as points, lines or polygons (Eastman, 1995). Storage requirements for vector data are less than their raster counterparts, but certain types of analyses are more time consuming with vector approaches (Congalton and Green, 1992). On the other hand, raster GIS stores data in a grid structure. The cell size in the grid structure determines the resolution with which objects are portrayed and is responsible for any distortion of an objects shape. The resolution of the grid depends on the quality of the data, the way in which they were input and GIS itself. Data in raster GIS are computationally easier to manipulate, but storage requirements are greater (Congalton and Green, 1992). **Table 1.5** describes the advantages and disadvantages of vector and raster datasets.GIS is an integrating system that brings together the ideas developed in many areas including the fields of agriculture, botany, computing, economics, mathematics, photogrammetry, surveying, zoology and of course geography, to name but a few (Maguire, 1991). Moreover, GIS is sometimes regarded as synonymous with other information acquisition and management systems such as computer-aided design (CAD), computer cartography, database management and remote sensing. On the contrary, while GIS may have certain elements or capabilities in common with these systems. It is a separate discipline. The relationship of GIS with these systems is depicted in **Figure 1.8**.

One of the primary sources of geographic data used in GIS is information about the earth that is obtained through remote sensing. Remote sensing data are usually acquired either as digital satellite imagery or aerial photographs. After these images are geometrically corrected, enhanced, analysed and interpreted, the results can be fed into the GIS and integrated with other geographic databases (FAO, 1999; Kapetsky *et al.* 1987).

Table 1.5. Illustrates the advantages and disadvantages of vector and raster datasets.

Data type	Advantages	Disadvantages
Vector	• Much less storage required, • Possibility of representing the original map in its original resolution, and • Multiple attributes can be easily represented.	• Spatial analysis functions are much more complex, and • Some continuously varying raster data such as satellite imagery cannot be easily made compatible.
Raster	• It is easier to write programmes for processing the data, • More compatible with raster-based inputs such as remote sensing digital imagery, and • More compatible with raster-based output devices such as inkjet plotters and many graphics terminals.	• Storage requirements are generally much larger for maps with many attributes, • Difficulties to accurately represent line (topographic lines, road, railroads, etc.) unless the cell size is small, and • Necessity to convert a digitised map from vector to raster.

Source: FAO, 1999.

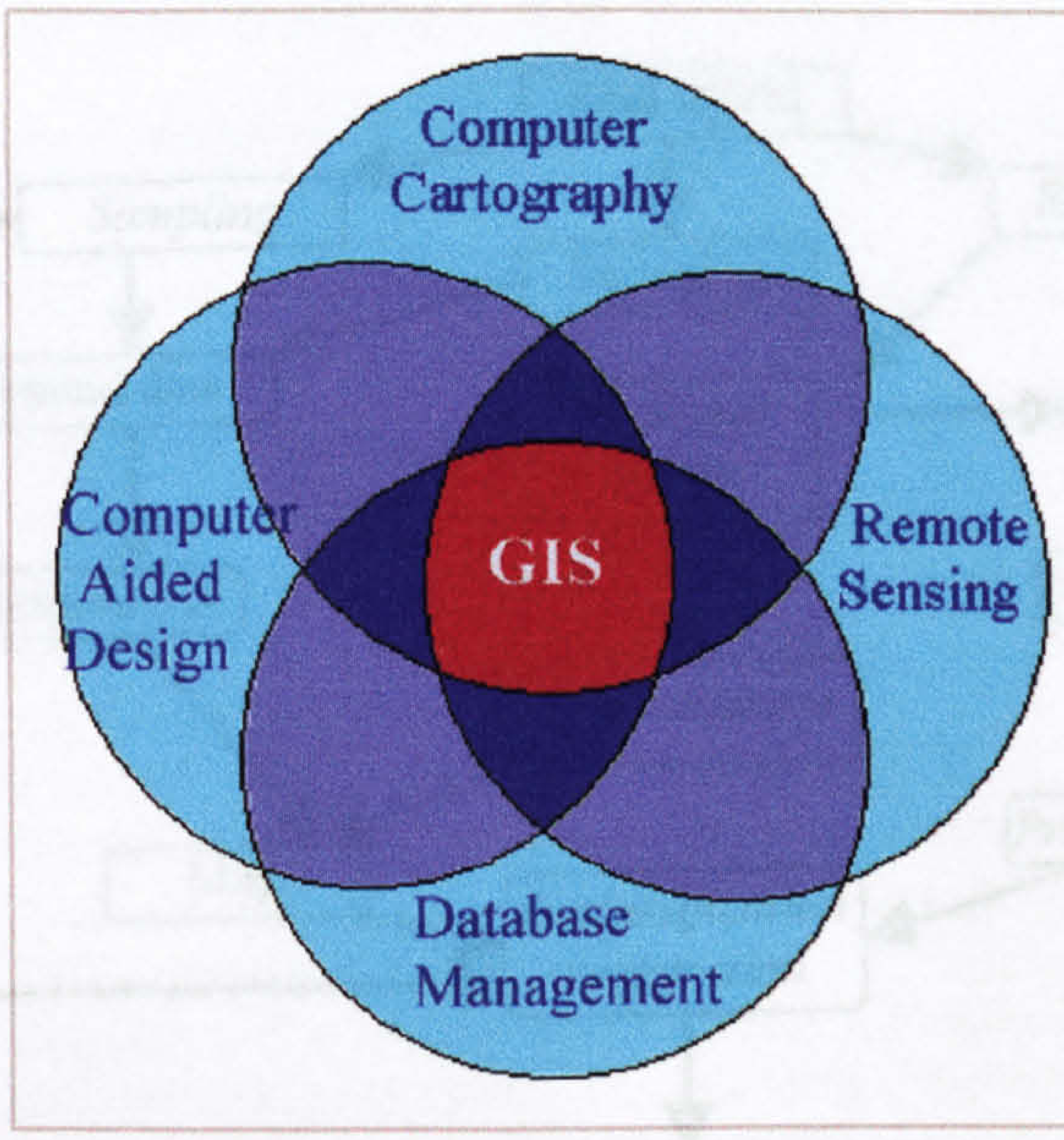

Figure 1.8. The relationship of computer aided design, computer cartography, database management and remote sensing with GIS (source: Maguire, 1991).

The GIS approach is particularly effective when used with remotely sensed data as input and GPS for field verification and accuracy assessment. Remote sensing technology has been used for over a century to acquire data concerning a variety of environmental applications (Green *et al.* 1996; Pheng *et al.* 1992). The integration of satellite image data into a GIS has developed rapidly and is routine although there has always existed the need for data such as maps and ground surveys in helping to analyse remotely sensed data. GIS have also had a need for remotely sensed data to correct, update, and maintain their cartographic databases (Klemas and Weatherbee, 1995). **Figure 1.9** illustrates the use of remote sensing in real world.

Remote sensing and aerial photography was used for coastal mapping, sea-grass distribution, submerged aquatic vegetation mapping and land use and land cover studies in south-east USA (Buffington *et al.* 1990). On the other hand GPS are now in use in many applications, ranging from GIS to route guidance, automatic vehicle location (AVL), air, land, and marine navigation, and many other transport and geographical based applications (Ibrahim, 1999; Tsakiri *et al.* 1998).

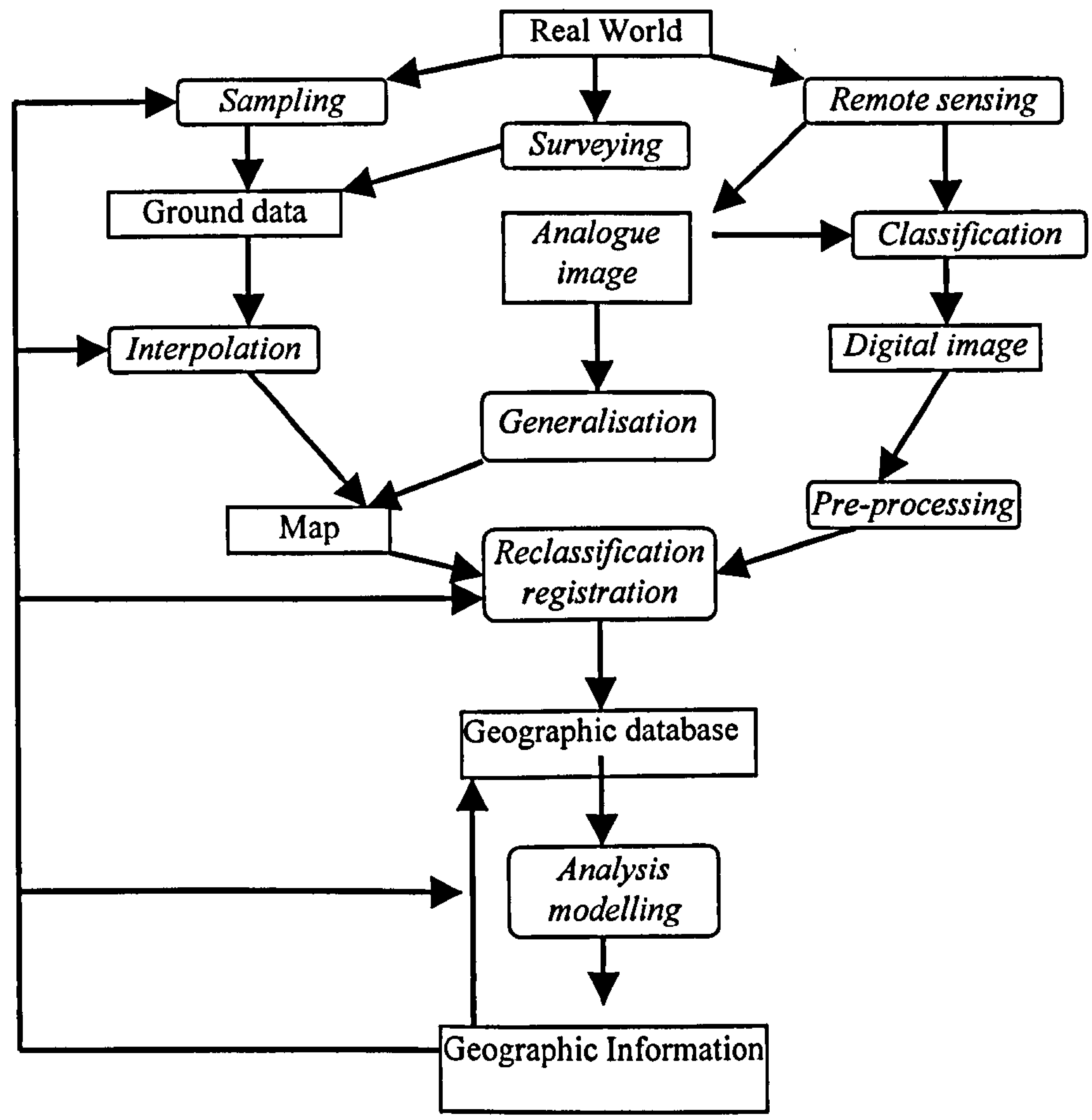

Figure 1.9. Remote sensing as a source of Geographic Information (source: Davis and Simonett, 1991).

GIS have developed rapidly during the last decade, and especially in recent years. This has been enabled by the massive increase in low-cost computing power with the result that very comprehensive tools for handling of spatial data are now available to a wide range of users. RS and GPS are superb data collection methods. However, it is GIS that gives an excellent modelling tool for environmental issues as well as a superb means of linking between biology, physiology, environment, systems and socio-economics (Ross, 1998). However, there is still little that has been published in the aquatic sciences and aquaculture. Database searches reveal less than sixty publication under "GIS and Aquaculture", whereas, there are more than 500 under "GIS and Modelling". A summary list of GIS application in the fields of aquaculture and fisheries is shown below in **Table 1.7.**

Table 1.6. GIS studies in the field of Fisheries and Aquaculture during 1987 to 1999.

Region/ Country	Resolution	Aim of work	Culture species	Author(s)	Date
U. K	10kmx10km	Siting trout farms	*Oncorhynchus mykiss*	Meaden	1987
Zimbabwe	30m x 30m	Regional aquaculture and fisheries development	-	Kapetsky	1987
Costa Rica	-	Regional site selection for oyster, mussel, clam, shrimp	oyster, mussel, clam and shrimp	Kapetsky *et al.*	1987
USA	-	Regional study for oyster culture potential assessment	Oyster	Paust *et al.*	1988
USA	-	Regional suitable site for channel catfish	Channel catfish *Ictalurus punctatus*	Kapetsky *et al.*	1988
Malaysia	-	Regional suitability of fish and shrimp	Fish and shrimp	Kapetsky	1989
USA	-	Regional catfish and craw fish potential assessment	Catfish, *I. Punctatus* and Crawfish, *Procmbarus clarkii*	Kapetsky *et al.*	1990
Ghana	-	Potential of tilapia and catfish farming	*Oreochomis nloticus & Clarias gariepinus*	Kapetsky *et al.*	1990
Chile	-	Salmon and mussels cage, pen and bed culture	Salmonids and mussels	Krieger & Muslow	1990
Mexico	49kmx49km	Regional warm water fish farming potential	Fish (Cichlids)*O.niloticus Cichlasoma urophthalmus*	Flores-Nava	1990
Canada	-	Potential spawning habitat for five fish species	Fish	Harper *et al.*	1990
Pakistan	75km x 75km	Siting carp farms	Major carps	Ali	1991
Mexico	-	Aquaculture and Socio-economic study	Fish	Aguilar	1992
Philippines	30m x 30m	Brackish water aquaculture	Fish and shrimp	Paw *et al.*	1992
Bangladesh	20m x 20m	Looking for coastal shrimp farming areas	Shrimp, *P. monodon*	Shahid *et al.*	1992
Nepal	2km x 2km	Siting carp hatcheries	Indian major carps	Karki	1992
Canada	-	Oyster, clamp and mussels habitat management	Oyster, clamp and mussels	Legault	1992
French Polynesia	20m x 20m	Oyster pearl culture site	Pearl oyster	Chenon *et al.*	1992
Norway	-	Siting Salmon and rainbow trout farms	Salmon and rainbow trout	Ibrekk *et al.*	1993
U. K	25m x 25m 10m x 10m	Sites for salmon cage culture	Salmonids	Ross *et al.*	1993
India	72.5m x 72.5m	Suitable site for coastal aquaculture	Fish culture	Sudarshana	1993
Africa	18km x 18km	Warm water fish culture in African continent	Fish culture, *O. niloticus* And *Clarias gariepinus*	Kapetsky	1994
Canada	-	Siting of Atlantic salmon	Atlantic salmon *Salmo salar*	Keizer	1994
USA	30m x 30m	Coastal water management	-	Klemas and Weatherbee	1995
Mexico	500m x 500m	Regional aquaculture model for carp and tilapia	Carp and tilapia	Gutierrez Garcia	1995
USA	-	Fish habitat assessment of the Edisto river basin, South Carolina.	Fish	O'Brien and Thomason	1995

Continued table 1.6

Region/ Country	Resolution	Aim of work	Culture species	Author(s)	Date
USA	-	Reservoir habitat management for pike and bass	Northern pike *Esox lucius,* Largemouth bass *Micropterus salmoides*	Rogers and Bergersen	1996
Vietnam	-	Potential for rice-fish and fish culture	Prawn and fish	Tran and Demaine	1996
Mexico	250m x 250m	Regional aquaculture model for shrimp culture	Shrimp, *P. vannnmei*	Aguilar	1996
Canada	1.1km x 1.1km	Regional suitable site for mussels, oyster, salmon and lobster	Mussels, oyster, salmon and lobster	Habbane *et al.*	1997
Bangladesh	30m x 30m	Site for shrimp farming	Shrimp, *P. monodon*	Shahid *et al.*	1997
Bangladesh	-	Site for shrimp farming.	Shrimp, *P. monodon*	Haque *et al.*	1997
Latin America	-	Continental assessment for tilapia, carp and tambaqui pacu culture.	tilapia, carp and tambaqui pacu culture	Kapetsky and Nath	1997
Thailand	-	Site suitability for shrimp Culture.	Shrimp, *P. monodon*	Jarayabhand	1997
U.S.A	100 x 100m	Habitat suitability model for Anchovy, spotted seatrout and pinfish.	*Anchoa mitchilli* *Cynoscion nebulosus* *Logodon rhomboides*	Rubec *et al.*	1998
Africa	5km x 5km	Continental assessment for warm water fish culture of tilapia, catfish and carp.	Tilapia, catfish and carp	Aguilar and Nath	1998
Bangladesh	30m x 30m	Suitable site for brackish water shrimp & freshwater prawn and fish culture.	Carps and freshwater Prawn, *M.rosenbergii &* Shrimp, *P. monodon*	Salam and Ross	1999

Applications of GIS to fisheries can take many forms although there are limited examples of its use. It is convenient to categorise them first as applications in capture fisheries and in aquaculture. For capture fisheries, GIS can deal with the spatial aspects of the three main fishery "realms", both individually and collectively - the environment, the fishery resources and the fisheries. GIS using information from a variety of sources, including passive and active remote sensing, can predict where the fish will be, can be used for management, control and surveillance (e.g. monitor fishing) and can optimise fishing operations such as trade-offs between distance to fishing grounds and markets (Isaak and Hubert, 1997; Rubec *et al.* 1998).

In aquaculture, GIS has been used to forecast development prospects using suite of parameters that vary geographically. Basically, this kind of application reduces to two broad questions: a) what is the suitability of any given area for the culture system (e.g., soil suitability for the construction of fishponds) and b) what is the suitability of an area for fish growth (e.g. favourable temperature regime). Another GIS application is for the management of expanding aquaculture in the context of other, competing uses of land and water (Kapetsky *et al.* 1990).

GIS models can be based on very large or very small areas, with appropriately different spatial resolutions used for different purposes. Several regional investigations of aquaculture potential have been made, particularly for Africa and Latin America, using relatively simple environmental and resource availability models (Kapetsky, 1994; Kapetsky and Nath, 1997; Aguilar and Nath, 1998). A number of national or state level investigations have been conducted successfully, based on a wide range of data on environment, infrastructure, resource availability and socio-economics (Aguilar and Ross, 1995). Further, characteristics of various attributes could then change over time to determine the probable impacts of changing circumstances, such as the effects of drought, the rise or fall of domestic or world market prices, or the development of additional roads (FAO, 1999).

Site selection issues range from meso-scale decisions to very local ones. GIS models based on environmental and system considerations have been shown to be an excellent tool for detailed facility location, once a preliminary choice of site has been made (Ross *et al.* 1993). In conjunction with remote sensing and direct data collection, GIS can also form the basis for continued monitoring of a site (Chacon-Torres *et al.* 1992; Isaak and Hubert, 1997).

Several authors have shown the modelling capability of GIS for specific site selection for aquaculture. These studies have been on a regional, country wide and also continental basis for cultured species. Krieger and Mulsow (1990) used GIS to develop siting models for mussel culture in the sub-tidal regions of Yaldad Bay, Southern Chile. Harper *et al.* (1990) also used GIS to model the potential and critical spawning habitat on the Lake Ontario littoral-zone between the town of Grimsby and the Niagara River. Habbane *et al.* (1997) integrated GIS and remote sensing image for siting areas suitable for mussel aquaculture in Bate des Chaleurs, Eastern Canada. They used several environmental characteristics such as water temperature, salinity, current speed and chlorophyll-a pigments for this GIS model.

Meaden (1987) carried out a detailed study of locations for potential sites of trout (*Oncorhynchus mykiss)* farms, using a spreadsheet approach in England and Wales. Sixteen different spreadsheets were developed as map layers with production functions. The layers were weighted according to feedback from established trout farms in Britain for the final result. Based on all the information layers, Meaden's model identified new areas, where trout farming is not carried out and others, which showed limited growth potential. The outcome was in spreadsheet representation; however, the study did not use any GIS package rather than the principle. Moreover, Pauly *et al.* (1997) developed software, B: RUN based on common spreadsheet for data entry and production of low-level geographic information system. It has been used to assess stock dynamics of demersal fishes, oil spills in the Ocean and fleet operations in the coastal waters of Brunei Darussalam.

Likewise, the basis of GIS modelling is to illustrated in a very simple example, where spreadsheet simulation was used to develop a simple GIS for carp culture in Pakistan (Ali, 1991). In this case seven environmental variables were used to indicate areas appropriate for carp culture on a macro-scale across the whole of Pakistan.

An early application of GIS in aquaculture for catfish (*Ictalurus punctatus*) farming was undertaken by Kapetsky *et al.* (1988). GIS was used to identify and inventory areas which were physiographically suitable for further extension of catfish farming, based on soil characteristics and susceptibility to flooding, in Louisiana state, USA. The region had, over 1,000 ha of farms producing nearly 1,000 tons of catfish from 40 different sites in 1986. A good correspondence was obtained between the locations of existing catfish farms and suitable locations determined by the GIS. The potential use of GIS for assisting the location of new sites was very encouraging. **Figure 1.10** illustrates the outcome of GIS modelling by Kapetsky *et al.* (1988) in Louisiana State, USA.

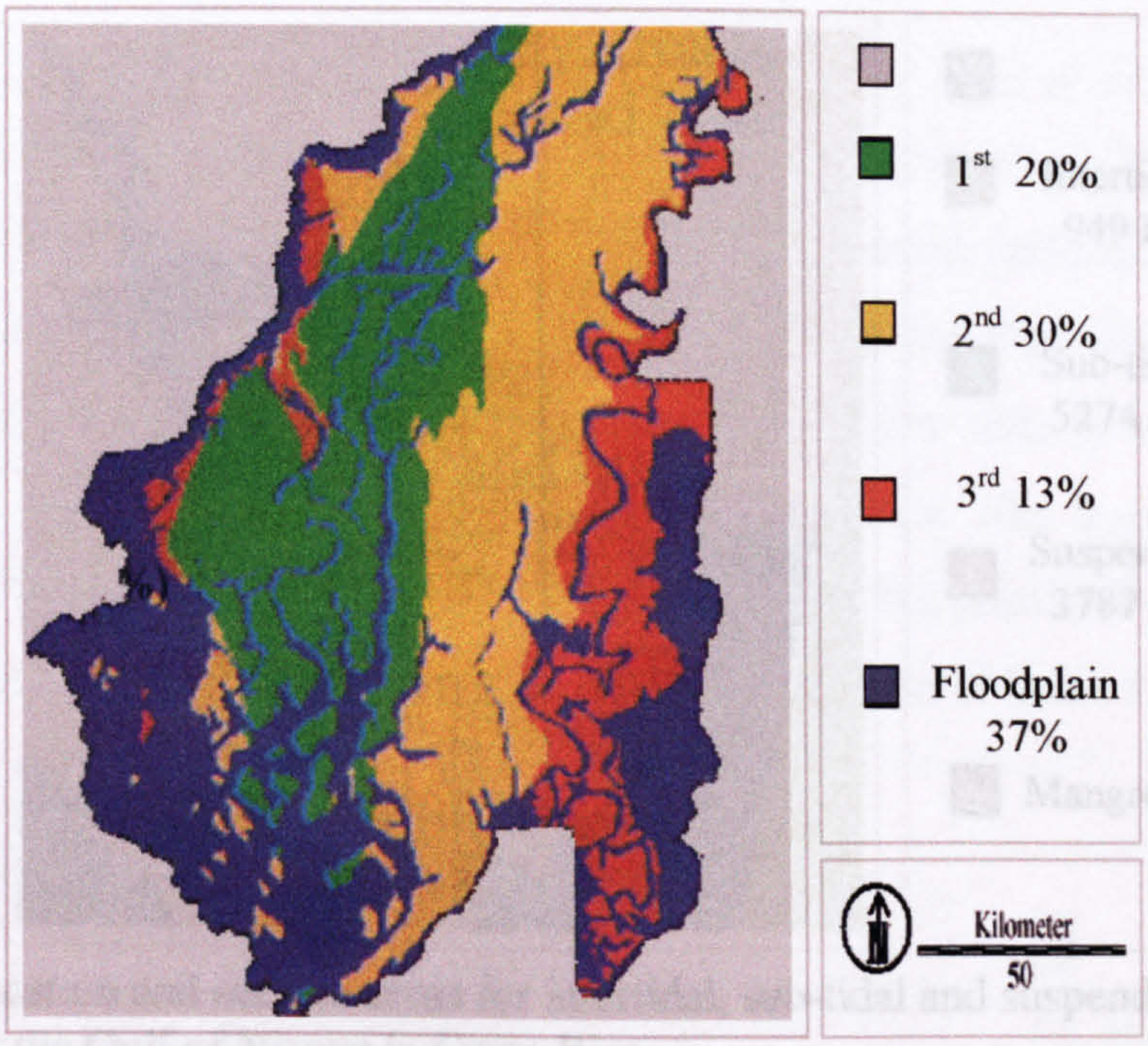

Figure 1.10. The suitability of soils for catfish farming which is outside of 100 years flooding.

Kaptsky *et al*. (1987) carried out a study in Costa Rica, using GIS and remote sensing techniques for expansion of aquaculture in the Gulf of Nicoya. They used Earth Resources Laboratory Applications Software (ELAS) to find the most suitable area for aquaculture development in the inner Gulf and inland. Two types of criteria were used in the study: common criteria (water quality, infrastructure and salinity) and specific criteria (site acquisition, site development costs and proximity to salt water and perennial rivers). Moreover, proximity to the water-mangrove interface was used as an indicator of post larvae abundance. Special criteria for mollusc culture were bathymetry, shelter and security. The results of the study indicated that 14% of the inner gulf area of 72,600 ha was suitable for mollusc culture. Twenty out of eighty existing solar salt ponds were suitable for extensive shrimp farming, representing an area of 150 ha out of total area of 656 ha. A land area of 2,232 ha was found to be suitable for semi-intensive shrimp farming. However, according to the authors the results were indicative and can be used for general planning purposes only. **Figure 1.11** showed the result obtained in this study.

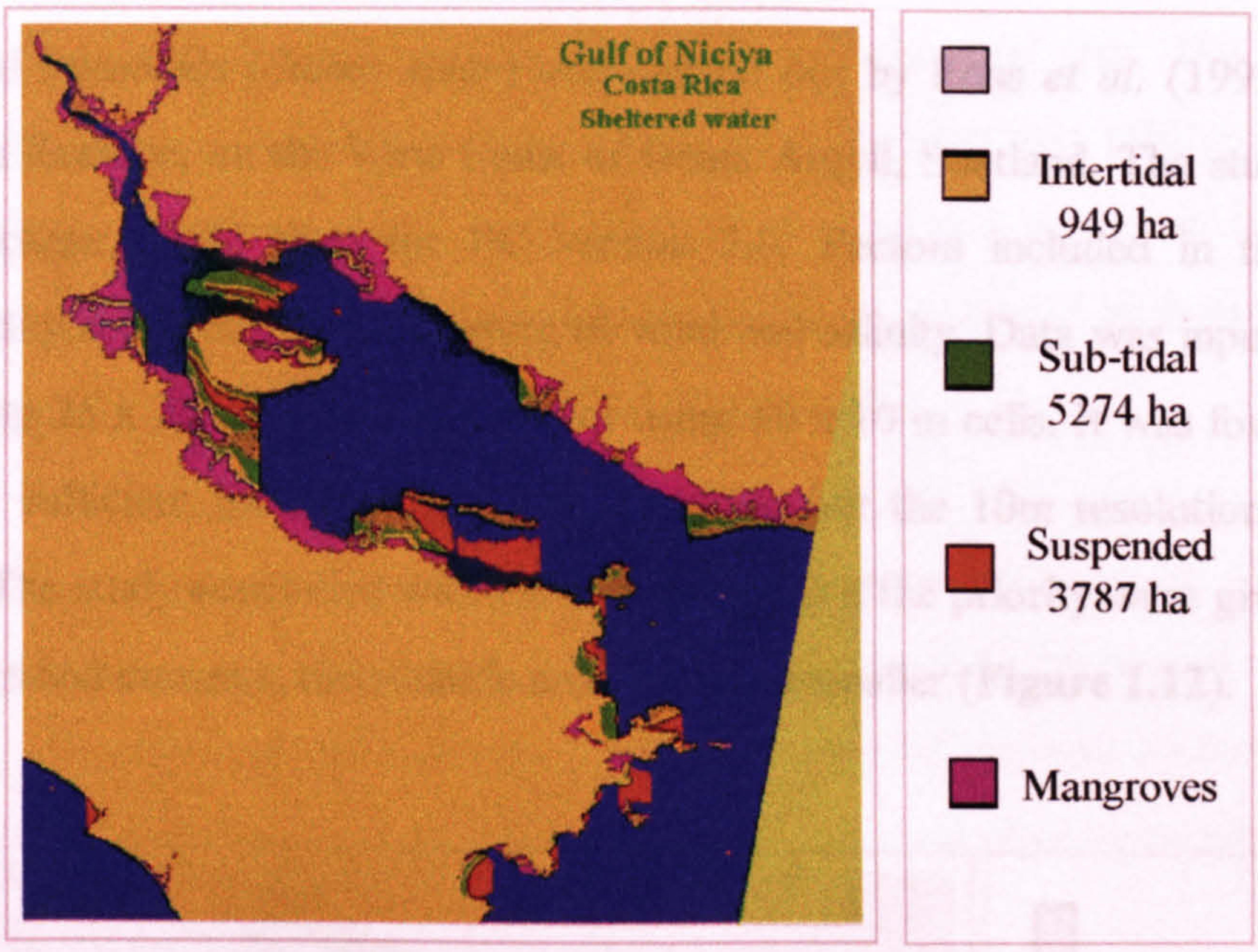

Figure 1.11. Location and surface areas for intertidal, sub-tidal and suspended mussel culture in the Gulf of Nicoya in Costa Rica.

Another dynamic work was done by Kapetsky (1989) in Johor State, Malaysia for further expansion of shrimp culture in ponds and fish culture in cages, using GIS and remote sensing techniques. Several environmental and infrastructural parameters were used to identify the potential sites for shrimp farming as well as cage culture. About 193,000 ha of coastal land were within easy reach of water sources for shrimp farming in the state but only 6% of this land were suitable according to soil texture and pH. On the other hand, only 12% of the state's coastal water were suitable for cage culture, although most of the water body is well sheltered.

A similar GIS application in the field of integrated aquaculture study was taken by Kapetsky *et al.* (1990), for catfish (*Ictalurus punctatus*), and crawfish (*Procambarus clarkii*) and crawfish/rice and crawfish/grain sorghum double cropping systems in the Louisiana State, USA. The GIS modelling showed that there were ample opportunities for the expansion of catfish farming on the flatlands based on soil suitability and length of the growing season. The study also showed that crawfish culture occupied most of the best suited soils and included those with the longest growing seasons. The potential to further integrate crawfish with rice and with grain sorghum in double cropping systems was good. The results demonstrated that a GIS could be used to aid large area aquacultural planning.

Cage culture of salmonids (*Salmo salar*) was carried out by Ross *et al.* (1993) in a small bay Camas Bruaich Ruaidhe, on the West Coast of Oban, Argyll, Scotland. The study used a raster-based GIS package, OSU Map for PC version 3.0. Factors included in the analysis were topography, bathymetry, currents, exposure to wind and salinity. Data was input in two different scales, one using 25 x 25 m cells and the other using 10 x 10 m cells. It was found that the 25 m resolution was sufficient for siting a raft of 20 cages, but the 10m resolution was needed for smaller cases. The study concluded with the comment that if the priority were given to reverse the weight of waves and currents, the suitable area would be smaller (**Figure 1.12**).

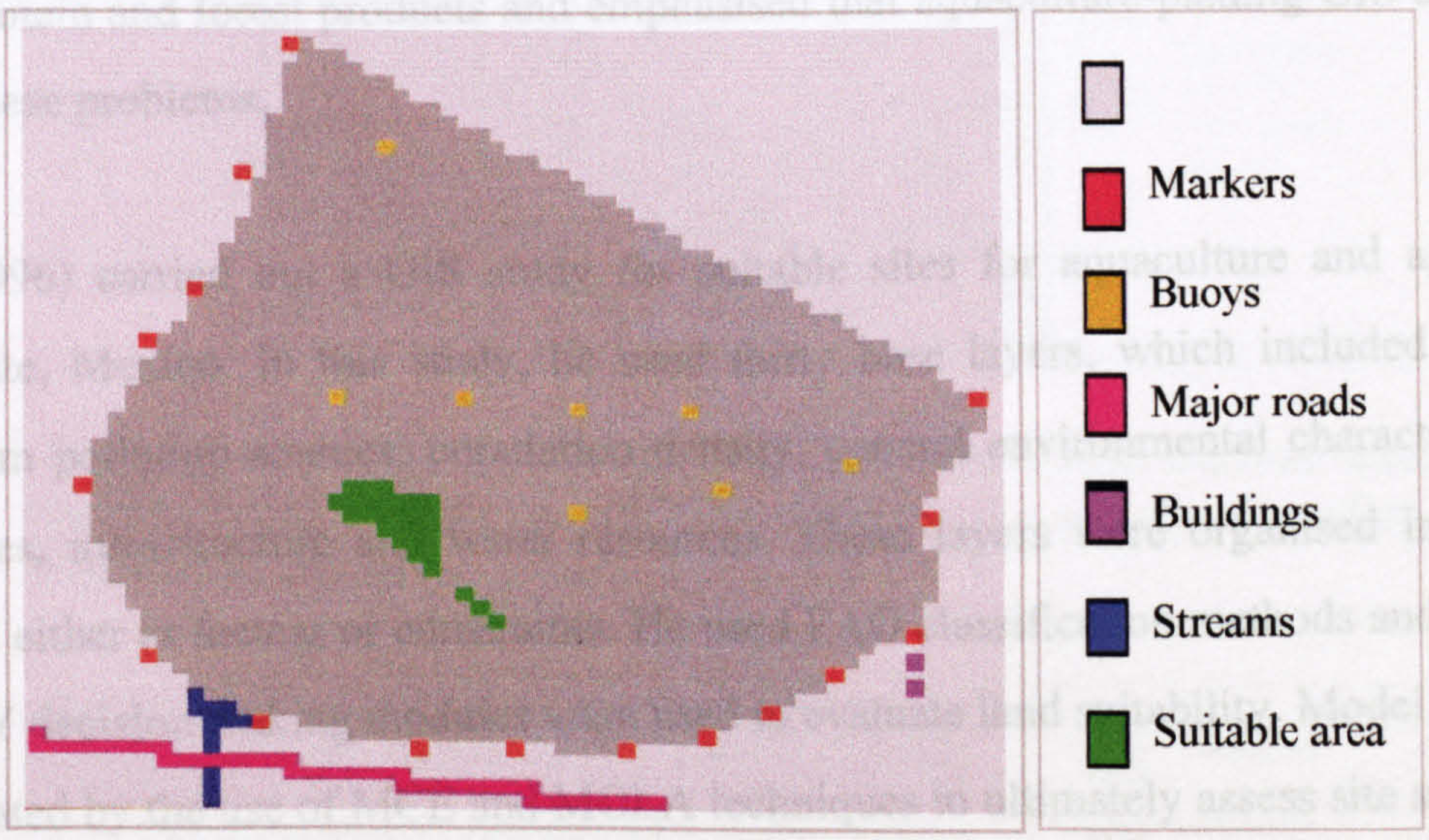

Figure 1.12. The salmonid cage culture potential in the Camas Bruaich Ruaidhe bay, on the West Coast of Oban, Argyll, Scotland.

Using a Coastal zone management program called LENKA a Nation wide assessment of the suitability of the Norwegian coastal zone and rivers for aquaculture was carried out by Ibrekk *et al.* (1993). The program aim was to develop an efficient and standardised tool for coastal zone planning. As part of this, a methodology for assessing the suitability of marine waters for aquaculture was developed. The main steps in the development of the capacity assessment were as follows: (1) An assessment of the maximum acceptable organic loading of the water body of the marine areas, which is arrived at by subtracting the existing inputs of organic loading and nutrients from the natural capacity of the area to tolerate organic loading and nutrients. (2) An assessment of the area available for aquaculture development, which is arrived at by subtracting all unsuitable areas and all areas already, occupied from the total area. The LENKA program all unsuitable areas and all areas already, occupied from the total area. The LENKA program showed that 9% of the Norwegian coastal water are suitable and available for aquaculture purposes using the techniques. The annual production of salmon and trout, which in 1990 was 161,000 tones, and according to their prediction it could be increased by approximately 600,000 tones without causing detrimental effects on the environment.

In a study of a small area of northern Luzon, Philippines, Paw *et al.* (1992) showed the usefulness of GIS in planning for better management. They zoned the coastal areas to protect the natural ecology, which were suffering from severe ecological pressure because of the needs for both fish protein and forest products and emphasised that aquaculture-planing GIS could help to minimise these problems.

Aguilar (1996) carried out a GIS study for suitable sites for aquaculture and agriculture in Sinaloa State, Mexico. In this study, he used thirty base layers, which included information ranging from pollution sources, population density, general environmental characteristics, land use practices, infrastructure and water resources. These layers were organised in 14 criteria, represented either as factors or constraints. He used FAO classification methods and BOOLEAN and FUZZY decision making modules were used to evaluate land suitability. Model outputs were then integrated by the use of MCE and MOLA techniques to ultimately assess site suitability and resolve land use conflicts relevant to aquaculture and agriculture activities (**Figure 1.13**).

Production outputs from potential systems can be calculated within GIS by making simple assumptions of performances. This also makes possible to further develop the model by using relatively simple models of fish growth as modules external to or additional to a GIS package. The data produced can then be used to map potential annual yield. This approach was used in a continental study of Latin America (Kapetsky and Nath, 1997) and was further refined for a study of the African continent (Aguilar and Nath, 1998). In both cases the POND model was used (Bolte, Nath and Enst, 1995) which depends upon relatively few variables including fish weight, food availability, photoperiod, temperature, D.O and ammonia levels. Using this method, basic suitability outcomes over a large area were enhanced by assigning potential yields in terms of crops per year for tilapia and African catfish culture (**Figure 1.14** and **Figure 1.15**).

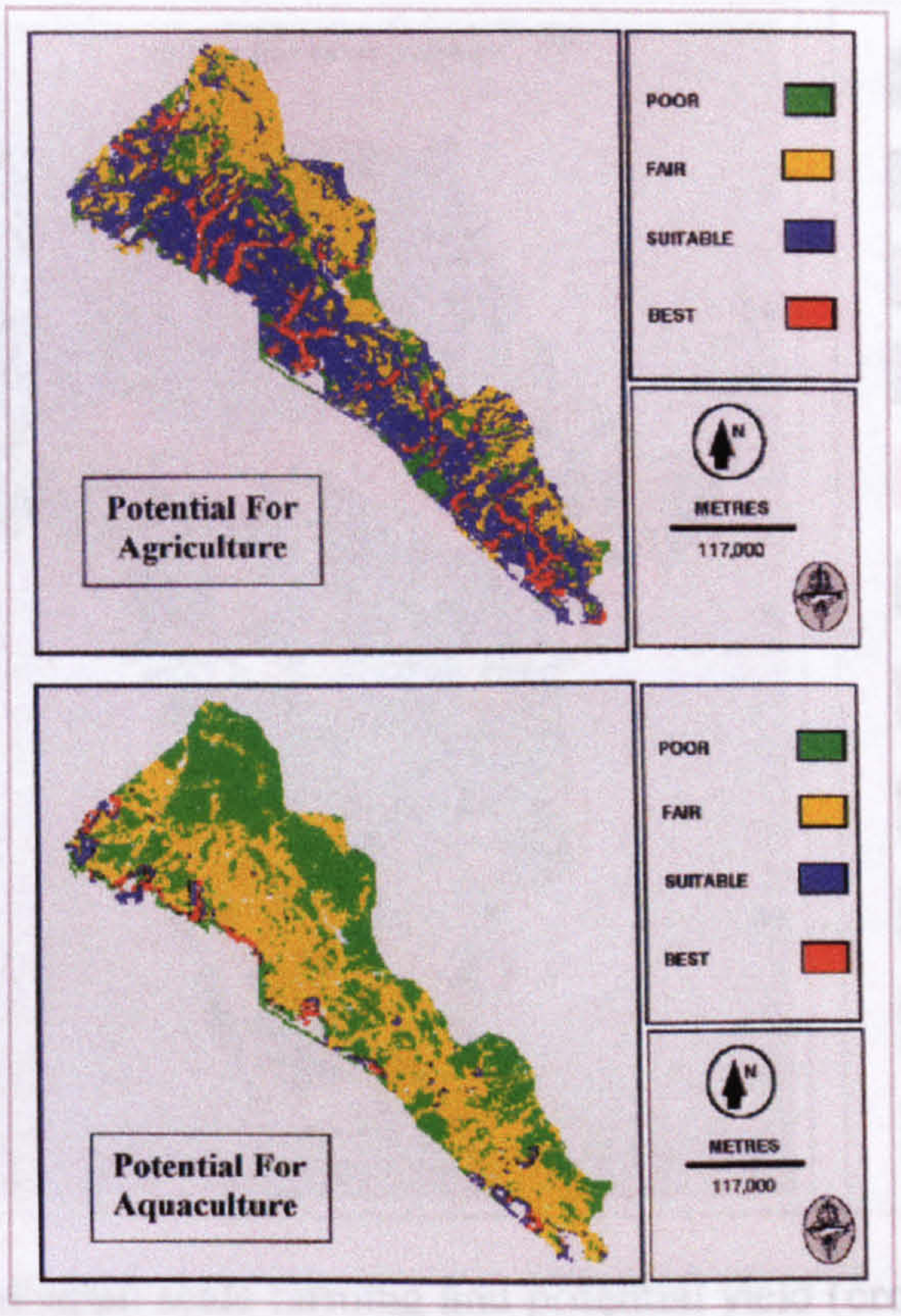

Figure 1.13. A hierarchical modelling scheme using MCE and MOLA to evaluate suitability of locations for aquaculture and agriculture and resolve associated conflicts, in the Sinaloa State, Mexico.

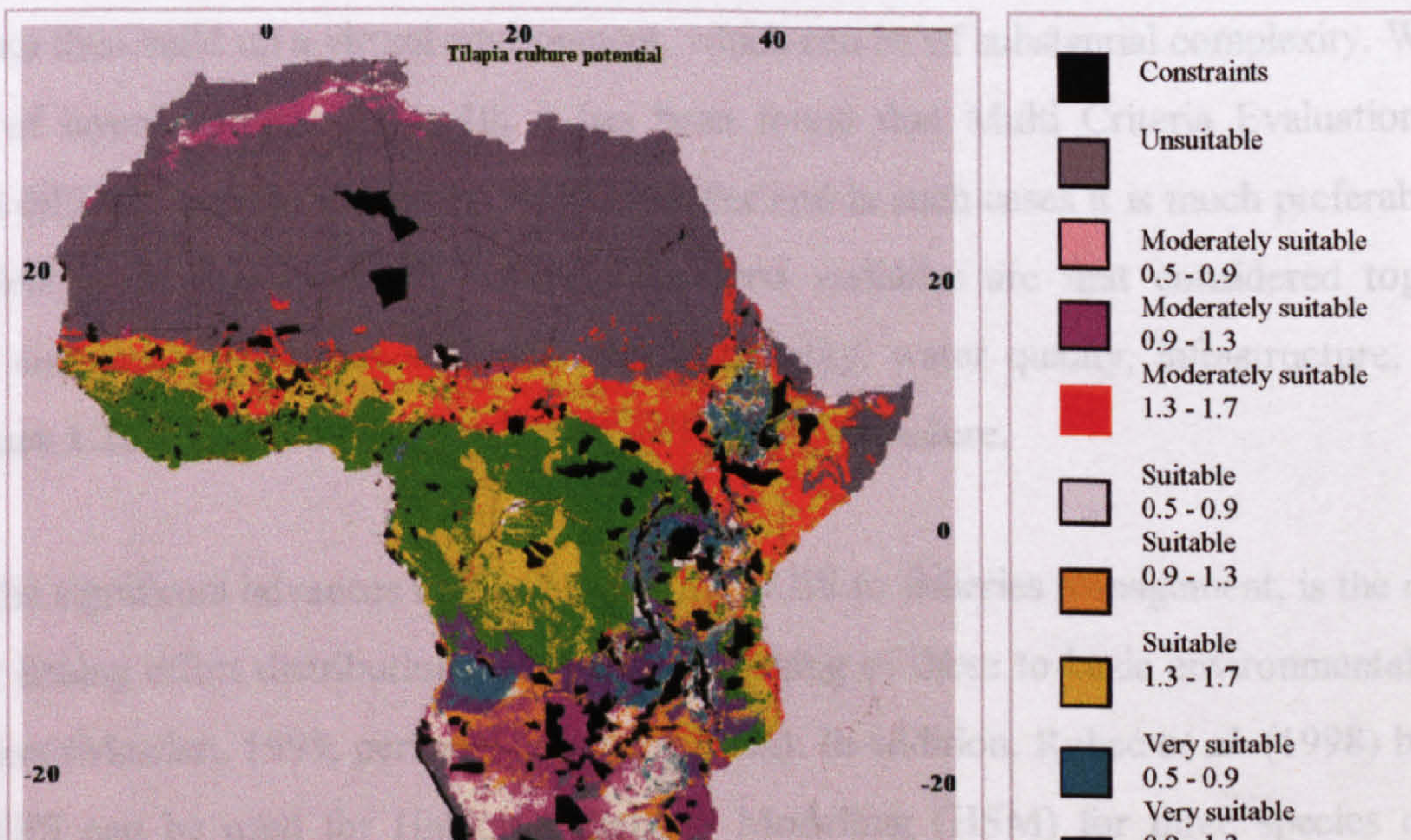

Figure 1.14. Suitability of small scale farming and potential yield (crops/y.) of Nile tilapia culture in Africa (after: Aguilar and Nath, 1998).

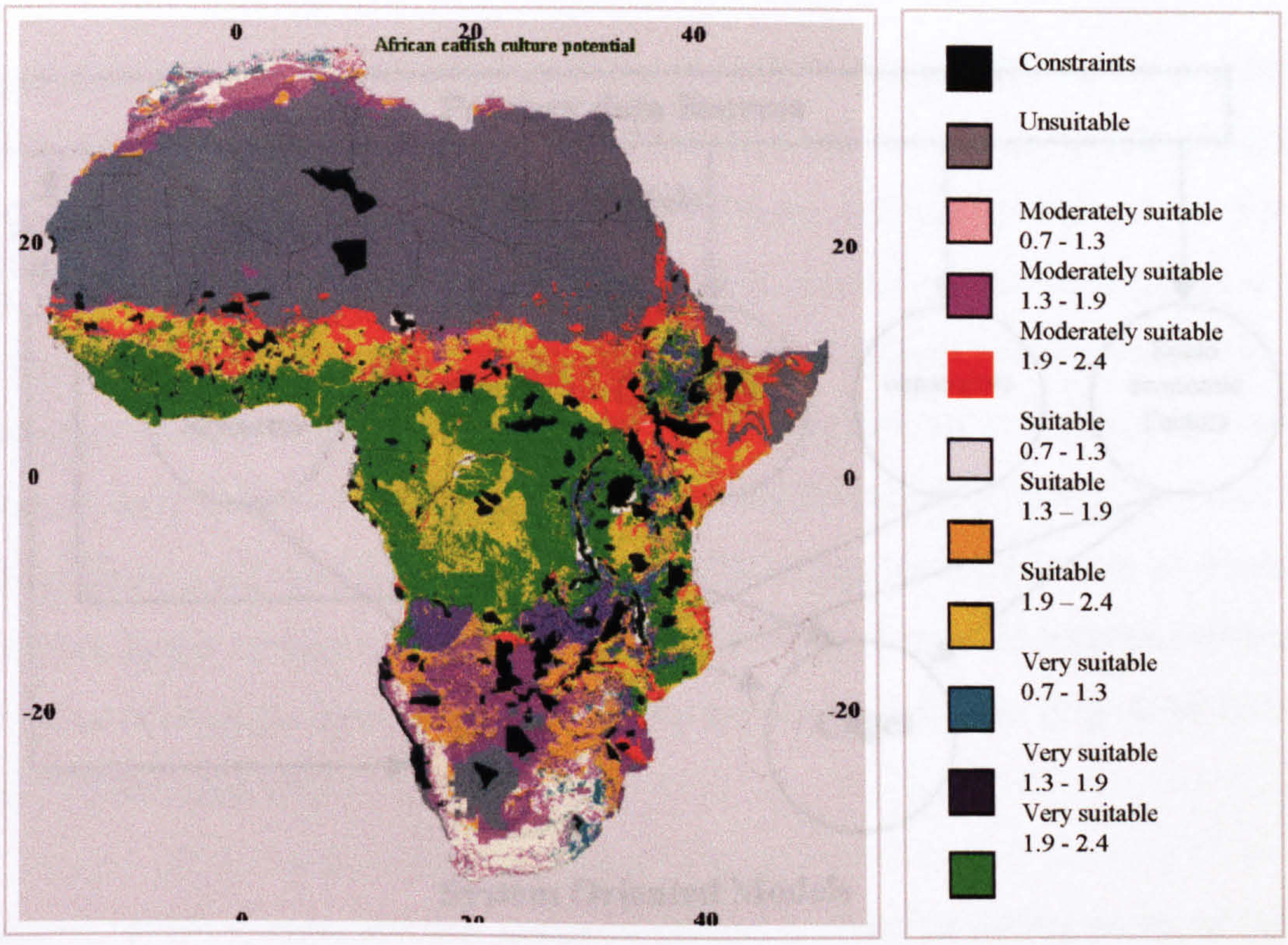

Figure 1.15. Suitability of small scale farming and potential yield (crops/y.) of African catfish culture in Africa (after: Aguilar and Nath, 1998).

Ross (1998) mentioned that comprehensive representation of the real world in a GIS database might result in a large number of source variables, which are then processed into GIS layers. These data then build up a virtual environment, which can be of substantial complexity. Where the number of layers exceeds about 10, it has been found that Multi Criteria Evaluation (MCE) becomes difficult, even to the experienced modeller and in such cases it is much preferable to use sub-modelling. In this approach, naturally grouped variables are first considered together to produce sub-model outcomes such as water availability, water quality, infrastructure, markets, etc. **Figure 1.16** illustrated the flowchart of sub-model procedure.

One of the significant advances in the application of GIS to fisheries management, is the mapping of catch or fishing effort distributions, and in the matching of these to basic environmental or habitat parameters (Meaden, 1999, personal communication). In addition, Rubec *et al.* (1998) have shown how a GIS can be used for Habitat Suitability Modelling (HSM) for three species of anchovy (*Anchoa mitchilli*), spotted seatrout (*Cynoscion nebulosus*) and pinfish (*Logodon rhomboides*) in the Florida Bay, USA (**Figure 1.17**). Indeed, these habitat suitability models, when linked to a GIS, may provide a means of mapping species distributions in these estuaries, which have not yet been surveyed.

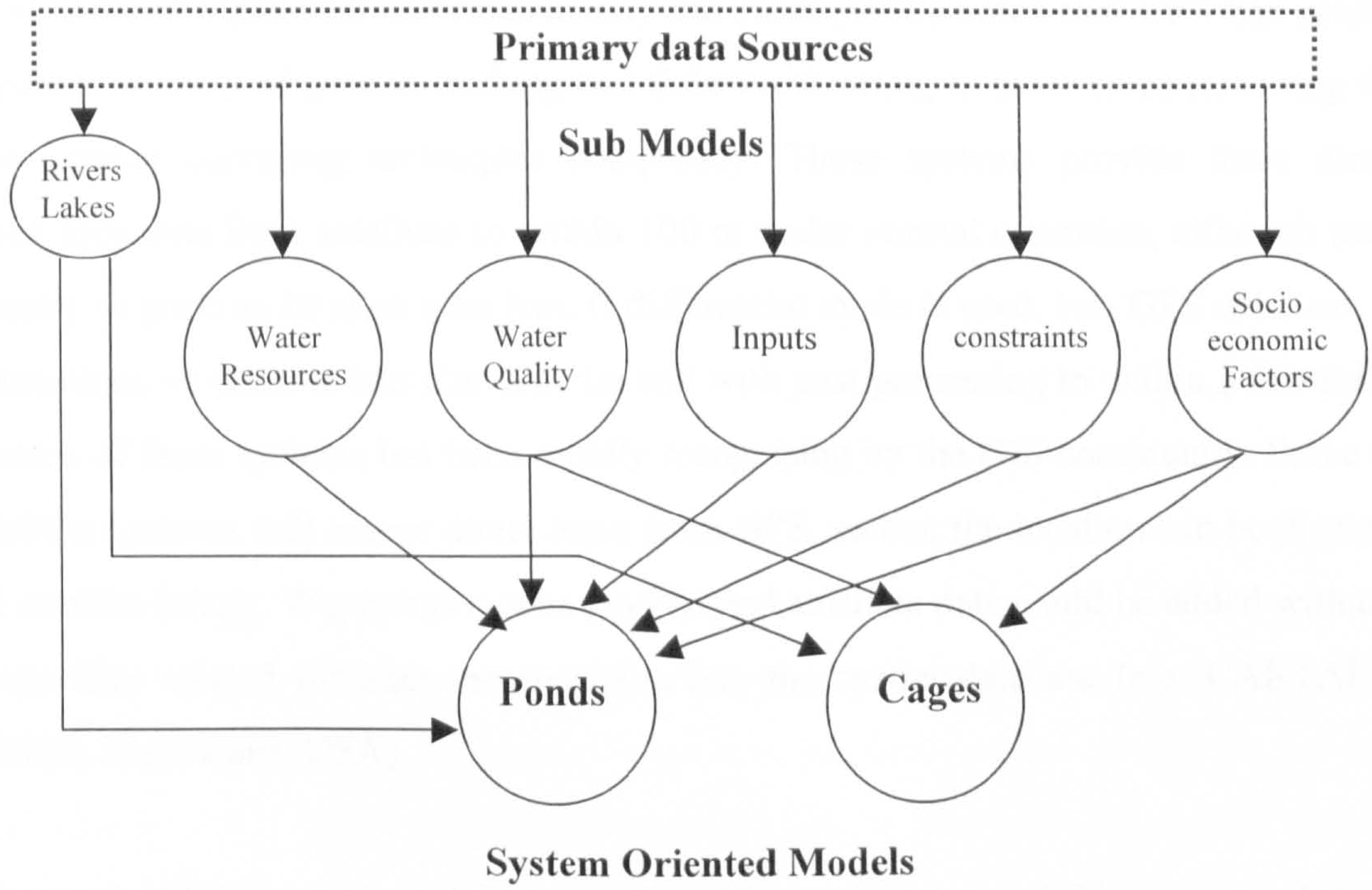

Figure 1.16. Sub-models derived from primary data sources (after: Aguilar and Ross, 1993).

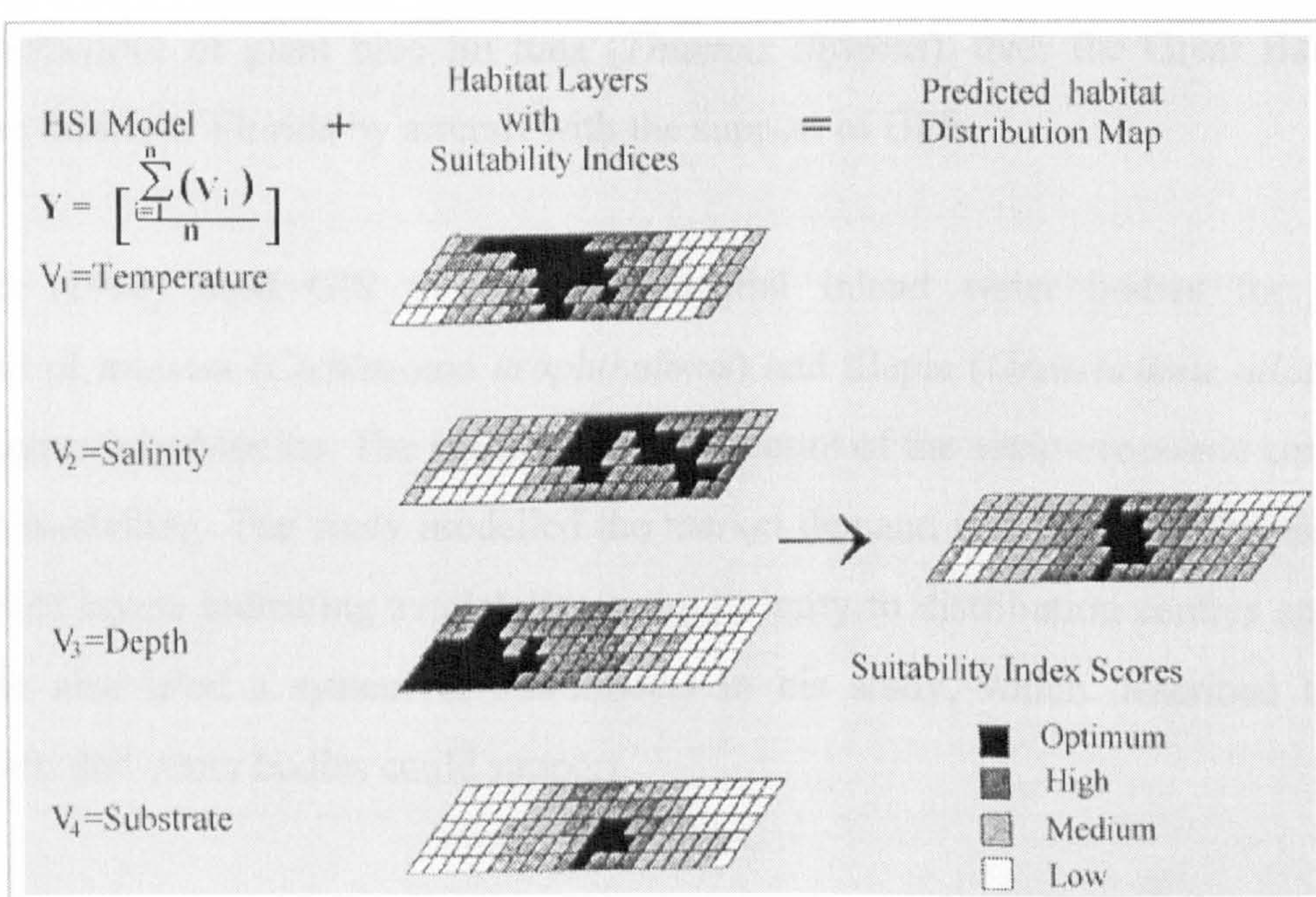

Figure 1.17. The structure of Rubec *et al.* 1998 GIS based "Habitat Suitability" model.

Nath *et al.* (1999, personal communication) and Ross (1998) noted that GPS has greatly aided the spatial accuracy of ground-truthing and field verification, in most cases removing the needs to use optical surveying techniques completely. These systems provide three dimensional position locations from satellites to within 100 m under normal operation, although accuracy is frequently as good as 20 m or even less. If differential mode is used, two GPS units can give real time locations accurate to less than a meter and with post processing to within a few millimeters. The value of these systems has been rapidly recognising by the GIS community. Some GIS data acquisition systems will accept direct input from GPS, so that the location can be displayed over a real satellite image. Waypoints can be marked and attribute data could be added with automatic attribute files created for later incorporation into the spatial database (e.g. CARTALINX and IDRISI32, Clark Labs, USA).

Robins *et al.* (1998) investigated the impact of GPS on the relative fishing power of the northern prawn fishery fleet on tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) from commercial catch data. They reported that the boats that used a GPS alone had 4% greater fishing power than boats without a GPS. Likewise, Lutcavage, *et al.* (1996) surveyed the apparent abundance and migration behaviour of giant blue fin tuna (*Thunnus thynnus*), over the Great Bahama Bank region of the Straits of Florida by aircraft with the support of GPS.

Flores-Nava (1990) used GIS to identify potential inland water bodies for aquaculture development of mojarra (*Cichlasoma urophthalmus*) and tilapia (*Oreochromis niloticus*) in the Yucatan Peninsula in Mexico. The study took into account of the socio-economic components in aquaculture modelling. The study modelled the market demand and social environment through the creation of layers indicating availability and proximity to distribution centres and extension services. He also used a system of sub-models in his study, which described the level of intensification that water bodies could support.

Socio-economic factors have a large influence over the development of aquaculture, as recently recognised and reviewed by various authors (Aguilar and Ross, 1993; Born *et al.* 1994; Primavera, 1997). Gutierrez Garcia (1995) in a GIS based socio-economic model for Tabasco State, Mexico, identified the most important socio-economic factors that influence aquaculture development and grouped them into logically associated factors in three sub-models: social factors, production modifiers and markets (**Figure 1.18**). Her base model can be adapted according to the situation for other GIS based aquaculture models.

In the past 10 years, geographic information systems have been widely used in urban and regional planning in developed countries, such as Australia, North America and Europe. However, the use of GIS in urban and regional planning in the developing countries is limited and still at an early stage of development. In developing countries, GIS has degrees of use and is at different stages of development (Yeh, 1991). Some countries have developed more comprehensive GIS and have more experience in using GIS than others. It is expected that within a few years there will be a significant increase in the installations of GIS in the developing countries (Yeh, 1991). Today these countries are seeking to use this technology for their planning and development programmes, but it has been greatly hampered for financial reasons. Consequently, as it is imported technology from the developed world, GIS has been approached by developing countries with both optimistic acceptance and pessimistic rejection (Perera and Tateishi, 1995). This is now set to change to a system where CD data become more widely available.

GIS are more developed at the regional level than at the national or urban levels, since the former are much easier to develop than national or urban GIS. A national GIS is very expensive and involves much organisation and co-ordination to develop. It also depends upon a good and reliable telecommunications network, which is not always assured in many developing countries. Most countries are at an early stage of the development of GIS. They are still experiencing difficulties with their setting up and management or applications and are not ready yet to develop a national GIS (Yeh, 1991).

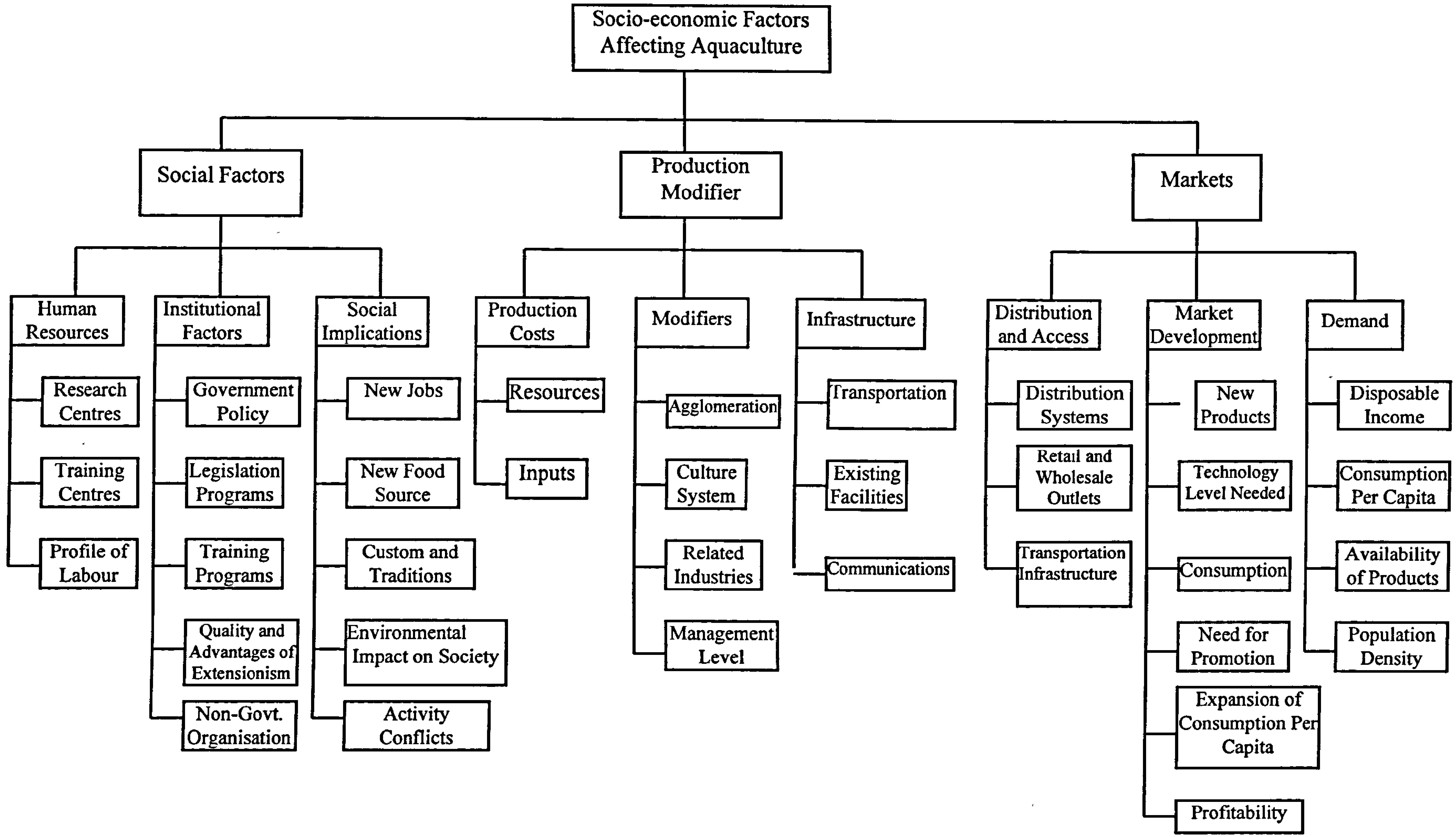

Figure 1.18. Schematic diagram of socio-economic factors sub-models which affecting aquaculture (after: Gutierrez Garcia, 1995).

Asia promises to be one of the boom markets for the Geographic Information industry. Throughout Asia GIS is being recognised as an essential tool to complete base mapping to enable property normalisation, and as an important component in planning, infrastructure development, asset monitoring, urban development and natural resource management (Grant and Krogh, 1995). GIS is being set up to manage the rapidly growing metropolitan areas such as Bangkok, Guangzhou, Hong Kong, Manila, Singapore and Dhaka. Moreover, GIS and remote sensing technologies are being developed in Southeast Asian countries such as Laos, Thailand and Vietnam to meet a growing demand for up to date information in resource management and environmental protection. Major GIS and remote sensing facilities are available in Bangkok, Thailand, in the headquarters of United Nations organisation that conducts research and develops projects in the lower basin of the Mekong River (Michelson, 1993). However, GIS data on aquaculture development in Asia is still relatively sparse.

The application of GIS in Bangladesh started only a few years ago in the early 1990s. GIS is now being used in Bangladesh for planning and development purposes both in physical and human resource sectors. Since the introduction of GIS in Bangladesh, its use and application has broadened. In 1991, there were only five operational GIS used by various organisations but by 1998 there were about 30 installations in the country, about half of these being operational (**Table 1.7** and **Table 1.8**). Almost all of these GIS installations are donor supported, maintained, and operated by foreign experts, with limited local personnel. Most of the installations are project oriented and there are very few establishments to develop the skills of local experts in Bangladesh except the Universities. The Department for International Development (DFID) of the UK government has used funds to develop an academic and research base in GIS and also to develop a GIS training and resource centre at Jahangirnagar University, Dhaka. Other than this, only a few GIS firms are in operational stage in the private sector.

In Bangladesh, application of GIS and remote sensing techniques for planning and managing fisheries and aquaculture are still new. Remote sensing techniques have been used to assess the impact of shrimp culture activities on mangrove ecosystems in the coastal region of Bangladesh (Quader, 1987). At the same time, satellite images were used to determine the surface features of water dynamics of the Bay of Bengal. NOAA AVHRR and Landsat TM data were used to detect the flood in 1988, which inundated two-third of Bangladesh land and created world-wide attention to the matter (Giri and Shresthra, 1996). Low altitude photographs, thematic map data and Landsat MSS digital data were used to identify, locate and classify shrimp farms along the Bangladesh coast (Shahid *et al.*1992 and 1997).

Haque *at al.* (1997) used GIS technology for potential coastal shrimp farming area selection in a small area in Khulna, Bangladesh. They used only overlay techniques in the their study. Another GIS study was carried out by EGIS (1997) for floodplain fish habitat study and monitoring in Tangail district Bangladesh principally based on database query in Arc-View. GIS would be an appropriate technology to prepare future generations of natural resource specialists and flood hazard managers which could considerably affect the future decisions of the people of Bangladesh (Rosenfeld, 1994).

Table 1.7. Summary of Major Organization having GIS facilities in Bangladesh

Host Organisation	Sponsor/Donor Agencies	Major Hardware	GIS Software/ Books	Year started
Department of Geography and Environment, Jahangirnagar University	Jahangirnagar University, Durham University (UK) ODA, ESRI ICIMOD, UNFPA/ Population Council	486DX2/Pentium Computers, Optical drive, CD Drive, Tape Drive, Printer, Scanner, GPS, Multimedia	PC Arc/Info for DOS, PC Arc/Info for Windows, Arc View, Erdas Imagine, Idrisi, Stata, Pop Map, HG, with manuals and books on GIS	December 1992
Department of Geography and Environment, University of Dhaka	Dhaka University, ESRI/ UNFPA/ Population Council	486DX2/ 586 Computers, Digitizers, Plotter, CD Drive, Printer, Scanner, GPS	PC Arc/Info for DOS, PC Arc/Info for Windows, Arc View, Idrisi for windows	July, 1993
Bangladesh Bureau of Statistics (BBS)	UNFPA, CIDA, World Bank, ADB, The Netherlands Government	PS/2 Model 9595 Pentium, CD ROM, Multimedia	PC Arc/Info, SPANS, Views, PopMap	June,1995
Bangladesh Centre for Advanced Studies (BCAS	The Netherlands Government	386/486 Computers, Plotter, Digitizers, Laser Printer,	PC Arc/Info, Idrisi	June 1993
CDA, Ministry of Works	UNDP and UNCHS (Habitat)	486 Computers, CD ROM, Plotter, Digitizers, Printer,	Arc/Info, Arc View,	February 1994
Development Design Consultants Ltd. (DDC)	DDC Ltd.	Pentium Computers, Laser Printer, GPS Receiver, Digitizers, Plotters, Scanner	PC Arc/Info, PC TIN ArcCAD, Arc View, Idrisi, MapInfo	September 1991
Local Govt. Engineering Department (LGED)	UNDO, ICIMOD, SIDA / NORAD	486 Computers, Digitizers, Pen Plotters, Printer,	Arc/Info, Arc View	November 1992
Ministry of Agriculture (MoA)	IDA/EEC	486 Computers, Optical Disks, Digitizer, Plotter, Colour Printer, Tape Drive, Printer	PC Arc/Info,	September 1994
RAJUK (Ministry of Works)	UNDP and UNCHS (Habitat)	486 Computers, CD ROM, Tape Drive, Plotter, External HD, Laserjet printer	Arc/Info, Arc View	February 1993
Space Research and Remote Sensing (SPARRSO) Ministry of Defence	UNDP and FAO	486 Computers, Tape Drive, Cipher GCRC Cache, Nine Track reel to reel; Drive, Archine Drive, Tektronix Printer, Plotter, Digitizers etc.	PC TIN, PC Arc/Info, Erdas	December 1991
Forest Department (FD)	UNDO- World Bank	PC586/486DX2, Plotter, Printer, Digitizer, Scanner	PC Arc/Info,	1995
Soil Resources Department Institute (SRDI, MoA)	DANIDA	Pentium. SUN SPARC, Classic X, Plotter, Printer, Digitizer SUN	Arc/Info Unix, PC Arc/Info , Arc View,	1995
Department of Geography and Environment, Rajshahi University	Rajshahi University, UNFPA/ Population Council	486 computers, Printer, Digitizer,Plotter etc.	Idrisi, MapInfo, PopMap	1993
ISPAN/EGIS	The Netherlands Government	Alpha Work Station , Pentium/486 Computers, Plotter, Printer, Digitizer, Scanner, Tape Drive, GPS	Arc/Info , Arc View, PC TIN, Erdas Imagine, Idrisi, Earth View, Surfer and Lantastic Network	1991
Department of Environment (DOE)	Government of Bangladesh, and others	486DX2 Computers, PENT90, SUN-WS, Printer, Digtizer, Plotter, Scanner	Arc/Info , Arc View, Idrisi, WS-Imagine	1994
Surface Water Modelling (SWMC), River Research Institute (RRI)	DANIDA	HP Workstation Printer, Digtizer, Plotter,	Arc/Info , Arc/Info for HPUX (with grid)	1994
National Minor Irrigation Project (NMIDP), Ministry of Agriculture	Ministry of Agriculture	486DX, Printer, Digtizer, Plotter, Scanner	Arc/Info, Idrisi, AutoCAD, Arc View	1993
Department of Urban and rural Planning, University of Khulna	University of Khulna, UNFPA/ Population Council	486DX12 Computers, Printers, Digtizer, Plotter, etc.	PC Arc/Info, PopMap, Idrisi, Arc View	1992-93

Source: Rashid and Ali (1997)

Table 1.8. Major Application of GIS in Bangladesh

Organisation	Field of Application	Main Purpose of GIS Installation
BBS	Population Database	to develop census based population and demographic data in GIS format
BBS	Land Information	to develop common database to make and update lowest level (mauza) maps and thematic maps and to develop user service facility
BBS	Decision Making	to develop a national data bank to meet the requirements of planning commission, MP's office, IMED, ERD, finance division and research organisations
BDAS	Resource Management	to assess the vulnerability of coastal areas to climatic change, to implement the GIS applications in environmental, resources management and to become a GIS resource centre for the NGO's in Bangladesh
RAJUK/CDA	Urban Planning	to prepare thematic maps for urban land use planning at scales ranging from strategic (1:50 000) to detailed (1:3960) using spatial and attribute data
FAP 19 and FAP 25	Flood Action Plan	to provide a GIS facility and facilitate the management to data and information needed for Flood Action Plan and to enhance the capability in Bangladesh to utilise GIS for water resources planning and management and also to develop a model for floods in Bangladesh
LGED	Rural Development	to facilitate establishment and maintenance of computerised national data base for implementation of the rural infrastructure development programme
Forest Dept. (FD)	Forest Resources	to prepare forest maps for site specific matching
MoA	Remote Sensing and GIS	to develop institutionalise applications of remote sensing and GIS technology for resource inventory, mapping and disaster monitoring and creation of data bases for planning and management
SPARRSO	Strategic Planning	to develop SPARRSO user-oriented information services by conducting applications sector projects which directly involve SPARRSO and user agencies
Jahangirnagar University	Education, Training and Certificate Course, Research	to develop degree oriented academic curricula at gradute and post-graduate level; to create training opportunities for government and NGO's and also to accomplish collaborative research works with local and foreign organisations and institutions/universities
University of Dhaka	Education, Training and Certificate Course, Research and Service	to develop degree oriented academic curricula at gradute and post-graduate level; to create training opportunities for government and NGO's and also to accomplish collaborative research works with local and foreign organisations and institutions/universities
DDC Ltd.	Consultancy	to provide consultancy in GIS related fields
Rajshahi University	Education, Research	to develop degree oriented academic curricula at gradute and post-graduate level; to create training opportunities for government and NGO's and also to accomplish collaborative research works with local and foreign organisations and institutions/universities
Khulna University	Research, Training	to develop degree oriented academic curricula at graduate and post-graduate level; to create training opportunities for government and NGO's
ISPAN/EGIS	Research, Training, Consultancy	to strengthen the capability of the Ministry of Water Resources and Warpo to plan design and implement environmentally sustainable development programs through the spatial information technology and environmental assessment processes
National Minor Irrigation Project (NMIDP), Ministry of Agriculture	Research	the project supports the expansion of minor irrigation through private sector investment

Source: Rashid and Ali (1997)

Coastal aquaculture is clearly very important for Bangladesh, creating employment, producing protein and generating income. In order to ensure a stable and sustainable development of this sector, it is important that the activity integrates well with all other uses of natural resources and space. Thus, the impact on mangrove must be minimised, or absent, and pollution potential must be low. To achieve this, a more comprehensive approach to development modelling is needed, and GIS provides an excellent tool for this purpose.

This thesis develops this theme, with the following primary objectives:

- to use GIS supported by Remote Sensing to generate models which can be used in aquaculture and fisheries management in the coastal regions of Bangladesh
- to use GIS modelling to explore the range and location of suitable sites for shrimp, prawn, carp, tilapia and crab culture
- to compare the cost effectiveness of shrimp culture and other land uses
- to use GIS modelling to evaluate land use conflicts between shrimp culture and other land uses

The following secondary objectives are also considered.

- to investigate any potential interaction between shrimp culture and the reserve mangrove forest, the Sundarbans
- to use GIS modelling to see the impact on Bangladesh of global warming and sea level rise

Chapter 2

Study area: Khulna, Bangladesh

2.1 Geographical position

The study area is situated at the Southwest end of Bangladesh, where the climate is tropical. Its location is between latitudes 21^0 50$'$ and $24^015'$ North and $89^000'$ and $90^005'$ East longitudes (**Figure 2.1**). The area is bounded in the North by Rajshahi division, Northeast by Dhaka, Southeast by Chittagong, South by Bay of Bengal and in the west by India. It encloses a surface area of 14,000 km^2 comprising of 6 major district towns namely Khulna, Jessore, Satkhira, Narail, Gopalganj and Bagerhat. The area contains an International Seaport at Mongla in Bagerhat, one inland port and one regional airport in Jessore. The area is one of the most promising for aquaculture due to the largest mangrove forest the Sundarbans, which acts as a transitional zone between the fresh and brackish water.

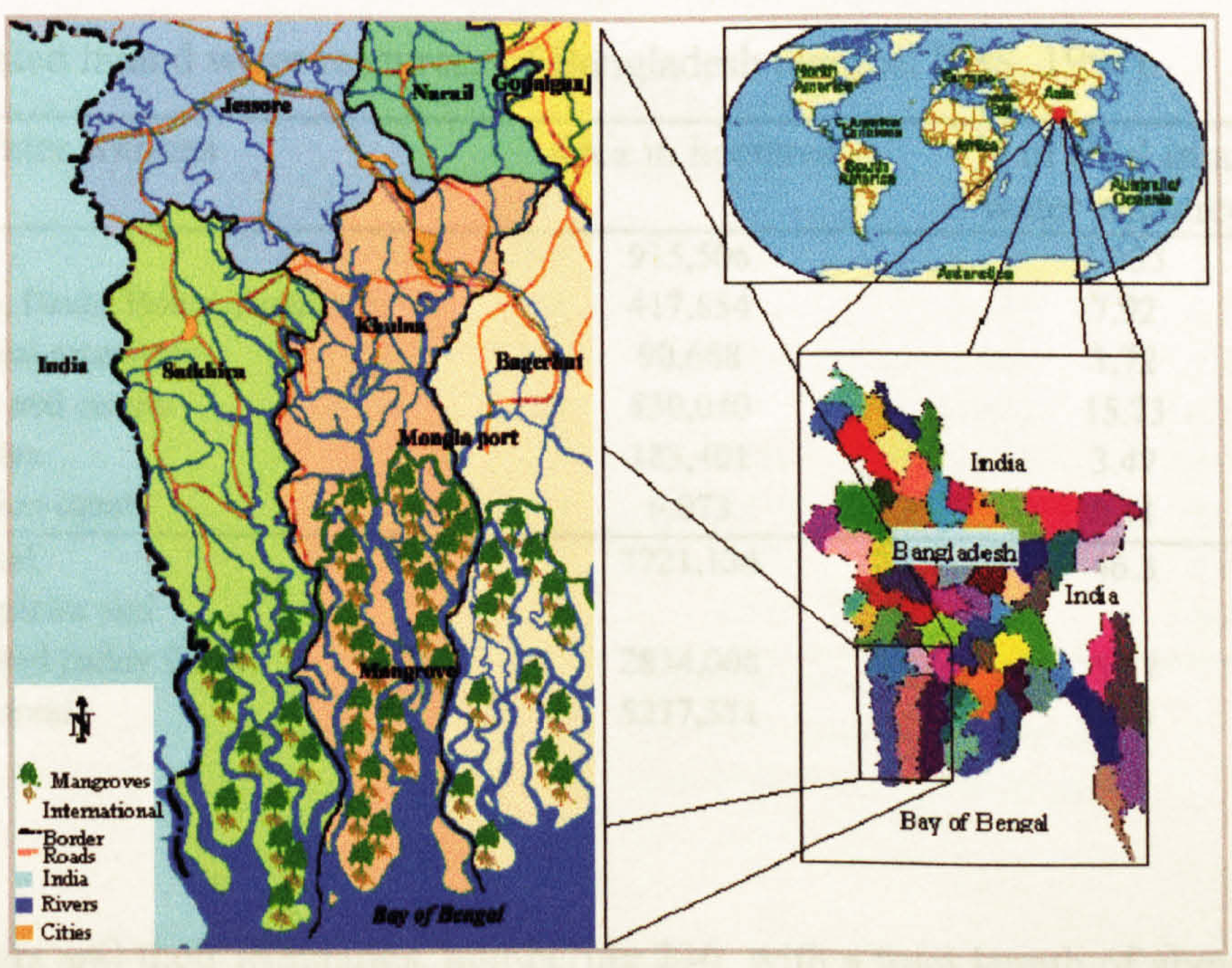

Figure 2.1. Map showing the study area, Khulna, Jessore, Satkhira, Narail, Gopalganj, Bagerhat and the Sundarbans Mangrove forest.

2.2 Environmental parameters

2.2.1 Water resources

Water is the most important resource that influences agriculture and aquaculture in Bangladesh. The characteristic duality in water availability during the year, in general, affects life, livelihood, agriculture and aquaculture in the country. Too much at one time, too little at another, sometimes too soon or too late are extremes which make Bangladesh a flood prone and semi-arid country all at the same time. The highly skewed distribution of rainfall inland and up-country is mainly responsible for this (Khan, 1998).

Bangladesh has one of the largest fresh water resources in the world (EGIS, 1997). It has vast water bodies in the form of ponds, didhis, beels and hoars (natural depressions), baors (ox-bow lakes), canals, rivers, flood plains, reservoirs and impounded brackish water. **Table 2.1** shows the estimation of the inland water resources of Bangladesh.

Table 2.1. Estimated inland water resources of Bangladesh (source: BBS, 1997).

Water sources	Area in hectares	% of total inland water resources
Ponds	915,506	17.35
Dighis, Beels, Boars, Hoars etc.	417,854	7.92
Artificial reservoirs	90,688	1.72
Rivers and canals	830,040	15.73
Estuaries	183,401	3.47
Irrigation canals	6,073	0.11
Sub total	7721,134	46.3
Flood plains and inundated paddy fields	2834,008	53.7
Grand total	5277,571	100

A network of rivers and their tributaries, numbering 230, with a total length of about 24,140 km cover an area of 9,380 km^2 (6.5% of the total area of Bangladesh), all flow down to the Bay of Bengal (ESCAP, 1988). The three major rivers, the Ganges, the Brahmaputra and the Meghna, account for 85% of the dry season stream flow passing through the coastal zone of Bangladesh. The surface water flow varies from a maximum of 102,000 m^3/s in August to a minimum of

7,030 m^3/s in February with an occasional flow exceeding 140,000 m^3/s (MPO, 1985). Twenty big to medium size channels, which are connected with innumerable criss-cross streams and streamlets, are spread along the 480 km long coastline. About 35 islands with sizes varying from a few hectares to several hundreds km^2 have been mapped earlier using Landsat images (Quader, 1987).

Tides in Bangladeshi waters are predominantly semi-diurnal in character, having natural periods of oscillation of about 12 hours. The tides that affect the coastal zone originate in the Indian Ocean, travel past the deep parts of the Bay of Bengal and reach the ten-fathom contour line at Hiron Point and Cox's Bazar at about the same time. The tidal range at the head of the Bay of Bengal is very wide, ranging from 2.2 meters at low tide to about 3.9 meters at high tide near Mongla (BIWTA, 1996). This range is, however, reduced toward the south along the western shore of the Bay of Bengal. Similarly, 3.2 meters neap tides and 6.0 meters spring tides are observed in the Sandwip area (latitude 22^{0}29' and longitude 91^{0}26'). This range is reduced toward the south along the Eastern Shore of the Bay of Bengal (**Table 2.2,** BIWTA, 1996).

Table 2.2. Tidal range of selected stations in Bangladesh coast.

	MLWS	MLWN	MSL	MHWN	MHWS
Hiron point	0.225	0.905	1.7	2.495	3.175
Mongla	0.325	1.194	2.31	3.427	4.296
Cox's bazar	0.205	1.023	1.994	2.967	3.785
Sandwip	0.238	1.634	3.243	4.851	6.248
Khepupara	0.195	1.025	2.06	3.096	3.925
Barisal	0.434	0.692	1.539	2.386	2.644
Chandpur	0.256	0.493	2.172	3.852	4.088
Patuakhali	0.242	0.74	1.575	2.409	2.907

MLWN=Mean low water neap
MLWS=Mean low water spring
Source: (BIWTA, 1996)
MSL=Mean sea level
MHWN=Mean high water spring
MHWS=Mean high water spring

The topography of the coastal zone and the tidal patterns of the Bay of Bengal play an important role in the economy of the area. During the dry season (April-May), the tide penetrates up to 170 km north in the Satkhira-Khulna area and as far as 340 km in the Northeast region (Sylhet area). Along the East Coast, the tide penetrates from zero to 50 km depending on the topography and presence of channels in the area (BIWTA, 1996, **Figure 2.2**).

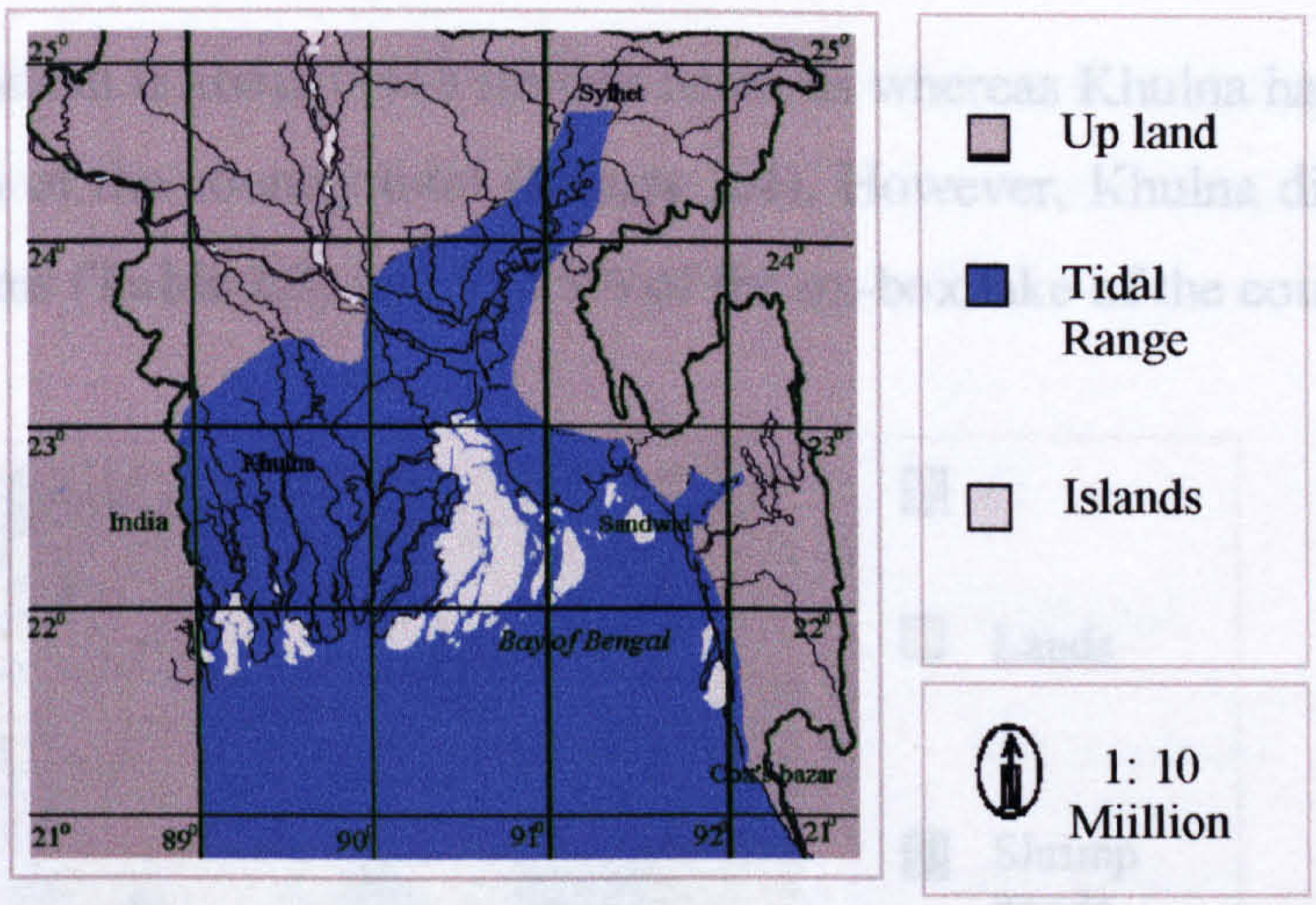

Figure 2.2. Tidal water intrusion into the land up to Sylhet region.

Khulna division offers a cluster of islands with thousands of meandering streams, creeks, rivers and their tributaries. Hundreds of large and small inflowing rivers and their tributaries pass through the area (**Figure 2.3**), and these are important nursery and shelter areas for crustaceans and other white fishes and their fry. The whole area is strongly influence by the tides. During the ebb tide and at high tide the entire territory of the lower area can be flooded.

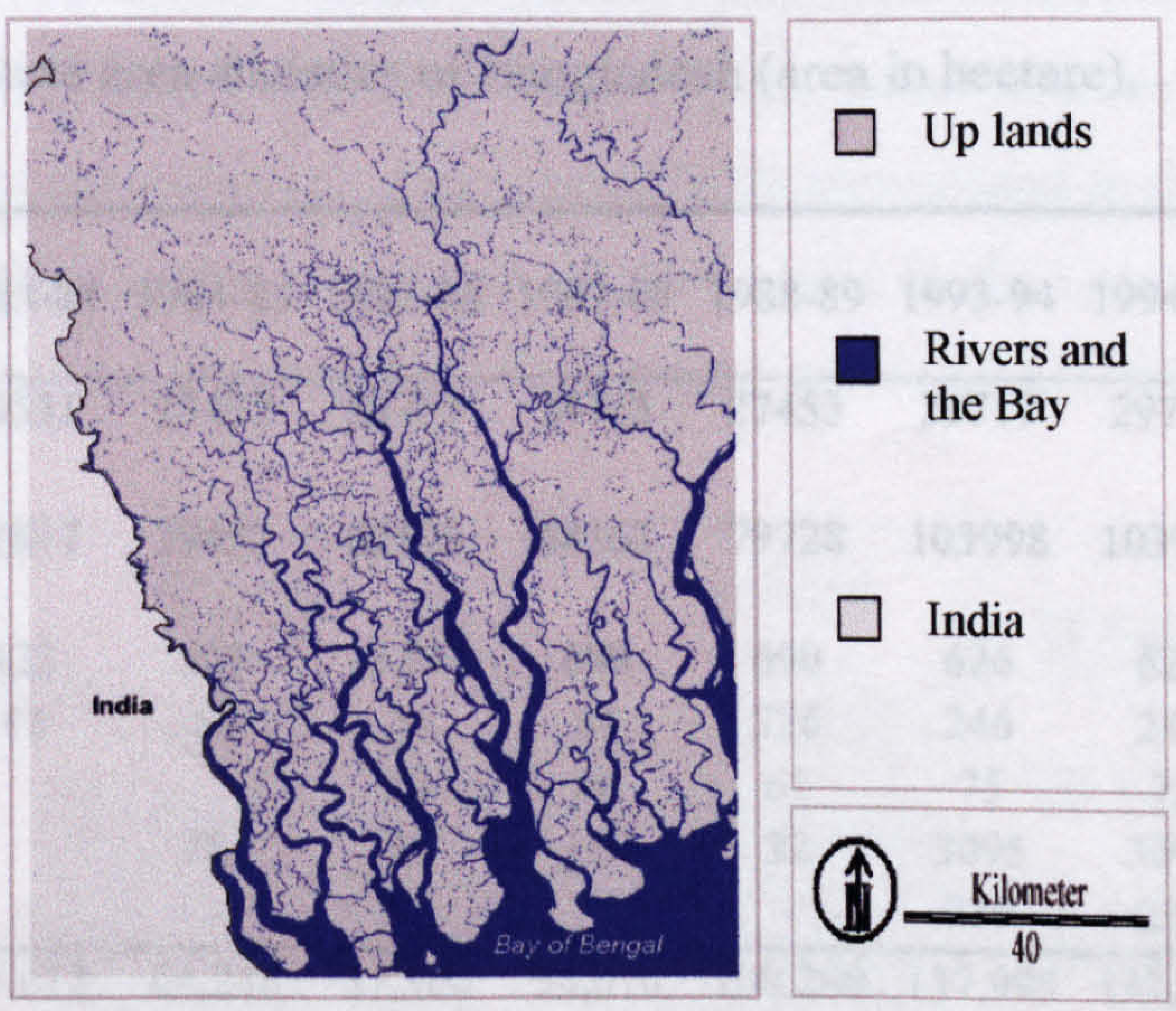

Figure 2.3. Distribution of rivers, their tributaries and canals in Khulna region extracted from Landsat TM image of 1996.

Except for the rivers and their tributaries, small water bodies, which are not connected with the open water i.e. with the river systems, are also abundant in the area. They are particularly, ponds, dighis, ox-bow lakes and coastal brackish water fish and shrimp farms. The total area of fresh water ponds in Bangladesh is about 0.418 million hectares whereas Khulna has 0.023523 million hectares, which is 9% of the country total (**Figure 2.4**). However, Khulna division has 75% of the coastal shrimp farms (**Table 2.3**) and 55.85% of the ox-box lake of the country.

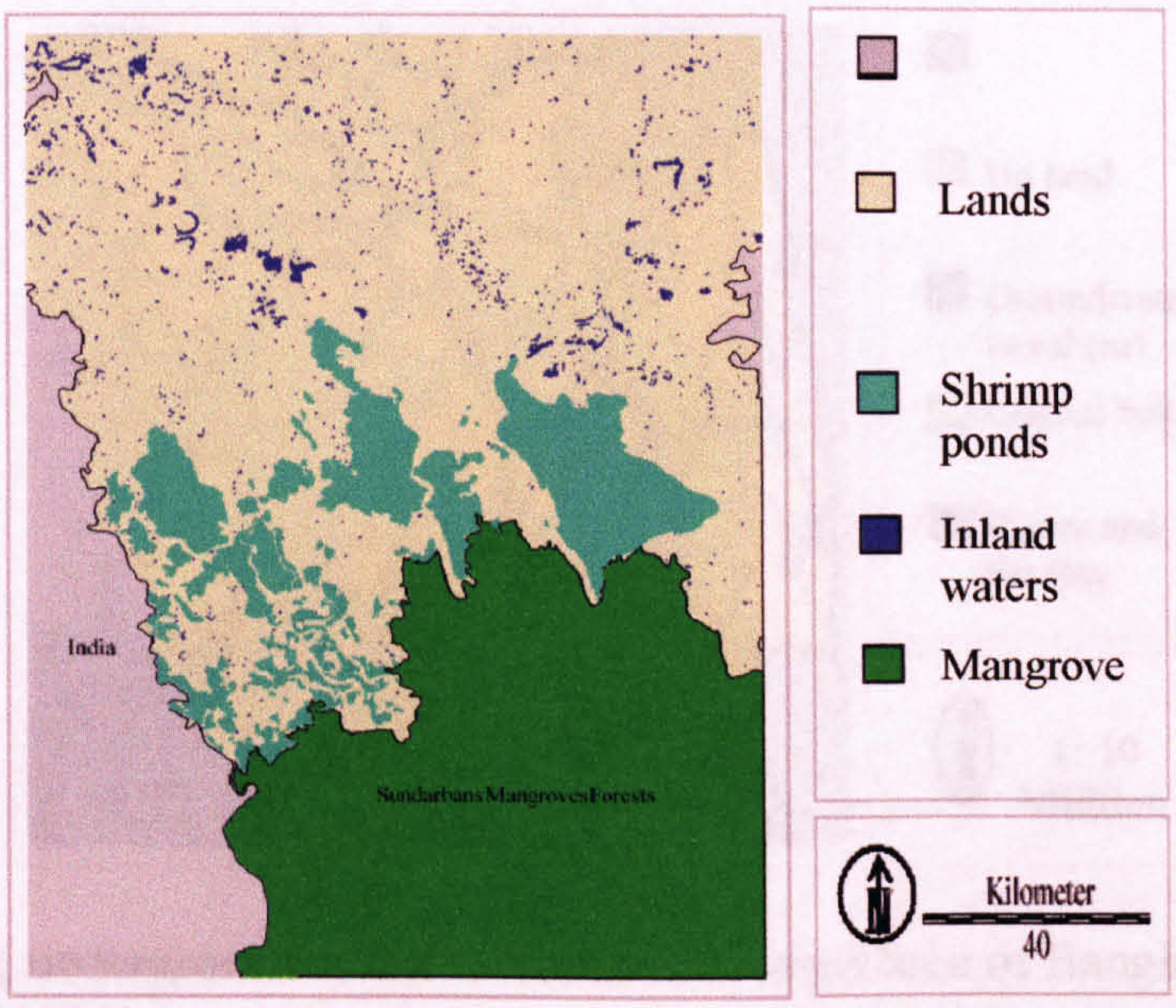

Figure 2.4. Distribution of small water bodies along with coastal shrimp ponds in Khulna region.

Table 2.3. Shrimp culture area statistics of Bangladesh (area in hectare).

Name of district / Year	1983-84	1984-85	1985-86	1987-88	1988-89	1993-94	1994-95	Rate of increase % (from base year)
Chittagong and Cox's Bazar	19531	23437	24755	24755	27453	29717	29717	52
Khulna, Satkhira and Bagerhat	31817	39453	62120	68363	79728	103998	103998	227
Jessore	422	523	328	690	690	626	626	48
Patuakhali	42	52	26	64	326	246	246	486
Noakhali			26	26	61	75	75	188
Barisal		781	45	112	22	3095	3095	296
Dhaka Division	-	-	-	-	-	239	239	
Country total	51,812	64,246	87,300	94,010	108,280	137,996	137,996	166

Most of the inland water bodies receive their water from rain which is seasonal and occurs mainly from May-September (DOF, 1994-95). In the coastal area, brackish ground water is available within 0 to 2.5 m below the ground surface (**Figure 2.5**). In some regions, low salinity ground water is available in deep aquifers at a depth greater than 150 m. It is believed that a continuous flow of fresh water in these deep aquifers from north to south has pushed saline water towards the sea. Pockets of fresh water are also available around low-saline surface water sources, usually beneath the old ponds and the rivers (**Figure 2.6**).

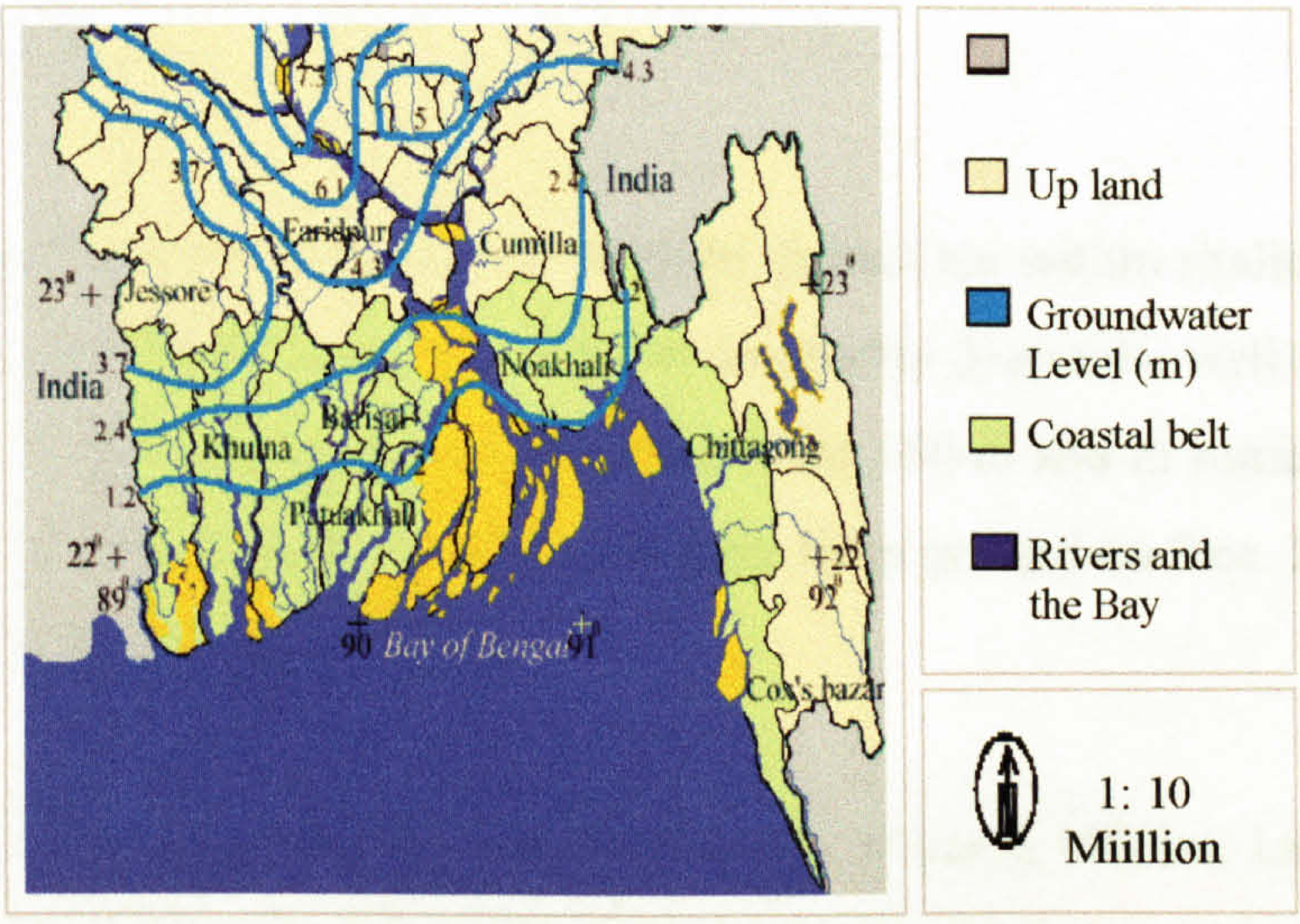

Figure 2.5. Showing underground water levels in the coastal area of Bangladesh (source: ESCAP, 1988).

The lens of fresh water as shown in **Figure 2.6** has been formed over the years from the outflow of fresh water or accumulated rainwater from surface water sources into the aquifer. The thickness of the lens of fresh water beneath a pond is directly related to the age of the pond. The low saline water in and around most of the 81,000 ponds in the coastal area is considered a potential source for low cost water supply in the coastal area (ESCAP, 1988).

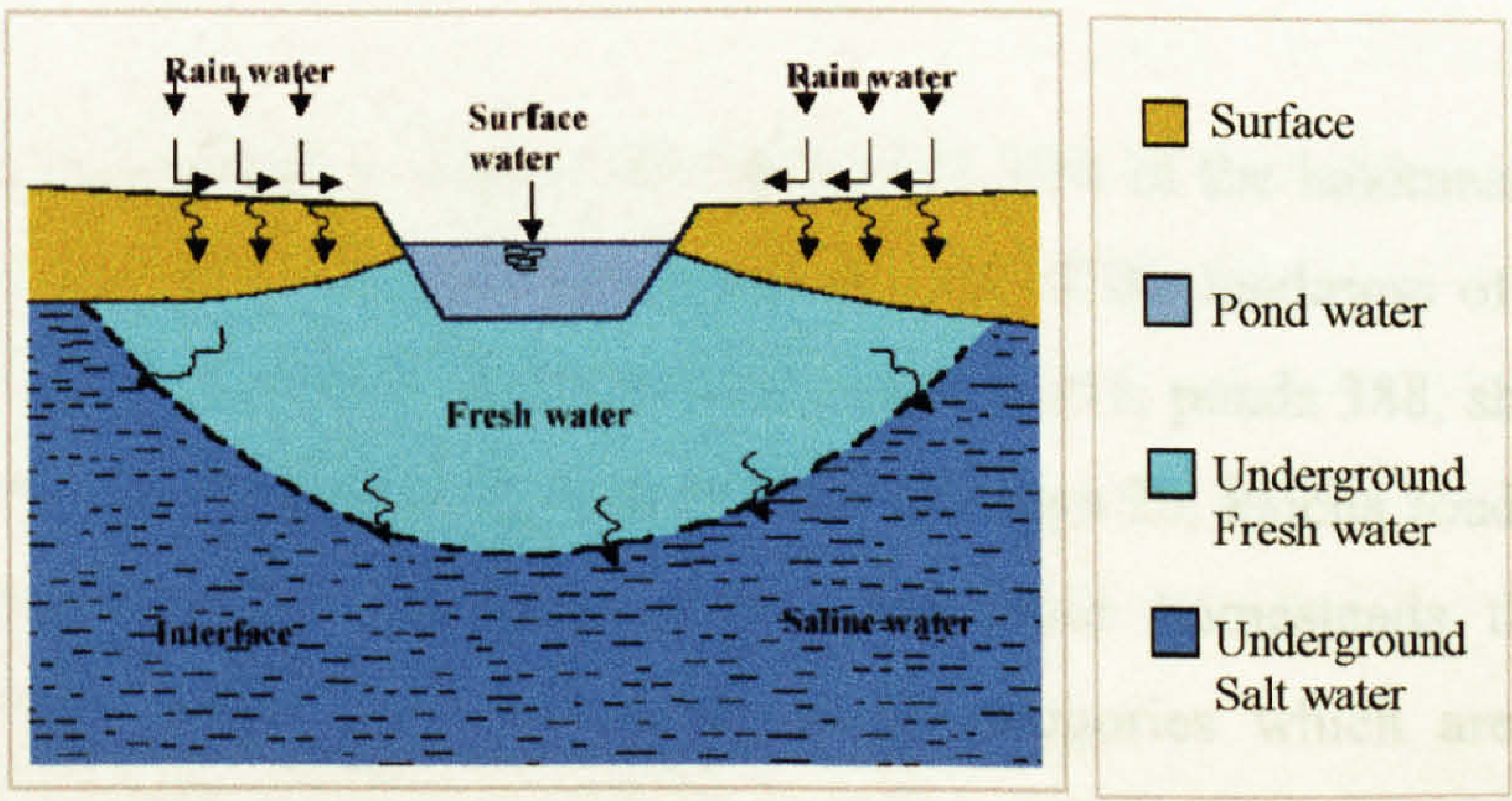

Figure 2.6. Fresh water aquifer beneath the surface water source (source: ESCAP, 1988).

Based on the availability of fresh ground water, the department of public health engineering (DPHE) has divided the coastal region into three types:

(a) shallow tube well area,

(b) partial shallow and partially deep tube well area, and

(c) deep tube well area.

Among these, Bagerhat district and part of Satkhira district are within shallow tube well areas. In contrast, the Khulna district is partly in a shallow and partly deep tube well area. In the deep tube well area, fresh water is available at a depth greater than 150 m and in some areas lenses of fresh water are available at a very shallow depth, less than 10 m ground surface. However, none of the project area is within deep tube well area.

Bangladesh is also rich in her marine water resources. It has a 480 km long coast line and the continental shelf extends over an area of about 69 km^2, which is not deeper than 50 m. The territorial waters of Bangladesh extend for 19 km from the coastline and within this area, the Republic has the exclusive right to exploitation of all kinds of fisheries resources. The territorial waters cover an area of about 1 million hectares. An economic zone of 320 km from the coast covers an area of about 43,302 km^2. However, the effective area of the marine fishing ground is estimated to be around 10,000 km^2 and that of shrimp ground is further restricted to about 5,000 km^2.

2.2.2 Land

The total area of Khulna division is roughly 42,740 km^2 or 30% of the landmass of Bangladesh, however, the study area is about 14,000 km^2 which is 10% of the landmass of Bangladesh. Of this, the Sundarbans cover 5,892 km^2. Beels and baors cover 151, ponds 388, shrimp farms 808, rivers and estuary 5,675, homesteads 8,548, roads and railways 20, katcha roads 83, permanent crops (mango, litchi, jackfruit, pineapple, guava, and other homesteads threes) 362 km^2 respectively. Altogether 21,926 km^2 falls under these categories which are apparently not available for use of aquaculture or any other activities (Khan, 1998, **Figure 2.7**). After deducting those amount of land the region has approximately 20,032 km^2 available to sustain a current population of 26 million. Considering the increasing need for housing, roads, civic infrastructures (schools, hospitals, offices etc.), additional inroads on the availability of cultivable land will be made every year. The rate at which the population of Bangladesh is increasing, and the present level of technology, make it impossible to produce enough food for its population in the future. Population pressure has already begun to affect the aquatic environment and agricultural sustainability. With current technology it would be possible to produce 31.95 million tones of food by the year 2010 (Mahtab and Karim, 1992). Moreover, land availability projections for aquaculture and agriculture need to be made taking into account the future needs and further intrusion into the agricultural land needs to stopped. To achieve this housing should be limited to vertical expansion only, in both the urban and rural areas if current food and fish production levels are to be maintained for the increasing population in the country.

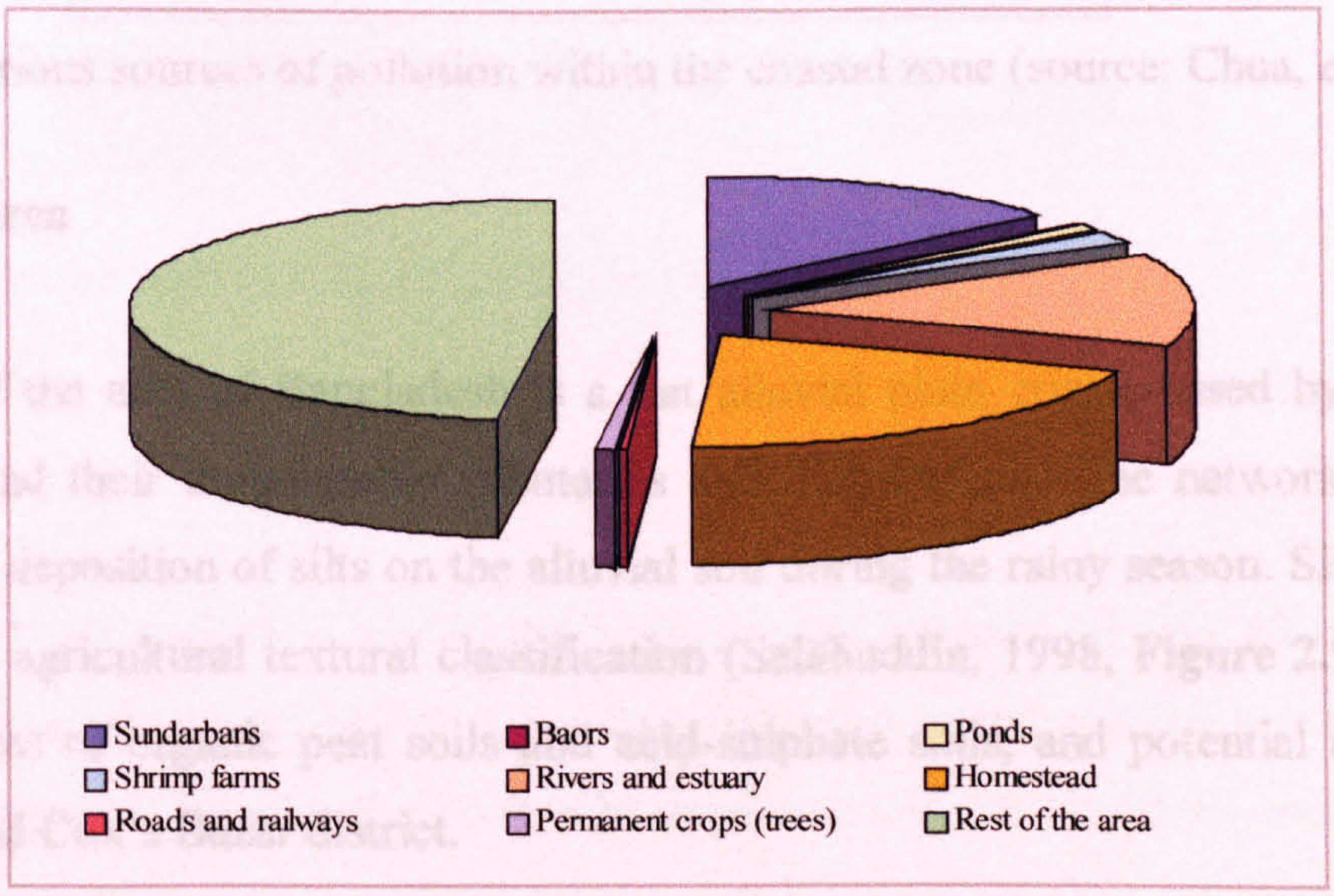

Figure 2.7. Land use pattern in different sectors in the area (source: Khan, 1998).

Land degradation due to improper and incorrect use of biocides/ pesticides/ fungicides is increasing in the country annually (**Figure 2.8**), although use of such biocides is still under control in Bangladesh as a whole. Indiscriminate use of insecticides like Thiodin smuggled from India in to the region with environmentally unsafe compounds have been reported which are contributing to land degradation as well as threatening the biosphere including humans (Rahman *et al.* 1995). Import and use of such pesticides, which have been discarded or banned in their country of origin, must be stopped through policy directives.

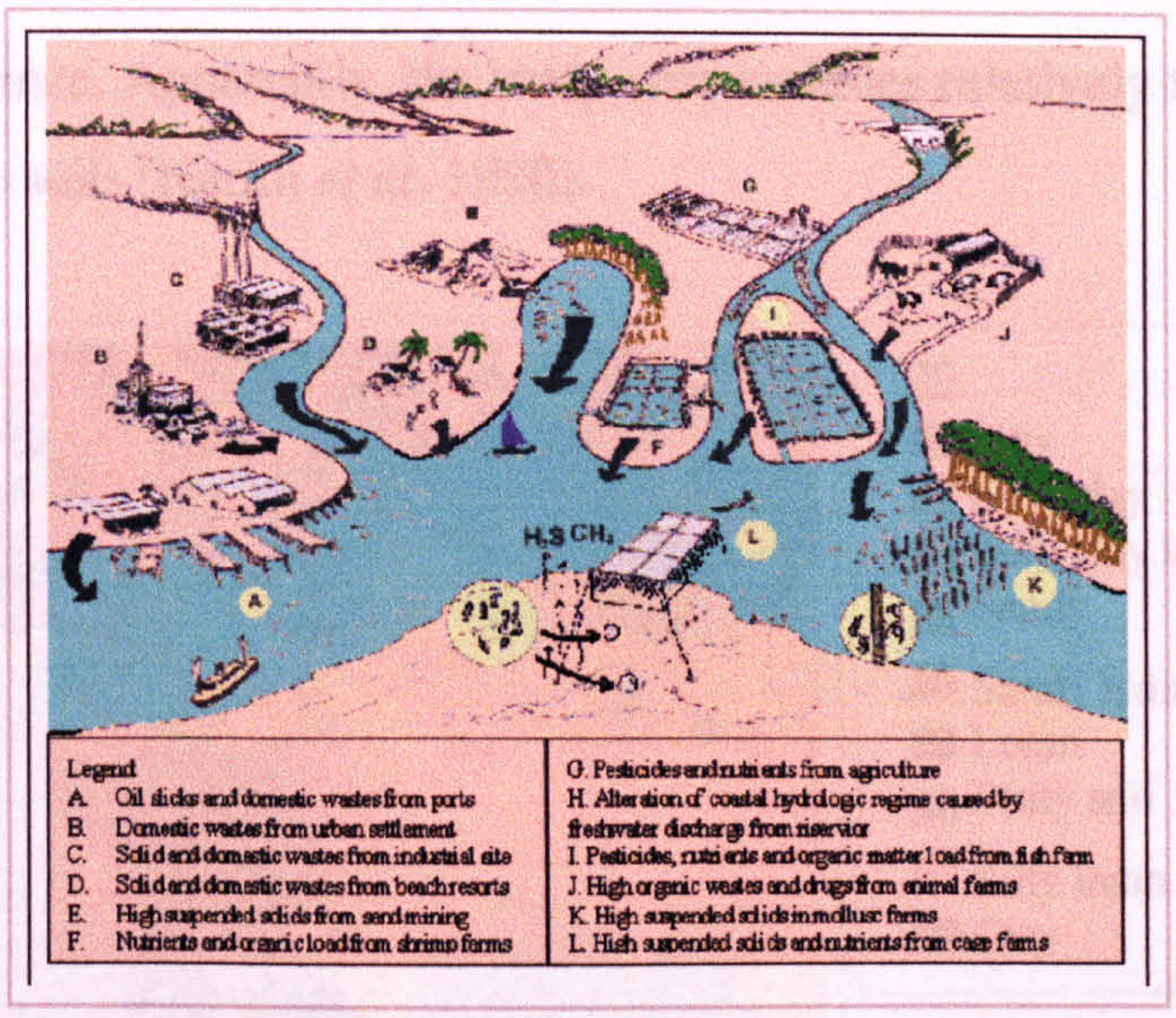

Figure 2.8. The various sources of pollution within the coastal zone (source: Chua, *et al.* 1989).

2.2.3 Soils of the area

More than 85% of the area of Bangladesh is a flat alluvial plain criss-crossed by an intricate system of rivers and their innumerable tributaries and distributions. The network of rivers is responsible for the deposition of silts on the alluvial soil during the rainy season. Silty clay loam is the predominant agricultural textural classification (Salahuddin, 1998, **Figure 2.9**). There are some localised areas of organic peat soils and acid-sulphate soils, and potential acid-sulphate soils in Satkhira and Cox's Bazar district.

The majority of the soils is fertile and responds well to nitrogen, phosphorus and potassium fertilisers and also to application of manure. The soils are young and most contain calcium carbonate or considerable amounts of exchangeable calcium. However, some soil deposits in Satkhira district are low in available calcium. Soil salinity in the area varies from non-saline to strongly saline as a result of the degree of normal tidal inundation and tidal surges associated with storms.

Some soils (6,200 ha), particularly peaty soils in the most saline portions of Satkhira and Cox's Bazar district, have developed a chemical condition wherein they may become acid-sulphate (Uddin and Islam, 1998). This condition develops in cases where deep drainage or drying takes place. During their formation, these soils were submerged under saline water and free oxygen and in many instances sulphur from sea-water sulphates formed into insoluble sulphides during the period of submergence. Apparently, the study area includes relatively few areas of existing or potential acid-sulphate soils (Karim *et al.* 1990).

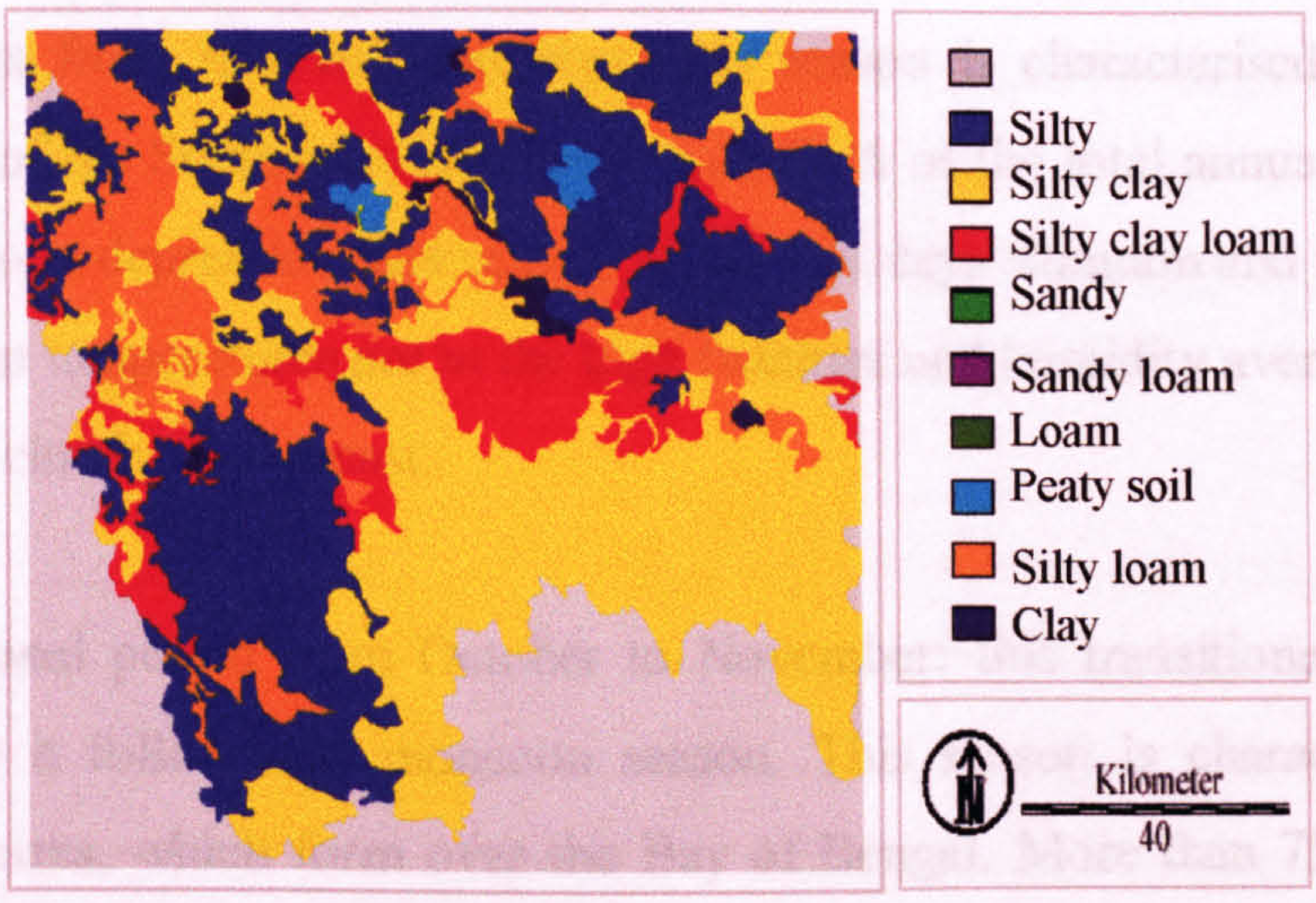

Figure 2.9. The different type of soils in the Khulna region.

2.2.4 Climate

The coastal area of Bangladesh is within the tropical zone between 21 and 23 degrees north latitude. Like the country as a whole, there are four distinct seasonal weather patterns governed mostly by two monsoons, namely, the Southwest monsoon and the Northeast monsoon. These are categories as follows:

The dry winter season from December to February: rainfall is infrequent under the influence of dry air circulation of the land origin mostly from the Northeast monsoon. The wind blows from a North-easterly direction at the beginning of the season, changes to northerly or westerly. Temperatures in the low twenties during the day and in the low teens at the night are common in this season. The humidity gradually decreases during this season. The sky is generally clear.

The transitional period from March to May: this period is termed the pre-monsoon season and is characterised by short-duration thunderstorms of land origin, often associated with violent squally winds. This is the general pattern in the months of March and April. The climate in May is severe, most frequently occurs cyclonic storms originating over the Bay of Bengal. This is the hottest month of the year and the daytime temperature may rise to about 40^0 C in the North-western part of the coastal area.

The monsoon season from June to September: this season is characterised by heavy rainfall under the influence of the South-west monsoon, with 75% of the total annual rainfall occurring in this period. Monsoon depressions are usually of several days' duration and rainfall is steady at moderate rates. Mean temperatures are in the high twenties and humidity averages 85% or more. The sky is normally cloudy to overcast.

The second transitional period from October to November: this transitional period is termed post-monsoon since it follows the monsoon season. This season is characterised by violent tropical cyclonic storms, which form over the Bay of Bengal. More than 75% of the cyclonic storms strike the coastal area occur during this season and in the month of November. The storms of this season are, however, more severe and destructive than in May.

The mean annual rainfall varies from approximately 1,500 mm in the Northwest portion of Khulna region to over 3,800 mm south of Cox's Bazar. The heaviest rainfall occurs in July and ranges from about 360 mm during that month near Khulna to over 900 mm at Cox's Bazar. There is practically no rain during the dry winter months of December through February (**Figure 2.10**).

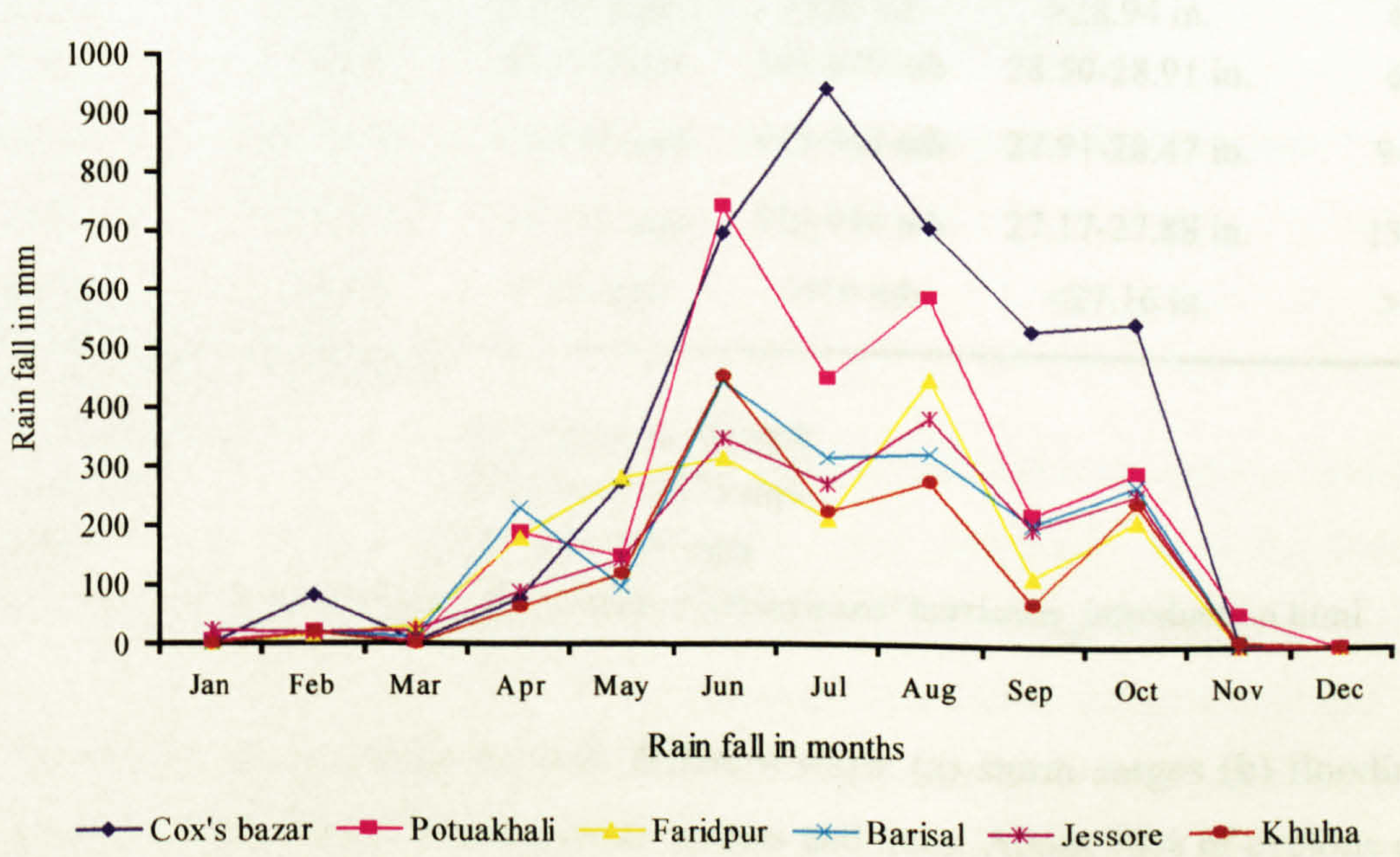

Figure 2.10. Monthly rainfall in selected stations in 1996 (BBS, 1997).

2.2.5 Cyclones

Cyclonic storms are an important feature of the Bangladesh climate and have caused great suffering to the people and damage to structures in the cyclone path (Nicholls, 1995). The storms usually form in the south-east portion of the Bay of Bengal, move in a northerly or north-westerly direction and often turn north-easterly or easterly towards the east of the country (Choudhury *et al.* 1998).

Two different types of cyclones form in the bay, one is the tropical cyclone, which forms during the pre and post monsoon seasons, and the other is the monsoonal depression, which develops during the Southwest monsoon season. Dynamically they are different. Tropical cyclones are the most destructive. Examples include, the May 1985, Urir Char cyclone, the November 1970 cyclone, the great cyclone of 1919, the Bakerganj cyclone of 1876 and the Barisal cyclone of 1584. The characteristics of tropical cyclones, tropical storms and hurricane are described in **Table 2.4.**

Table 2.4. Saffir Simpson scales for Hurricane classification.

Strength	Wind Speed (kt)	Wind Speed (mph)	Pressure (millibars)	Pressure (inches Hg)	Storm Surge (ft.)
Category 1	65-82 kt	74-95 mph	>980 mb	>28.94 in.	4-5 ft.
Category 2	83-95 kt	96-110 mph	965-979 mb	28.50-28.91 in.	6-8 ft.
Category 3	96-113 kt	111-130 mph	945-964 mb	27.91-28.47 in.	9-12 ft.
Category 4	114-135 kt	131-155 mph	920-944 mb	27.17-27.88 in.	13-18 ft.
Category 5	>135 kt	>155 mph	<919 mb	<27.16 in.	>18 ft.

Tropical Cyclone Classification

Tropical Depression	20-34 kt or 23-39 mph
Tropical Storm	35-64 kt or 40-73 mph
Hurricane	65+ kt or 74+ mph

Source: http://www.sunysuffolk.edu/~mandias/38hurricane/ hurricane_introduction.html

Cyclones generally cause damage in three different ways: (a) storm surges (b) flooding due to excessive rainfall and (c) wind blowing away houses and trees. About 90% of cyclone casualties are caused by storm surges generated by cyclones. Storm winds move at speeds of up to 240-250 km per hour and cause widespread damage. The most destructive element, however, is the water surge caused by a large mass of water at and around the storm centre accumulating in a mound higher than the mean sea level (MSL) and progressing with the storm as a wind driven storm surge. As the storm reaches the shallow water near the coast of the Bay of Bengal, the surge is intensified as it sweeps inland. Coincidence of the storm's passage with the high or low tides would tend to increase or moderate water damage.

Storm surges of recent cyclones have been noted to be some 3 to 6 m in height. Theoretical analyses of surge heights using data on actual cyclones and considering the shape and configuration of the Bay of Bengal and the coastline suggest that cyclonic storm surges of up to 7.5 m can be expected (ESCAP, 1988). Waves approaching the shore tend to expend their energy by running up a sloping beach and thereby cause inundation to heights even greater than true height to the offshore storm surge (**Figure 2.11** shows a Tropical Hurricane from satellite).

Figure 2.11. A tropical hurricane in the Arabian Sea near Pakistan and Indian coast (source: NOAA, 1999).

2.2.6 Relief and topography

The flat deltaic lands are interlaced by an intricate river and tidal channel systems, which cut the lands into numerous separate areas. The channels carry floodwater from the Ganges, the Brahmaputra, the Meghna and other rivers and also act as conveyance channels for rainfall and tidal water to the Bay of Bengal. Many of these separate lands have saucer like shapes with the higher elevations on natural banks adjacent to the rivers, owing to heavier sediment deposition near the point of bank overflow. This pattern is altered in cases where the rivers have recently changed course and cut through the centre of the saucer. The land masses are generally at elevations slightly above the MSL but are subject to inundation at the higher portion of the tidal cycle. Ground levels vary from below sea level to 7 meter or more above the sea level. The usual maximum level seldom exceeds 4 m (**Figure 2.12**).

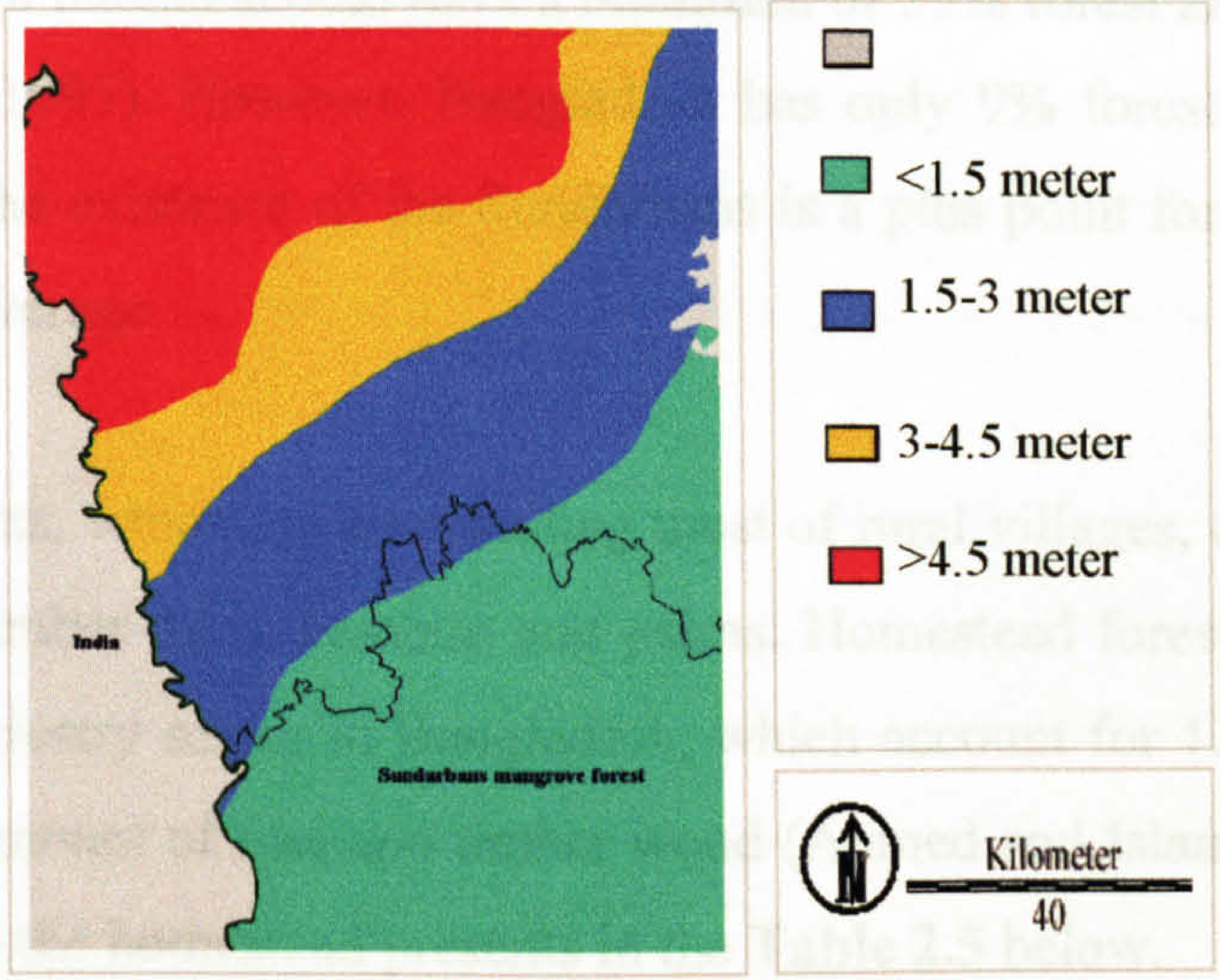

Figure 2.12. Elevation of the study area, South-western region of Bangladesh (source: Graphosman, 1996).

2.2.7 Geology

The coastal zone of Bangladesh is part of the Bengal basin formed by sediments over millions of years, covering old sunken rocks of the Gondwana continent. The Bengal basin is flanked by one of the world's major subduction faults in the north (the Himalayan ranges) and a major transform fault in the east (the Indo-Burma ranges). The Bengal basin and its adjacent areas are considered one of the most active tectonic regions of the world. In the recent past, the results of many tectonic movements have been noticed in the form of changing river courses (Brahmaputra to Jamuna and Atrai to Tista) and bank erosion and accretion in the Noakhali-Barisal area. These tectonic movements may be due to presence of a major fault at depth or a subsiding trough along the axis of the Jamuna -the Padma-the Meghna river system (Rashid, 1977).

Geologists found the world's largest sand deposit over basement rocks in the Himalayas, which are also the world's highest mountains. The Ganges-Brahmaputra river system carries billions of tons of sediment from the Himalayas to the Bengal basin, so there is a high expectation of land formation in the mouth of the Ganges, the Brahmaputra and the Meghna river system.

2.2.8 Vegetation

Ideally, any terrestrial habitat should have a minimum of 25% forest area to provide for a healthy environment (Viju, 1995). However, Bangladesh has only 9% forest of its land mass (Ahmed and Islam, 1998). The existence of the Sundarbans is a plus point for the region accounting for about 13% forest coverage.

The homestead forests, which are surrounding most of rural villages, consist of groves of mixed fruit trees, shrubs, timber trees, bamboo and palms. Homestead forests are the most productive component of the forestry sector in Bangladesh, which account for 12% of total forest area but supply the highest amount of fuel and timber wood (Ahmed and Islam, 1998; USAID, 1990). A list of trees grown in the homestead presents in the **Table 2.5** below.

Table 2.5. Shows the vegetation grown in the homestead of Khulna region.

Scientific name	Vernacular name	Type of trees
Cocos nucifera	Coconut	Fruit
Areca catechu	Betel nut	Fruit
Mangifera indica	Mango	Fruit
Artocarpus heterophyllus	Jackfruit	Fruit
Samanea saman	Rain tree	Wood
Albizia procera	Silkoroi	Wood
Phoenix sylvestries	Date palm	Fruit
Spondias mangifera	Fog plum	Fruit
Erythrina indica	Mander	Wood
Musa sapientum	Banana	Fruit
Psidium guajava	Guava	Fruit
Carica papaya	Papaya	Fruit
Eugenia javanica	Jamrul	Fruit
Bambusa spp.	Bamboo	Wood
Citrus limon	Lemon	Fruit
Swietenia mahagani	Mahogani	Wood
Acacia nilotica	Bubla	Fruit
Bombax ceiba	Silk cotton	Cotton
Azadirachta indica	Neem	Wood
Aegle Mermelos	Bel	Fruit
Anthocephalus chinensis	Kadam	Wood
Anona squamosa	Custard apple	Fruit
Tamarindus indica	Tatul	Fruit
Eugenia jambolana	Black berry	Fruit
Averrhoa carambola	Kamranga	Fruit
Diospyros embryopteris	Gab	Fruit
Ficus bengalensis	Bat	Wood
Amoora rohituca	Pitraj	Wood
Eleocarptus floribundus	Olive	Fruit
Tectona grandis	Teak	Wood
Litchi chinensis	Litchi	Fruit
Polyalthia longifolia	Debdaru	Wood
Eucalyptus camaldulensis	Eucalyptus	Wood
Sntalum album	Red chandan	Wood
Achras sapota	Safeda	Fruit
Lecaena leucocephala	Ipil ipil	Wood

Source: Modified after Ahmend and Islam, 1998

The natural vegetation of the Sundarbans forest is composed of halophytic tree species, which is termed mangrove (Chaffey *et al.* 1985). The forest canopy is seldom more than 10 m above the ground level and is more or less open, permitting some direct sunlight to reach the forest floor. Much of the forest is two storied, with scattered trees attaining a height of 20 m. Stem diameters are generally less than 20 cm at breast height. However, one or two species attain much bigger diameters. Epiphytes and woody parasites are common on tree crowns.

Due to the salinity to which the vegetation must be adapted, the forest flora is not particularly species rich. They are dominated mostly by two species, sundari *(Heritiera fomes)* and gewa (*Excoecaria agallocha*). There is about 25 other tree species that are common but considerably less frequent in their occurrence than the above two. A brief list of the most important plants of Sundarbans is given in **Table 2.6.**

In general the forest in the northern and eastern parts of the Sundarbans, is better supplied with freshwater, and is floristically richer than that in the south and west. Golpata palm (*Nypa fruiticus*), which forms thick fringes along the riverbanks in the north and east, becomes progressively less frequent towards the south and west (**Figure 2.13**). Species such as jhanna (*Rhizophora mucranata*) and goran (*Ceriops decandra*), members of the Rhizophoraceae being most frequent in the most saline areas also occur infrequently in the North and East. *Bruguiera gymnorhiza,* a member of the Rhizophoraceae family, occurs throughout and does not appear to reflect salinity differences.

In addition to sundari from the Sterculiaceae family, the other major components of the mangrove flora of the Sundarbans representatives of the Avicenniaceae, Rhizophoraceae and Sonneratiaceae. The first of these is represented by *Avicennia officinalis* and *Avicennia alba.* The second is represented by *Ceriops decandra, Kandelia candel, Rhizophora mucranata* and *Bruguiera gymnorhiza.* The Sonneratiaceae family, represented by *Sonneratia apatala* and *Sonneratia caseolaris,* forms the third group.

Some plants of ficus species, *Eugenia fruticosa* and *Diospyros peregrina* of the *Moraceae, Myrtaceae* and *Ebenaceae* families respectively, occur in places of lower salinity, usually in raised land. These are species of dry land and are only marginally salt tolerant. Examples of these are jir (*Ficus* spp), jam (*Eugenia fruiticosa*) and gab (*Diospyrus peregrina*).

Figure 2.13. Nypa palm trees making a fringe in the riverbanks in the eastern part of the Sundarbans.

A number of factors are involved in controlling the Sundarbans ecosystem in addition to soil and plant interaction. The ecological conditions that are essential for development of mangrove vegetation are: shallow water with thick mud, silty clay to sandy clay soil with a fair amount of organic matter and high humidity in the atmosphere and cloudy weather (Chaffey *et al.* 1985).

Table 2.6. Genera and species are available in the world and in the Sundarbans (source: Ismail, 1990; Tomlinson, 1994).

Family	Genus	No. of species	In Sundarbans
Major components			
Avicenniaceae	*Avicennia*	8	*Avicennia officinalis*
			Avicennia alba
Combretaceae	*Laguncularia*	1	
	Lumnitzera	2	*Lumnitzera racemosa*
			Lumnitzera littorea
Palmae	*Nypa*	1	*Nypa fruiticus*
			Phonix paludosa
Rhizophoraceae	*Bruguiera*	6	*Bruguiera gymnorhiza*
	Ceriops	2	*Ceriops decandra*
	Kandelia	1	*Kandelia candel*
	Rhizophora	8	*Rhizophora mucranata*
Sonneratiaceae	*Sonneratia*	5	*Sonneratia apatala*
			Sonneratia caseolaris
Total	9	34	
Minor components			
Bombacaceae	*Camptostemon*	2	
Euphorbiaceae	*Excoecaria*	1	*Excoecaria agallocha*
			Sapium indicam
Lythraceae	*Pemphis*	1	
Meliaceae	*Xylocarpus*	2	*Xylocarpus granatum*
			Xylocarpu mekongensis
	Amoora		*Amoora cuculata*
Myrsinaceae	*Aegiceras*	2	*Aegiceras comiculatum*
Myrtaceae	*Osbornia*	1	
Pellicieraceae	*Pelliciera*	1	
Plumbaginaceae	*Aegialitis*	2	
Pteridaceae	*Acrostichum*	3	
Rubiaceae	*Scyphiphora*	1	
Sterculiaceae	*Heritiera*	3	*Heritiera fomes*
Total	**11**	**20**	
Grasses			
Gramineace			*Eriochloa procera*
			Saccharum cylindricum
			Typha elephantina
Acanthaceae	Only found in Sundarbans		*Acanthus ilicifolius*
Apocynaceae	"		*Cerbera odollam*
Barringtoniaceae	"		*Barringtonia racemosa*
Caesalpiniaceae	"		*Dolichandrone rheedei*
Cauaarinaceae	"		*Casuarina equisetifolia*
Cauaarinaceae	"		*Casuarina equisetifolia*
Ebenaceae	"		*Diopyros embryoptetis*
Fabaceae	"		*Afzelia retusa*
	"		*Cynometra racemosa*
	"		*Dalbergia spinosa*
	"		*D. torta*
	"		*Erythrina indica*
	"		*Pongamia pinnata*
Malvaceae	"		*Hibiscus tiliaceus*
	"		*Thespesia populnea*
Tiliaceae	"		*Brownlowia lanceolata*
Verbenaceae	"		*Clerodendron inerme*
	"		*C. nerifolium*
	"		*Vitex negundo*
	"		*V. trifolia*

2.3. Land Uses for Fisheries and Aquaculture

2.3.1 Aquaculture

Aquaculture plays an important role in nutrition, income, employment and foreign exchange earnings in Bangladesh. Fish contributes 80% of animal protein intake, 3.5% of gross domestic product (GDP) and 7% of export earnings in the country. Aquaculture comprises of fresh water aquaculture and brackish water aquaculture. At present, 0.15 million hectare of land are under fresh water aquaculture, whereas, brackish water aquaculture covers an area of 0.11 million hectare (Mazid, 1998).

A total of 257 species of fishes have so far been identified in freshwater of which 200 are considered truly freshwater fish and the rest are brackish and marine species which enter into the rivers and freshwater bodies during certain stages of their life cycle. With a few exceptions, most of these 200 species enter all types of freshwater impoundment. However, at present only major carps such *as Catla catla, Labeo rohita, Cirrhinus mrigala* and *Labeo calbasu* with the exotic carps, silver carp, grass carp, common carp and Thai barb are commonly cultured in a polyculture system in ponds. In some places, Asian catfishes such as, *Clarias batrachus* and *Heteropneustes fossilis* and climbing perch *Anabas testudineus* are cultured exclusively in the impoundments.

Bangladesh is world's largest producer of freshwater prawn (*Macrobrachium rosenbergii*; Viju, 1995). There are about 23 species of freshwater prawn available in Bangladesh water. Out of these, giant freshwater prawn is commonly cultured in brackish water and low lying areas in the coastal regions along with brackish water shrimp and other parts of the country in freshwater ponds along with carps and rice. The perennial inland open water bodies are the natural habitats of other *Macrobrachium* spp, where they are caught throughout the year.

Production figures shows that 269,742 metric tons of fish were produced from ponds during the period 1994-1995, equivalent to about 23% of the country's total production. Department of Fisheries 1996 reported an average production of fish from ponds of 2759 kg/ha, which is two and half times higher than the production in 1984 reported by SPARRSO. **Figure 2.14** illustrates the increase of fish production over time in the country. Different culture systems will be discussed later in this chapter.

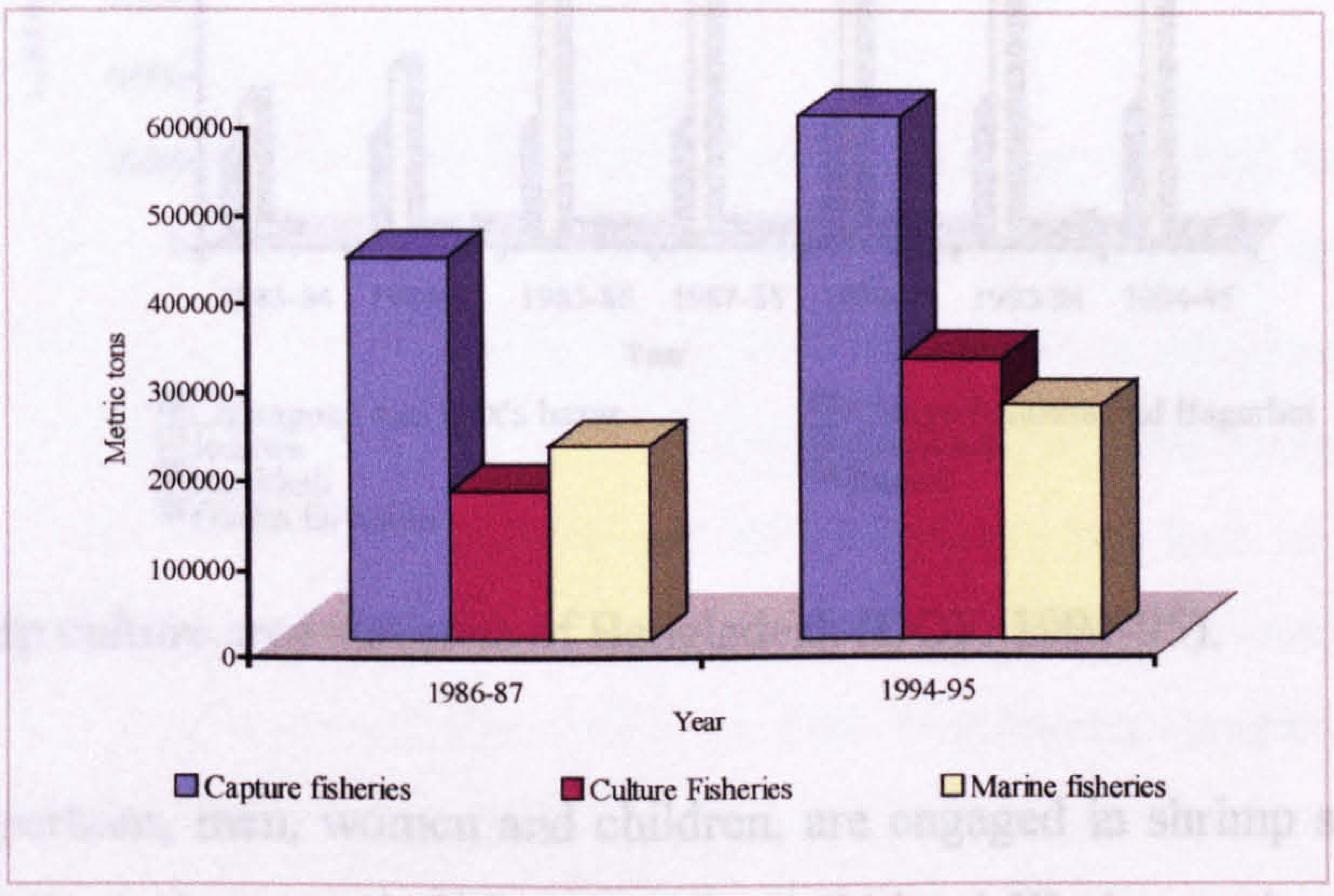

Figure 2.14. Compares between 1986-87 and 1994-95 of capture, culture and marine fisheries of Bangladesh.

Brackish water aquaculture plays an important role in the national economy of Bangladesh. Shrimps comprise the main varieties of cultivable species in brackish water aquaculture. The country has extremely favourable conditions for shrimp culture with low production costs. With the increase in demand and price in the international market, shrimp culture started expanding in the 1970s. Tidal lands with embankments for protection from brackish water intrusion for rice cultivation have been converted for shrimp culture. In 1982-83, there was only 0.0052 million hectare land under shrimp culture, whereas, by 1996, 0.11 million hectare land had been brought under shrimp cultivation (Mazid, 1998). About 70% of this land is located in Khulna (19%), Bagerhat (31%) and Satkhira (20%) districts in the Southwest, the remainder being in the Cox's Bazar (30%) district in the south-eastern region of the country (Khan and Hossain, 1996; Viju, 1995, **Figure 2.15**). In Khulna region, shrimp is cultured in the dry season and paddies in the rainy season while in Cox's Bazar area, shrimp culture and salt production is carried out alternatively.

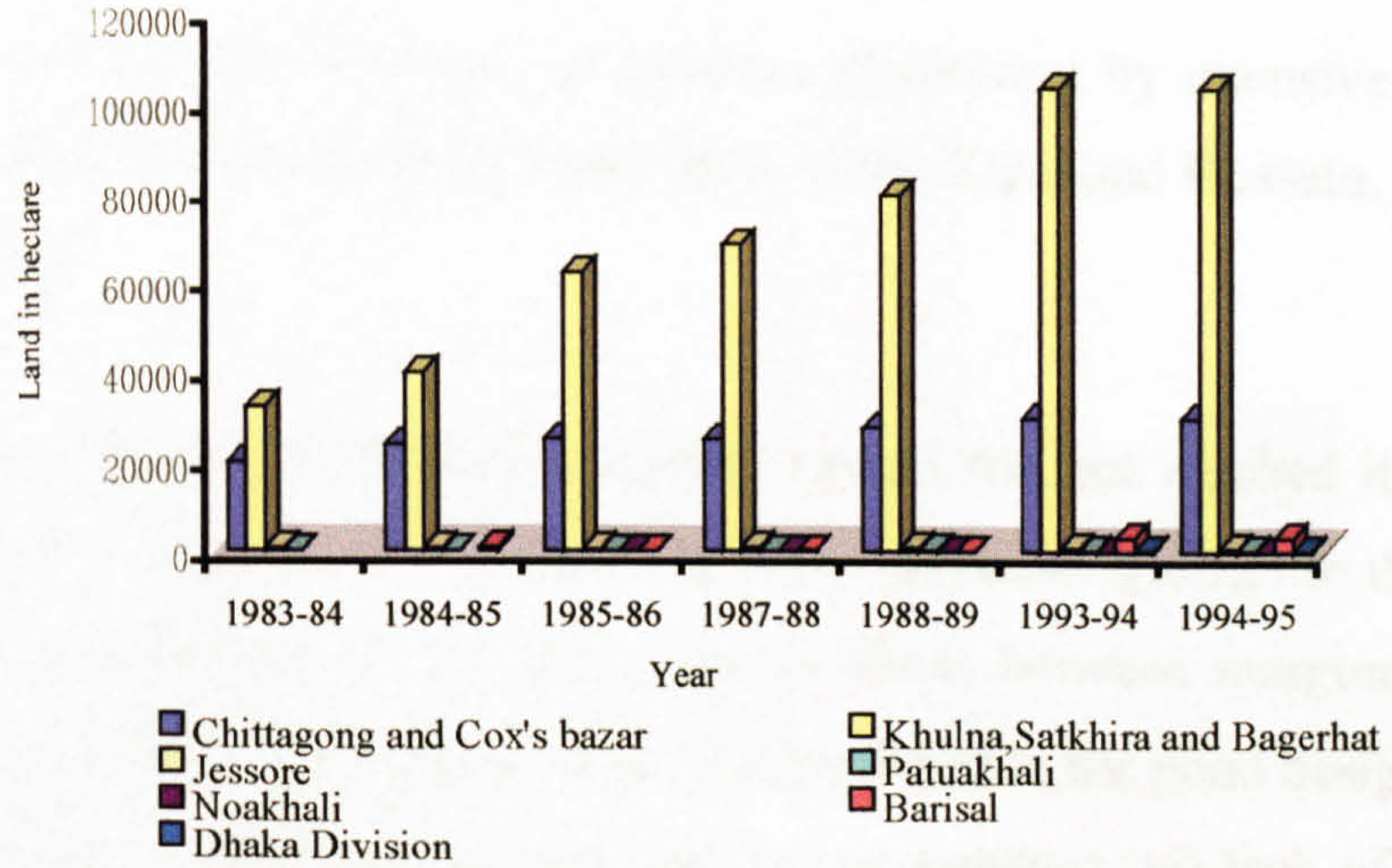

Figure 2.15. Shrimp culture area statistics of Bangladesh (DOF, 1994-95).

More than 40,000 persons, men, women and children, are engaged in shrimp seed collection in the coastal belt of Cox's bazar and Chittagong. In Satkhira / Khulna regions, the number is estimated to be three times higher than Cox's bazar area (Ubinig, 1990). Most of the shrimp collectors are land-less and poor who have no other means to manage their livelihood (**Figure 2.16**).

Figure 2.16. Children are engaged for catching shrimp fry in a river in the Khulna region.

Shrimp production varies from different culture systems in the country. Sixty to two hundred kilograms (kg/ha/y) of shrimp are harvested from traditional extensive methods but this is less common these days. On the other hand, 600-1000 kg/ha/y yields have been recorded in Cox's bazar, Khulna, Satkhira and Bagerhat area from improved extensive systems. Using the same semi-intensive method, production of 2000-6000 kg/ha/y has been recorded in Cox's bazar area, although this is rare in the study area. In contrast, production by intensive culture methods is about 5-10 tones/ha/y but rare in Bangladesh (Deb, 1998; Khan and Hossain, 1996; Mazid, 1998; Nuruzzaman, 1991).

Despite the current state of development, shrimp culture has not reached its full potential and most farms have only one harvest per year. The main problems specific to this activity include: (i) availability of natural post larvae; (ii) social conflicts between marginal land owners and shrimp farmers; (iii) lack of trained personnel; (iv) problems in the pond design, construction and operation of the farms; (v) culture practised are not systematic; (vi) lack of hatchery produced post larvae; (vii) need for funding from out side as well as foreign investment; (viii) lack of quality feed supply; (ix) disease problems and (x) lack of planning (proper site selection) and management (Mazid, 1998).

2.3.2 Fisheries resources

The inland fishery resources of Bangladesh are among the richest in the world with only China and India producing more inland fish than Bangladesh (Nuruzzaman, 1993). Estimates of total yearly harvest range from a low of 750,000 to a high of 1,500,000 tones (FAP-17, 1994), with open water harvest accounting for the largest share. Fishery and aquaculture activities in Bangladesh include freshwater fishery and aquaculture, coastal and deep-sea fishery, and marine and brackish water aquaculture. The reproduction and growth of fishery resources rely on the availability of large nutrient rich flooding areas during annual monsoon flooding cycles. Thus, the continued presence of such widespread flooding is crucial for maintaining a large fish production.

2.3.3 Freshwater fisheries

Freshwater fisheries are major sources of fish as well as employment for the rural poor. Fishing is carried out by individuals or by small groups of fishermen with native boats and traditional gears. The single most important species for the inland capture fisheries is Hilsa or river shad (*Hilsa ilisa*, **Figure 2.17**). This migratory species represents more than 50% of the inland capture fisheries and 19% of the total fish production. About 200,000 full time fishermen are dependent upon Hilsa for their livelihood (Viju, 1995).

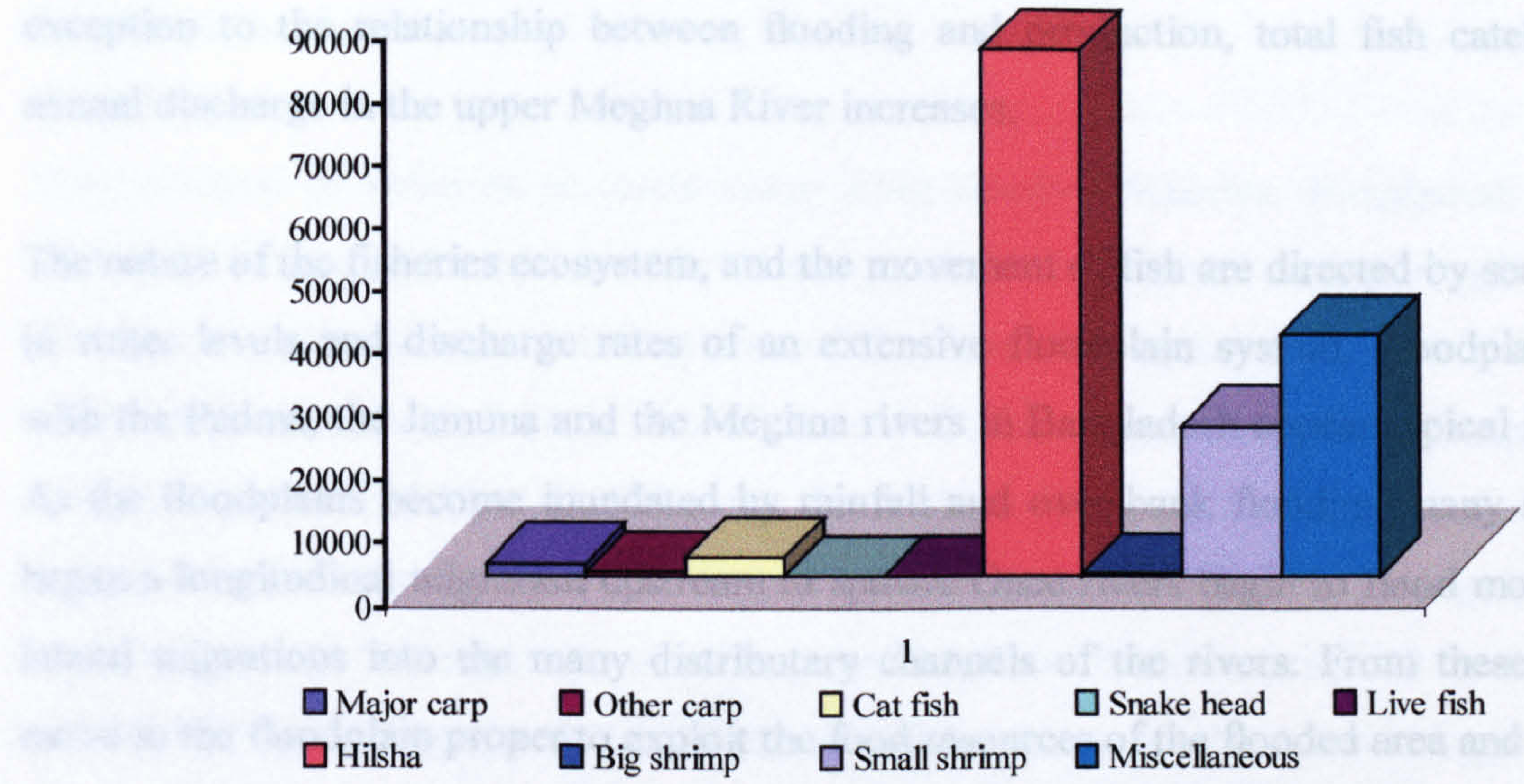

Figure 2.17. Annual total catch of fishes by species in Bangladesh (DOF, 1994-95).

The development activities in the agriculture sector have adversely affected the fishery resources in the country. Flood control, drainage and irrigation projects have affected fish migration, breeding, recruitment and production (Hoggarth, 1999; Nuruzzaman, 1998). A good example of these effects is elimination of breeding grounds of carps due to the straightening of the Halda river channel, which is one of the biggest breeding ground for carps in the country. Further, the contamination of waters by pesticides and other chemicals is also adversely affecting the fish population.

2.3.4 Floodplain fisheries

The flood cycle is an essential element in the life history of most fishes in Bangladesh rivers. Inundation of the floodplain provides the spawning grounds, nursery areas, and major feeding opportunities for a wide range of fish and prawn species. More than 256 species of indigenous fish and over 20 species of indigenous prawns have been recorded in the open inland water system (Rahman, 1989). Many of these species migrate considerable distances upstream, under the stimulus of rising water, to reach the spawning areas; the fish then move out over the floodplain as the waters extend laterally. A direct relationship can be drawn between the magnitude of the annual flood event and total fish production (FAP-6, 1993), and this relationship has been demonstrated throughout the tropical ecosystems. Bangladesh is no exception to the relationship between flooding and production, total fish catch increases as annual discharge in the upper Meghna River increases.

The nature of the fisheries ecosystem, and the movement of fish are directed by seasonal changes in water levels and discharge rates of an extensive floodplain system. Floodplains associated with the Padma, the Jamuna and the Meghna rivers in Bangladesh appear typical in this respect. As the floodplains become inundated by rainfall and over-bank flooding many species of fish began a longitudinal migration upstream to spawn. Once rivers begin to flood most fishes begin lateral migrations into the many distributary channels of the rivers. From these channels fish move to the floodplain proper to exploit the food resources of the flooded area and to spawn.

The productivity of a floodplain can be correlated with the area that is inundated and the flood season represents the major period of growth for all sizes of fish. As the floodwaters recede, fishes migrate from the floodplain and the first fish to migrate are the adults, followed by large numbers of juveniles produced during the spawning season. During these phases of migration fish populations are at their peak and they become concentrated in the channels and tributaries leading back to the main river (Aguero *et al.* 1989). Fish are most vulnerable to fishing activities during this migratory phase. **Figure 2.18** shows the concentration of fishes in the floodplain during flooding.

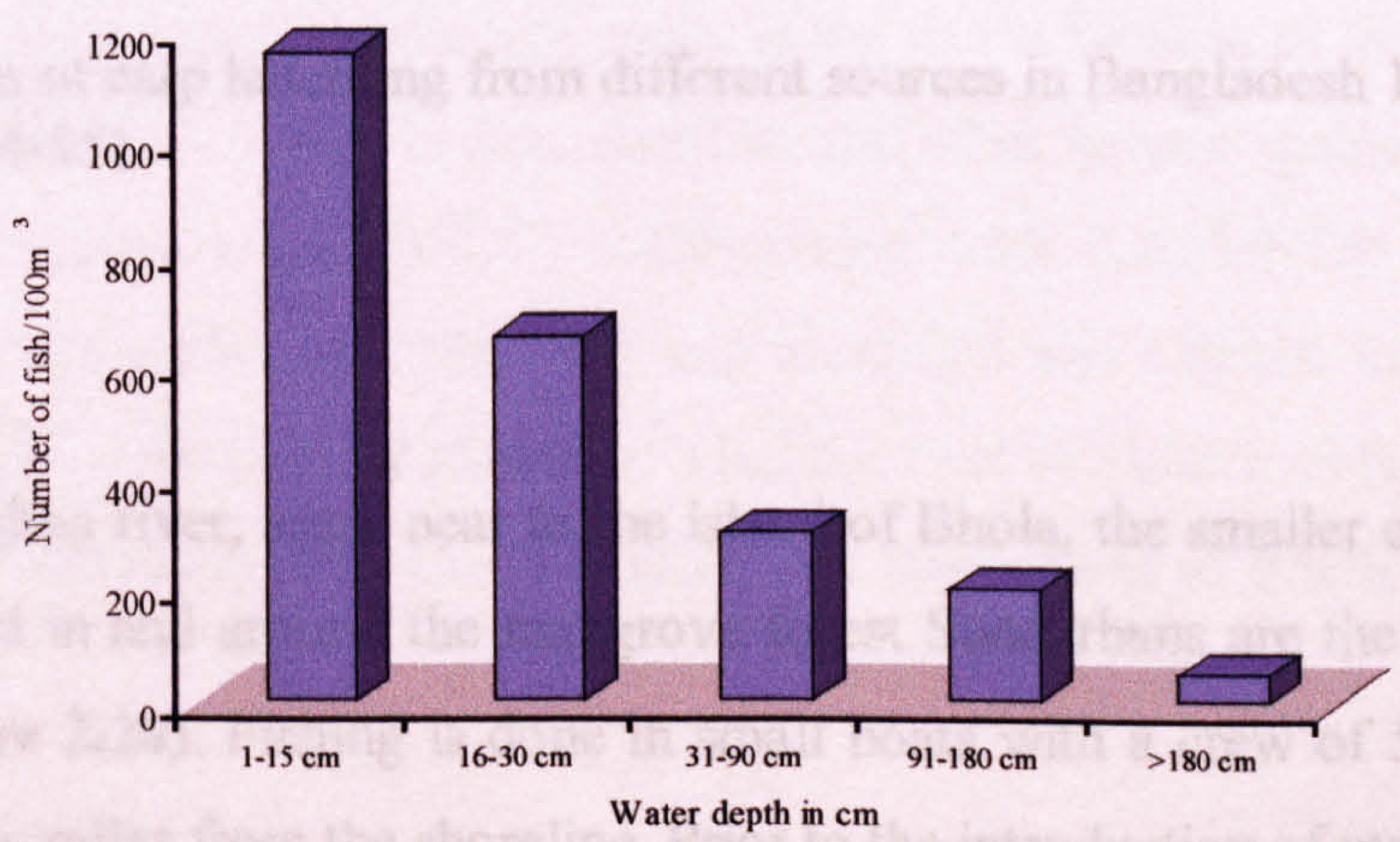

Figure 2.18. Average fish concentration by depth class occurring in the Bangshi-Dhaleswari floodplain during June16 –October'31, 1996 (source: EGIS, 1997).

2.3.5 Riverine fisheries

Sixty percent of fisheries products come from riverive fisheries. Bangladesh has very rich freshwater resources. Hundreds of fertile and productive rivers and their tributaries are spread all over the country and the catchment area of the three river systems is about 1.61 million km^2. Other important rivers include the Tista, old Brahmaputra, Karnafuli, Buriganga, Karatoa, Surma, Rupsa, Shitalakha, Aryalkha etc. These three rivers are the original abode of the three delicious major carp species of the sub-continent (catla, rohu and mrigal). Rivers have traditionally been the major source of carp seed and have been the principal seed supply for fish culture systems before the development of private sector hatchery technology in the country (**Figure 2.19**).

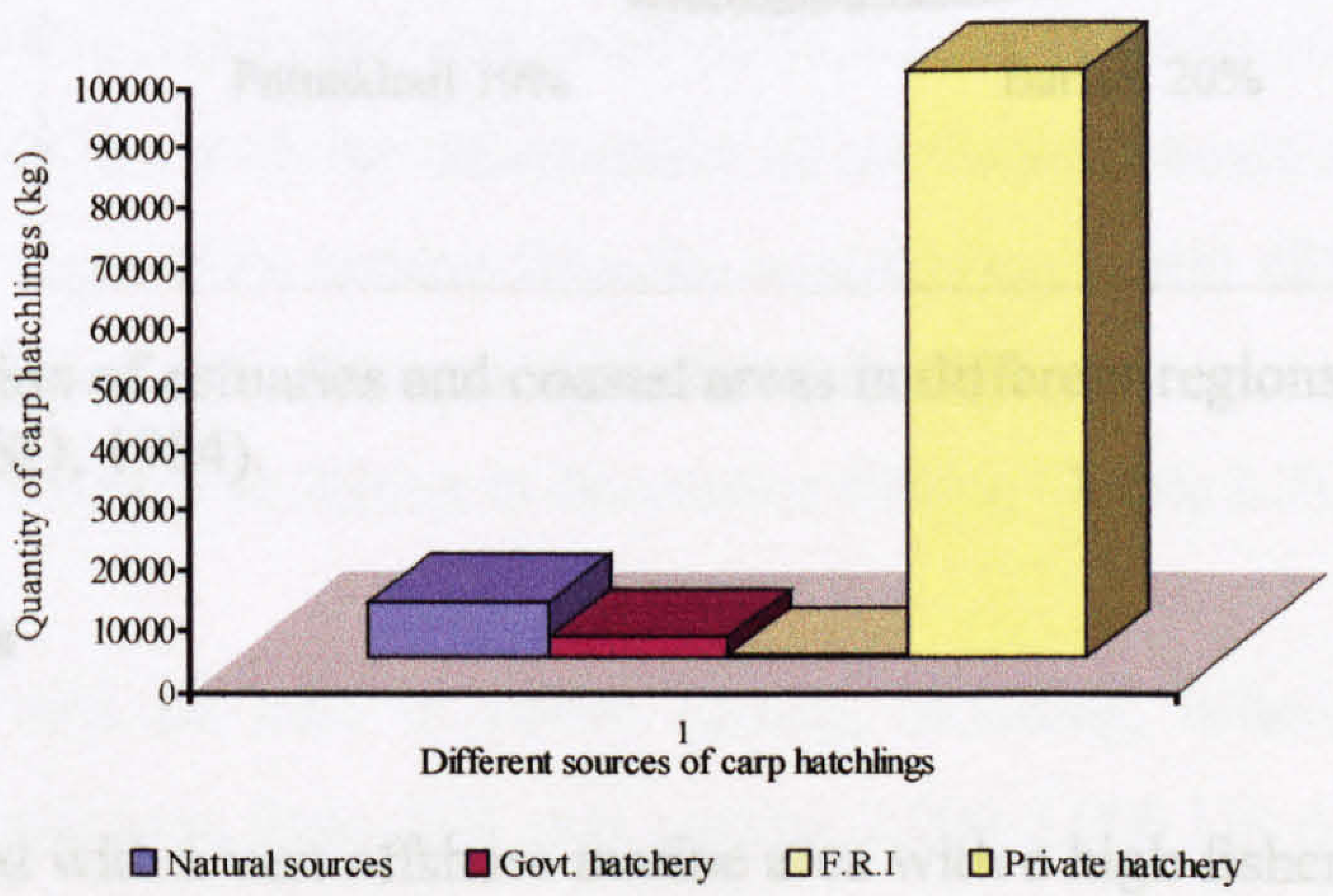

Figure 2.19. Production of carp hatchling from different sources in Bangladesh 1995 (source: DOF, 1994-95).

2.3.6 Coastal fishery

The estuary of the Meghna river, areas near to the island of Bhola, the smaller estuarine areas in the Chittagong area and in and around the mangrove forest Sundarbans are the major zones for coastal fisheries (**Figure 2.20**). Fishing is done in small boats with a crew of 5-10 people who fish not more than a few miles from the shoreline. Prior to the introduction of mechanised fishing boats in the late 1960s, traditional sailboats or rowing boats carried out fishing. The fishing season was confined to the calm months of October through March. Currently, the operation of mechanised fishing craft (9-14 m long, powered with 6-45 Horse Power engines) has extended. These boats operate eight months in a year. In addition, about 14,014 non-mechanised country fishing boats are also fishing in the coastal waters (DOF, 1994-95). Because of the declining trend in capture fisheries production in the inland open waters caused by habitat reduction and modification, primarily by flood control and drainage projects, environmental degradation through pollution and increased fishing pressure, capture fisheries in the coastal areas and the deep sea are becoming important in relation to the domestic demand for the fish in the country.

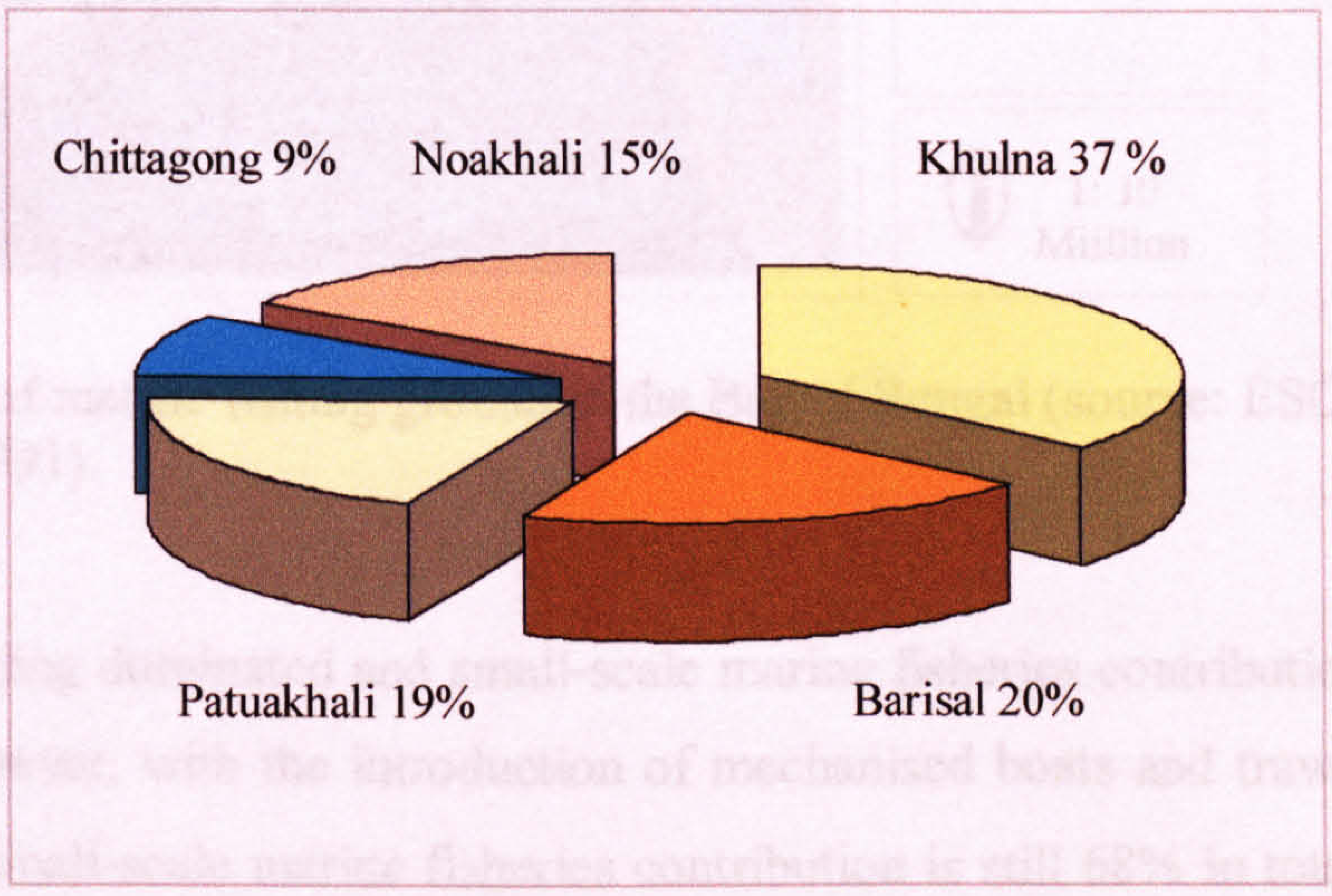

Figure 2.20. Distribution of estuaries and coastal areas in different regions of Bangladesh (SPARRSO, 1984).

2.3.7 Marine fisheries

Bangladesh is endowed with a vast offshore marine area with a high fisheries potential. This area is considered to be one of the most productive zones in the world because of the presence of the Sundarbans mangrove forest. It is rich in fish, shellfish and other aquatic resources. Bangladesh Fisheries Development Corporation (BFDC) collaboration with FAO/UNDP have conducted several surveys during the period of 1958-1971 and identified and charted four major fishing grounds, namely, Swatch of No Ground (South of Khulna), East of Swatch of No Ground (South of Patuakhali), South Patches (beyond Cox's Bazar), and South-west of South Patches (**Figure 2.21**, Hussain, 1982).

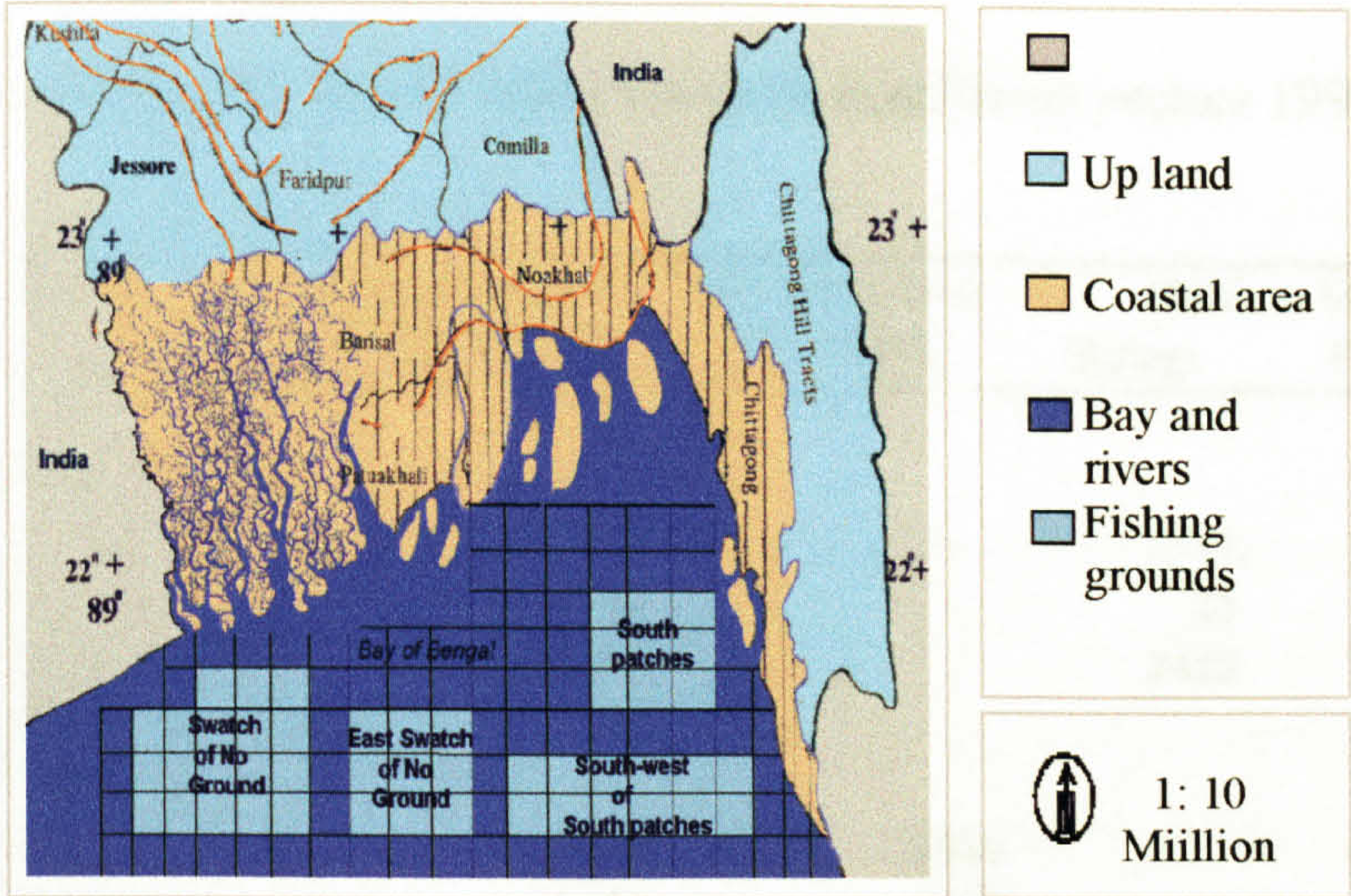

Figure 2.21. Location of marine fishing ground in the Bay of Bengal (source: ESCAP, 1988; Hasan, 1991).

In 1960, traditional fishing dominated and small-scale marine fisheries contribution was 90-95% to the total catch. However, with the introduction of mechanised boats and trawlers, they have lost their position but small-scale marine fisheries contribution is still 68% in total marine catch (DOF, 1994-95). At present, 41 shrimp and 12 fish trawler, 3,317 mechanised and 14,014 non-mechanised boats are engaged in fishing in the marine fishing (**Table 2.7**).

Four types of fishing nets are used in marine fishing, including, behundi (set bag net), funda (stake nets), gill nets and long lines. Gill nets costing 2,000-3,000 US dollar, depending on the length and weights of the nets, are almost all drift nets with generally 100 mm mesh used to catch hilsa, pomfret, mackerel, croaker, red snapper, grunter, shark and catfish. On the other hand, behundi is a fixed bag net used to catch shrimp, bombay duck, promfret, large croaker and Spanish mackerel, one of which costs 400-800 US dollar depending on size. Funda or stake nets are 55 m long with 4-inch mesh used to catch perch and Indian salmon. Price of a funda net is about 400-600 US dollar. Long lines are usually about 500 m long and bear 1,000-1,500 hooks. The main species caught are croakers but thread-fins are also caught.

Table 2.7. Annual total catch of the Marine Fisheries in different sectors 1994-95.

Type of Fishing	Number of Craft (Trawler/Boat)	Number of Unit (Gear/Net)	Catch in Metric tones Shrimp	Fish	Total
A. Industrial					
(1) Trawl Fishing					
a) Shrimp	41	–	2391	4856	7247
b) Fish Trawler	12	–	25	4443	4468
Total Industrial	**53**	–	**2416**	**9299**	**11715**
B. Artisanal					
(1) Gill Net Fishing					
a) Mechanised	2880	2880	–	134308	134308
b) Non -mechanised	3509	3509	–	19602	19602
Sub Total	**6389**	**6389**	–	**153910**	**153910**
(2) Set Bag Net Fishing					
a) Seasonal (M.B)	182	5400	5130	46115	51245
Seasonal (N.M.B)	2680				
b) All season (N.M.B)	4590	7215	11102	13563	24665
Sub Total	**7452**	**12615**	**16232**	**59678**	**75910**
(3) Long Line Fishing					
Jew fish long line					
a) Mechanised	255	1121	–	7965	7965
b) Non -mechanised	127				
c) Other long line	1000	963	–	2403	2403
Sub Total	**1382**	**2084**	–	**10368**	**10368**
(4)Trammel Net Fishing	500	500	522	4790	5312
(5) Other gears Fishing	1608	2222	1193	6242	7435
Total Artisanal (M.B.)	**3317**	**23810**	**17947**	**234988**	**252935**
(N.M.B.)	**14014**				
Grand total	**Trawler 53**	**Gill net 6389**	**20,363**	**244,287**	**264,650**
(Industrial+Artisanal)	**(M.B.) 3317**	**SBN 12615**			
	(N.M.B.) 14014	**Long line 2084**			
		Others 2222			
		Trammel 500			

M.B.=Mechanised Boat, N.M.B.= Non Mechanised Boat, SBN= Set Bag Net

2.4 Culture systems in the region

Bangladesh is mainly dependent upon agriculture, although it is slowly progressing towards industrialisation. However, even industrial development is still dependent on agriculture. Fishery is a vital industry in Bangladesh. The sector accounts for about 10% of agricultural Gross Domestic Product (GDP), 3.5%of GDP, 7% of total export earnings, and a major source of the country's protein intake (Mazid, 1998). It employs almost 2 million full-time fishermen and 12 million people working part-time. A large and rapidly growing number of very poor people depend on fishing or nutrition and income. The contribution of the sector to national food supply and GDP needs to be optimised in order to support economic growth and employment.

2.4.1 Historical development

In the past, Bangladesh had abundant of wild fishes, which met the requirements of the country and therefore people were not interested in fish culture. However, fish culture was carried out unwilling in the ponds, tanks and ditches, which were created by the ancient rulers for drinking water, household work and irrigation purpose. In the sub-continent, the first fish culture was introduced by an Indian scientist, Dr. S. L. Hora (1932-1947) and one of his fellow researchers, Dr. Nazir Ahamed successfully introduced major carp culture in Bangladesh (Hasan, 1991). In 1967, the Faculty of Fisheries was established in Bangladesh Agricultural University (BAU) with a view to boost the standard of fisheries education and research, which is considered to be a milestone in the development of aquaculture in the country.

2.4.2 Carp culture

Fish culture in ponds is an age-old practice in the country. Traditional fish culture involves no inputs and with natural stocking of seeds. Every year the pond is filled with floodwater by opening a dike, which allowed carp seeds as well as other fishes to enter into the ponds. Sometimes, ponds are stocked with fish seed from out side but species are not carefully selected. Ponds are not managed properly, as no fertiliser is applied and predators are not removed from the ponds. Consequently, production remains very low. This practice still exists in many parts of the country. However, fish farming in Khulna region is being conducted at a relatively higher level of technology as compared to that in other parts of the country. The pond fish production in Jessore district is recorded 2262 kg/ha/year, which is the highest average production in the country (Nuruzzaman, 1998).

With the improvement of carps breeding techniques, fish culture in ponds has a great momentum. Carps seeds are stocked either individual species or four to six species of fish seeds at the same time such as catla, rohu, mrigal, silver carp, grass carp, big head carp, which is called polyculture or composite culture. Sometimes a combination or polyculture is made with carps and tilapia (*Oreocromis mosasambica,* and *O. niloticus*) or Thai barb (*Puntius gonionotus*), in order to increase production. In this type of culture method, ponds are managed intensively. Aquatic weeds, predators and other unwanted species are removed during pond preparation. Sometimes the pond is sun dried for removal of fouling gasses and predators. If dewatering of ponds is not possible, rotenone, tea seed cake or phostoxin tablet is applied to remove predators, insects and other species from the pond. Prior to release fish fry, lime and fertilisers are applied to the pond. Supplementary feeds are used, water is added in the ponds whenever needed rather than for exchange purposes. However, production is still lower than most of the Asian countries.

2.4.3 Shrimp culture

The technological advances of Asian shrimp farming systems have not only contributed to a rapid expansion of Asian shrimp culture, but have also created greater opportunities for foreign exchange earnings in the1980s and 1990s. Current trends, however, indicate that competition has significantly increased in world shrimp markets, as many Asian countries initiate or expand shrimp culture. Over supply of cultured shrimp products in the global market has already occurred in the early 1990s. Consequently market prices of shrimp have dropped and profit margins have been squeezed (Chong, 1990).

Four types of shrimp culture methods are practised in Bangladesh at present (**Table 2.8**).

Traditional extensive: In this method, ponds of varying sizes from a few hectare to over 100 hectare are tide fed. Collection of seeds is done, mostly by trapping from the wild during high tide. No liming, fertilisation and feeding is done but water is partly changed during spring tide. Production is very low from 60-200 kg/ha/y. Other organisms such as fishes and crabs are also kept and harvested during this method.

Improved extensive: A few to 50 ha ponds are normally tide fed but smaller ponds at higher elevation are sometimes fed by pump. Two to three juveniles are stocked/m^2. Lime and fertilisers are used and feeding is done but not systematically. Fifty percent of the water is exchanged during each spring tide cycle or 5-7 cm water is exchanged every alternate day. Production in this type of operation is 200-1,000 kg/ha/y in two crops.

Semi-intensive: In this system 10-35 post larvae (PL)/m^2 are stocked in smaller ponds ranging from 0.4-5 ha. They are given mostly pelleted feed but also subsist partly on natural foods. Ponds are generally aerated and 10-20% water is exchanged daily by gravity drainage. A production of 2-6 t/ha/y is obtained in this system.

Intensive system: About 35 PL/m^2 are stocked and ponds of 0.1 to less than 1 ha are generally used. Water is aerated and at least 30% water is exchanged daily. Shrimp are completely dependent on artificial feed. Production is about 5-10 t/ha/y. However, this type of culture practice is rare in Bangladesh (Deb, 1998; Khan and Hossain, 1996; Mazid, 1998; Nuruzzaman, 1991).

Table 2.8. General comparative scenario of different shrimp culture system in the coastal areas of Bangladesh (source: Deb,1998).

Issues	Shrimp culture system in Bangladesh			
	Traditional extensive	Improved extensive	Semi-intensive	Intensive
Pond size	5-100 ha or larger	5-50 ha or larger	0.4-10 ha	0.1 to <1 ha
Pond dikes	Low, ordinary	Low, ordinary	Stable	Designed, stable
Water control	No/ordinary	Ordinary wooden gates	Strong concrete sluice	Strong concrete sluice
Design and layout	No	Little or no	Planned	Well-planned, designed, stable
Technical manpower	Experience based	Experience based	Skilled manpower required	Skilled manpower required
Fry source	Wild	Wild	Wild/imported	Wild/imported
Stocking/M^2	1-1.5	2-4	20-40	40-60
Water management	Little or no	Ocational tidal exchange	Tidal exchange, pump, aeration	Reservoir, pump, aeration, wheels
Culture period	4-6 months	4-6 months	3-4 months	3-4 months
Crops/year	1-2	1-2	2-3	2-3
Feed used kg/ha/yr	Natural	Natural, little low cost feed	Natural and pelleted feed	Formulated complete feed
Survival rate	50% or less	50% or less	60-70%	70-80%
Lime used kg/ha/yr	Little or no	<100 kg	250-400kg	500+ kg
Fertilizers used kg/ha/yr	Little or no	Cowdung 500kg, Little or no urea/ TSP	Cowdung 2000kg+ Urea 500kg+ TSP 100kg	Cowdung 4000kg+ Urea 500kg+ TSP 200kg
Chemicals	No	No	Used	Widely used
Production ka/ha crop	60-200	100-500	1000-3000	2000-5000
Labour days/ha/yr	50-100	150-250	1000-1500	2000
By product	Salt, fish, rice	Salt, fish, rice	Occasionally Fish/crab	Occasionally Fish/crab
Acclimatization of fry	Not applicable	Not applicable	Done	Done
Economics	Subsistence	Subsistence	Commercial	Entrepreneurial
Environmental impact	No/little	No/little	Moderate to high	High

Out of these four-culture practices, extensive shrimp culture operation is becoming less important due to low productivity and vast amount of land is needed. On the other hand farmers are adopting improved intensive shrimp culture operation as they becoming efficient to handle the culture operation with the time and getting more profit from a small land. Semi-intensive shrimp culture practice is more common in the Cox's Bazar coastal region than in the Khulna area. However, there are few farms are under this culture system in the area. Only 0.8% land is under intensive culture operation in the coastal area which is rare in the Khulna region (Deb, 1998). Improved traditional, semi-intensive and intensive shrimp culture need quality feed, which is short supply in the country.

2.4.4 Freshwater prawn culture

Most of the freshwater prawn species, especially *Macrobrachium rosenbergii,* have wide ranges of environmental tolerance. *M. rosenbergii* can grow well in freshwater to saline water up to $15^0/_{00}$ (Venugopalan and Thampy,1992) and up to $25^0/_{00}$ in cages, in ponds and in a wide range of temperatures (New, 1995). There are about 125 species of freshwater prawn in the world, of which 49 are known as commercially important (Hossain, 1995). In Bangladesh there are about 23 species of freshwater prawn including 10 species of *Macrobrachium* spp. (Akand and Hasan, 1992; Hassan, 1991; **Table 2.9**). Of these, giant freshwater prawn *Macrobrachium rosenbergii,* and monsoon river prawn, *Macrobrachium malcolmsonii,* are the two commercially important species.

M. rosenbergii is commonly cultured in brackish water ponds or low lying areas in the coastal region of Bangladesh along with penaeid shrimps. It is also cultivated alone or with carps in the ponds or rice fields in coastal districts and other regions of Bangladesh. In Bagerhat area, freshwater prawn is largely cultured in rice fields as farmers receive larger profit from prawn cultivation compared to rice (LIVE, 1997).

Table 2.9. Available commercially important *Macrobrachium* species in Bangladesh.

Family name	Species name	English name	Vernacular Bengoli name
Palaemonidae	*Macrrobrachium rosenbergii*	Giant freshwater prawn	Golda chingri
	M. malcolmsonii	Monsoon river prawn	Chakta icha
	M. villosimanus	Freshwater prawn	Dimua icha
	M. birmanicus	Freshwater prawn	Thengua icha
	M. rude	Freshwater prawn	Goda icha
	M. dayanus	Freshwater prawn	Kaira icha
	M. dolichodactylus	Freshwater prawn	Goda icha
	M. mirabile	Freshwater prawn	Lutia icha
	M. lamerrei	Freshwater prawn	Kunchuicha
	M. idae	Freshwater prawn	Goda icha

In South-western Bangladesh, prawn culture season generally operates from May/June to December/ January. Farmers usually collected PL from different sources **(Figure 1.3)**, in April /May and culture them for up to 5-6 months. They harvest their prawns in November /December. Generally they have one crop per year. However, few farmers maintain their culture all the year round. First of all, farmers prepare the dikes surrounding the rice field or repair the existing dikes. Furthermore, farmers remove the predators, harmful and unwanted fishes from the pond using rotenone powder. Sometimes they use fine mesh net to remove the fishes and insects from the pond. Few farmers dried up their ponds in order to remove the weeds, insects, unwanted fishes and predators. Following that, liming and fertilisation in the ponds is carried out. **Table 2.10** shows details of fertiliser inputs in the ponds.

Table 2.10. Shows amount of fertiliser inputs in prawn culture ponds in the South-western region of Bangladesh (source: BAFRU, 1995).

Fertiliser	Amount (kg) / ha
Cattle manure	1235-1730
Compost	1975-2470
Poultry manure	740-1235
Urea	24-37
TSP	12-18

Usually 30,000-37,000 PL are released per hectare water body. Most of the farmers (74%) release other white fishes along with the prawn, such as catla, rohu, Thai barb and silver carp (LIVE, 1997, **Table 2.11**). Apart from the natural food present in the ponds, the prawns are fed with artificial diets such as snail meat, mustard oil cake, fishmeal, ground mussels, trash fish and wheat bran. At the final stage, farmers apply pelleted feed to have a good harvest. However, flood hazard and theft is the main obstacle in prawn farming in the region (Khulna Correspondent, 1999).

Table 2.11. Describes density of other fish species used in prawn culture system in the Southwest of Bangladesh (source: BAFRU, 1995).

Name of species	Number of fish released/ ha
Macrobrachium rosenbergii	7,900-8,650
Catla (*Catla catla*),	1,000-1,250
Silver carp (*Hypophthylmichthyes molitrix*)	2,200-2,400
Grass carp (*Cytenopharyngodon idella*)	250-500
Rohu (*Labeo rohita*)	1,700-2,000
Shar barb (*Puntius gonionotus*)	250-500
Total	13,300-15,300

Intensive management techniques are applied in prawn culture, as nursery reared PL are stocked in the ponds, water quality is tested regularly, shelter for the PL is placed in the ponds to protect them from excessive sunlight and predatory birds. Fertilisers are used weekly or monthly to increase the natural food after releasing the fry (**Table 2.12**) and the ration of supplementary feed is increased subsequently every week according to the biomass in the ponds (**Table 2.13**).

Table 2.12. Fertiliser used daily/weekly to increase the natural feed in per hectare area of *Macrobrachium* spp pond (source: BAFRU, 1995).

	Fertiliser	Amount (kg)/ ha
Daily	Cattle manure or	50-60
	Compost	75-100
	Urea	1-1.2
	TSP	0.75
Weekly	Cattle manure or	500
	Compost	750
	Urea	8.5-10
	TSP	5-6

Table 2.13. Supplementary feed applied weekly in the *Macrobrachium* spp ponds.

Month	Amount of feed applied per hectare water body			
	Rice husk/ wheat bran (kg)	Oil cake (kg)	Snail meat (kg)	Total amount of feed (kg)
1st	1.5	3.5	2	7
2nd	2.5	6	3.5	12
3rd	3.5	8.5	5	17
4th	5	11	6	22
5th	5	12	7.5	24.5

Source: BAFRU,1995.

Prawns are harvested during November-December, normally 10-12 times in every season by cast net, depending on the market price and farmers financial condition. After harvest, prawns are usually cleaned with pond water and beheaded. Beheaded prawns are washed with tube well water and kept in a cool place, and then are taken to the local depot either by van or manually. In the depot, they are graded into different grades and sold. Prawns destined for export are kept with ice and packed in bamboo basket for transport to the processing plant once each day (**Figure 2.22**). However, prawns are sold with head to reduce contamination after a European embargo was imposed on Bangladeshi shrimp imports in 1998 (Personal communication). In this procedures farmers sell their crops to the deport where they are kept with ice prior to transport to the processing plant where they are beheaded by the skilled persons and cleaned with fresh running water before quick freezing for export.

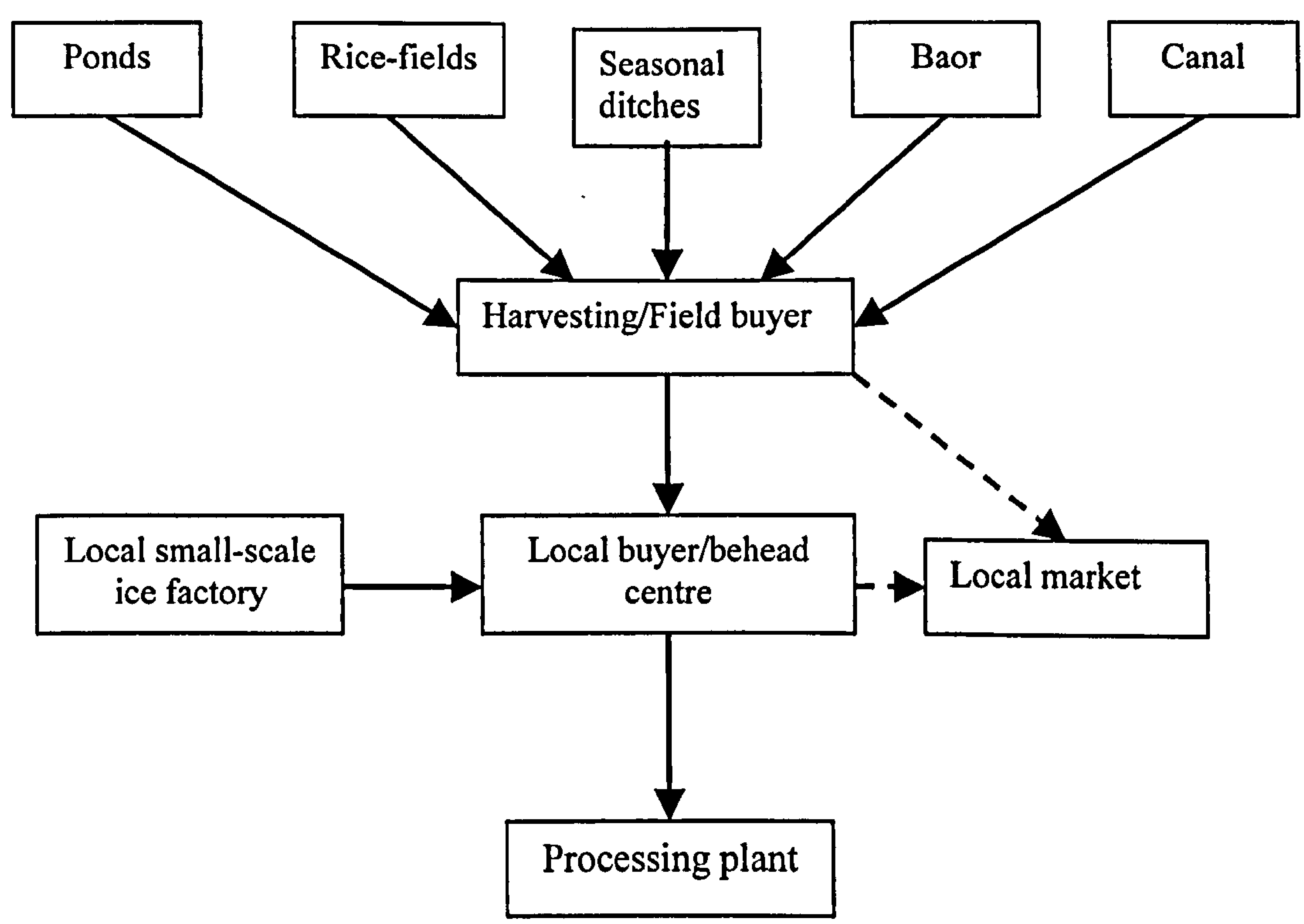

Figure 2.22. Prawn marketing chain in the South-western Bangladesh (source: Hossain, 1995).

2.4.5 Fish culture in rice field

Rearing fish in rice fields has long been practised in South Asian countries. However, rice fish culture is not so popular in Bangladesh due to excessive flood or scarcity of water. Most of the rice fish culture is carried out in the coastal region in the country. During the months of July and August, when the salinity in the brackish water ponds and the adjacent water becomes less saline or fresh, farmers drain saline water and rain water is allowed to accumulate and drained out to remove salinity from the field. During this process, fin fish like parse (*Liza parsia*), Khorsula (*Rhinomugil corsula*), bhetki (*Lates calcarifer*), tengra (*Mystus* spp), terre (*Eleutheronema tetradactylum*) and bele (*Glossogobius giurus*) from inundated fields are allowed to take shelter in the deeper channels. Simultaneously, land is prepared for planting transplanted aman rice seedlings. After the plantation of rice seedlings, rainwater is allowed to flood the land to a depth of 60-100 cm. At this time, fishes retained in the deeper canals move into the inundated land, where they feed and grow until harvested in November-December. At the same time, PL of the giant freshwater prawn and fingerlings of rohu, mrigal, catla, and tilapia are also released in the inundated rice fields. **Figure 2.23** shows a typical rice fish field in Khulna region.

In Bangladesh, fish production from rice fields is still by capture methods. However, several attempts have been made to culture fishes in rice fields in different parts of the country since 1980 and fish and rice production has increased significantly by approach (Das and Mukhopadhyay, 1991; Haroon and Pittman, 1997). In addition, when fish culture is carried out in rice fields, less effort is needed for weed and pest control as the fishes graze on it (Khamarkunj, 1997).

Figure 2.23. Typical rice cum fish culture field in the South-western region, Bangladesh.

2.4.6 Crab culture

The mud crab (*Scylla serrata*), commonly known as "green crab" or "mangrove crab" and locally called "habba kankra" or "kankra" occurs abundantly throughout the tidal coastal areas of Bangladesh (Azam *et al.* 1998). It is one of the popular sea-foods in many parts of the world particularly in the south-east Asian countries. Its excellent and distinctive flavour makes it one of the most delicious and costly food items (Khan and Alam, 1992). However, information on it is poor in the country.

The crab is widely distributed in the Indo-Pacific region in countries such as Thailand, Malaysia, India, Sri Lanka, Indonesia, Bangladesh, Vietnam, the Philippines and Myanmar (Samarasinghe *at el.* 1992). Currently, culture trials are in vogue to produce this species, in cages and fattening is done for 15 to 30 days.

Scylla serrata is common in the mud flats of the littoral and inter-tidal zones of the Bay of Bengal. The species hardly occurs in sandy and rocky areas. It is distributed over a wide range of salinity, from 2 ppt. to oceanic waters, from the coast to the interior brackish water. Though the crabs prefer mangrove swamp, they also exist in large numbers in shrimp ponds and in the burrows of the peripheral dikes. They are essentially euryhaline, but die at once in 70 ppt of salinity. *Scylla serrata* rarely tolerates turbid water.

The crabs live in mud burrows, which occur densely in internal mangrove swamps, a little above the low tide mark. The burrows are also frequent in embankments of shrimp culture ponds and coastal irrigation projects. The density varies with seasons, increasing with rains and then gradually decreasing during the cool, dry winter. Crabs usually take shelter in burrows during the day and during high tides at night they swim around in search of food. About 80% of catch from burrows are males. Each crab burrow is oblique, 1-2 m deep and 8-16 cm wide at the opening.

Mud crab has been an incidental product of culture operations meant to raise milkfish, prawn and other fin fishes, in Southeast Asian Countries (Chandrasekaran and Perumal, 1993). The culture of mud crabs in many countries generally falls under two major categories, (i) fattening in cages and (ii) growing out in ponds.

Most fattening procedure is done in cages made of bamboo. However, nets, earthen ponds or ditches are also used. Crabs of about 150-200 g are reared in bamboo cages in individual compartments and fattening is done for 15 to 30 days. Stocking density varies from 30 to 60 kg/cage, depending on the supply and depth of the cages. Feeding with trash fish, soft-shelled snails, animal offal and other materials is carried out daily. A few farmers supplement trash fish with fish offal, obtained from fish sellers, or shrimp head, obtained from farmers. Kitchen offal is also offered to the crabs while trash fish and offal become scarce. However, in grow out system, relatively small sized crabs, caught from wild, which were discarded by the wholesaler (less than 5 crabs /kg) are grown for a longer period (one to several months) until they attain marketable size (Prinpanapong and Youngwanichsaed, 1992).

Ponds for crab culture can be any size but small ponds having an area of about 350 to 500 m^2 are preferred which are more efficiently manageable than the bigger ponds (Felix *at el.* 1995). The depth of the pond should be as much as 1 to 2 meters, while gradient or slope of the dikes should be steep, to prevent escaping. Pond dikes are made of mud blocks and fenced with bamboo mats of 1.5 to 2 m high. Mats should be installed from 30 cm deep into the mud to avoid crabs escaping during low tide by borrowing through dikes. It will also prevent them escaping by climbing over. **Figure 2.24** shows construction of a pond for crab culture.

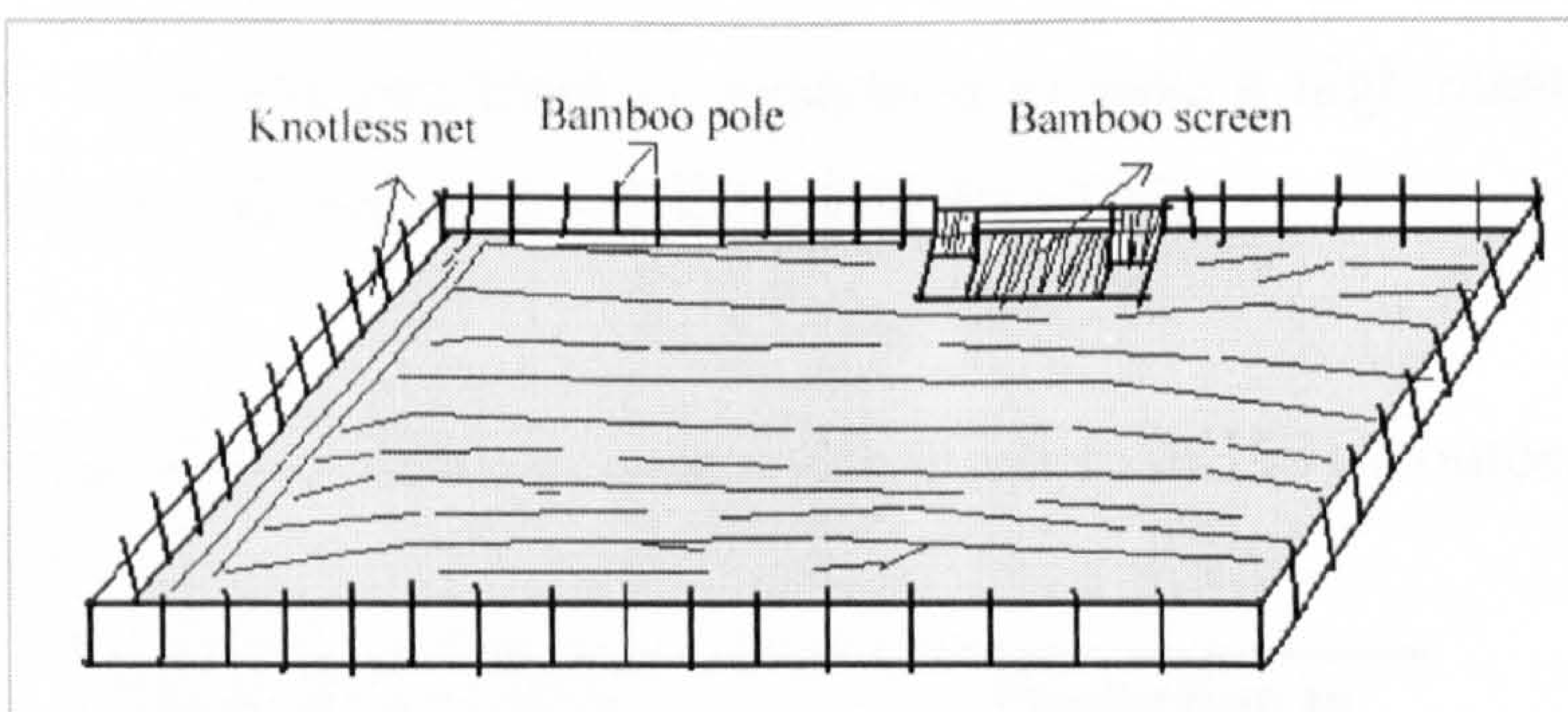

Figure 2.24. Earthen pond for mud crab culture enclosed with knot less net for preventing them from escaping from the pond (Source:Rattanachote and Dangwatanakul, 1992).

Ponds are treated with lime at about 350-600 kg/ha and kept exposed to the sun for 5-7 days. Then water is drained into the ponds until a 1.5 m depth is attained. Water exchange is done daily or periodically by pumping or tidal effect.

After two to three days of pond preparation, locally caught crab larvae are stocked at a rate of 3-5 crab/m^2 at around 0700- 0800 h. Animal food, such as trash fish, snail meat, cattle or poultry offal, fish viscera, or kitchen wastes are used as feed. Fresh water soft-shelled snails are the most important food items of crabs (Felix *at el.* 1995). Crabs are fed at a rate of 7-10% total body weight per day. Enough food is given to prevent cannibalism. The culture period is dependent on the initial size of crab stocked and size desired at harvest. Precise growth data are not available, as crabs of various sizes are stocked in the same pond on a continuous basis and partial harvesting is carried out from time to time. However, available data indicates that the growth of mud crab ranges from 1.22 to 1.41 g/day.

Water exchange in fattening cages is comparatively easier than the ponds as cages are placed in ponds or rivers, and are particularly dependent upon currents in water exchange. Bio fouling of crab cages is minimal as the crab crawling along the nets or bamboo probably helps to reduce fouling. Water exchange in crab ponds is mostly done by tidal exchange. The amount of water exchange each time depends on tidal fluctuations. Salinity, temperature, dissolved oxygen and pH should be 10-30 ppt, 21-35^0 C, 4-9 PPM and 5-9 respectively.

Crabs weighing of 220-250 g and with carapace widths of 12-15 cm are harvested in 5-6 months. The survival rate varies with the culture practice, ranging from 50-70%. The harvesting should be made before the crabs come into reproductive conditions to have a high meat yield and secure good price. **Table 2.14** shows the production in Bangladesh in 1991.

Table 2.14. Crab production from different zone in Bangladesh in 1991 (source: Khan and Alam, 1992).

Name of the region	Production in (MT)
Cox's Bazar	992
Khulna	439
Barisal and Potuakhali	35
Satkhira	45
Bagerhat	606
Total production	2117

Harvesting is done with the help of dip net and lift net baited with trash fish. Plastic pipes are placed sometimes on the bottom for harvesting. When the crab hide in the pipes, it is lifted and harvest is done. For effective harvesting, during construction of the pond itself, a water inlet tank of 1.5 m^2 is made in the centre of the pond. When water enters in the tank, crabs congregate there and are collected (Felix *et al.* 1995).

The trading pattern of the mud crab involves a series of intermediaries between the catcher/farmer and the consumer or exporter (**Figure 2.25**). The marketing system expanded during the end of the eighties and early nineties with foreign markets opening up. Before that, crabs were marketed only locally. However, as domestic consumers are generally poor, the price is much lower than in the export market (Khan and Alam, 1992).

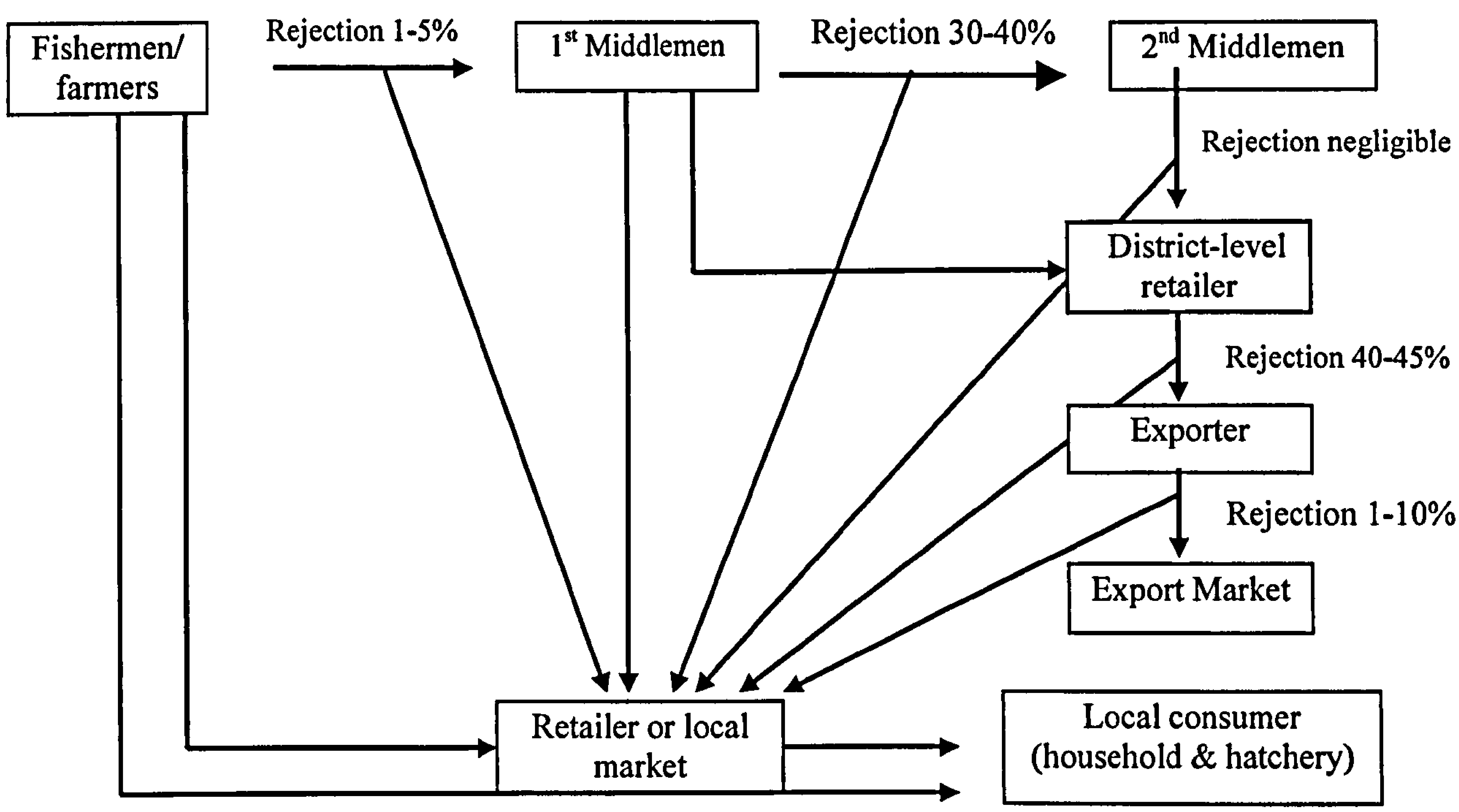

Figure 2.25. Schematic diagram shows the marketing channel of mangrove crab (modified after: Cholik and Hanafi 1992; Khan and Alam, 1992).

Fishermen usually market their catch 2 to 3 days after capture. During this time the crabs are kept in their homes or boats, either in water or in cages, without water. Male crabs weighing less than 200 g and female crabs of less than 150 g are rejected and are sold locally. The present domestic market is based mainly on this supply. Males and females are separated at the district level market or at the fourth or fifth local marketing step and, in some cases, even at the production point. The marketing trend is for improvements in both quality and price.

Present international markets for crabs are Singapore, Hong Kong and a few other Southeast Asian countries. More than 95% of export involves live crabs. Processed and frozen exports are negligible.

2.5 Other Land uses

2.5.1 Population density

Bangladesh has the highest density of population in the world (Viju, 1995). Like other developing countries, the major constraint on sustainable management of natural resources in Bangladesh is its huge and rapidly increasing population. Assuming an average annual growth rate of 2.4%, conservative estimates project that there will be a population of 140 million by the end of 2000. During the period of 1951-1981 the population in the country doubled from 44.2 million to 89.9 million (Brammer, 1996), thus also doubling the pressure on the limited resources in the country. The demographic composition of the population shows that about 54% of the population is below 15 years of age. So, in the next decade, a large number of people will enter into the labour market and this poses serious pressure on available land and natural resources. **Figure 2.26** shows the population density in the study area.

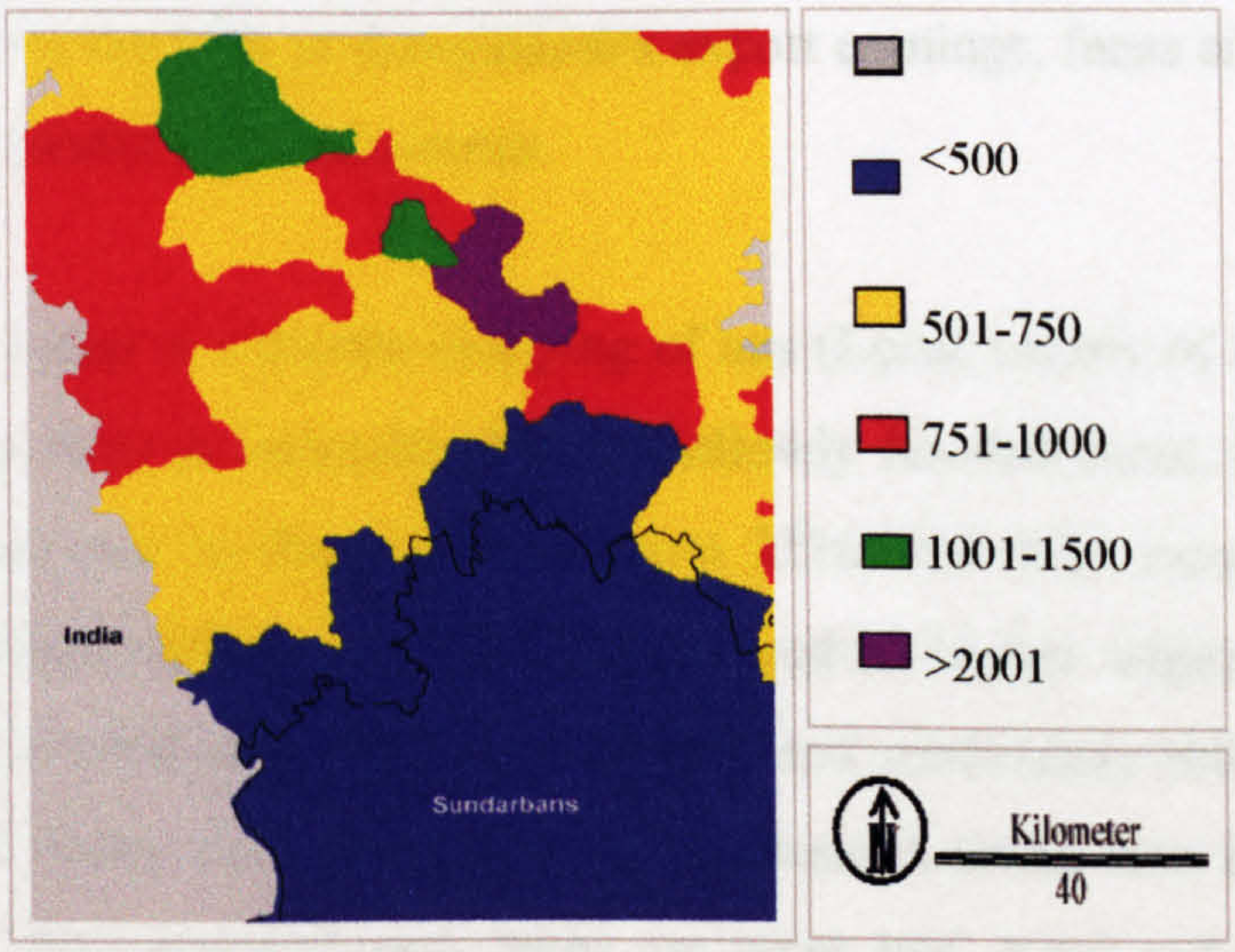

Figure 2.26. Illustrates the population density in the Khulna region, Bangladesh.

Urbanisation is proceeding rapidly. The areas around the capital city, Dhaka, and around Comilla are the most densely settled. The Sundarbans, an area of thick tropical mangrove forest inland from the coastline on the Bay of Bengal, and the Chittagong Hill Tracts on the south-eastern border with Burma and India, are the least densely populated areas. About 98% of Bangladeshis are ethnic Bengali and speak Bengali. Urdu speaking, non-Bengali Muslims of Indian origin and various tribal groups, mostly in the Chittagong Hill Tracts, comprise the remainder. Most

Bangladeshis (about 83%) are Muslims, but Hindus constitute a sizeable (16%) minority. There are also small numbers of Buddhists, Christians, and animists. English is spoken in urban areas and among the educated.

2.5.2 Agriculture

Most of the people of Bangladesh earn their livings directly or indirectly from agriculture. Rice and jute are the primary crops, although wheat is assuming greater importance; tea is grown in the hilly regions of the Northeast. The country's fertile soil and normally ample water supply yield three rice crops in many areas. Through better flood control and irrigation measures, more intensive use of fertilisers and high-yielding seed varieties, increased price incentives, and improved distribution and rural credit networks, the country's labour-intensive agricultural sector has achieved steady increases in food grain production over the last decade. Rice is Bangladesh's principal crop, although yields per hectare are still among the lowest in Asia. Wheat production is also expected to rise from 1 to about 1.36 million metric tons in 1996 (BBS, 1997). Jute, which historically has accounted for the bulk of Bangladesh's export earnings, faces an uncertain future due to competition with synthetic fibre substitutes.

The major rice cropping system is a double cropping of aus (Local variety of rice) followed by transplanted aman (autumn rice) in intermittently or shallowly flooded areas. Boro rice (winter rice) generally replaces aus rice to the extent of about 25%. Recently, cropping of aus rice followed by robi crops (mixed winter crops) is also practised on higher ridges of intermittently flooded land. Moderately flooded land with flood hazard, and moderately saline soil is mainly cropped with transplanted aman rice. Boro rice or broadcasted aman rice is also grown on moderately flooded land. The principal cash crops are betel leaf, betel nut, mustard, pulses, spices and coconut grown around homesteads. Cropping patterns in the region is shown in the **Table 2.15**.

Table 2.15. Contributions of different crops to cropping intensities of different land types in the coastal regions (Source: Karim *et al*, 1990).

Crops	Regions												
	Noakhali		Chittagong			Khulna			Barisal			Patuakhali	
	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1
B.aus	14	7	20	23	13	-	5	-	23	19	-	8	8
HYV aus	16	-	13	6	-	-	-	-	-	-	-	3	2
B.aman	-	50	-	-	-	-	-	85	-	14	79	-	-
L.T.aman	65	-	13	33	8	57	79	-	39	74	-	93	99
HYV	19	-	29	14	-	26	5	-	2	-	-	1	-
aman	-	-	-	-	-	1	2	1	-	-	-	-	-
Jute	-	-	2	-	-	-	-	-	2	1	-	-	-
Sugarcane	-	-	-	1	1	-	1	1	1	2	2	1	2
Pulses	-	-	-	1	1	1	3	2	-	1	1	-	-
Oilseeds	2	-	1	1	-	-	-	-	-	-	-	2	1
Spices	2	-	1	3	1	-	1	-	-	1	-	1	1
Vegetable	-	-	2	-	-	15	-	-	25	-	-	6	-
Orchard													
Intensity	118	57	80	82	24	100	96	89	102	112	82	115	113

F_0=Highland (Never flooded), F_1=Medium highland (Flooded in extreme condition) and F_2=Medium low land (Regularly flooded), B.aus =Broadcasted aus rice, B.aman = Broadcasted aman rice, L.T.aman = Local transplanted aman rice, HYV= high yielding variety.

2.5.3 Forest resources

The forests of Bangladesh can be classified under three major groups: tropical evergreen/ semi-evergreen, the mangrove forest (Sundarbans) and the moist/ dry deciduous forest called Sal forests. Tropical evergreen forests are seen in the eastern hill districts of Sylhet, Chittagong hill tracts and Cox's Bazar. The tidal mangrove forests are found along the South-west coasts. The Sal forests are seen in the central plain north of Dhaka, capital of Bangladesh. These forests are not suitable for commercial purposes as they are pocketed by settlements and heavily degraded. In addition to the above three main groups there are village forests surrounding most rural villages. Bangladesh's forest actually covers only 1 million hectares and accounts for only 6% of the total land area. There is less than 0.02 ha of forest land per head, is one of the lowest of such ratios in the world (Jeffrey *et al.* 1991).

Among the different kinds of forest resources, the Sundarbans deserve special mention. Sundarbans cover an area of 580,000 ha of which 410,000 ha is mangrove forest and 170,000 ha is open water areas of rivers, channels and creeks. It has been managed as a forest reserve since 1817 (Ali, 1998). The mangroves provide a food source and nursery for the offshore fishery, protection of the coasts from storm surges and cyclones, domestic and commercial products, recreation and tourist services, habitat for shrimp cultivation, and habitat for the Royal Bengal tiger and other national heritage.

The Sundarbans alone account for about 74% of the total area designated as reserve forest in the country. About 500,000 to 600,000 people depend on the Sundarbans for their livelihood. It is estimated that on an average day, about 45,000 people work in the Sundarbans forests (Chaffy *et al.* 1985). Fuel wood from the Sundarbans is marketed over much of northern Bangladesh and as far as Dhaka for both domestic and industrial uses. The entire domestic demand for newsprint and hardboard is supplied from Sundarbans, in addition to that, about 10% of the fuel wood used in Bangladesh is also comes from the forest (Rahman, 1998).

Fish is another major output from the Sundarbans. Over 120 species of fish are supported by the forest, of which the main types are shrimp and *Hilsa* sp. As many as 200,000 fishermen depend directly on the Sundarbans fisheries from November up to the onset of the monsoon (Nuruzzaman, 1998).

2.5.4 Mining

Khulna region is not rich in mineral resources. However, zircon, monazite, rutile, ilmenite, leocoxene and magnetite have been found in the beach sands of coastal belt of Bangladesh, which are mostly radioactive in nature (Islam, 1998). Low quality coal (peat coal) is found in Gopalganj districts in the region. Expert opinion is that there is a strong possibility of finding oil and gas within the Sundarbans mangrove forest but it would be destructive for the environment and the ecosystem of the mangrove forest if it allowed exploring this area for oil and gas.

2.5.5 Livestock rearing

Livestock is a very important component in Bangladesh producing animal protein, fertiliser and fuel, although there is not enough grazing land for animals. However, shrimp culture has had an impact upon the situation in the study area. In the past, rice was seasonally grown and after harvesting of aman rice, the land was used for grazing. However, with the advent of shrimp cultivation, there was almost no open space left in the area for cattle. Of course, the whole country has had a trend of general decline of number of livestock since 1960 (**Figure 2.27**). However, this decline in the coastal area is much more dramatic than in other parts of the country.

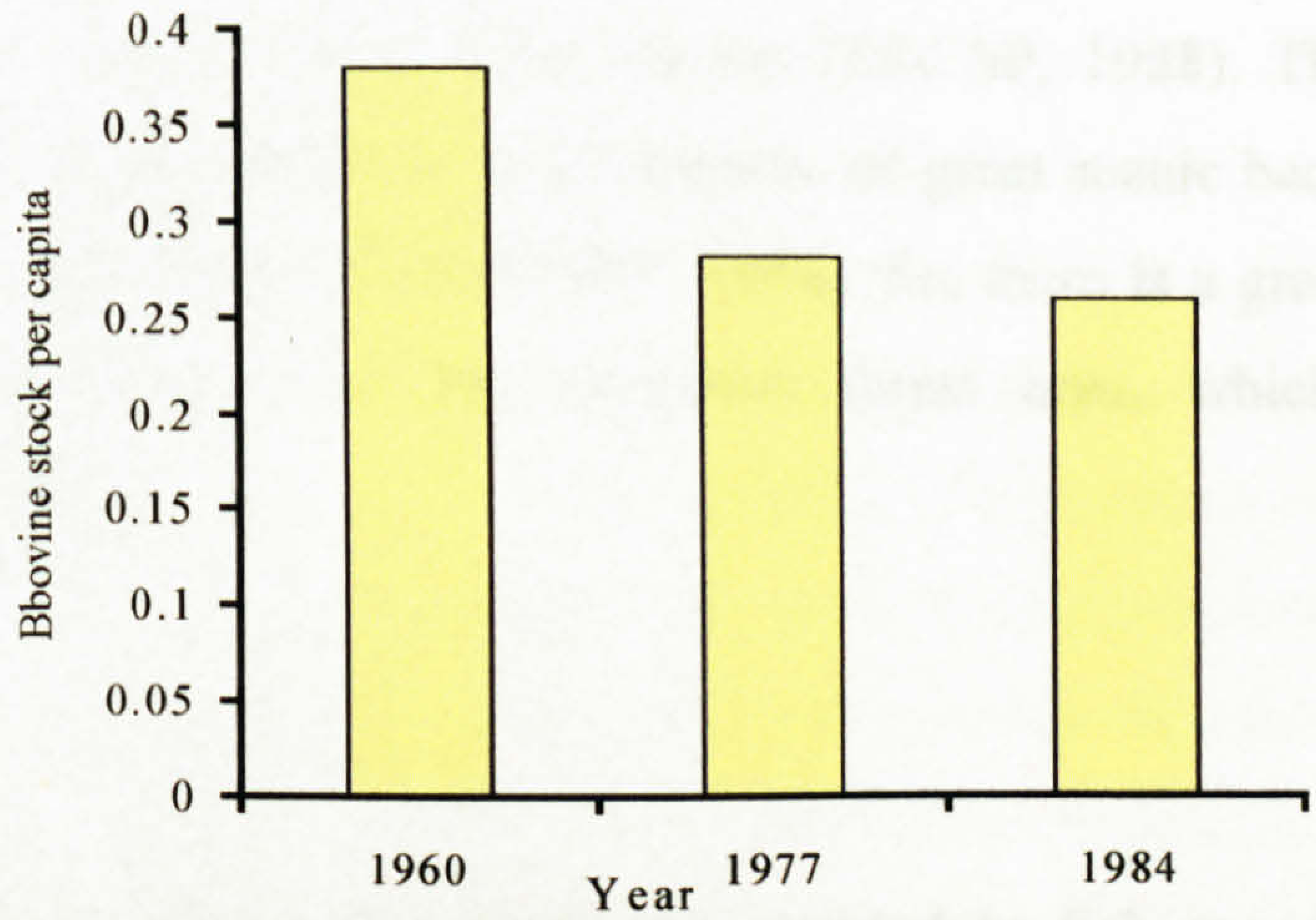

Figure 2.27. Per capita bovine stock in Bangladesh (BBS, 1997).

2.5.6 Communication

Communication in the Khulna region is not well established. However, river transport is used most frequently in the lower part of Khulna, which is cheaper than road transport systems and used to transport goods and passengers. There is a steamer service from Khulna and Bagerhat to Dhaka daily, which is comfortable but requires 24 and 18 hours respectively. All 43 administrative unit in the study area are not yet properly connected through paved roads. Khulna region has more or less 1751 km of roads, out of which 1121 km are paved roads, 293 km are partly paved roads, which are motorable all the year round and 336 km earthen roads, which are motorable only in the dry season (BBS, 1997). The area is connected with the capital by two different highways, one from Jessore which is also connected with India and wide enough to pass two vehicle side by side but requires one ferry crossing. The other one is from Bagerhat via Gopalganj, which has only one lane, and has two ferry crossings.

Khulna region has the country's 2nd largest seaport, dealing with 20% of the country's foreign trade at Mongla, Bagerhat. The region also has an inland port with the Indian border and a domestic airport in Jessore. Only Jessore and Khulna district are connected with railway to the other part of the country.

2.5.7 Tourism

Bangladesh has no significant tourist industry yet, although the nation has the world's longest wide sand beach (120 km) in Cox's Bazar and the world's largest area of continuous mangrove forest in Khulna, both almost unspoiled by tourism (ESCAP, 1988). The country also has a number of attractive locations, the Hill Tracts districts, of great scenic beauty and many sites of historical and architectural interest (FAO/UNDP, 1994). So, there is a great potential in tourism industry, especially eco-tourism in the mangrove forest area, which may create useful employment opportunities.

2.5.8 Industry

The most important industries in the region are oriented to fish processing plants and jute products. Most of the industries are concentrated in Khulna, followed by Jessore. A very few industries are located in the districts of Satkhira, Narail, Bagerhat and Gopalganj. Almost all the requirements of newsprint in the country is supplied by Khulna news print mill and most of the partex (Jute fiber board) and hardboard is also produced in the region. The region has insufficient garment industries, whereas, the garment industries are the major foreign exchange earner of Bangladesh, although the area has a seaport. Other industries include leather goods, pharmaceuticals, match factories, textiles, tobacco and dockyards for shipbuilding and repair.

2.5.9 Electricity

Bangladesh is deficient in energy. With the ever-increasing population, per capita consumption of electricity increased to 168 KW/hour in 1998-99 from 79 KW/hour in 1994-95, whereas, production has not increased much in the last few years. The country has only one hydroelectric plant in Kaptai, Rangamati district, most of the power plants in the country are run either by gas or fossil fuel. In 1998, a barge mounted 110 MW capacity power plant was set-up in the area, which joined with 250 MW power plant at Goalpara. Most of the area is not yet covered by electricity supply, which is an important factor for boosting aquaculture production. More than 90% of the population is dependent on biomass fuel for their cooking and domestic needs (Rahman, 1998).

2.6 Pollution

As in many countries of Asia, the coastal waters of Bangladesh have some degree of pollution. There has been little research work carried out assessing the impacts of pollution on aquaculture as well as on the environment, although there are several sources of pollutant coming down to the rivers and canals which ultimately find their way to the sea.

Like many other countries, Bangladesh has emphasised the need to develop its industrial sector but most of the industries do not have any existing facility for pollution treatment, although they produced lots of pollutants and release them into the natural environment. Among these, are effluents from steel mills, fertiliser factories, pesticides, asbestos, cement factories, textile mills, dying factories, sugar mills, paper and pulp factories, toxic chemicals and leather industries (Deb, 1998; ESCAP, 1988; Viju, 1995). Most of the industries in Khulna and Chittagong region discharge their untreated wastes directly into the river Passur, Bhairab and Karnahpuli or in to the Bay.

Khulna and Chittagong, the two most populous coastal cities, have very poor sanitary conditions and most of the household wastes as well as excreta are dumped in or around the drains and canals, which go to the nearby rivers. Septic tank effluents are also dumped in to the rivers and canals directly and cause localised water pollution surrounding the drainage outfalls. The rivers in the region directly receive raw excreta daily from a vast number of people living on both sides of the rivers. In addition, a considerable amount of offal from slaughtered animals is thrown away daily into the rivers of Khulna and Chittagong, which ultimately goes to the Bay of Bengal. During the high tide, the wastes reverse their flows and spread throughout the whole coastal areas, causing pathogenic microbial pollution (e.g., bacteria species of *Salmonella*, *Shigella*, *Vibrio*, *Clostridium*, *Escherichia* etc., protozoan species of *Entamoeba*, *Acanthamoeba*, *Giardia*, helminths species of *Echonococcus*, *Hymenolepis*, *Taenia*, *Faciola*, *Ascaris*, *Enterobius*, *Strongyloides*, etc., and numerous viruses, Dev, 1998) that poses serious health hazards during the rainy season and flooding periods.

A considerable amount of pollution also comes from the shrimp processing plants and shrimp culture itself (Das, 1998). After harvesting, shrimps are brought into the depots where they are beheaded, cleaned, iced and packed for onward transportation to the freezing plants in Khulna, Satkhira and Chittagong. The rest of the body, which is about 37% of the total body weight, is discarded into the rivers and canals and causes environmental degradation in the area. In 1992-93, Bangladesh exported 20,000 metric tons of shrimps and prawns. However, the processing industries discarded about 11,400 metric tons of head and other unwanted part of shrimps and prawns. These discards create bad smell and spread diseases in the locality and causes hazards in nearby water bodies, resulting in environmental pollution (Khan and Hossain, 1996; Scott and Salam, 1999).

The nutrient load and organic wastes comes from the shrimp ponds, influences the quality and quantity of organisms, including bacteria, phytoplankton and zooplankton, as well as the benthos. These cause algal blooms, release toxic materials and are particularly lethal to a range of marine organisms in the coastal water and open seas (Haq *et al.* 1998).

More than 50% of the oil pollution in the marine and coastal environment comes from urban and river run-off. Localised oil pollution is heavy in the vicinity of the Chittagong and Mongla harbours. There have also been persistent reports of oil slicks in the territorial waters of the country and upper Bay of Bengal. However, there is no monitoring system in place to document these occurrences systematically (UNEP, 1986).

Nearly 1,000 ships and 40-50 oil tankers visit Chittagong port and nearly 500 ships visit Mongla port annually. Moreover, numerous river craft, launches and steamers ply along the waterways and discharge waste oil, spillage and bilge washings. These vessels could be the main sources of oil pollution of the marine environment in the coastal areas of Bangladesh. Crude oil and its derivatives are among the worst pollutants that enter the Chittagong coastal area, owing to crude oil transportation operations in and around Chittagong port. Oil discharges due to dripping from hoses, overfilled pumps and deteriorated packing in flanges all contribute to chronic oil pollution within the harbours. There is also risk from leaking oil pipelines.

2.7 Conservation areas

Available data shows that 49% of the land is available for culture practice in the region (Khan, 1998). The remaining land is either already fully occupied by permanent structures or restricted by law for any development activities. The Sundarbans mangrove forest is protected by the

Forest Act 1927, which has reviewed and passed, by the authority in 1989 (Katebi and Habib, 1989). This forest supports many aquatic as well as terrestrial animals as their potential shelter and home. The rivers, canals, floodplains, lagoons, inlets, bays estuaries, swamps, wetlands and marshes, which are used by hundreds of thousands of fishes, crustaceans, zooplankton and phytoplankton for their feeding, breeding and migration purposes called critical ecosystems and not available for pond construction (Aguilar, 1996; **Figure 2.28**).

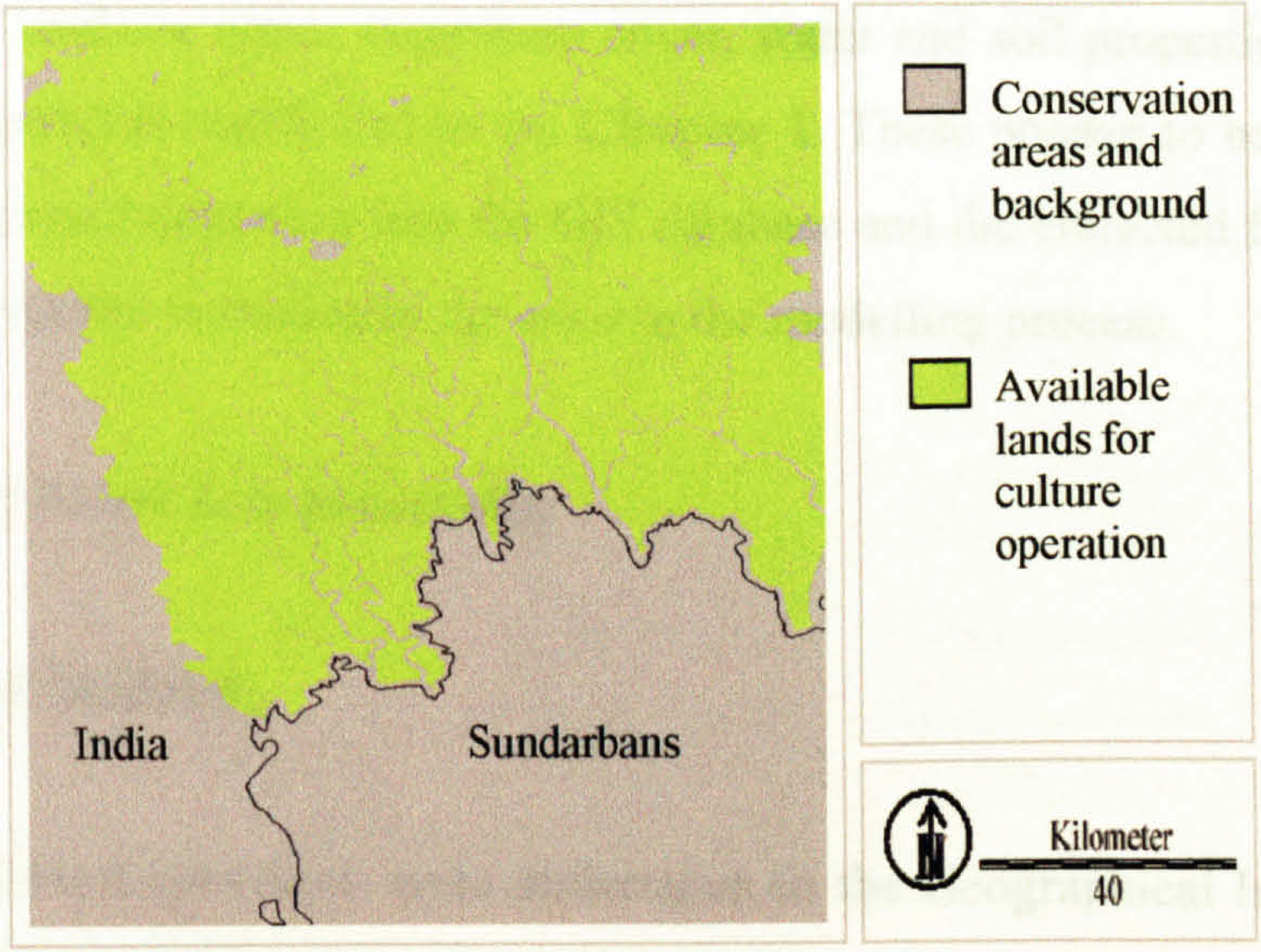

Figure 2.28. The conservation areas in the Khulna region, Bangladesh.

Chapter 3

Materials and Methods

3.1 Introduction

This study can be broadly divided into two categories: a) laboratory based data processing and b) field based data collection. Several types of field data were collected ranging from observation of land use types, vegetation cover, water and soil properties and other parameters to fulfil the objectives mentioned in the **Chapter 1.** These needed to be stored in an organised way for subsequent integration into the GIS database and the collected field data was processed as quickly as possible to minimise the error in the modelling process.

3.2 Laboratory based data processing

3.2.1 Computer facilities

All laboratory-based operations were undertaken in the Geographical Information Systems and Applied Physiology Laboratory (GISAP) of the Institute of Aquaculture (IOA) in Stirling University. GISAP is equipped with five GIS workstations, which are networked to the University servers on campus. Among the five workstations, one provides common services for all workstations such as printing, digitising, scanning, CD writing, tape backup etc. Desktop computer workstations used in the study are described in **Table 3.1.**

3.2.2 Operating system

The software used in this project was operated under Windows NT version 4 operating system (OS), Service Pack 3. The OS was upgraded to Service Pack 6a by spring 2000.

Table 3.1. Description of the GIS workstations and other computer resources used in the study.

Description /Computer	Identification number of the computer PC 14446	PC 14760	PC16002	PC10622
Function	GIS and image processing	GIS and image processing	GIS and image processing	Digitising, Scanning, CD writing, and Tape backing up
Manufacturer/Model	Hi-Grade Axion Pv	Dell Dimension XPS D333	Dell Precision 410	Clone
Hard Disk capacity (Gb)	4 + 8.	2 + 8+13	8+18+18	4
System	Microsoft Windows NT 4.0, Service Pack 6	Microsoft Windows NT 4.0, Service Pack 6	Microsoft Windows NT 4.0, Service Pack 6	Microsoft Windows NT 4.0, Service Pack 6
Processor speed (MHz)	P. Pro 200	PII 333	PII 2 x 400	PI 133
Processor type	x86 Family 6 model 5 stepping 1	x86 Family 6 model 5 stepping 1	x86 Family 6 model 5 stepping 1	x86 Family 5 model 2 stepping 12
RAM (Mb)	128	128	512	64
Monitor	iiyama Vision Master™21"	DELL 21" Trinitron	DELL 21" Trinitron	Mitsubishi Diamond Pro 900u 19"
Refresh frequency (Hz)	85	85	85	70
Settings	1280 x 1024	1280 x 1024	1280 x 1024	1280 x 1024
Graphics Adapter driver	Intergraph Intense 3D Pro	Intergraph Intense 3D Pro	Intergraph Intense 3D Pro	Matrox Graphics MGA Millenium II
Graphics card manufacturer	Intergraph Corporation	Intergraph Corporation	Intergraph Corporation	Matrox graphics
Adapter info	RealiZm II	RealiZm II	RealiZm II	Chip MGA 2064W-R1

3.2.3 File and data storage systems

Working with large raster format images, as in this study, requires substantial storage capacity as the project develops and hundreds of new images are generated. However, not all newly produced images are useful, and most of them can be discarded while modelling is done and storage space can then be reused. However, a group of selected images which are necessary for the persistence of the modelling process still utilises a lot of hard disk storage space.

Total disc storage capacity was substantially increased on all workstations used during the study period. Two additional processes were used to ensure effective storage. A HP DDS-2 Data Cartridge 5000-tape drive was used which can store 4 Gb of uncompressed data or alternatively 8 Gb with data compression option, the backup speed being 22 Mb/min. Regular backup was made fortnightly using two alternate tapes. A second technique was to back-up files on re-write-able compact disks. The CD was written from a Hewlett-Packard CD-Writer Plus 7200 series. Each CD has a storage capacity of 650 Mb, which was used to store critical files while tapes were used for whole system backup. Data was backed up on a fortnightly basis or more often, depending on the requirements. All storage media such as data tapes and CD's as well as purchased CD's with Landsat images were stored in a fireproof safe in the laboratory. **Figure 3.1** demonstrates different data storage systems.

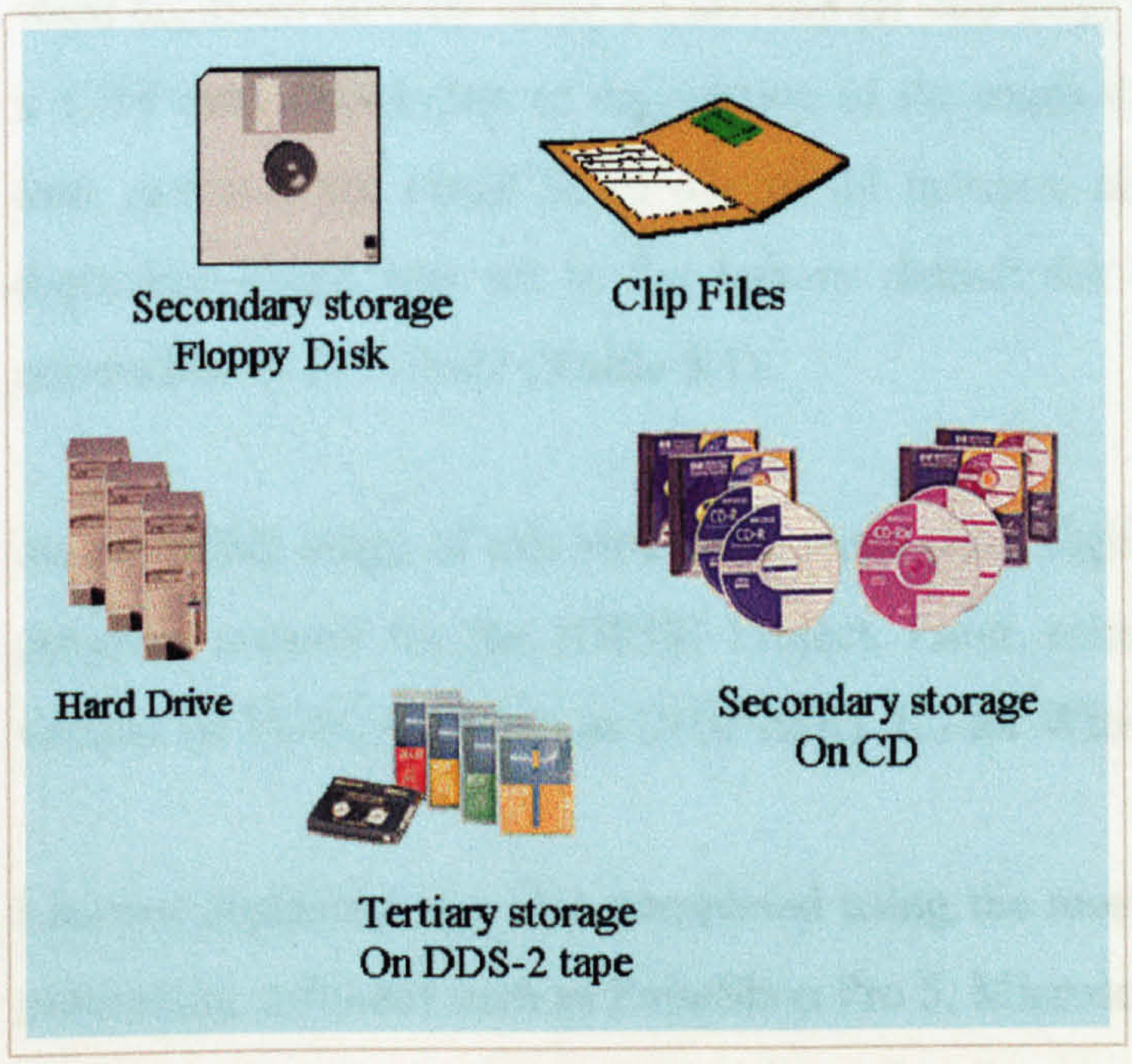

Figure 3.1. The different data storage systems used in the study.

The database contained several raster images extracted from 2 Landsat TM images of February 1996, and digitised from a wide range of paper maps and tabular data from different sources. Each band of the original Landsat image supplied by NPA Satellite Imaging Group's extent of 12,056 columns x 6,603 rows requiring 77 Mb of storage. A composite image of three-bands also required more than this storage space. However, only a portion of the purchased image was used. The area selected for this study covered six administrative districts, Khulna, Jessore, Satkhira, Bagerhat, Narail and Gopalganj. The entire mangrove forests of the Sundarbans and 37% of the country's coastal environment (**Figure 2.20**) was within the selected windows which covered an area of 3,676 columns by 4,915 rows, requiring approximately 17 Mb of storage. Creation of sub-models using the IDRISI image files could generate as many as 15 to 30 new intermediate image files each time. Initially, storage of these files absorbed much storage capacity, however, as the study matured, each sub-model developed was recorded as an IDRISI macro language file (IML). These macros were enabled to delete all the intermediate files generated during running the macros and only to retain the final results. This procedure was useful to maintain maximum storage capacity for further use and also kept the discs free from any unnecessary images.

3.2.4 Digitising facilities

Several paper maps such as physical, administrative and political from 1:10 million to 1: 50,000 were digitised directly using a Calcomp III digitising board, model 34480, with active area = 914 x 1219 mm. Resolution of digitisation of the maps was up to 400 lpmm, accuracy up to ±0.05 mm, and out put could be in one of 34 industry standard formats. The configuration for the digitising board was set to the factory default for CalComp 2000 ASCI and the board was controlled by PC 10622 (**Table 3.1**).

At the initial stage of this study, the maps were digitised using TOSCA software, a DOS based program created for the IDRISI Project. Later, other maps were digitised using an improved version of TOSCA known as DIGI-EDIT 1.0 for Windows.

Limited digitising was also completed using the mouse and on-screen tools accessible in image processing software such as PaintShop Pro 5, Microsoft Paint and in IDRISI, the GIS software.

3.2.5 Scanning facilities

Most of the relevant information for this study was available as printed images in very low resolution, which was difficult to digitize, such as 1:10 million atlas maps, or even smaller such as published papers. To adapt these sources for use in the study, images were scanned on a Hewlett-Packard flatbed scanner model ScanJet 3c (**Figure 3.2**), and saved as bitmap or gif images. The software, which supported the scanner, was Deskscan II version 2.8. The typical scanned resolution was at 600 dpi (Dot per inch). Scanning images is a very efficient and quick method of assembling information as raster layers into GIS. Vector layers were also derived from rasterized scanned images by using on screen digitizing utilities within IDRISI.

3.2.6 Printing facilities

A Hewlett-Packard LaserJet 4 Plus (Black and white) or Hewlett-Packard Professional Series 2000C inkjet colour printer were used to print out the results of the study. Both printers were networked and printing facilities were shared via a Local Area Network among the users of GISAP group (**Figure 3.2**).

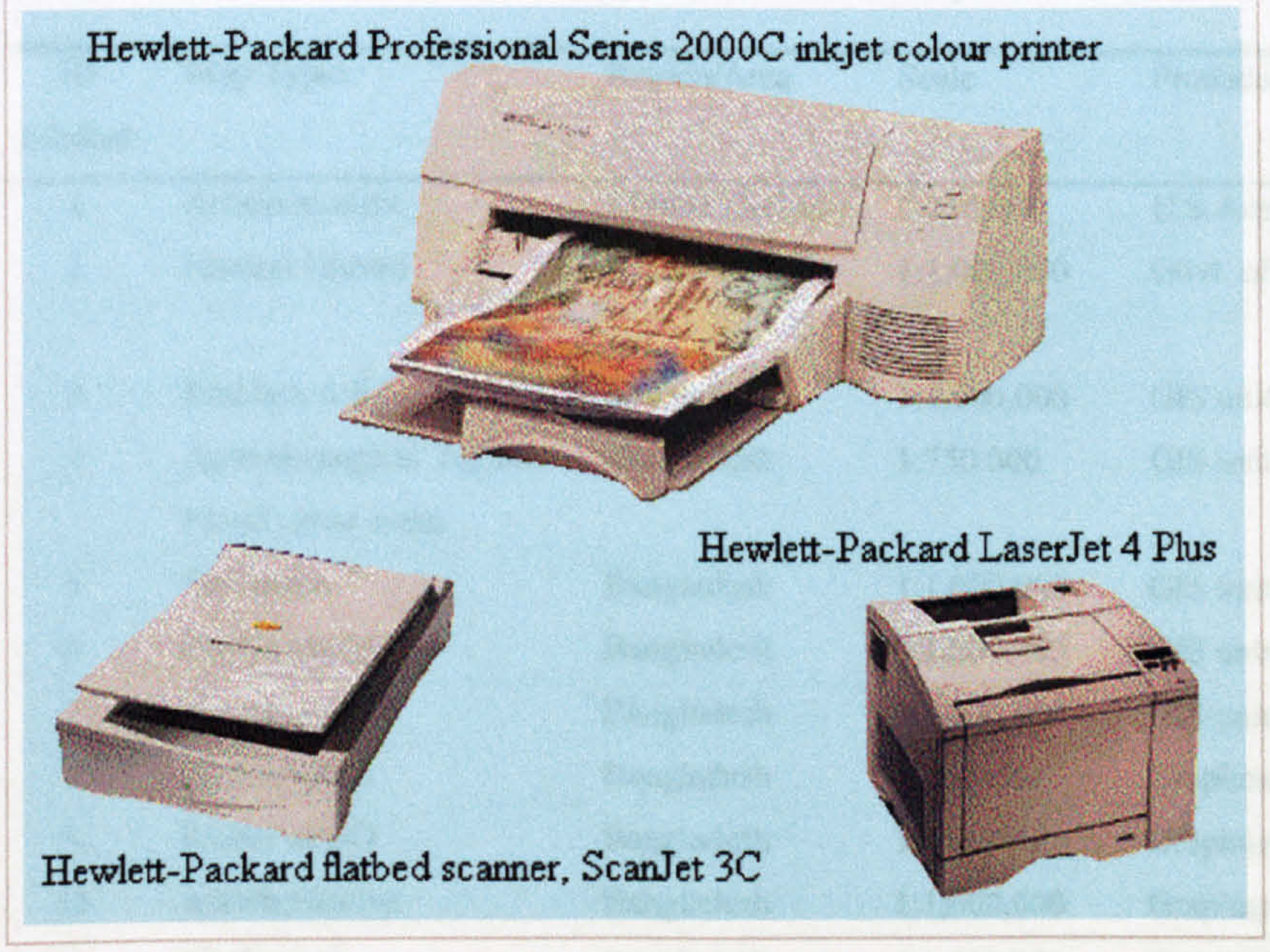

Figure 3.2. The scanning and printing facilities available in the GISAP laboratory.

3.2.7 Maps used in the study

During the study it proved difficult to find quality maps to build up the GIS database and to geo-reference the Landsat TM image. Maps produced by the Soil Resource Development Institute (SRDI) were fair in quality but were not good enough to geo-reference the satellite image as most of them were 1:1000,000 scale. Fortunately, a photocopy of a 1:250,000 map produced by Army Map Service, Corps of Engineers, U. S. Army, Washington, D. C. in 1955 was obtained from the National Library of Scotland at Edinburgh. This was used both to navigate while collecting data in the field and to geo-reference the satellite image.

Reconnaissance soil survey maps of 1973 purchased from SRDI were very good in resolution as well as content detail. However, it was very difficult to obtain some maps, which were published, available in stock, but not normally available for sale except through permission from the defence ministry, as they are confidential or reserved by the military authorities. However, some 1:50,000-scale topographical maps produced by Survey Bangladesh were obtained via contacts. In some cases, A-4 sized thematic maps from atlases and from some reports were included. All these maps were scanned as bitmap images and later incorporated into the GIS database by use of the import facility of IDRISI (**Table 3.2**).

Table 3.2. The sources of maps used in the study.

ID number	Map Types	Region/Area	Scale	Produced by	Identification	Date
1	Administrative	Khulna Division	1:250,000	U.S Army	NF-46-1	1955
2	Natural Hazard	Bangladesh	1:1,000,000	Govt. of BD, UNDP	HM.3, HM.4, HM.5	1992
3	Problem soil	Bangladesh	1:1,000,000	GIS unit, SRDI	-	1997
4	Agro-ecological regions Flood prone areas	Bangladesh	1:750 000	GIS unit, SRDI	-	1997
5	Soil maps	Bangladesh	1:1,000,000	GIS unit, SRDI	-	1998
6	Physiography	Bangladesh	1:1,000,000	GIS unit, SRDI	-	1997
7	Morphological	Bangladesh	1:1,000,000	GIS unit, SRDI	-	1997
8	Hydrological	Bangladesh	1:750,000	Graphosman	BGD-88-054	1997
9	Rivers of BD	Bangladesh	1:750,000	Graphosman	BGD-88-054	1997
10	Administrative	Bangladesh	1:1,000,000	Graphosman	-	1997
11	Geological	Bangladesh	1:1,000,000	SPARRSO	-	1990
12	Land Use	Bangladesh	1:1,000,000	U.S Geological survey	-	1990
13	Land use	Bangladesh	1:1,000,000	SRDI	-	1996
14	(Satellite mosaic)	Bangladesh	1:1,000,000	SPARRSO	Sheet-3	1984
15	Land zones (Satellite mosaic)	Bangladesh	1:1,000,000	SPARRSO	Sheet-2	1984
16	Forest (Satellite mosaic)	Bangladesh	1:1,000,000	SPARRSO	Sheet-2	1984
17	Land cover types (Satellite mosaic)	Bangladesh	1:1,000,000	SPARRSO	Sheet-4	1984
18	Reconnaissance soil survey map	District maps	1:125,000	SRDI	-	1973
19	Topographical map	Bangladesh	1:50,000	Survey Bangladesh	Sheet 1-12/F79, 12/E79, 16/E79	1973-1979
20	Forest inventory map	Mangroves	1:50,000	Overseas Development Administration (ODA)	-	1985

3.2.8 Landsat TM Remotely Sensed Images used in the study

The primary data sources for this study were satellite images, which were integrated into the GIS database (**Table 3.3**). The satellite images were acquired from NPA Satellite Imaging Group in London. Landsat TM images covered a large area of the Southern part of Bangladesh along with the coastal area and also extended as far as Calcutta in India (**Figure 3.3**). The images were received in Thailand from Landsat TM Satellite 5 and supplied on CD as full frame (185 km x 185 km). The images used in this study were of Path 137 and 138, and Row 44. Thematic mapper resolution is 30 meters. As images belonged to two different satellite paths, and in order to minimise cloud cover, image from two separate satellite passovers were used which were only 7 days apart (**Table 3.3**). Moreover, Landsat Satellite image was chosen in this study as it has a wide of range of spectral bands giving more flexibility to delineate the features from the image. Data from other platforms were also searched for this study but there was no cloud-free images of recent years for two different paths in one week interval, and therefore Landsat Satellite image was prefered.

Table 3.3. The Landsat TM images used in this study.

Image	Path	Row	Date	Correction level	Bands
1	137	44	09/02/96	5	2,3,4
2	138	44	16/02/96	5	2,3,4

All scenes supplied had the same level of basic radiometric correction consisting of an equalisation of the sensors in order to eliminate the striping effects of Landsat-TM data. No histogram equalisations were applied in relation to the sun elevation angle. Level 4 correction consists of a resampling along the lines to remove variations due to the satellite's mirror and to align the pixels between adjacent sweeps. Level 5 correction, also known as systems corrections consists of resampling in both directions and application of a cartographic projection of the user's choice. Level 5 correction includes geometric correction resampled using a nearest neighbour algorithm. Level 6 correction is identical to level 5, however, utilising the cubic convolution algorithm for resampling. All the images used in this study were purchased with level 5 correction.

3.2.9 GIS software used in the study

3.2.9.1 IDRISI v 2.0.

The GIS software used in most of this study was IDRISI for Windows version 2.0. IDRISI is a geographical information and image processing software system developed by the Graduate School of Geography at Clark University, Worcester, MA, USA. It is designed to provide professional-level geographic research tools on a low cost non-profit basis for research and teaching. IDRISI currently has a collection of over 100 program modules that provide facilities for input, display and analysis of geographic data. Modules used in this study will be indicated in capital letters.

IDRISI is the industry leader in raster analytical functionality covering the full spectrum of GIS and Remote Sensing needs from database query, to spatial modelling, to image enhancement and classification (Eastman, 1997). It is in active use in over 130 countries world-wide by a wide range of research, government, local planning, resource management and educational institutions. IDRISI's analytical modules are regularly updated and cleaned for bugs and made available to users as downloads from their web-site (http://www.clarklabs.org/13dnlds/13dnlds.htm). During the course of this study it was found that some analytical modules were not correctly functioning. These faults were communicated to the IDRISI support team, which they investigated and corrected, and made the corrected modules available for download on their web page.

3.2.9.2 IDRISI 32.

Idrisi32 was released in early 2000 and was used for some parts of this study. It is fully 32-bit software and uses the latest object-oriented development tools and is a considerable advance over IDRISI 2.0. Special facilities are included for environmental monitoring and natural resource management, including change and time series analysis, multi-criteria and multi-objective decision support, uncertainty analysis (Bayesian and Fuzzy Set analysis) and simulation modelling (force modelling and anisotropic friction analysis). TIN interpolation, Kriging and conditional simulation is also offered.

3.2.9.3 CartaLinx

The final GIS and digitising software used in some cases for this study was CartaLinx which is a Spatial Data Builder, a digital map development tool that serves as a companion to a variety of popular Geographic Information System (GIS) and Desktop Mapping software products, for example, Idrisi32, Idrisi 16-bit, Arc/Info, ArcView, MapInfo. CartaLinx can be used to digitally encode geographic data from existing map sheets using any of over 300 popular digitising tablets; digitise geographic information using any NMEA interface-compliant Global Positioning System (GPS); on-screen digitise from image data such as satellite images, digital photographs or scanned aerial photographs.

CartaLinx considerably facilitated field data collection (ground truth information) using image and map data in conjunction with the real-time GPS interface. CartaLinx's integrated waypoint facility allowed in-situ operations on existing fields, interactive feature inquiry, instants display of attribute data for any feature by simply clicking on that feature; and real-time route monitoring using a GPS unit with an image backdrop.

3.2.10 Image Manipulation

Image editing and manipulation was an important feature of the creation of the databases. There are several image-processing software available, Paint Shop Pro 5, a raster-format image editing software, proved to be a relatively workable and useful tool. Microsoft Paint also used to do the editing for the same purpose during the first stage of the study. In practice, images were manipulated and processed prior to or during the modelling phases carried out in the GIS environment.

Among the advantages of pre-treatment or editing of images is the elimination of some features, which are of no interest, while leaving others. An example of this is that all unwanted features in a scanned map such as legends, titles, scales, and text can be eliminated, while leaving only the selected subset of the map area and the thematic polygon features. This editing process is possible in IDRISI, but it is more awkward and time consuming than in Paint Shop Pro 5. Specifically, on-screen digitisation in IDRISI has limitations related to the buffer capacity for the vector file being worked on, often leading to the abrupt termination of the program due to insufficient available memory, and resulting in total loss of files in the digitisation process.

Paint Shop Pro 5 also allows direct scanning of images, editing, and saving in a wide variety of digital formats, including Bitmap, Gif or Tiff file format. In order to use the image files edited in Paint Shop Pro 5, resampling of the imported images in the IDRISI environment is essential.

3.2.11 Selecting a window of the study area

As illustrated in **Figure 3.3** and **3.4** the original two-scene mosaic of Landsat TM images covered the whole of Khulna and Barisal division, part of Chittagong division and up to Calcutta in India. However, the study concentrated only on the coastal area of Khulna division, as well as the Sundarbans mangrove forests and adjacent coastal areas. This selection of study area was made based on the location of most of the shrimp farms and DFO and CARE major project areas, without knowing that the area would fall across the two Landsat scenes. An alternative approach would have been to include the Barisal and Chittagong divisions to the East, which are in one Landsat scene. Such a change would have been less costly in terms of data but would have been time consuming and costly to make field visits all these areas. Not only that, Satkhira and part of Khulna districts might have been omitted and these are considered to be pioneer areas in case of Bangladeshi shrimp culture.

Usually, Landsat images can be displaced 10 to 15% north or south within the path without extra cost. The image was shifted 15% to the south in order to cover most of the coastal area in the South-western region of the country. The factors that directly affect fisheries and potential aquaculture development are within close range of the coastline and mangroves and in this context the subset image is considered appropriate.

Once the subset window of the study area had been successfully defined, it was extracted using the WINDOW option under the reformat menu in IDRISI. As well as individual manual windowing this option offers a batch window cutting process which will process multiple images for the same specified area, as determined by column and row, or if the image is geo-referenced, by geographical position. The area windowed out for the study covered from columns 4,459 to

7,241 and rows 585 to 6,578 (3,676 columns by 4,915 rows or 18067,540 pixels) of the original two Landsat images (**Figure 3.4**).

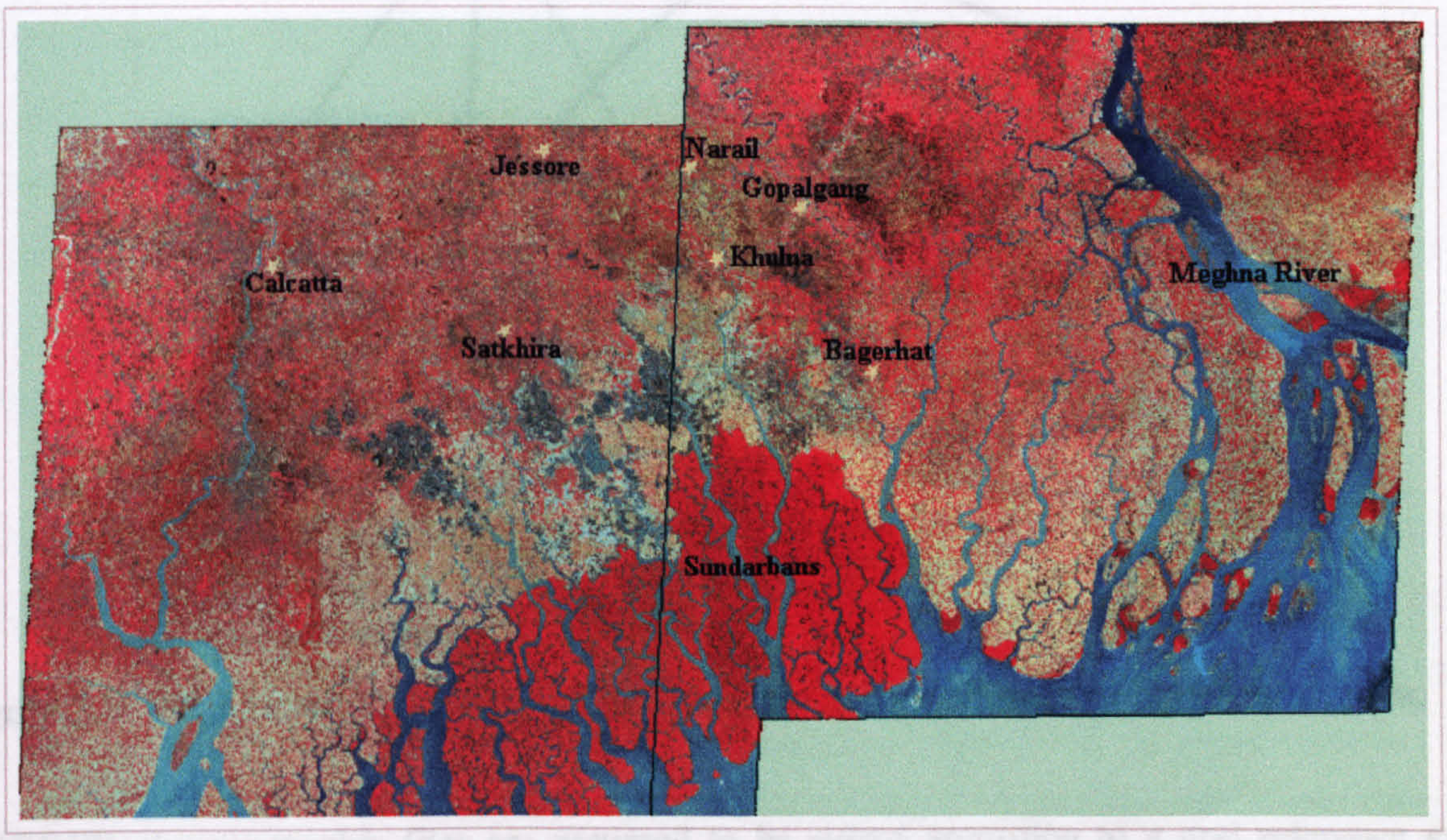

Figure 3.3. The mosaic of two Landsat TM image of 9 and 16 February 1996 of Khulna region.

3.2.12 Geo-referencing of the satellite image and maps used in the study

Geo-referencing refers to the location of an image or vector file in space as defined by a known co-ordinate referencing system. With raster images, a common form of geo-referencing is to indicate the reference system (e.g., latitude/longitude), the reference units in degrees, and the co-ordinate positions of the left, right, top and bottom edges of the image. The same is true for vector data files, although the left, right, top and bottom edges now refer to what is commonly called the bounding rectangle of the coverage, a rectangle that defines the limits of the study area.

In a GIS it is possible to transfer raster images and vector files from one grid reference system to another. In IDRISI for Windows two programmes are available for the purpose. In cases where the reference system is plane, RESAMPLE is used. In cases where both the input and the output reference systems are known and defined by the reference system parameter (.ref) files, PROJECT is used (Eastman, 1995).

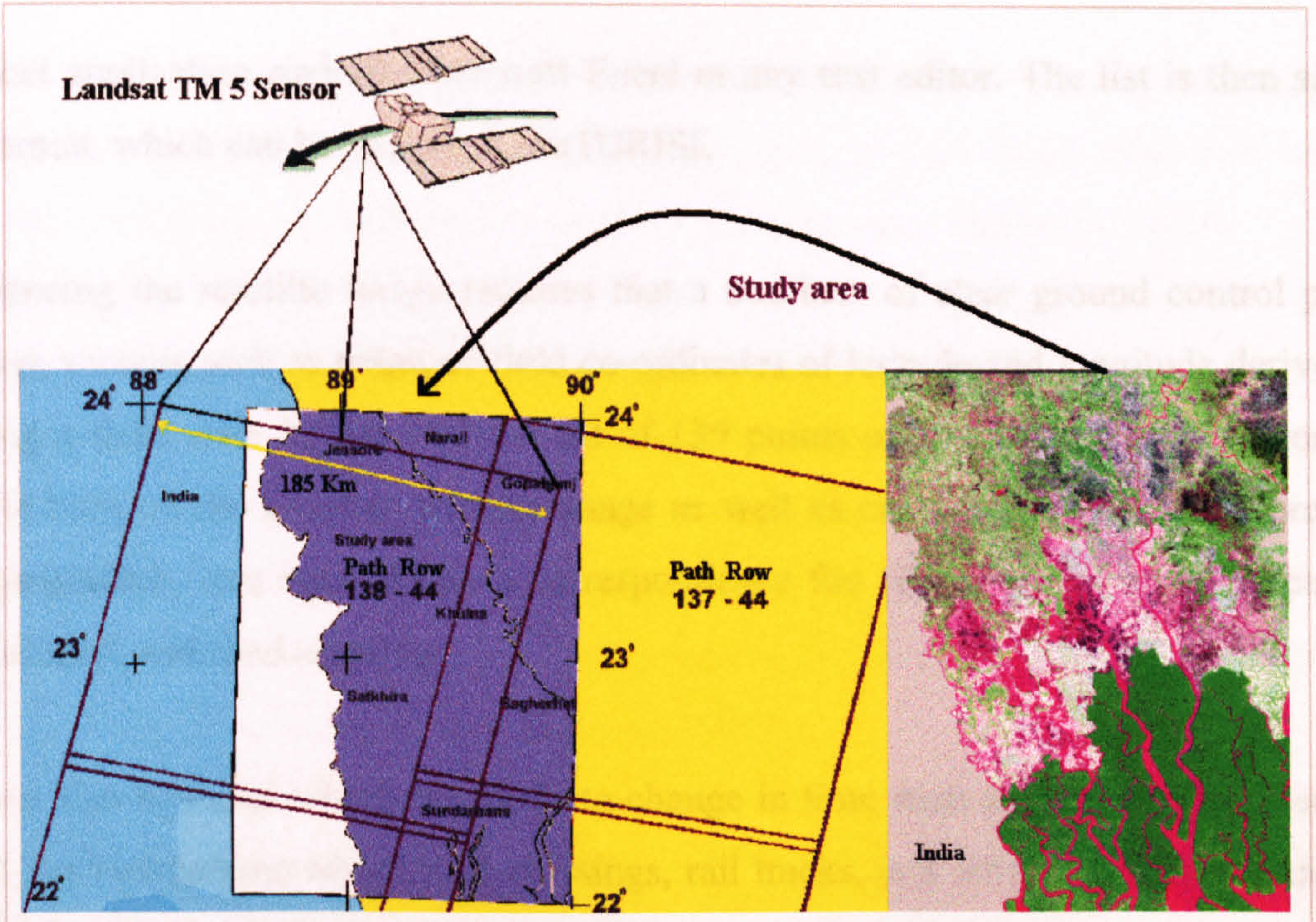

Figure 3.4. The Landsat TM 5 sensor's path and row and cutout window of the study area.

In IDRISI, the geographic files are assumed to be stored according to a grid reference system where grid north is aligned with the edges of the raster images or vector files. Documentation files for all images contain information about the reference system used by that file when referring to geographic locations. Each grid reference system must have a reference system parameter file. The only exception is the system identified as *plane*. Any image or vector file with a *plane* co-ordinate referencing system is understood to use an arbitrary plane system for which geodetic and projection parameters are unknown, and for which a reference system parameter file is not provided (Eastman, 1997).

The Landsat TM image was purchased already geo-referenced, but the import process using PARE modules in IDRISI did not retain co-ordinate information in latitude and longitude. Therefore, at the moment this image was imported into IDRISI, its reference system was re-established to *plane*, and needed to be geo-referenced. Geo-registration is also known as rubber sheeting or resampling. It is the process of stretching and warping an image to fit in a particular grid reference system. Identifying a series of x and y co-ordinates of two pairs of points that represent the same place within both a new and an old or previous co-ordinate system (Eastman 1997) accomplish resampling. The pairs of x and y, co-ordinates are entered into a correspondence file using the EDIT facility of IDRISI, or alternatively, they can be entered in a spread sheet application such as Microsoft Excel or any text editor. The list is then saved as a text file format, which can be imported into IDRISI.

Geo-referencing the satellite image requires that a numbers of clear ground control points are known from sources such as maps, or field co-ordinates of latitude and longitude derived with a GPS during a field visit. In this study, a list of 139 points of co-ordinates, which were clearly identifiable both on the Landsat satellite image as well as on topographical maps prepared by Survey Bangladesh, was entered into a correspondence file. These points were typically small islands, rail track and road crossings.

Points were also included which are likely to change in time such as river bends, river mouths, etc. inside the Sundarbans where road crossings, rail tracks, and other permanent structures are absolutely absent. For all these points, their co-ordinates in the Landsat image was noted along with their corresponding co-ordinates in degree, minute and decimal minute for the topographical maps. The co-ordinate pairs for the resulting vector file, which was used to geo-reference the Landsat image, is found in **Appendix 3.1**. Prior to geo-referencing, to the minimum x and y co-ordinates the windowed part of the full Landsat TM image is reset to zero. The maximum x and y then become the number of rows and columns spanned by the satellite image; in this case 3676 columns and 4915 rows.

Identification of the ground control points on the Landsat TM image was made on a false colour (RGB) composite image of bands 243 saturated at 2.5% created using the COMPOSIT module in IDRISI. The reason for choosing this band combination for the false-colour composite was that it provides a good contrast between reflectance's from water bodies and vegetation. The combinations showed urban areas in tones of purple, vegetation in familiar green tones and clear water bodies in dark black colours but turbid water bodies in shades of magenta. The contrast between soil and water interfaces is marked which facilitates identification of road and river crossings, which are commonly used for geo-referencing purposes.

The topographical sheets and all other digitised paper maps were then geo-registered to the Landsat image using the RESAMPLE module in IDRISI. The process uses polynomial equations to establish a rubber sheet transformation, as if one of the grids were placed on rubber and warped to make it correspond to the other. The actual process is one in which a new grid is constructed and a set of polynomial equations is developed to describe the spatial mapping of data from the old grid into the new one. The new grid is then filled with data values by resampling the old grid and estimating, if necessary, the new value (Eastman, 1997).

Cubic resampling was used with the nearest neighbour algorithm. In general, the lowest order of polynomial should be used that provides a reasonable solution since the effect of poor control point specification becomes dramatically worse as the order of equation used increases. An adequate number of control points is needed for the order chosen. Linear requires a minimum of 3, quadratic requires 6 and cubic requires 10. In practice, however, at least twice the minimum numbers are required for a reasonable fit (Eastman, 1997).

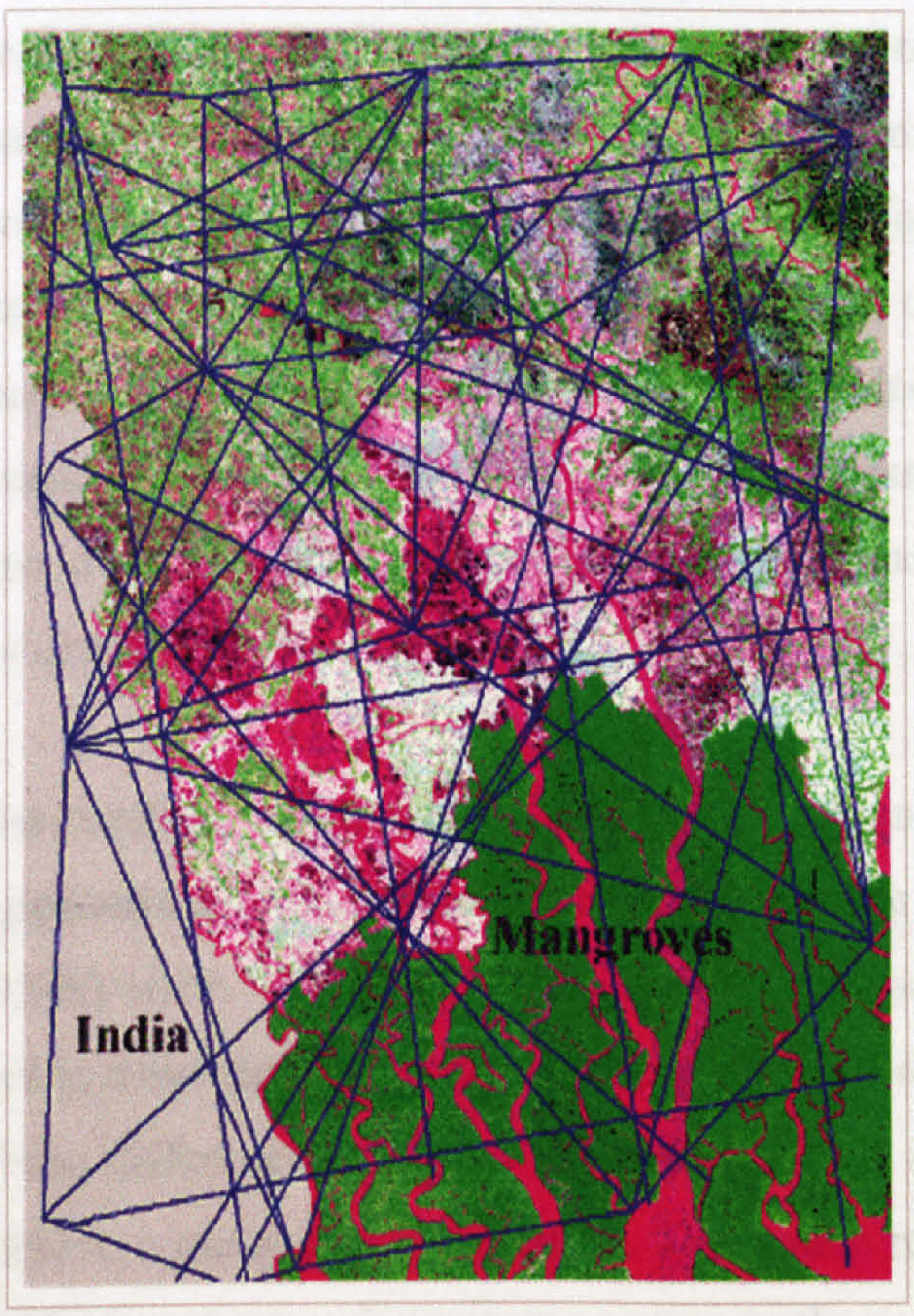

Figure 3.5. The line intersection technique used to develop additional control points for geo-referencing the Landsat TM image.

An unusual attribute of the study segment of the satellite image was that a large area (42.09%) is covered with mangroves, the Sundarbans and open waters, where ground control points are very difficult to choose. In coastal area sand, beach, mangroves or river islands represent important sites but at the same time they are very fragile and are not good ground control points for proper geo-referencing. However, some such points had to be used, as there was no alternative. Due to this problem, the first few resampling trial results were not satisfactory. Sometimes, the

RESAMPLE module stopped with floating point error message. In instances where this occurred regularly, a smaller window was cut in an area where ground control points are distinctive and this usually resolved the problem.

To overcome the problems associated with resampling and to increase the availability of good correspondence points, a technique was applied which is developed in the GISAP lab illustrated in **Figure 3.5**. The technique was to locate some very good reference points and then to join them by drawing lines. From the selected window some points was found beyond the Bangladesh and into the mangrove forests and coast which facilitated extending reference lines out to noteworthy points on the coastline
and inside the mangrove forests. Additional lines were also developed from other points so as to produce lines with reference points on the intersection of lines over open water and in the mangroves. In this way, new substantial control points were created for the correspondence file over the different featureless open water and forests ranges. Likewise, corresponding lines were drawn on topographical maps from the same control points as those used on the Landsat TM image. The intersection of the lines provided additional corresponding points with known latitude-longitude co-ordinates and this process substantially enhanced the geo-referencing. All latitudes and longitudes from digitised maps and GPS were represented in decimal degree format for use in IDRISI.

The resulting image is shown in **Figure 3.6** and a summary of the transformations is shown in **Appendix 3.2**. The accuracy of the resampling procedure is measured by its Root-Mean-Square (RMS) error. The RMS is a measure of the variability of measurements about their true values and is estimated by taking a sample of measurements and comparing them to their true values. These differences are then squared, summed and divided by the number of measurements to achieve a mean square deviation. The square root of the mean square deviation is then taken to produce a characteristic error measure in the same units as the original measurements. The RMS error is directly comparable to the concept of a standard deviation.

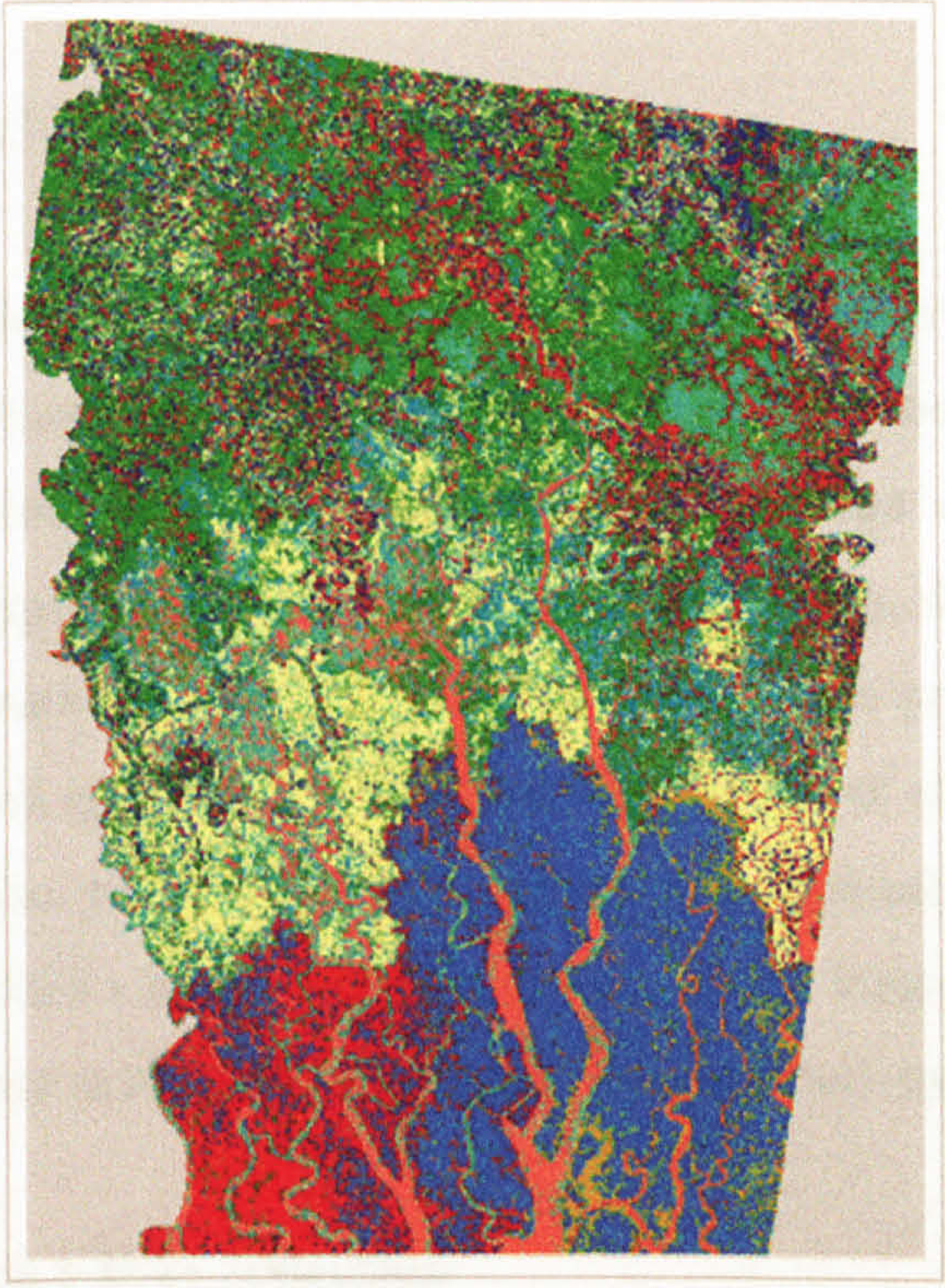

Figure 3.6. Resulting image of resampling of Landsat TM image from plane co-ordinate system to latitude and longitude co-ordinate system.

The overall RMS error achieved with the image resampling in this study was 8.716, which means that, theoretically, any pixel could be in error by as much as 261.5m. For Landsat TM data, the accuracy should be within 30 meters, and therefore the RMS error should be within 15m. Although, the RMS error found in this study was more than eight times higher than the recommended RMS error, the result was judged to be sufficient because a shrimp farm is usually bigger than 10 ha, sometimes more, so a pixel shift to 0.78 ha will not have any significant affect in the outcomes in such a large area where good quality up to date maps are scarce. However, considering the constraints, later on maps were geo-registered to the Landsat Image where RMS error was within the recommended level or bit higher.

3.2.13 Resolution of image

Resolution refers to the size of the smallest feature that can be determined in an image. It is basically the same as the scale of the image, except that stretching a small image into a bigger one and interpolating the in-between pixels increases the scale of the image, but it can not increase the resolution since no information is being added. Scale or resolution is usually measured in meters per pixel for raw images and degrees per pixel for map products. Image quality improves with higher resolution, but only up to a certain point, after which increasing resolution simply makes file sizes unmanageable without yielding any visible improvement to the image. Landsat TM images used in this study have a maximum resolution of 30m x 30m.

3.3 Field based data collection

Ideally, a study of this kind needs extensive field survey works to update existing databases, observe land use and for model verification. A major source of such information was the field visit program, which included meetings on site with each administrative district, fisheries department, Universities, research station, shrimp and fish farmers, hatchery owners, NGO's and processing plants. The objectives of the program were to obtain first-hand information, views and experiences. Examination of sites of shrimp and other fish culture activity in the area was also performed. Discussions with officials and scientists from the DOF, processing plants, NGO's and field workers were made. Examination of land use patterns and seasonal crops were also made. Finally, models were verified during field trips.

3.3.1 Data collection

In order to select a potential fish culture site, much data is needed (Meaden and Kaketsky, 1991) and the collection of this information is one of the most essential activities in the spatial decision making process. To determine the suitability of locations for aquaculture development in the study it was necessary to establish which of the factors or constraints found in Khulna region, were essential for the activity, and so an extensive review of information was conducted. To achieve this, extensive data collection was carried out in Bangladesh (Khulna, Jessore, Satkhira, Gopalganj, Narail, Bagerhat and Dhaka) during a two-month period in 1998 and a further fifteen days in 1999. The sources of collected information are presented in **Table 3.4**.

To sample such a large area (14,000 Km^2) in a short period of time it was necessary to have a vehicle, which could carry all the equipment and do necessary work in field. In 1998, Department for International Development (DFID) provided a vehicle and driver for 5 days. Data collection and land use verification began on 3^{rd} February 1998 from Jhikargaccha Thana in Jessore district and finished on 20^{th} February 1998. In 1999 data collection, land use and model verification began on 29^{th} January' 1999 with a field trip by boat to the Sundarbans. Further land survey work continued through a hired vehicle in the region. **Table 3.5** summarises the item warys and **Figure 3.7** illustrates the routes and names of the places stayed during field visit in the region.

Table 3.4. Sources of data for the environmental and socio-economic criteria for aquaculture development in Khulna region, Bangladesh

Criteria	Type of data collected	Sources	Location
Rainfall	Report	Bangladesh Bureau of Statistics	Bangladesh
Temperature	Annual mean temperature	Graphosman atlas	Bangladesh
Hurricane	Colourized Multi-channel Composite Hurricane	National Oceanic and Atmospheric Administration.	Arabian Sea near Pakistan and Indian coast
Mangroves	Landsat TM mosaic false color image	Space Research and Remote Sensing Organization	Bangladesh
Mangroves	Sundarbans Forest Inventory Project, Bangladesh	Overseas Development Administration	Khulna region
Soil types and texture	Reconnaissance soil survey maps	Soil Research and Development Institute	Khulna region
Soils	Soil map	Soil Research and Development Institute	Khulna region
Topography	Topographical survey map of Bangladesh	Survey Bangladesh	Bangladesh
Natural post larvae	Availability of natural post larvae	FAO/UNDP Report	Khulna region
Hatcheries	DIFD Report	Department of International and Foreign Development	Bangladesh
Shrimp farms locations	Landsat TM mosaic false color image	Space Research and Remote Sensing Organization	Bangladesh
Industries	Types of Industries	Graphosman atlas	Bangladesh
Cities, towns and villages	Landsat TM mosaic false color image	Nysel Press Associates	Khulna region
Urban developments	Population center	Graphosman atlas	Khulna region
Roads	Transport Systems of Bangladesh	Graphosman atlas	Bangladesh
Conservation areas	Sundarbans Forest Inventory Project, Bangladesh	Overseas Development Administration	Khulna region
Population density	Population census report	Bangladesh Bureau of Statistics	Bangladesh
Agglomeration	Location of shrimp farms	Space Research and Remote Sensing Organization	Khulna region
Markets	Topographical Survey maps and population size	Survey Bangladesh	Bangladesh
Government support	Administrative maps	Space Research and Remote Sensing Organization	Bangladesh
NGO support	Directory of NGO's	Association of Development Agencies in Bangladesh	Bangladesh
Support form research station	Administrative maps	Soil Research and Development Institute	Bangladesh
Salinity	Field data	District Fisheries Office, Khulna	Khulna region
Salinity	Report	Surface Water Modeling Center, Dhaka	Khulna region
Soil salinity	Report	Soil Research and Development Institute	Coastal Belt of Bangladesh
Surface water	Landsat TM mosaic false color image	Nysel Press Associates	Khulna region
Ground water	Hydrological Network, Bangladesh	Bangladesh Water Development Board	Bangladesh
Tidal Chart	Bangladesh Tide Tables	Bangladesh Inland Water Transport Authority.	Bangladesh
Fish Processing Plant	Report	Janata Bank	Bangladesh
Flood	Flood prone areas	Soil Research and Development Institute	Bangladesh
Cyclone	Cyclone affected areas	Soil Research and Development Institute	Bangladesh
Draught	Draught affected areas	Soil Research and Development Institute	Bangladesh
Animal waste	Report	Bangladesh Bureau of Statistics	Bangladesh
Inputs	Report	Bangladesh Bureau of Statistics	Bangladesh
Land use	Land use map	Soil Research and Development Institute	Bangladesh
Land use	Landsat TM mosaic false color image	Nysel Press Associates	Bangladesh
Fish Catch	Fish Catch statistics of Bangladesh	Department of Fisheries	Bangladesh

Table 3.5. Itinerary followed for sampling and land use verification in the Khulna region in 1998 and 1999.

Date	Name of the places covered	Over night base	Transport used	Comment
03/02/98	Jhikargaccha and Jessore	DOF Rest House, Jessore	DFID Land Rover	Work started in the afternoon on the way from Dhaka.
04/02/98	Jessore, Kalaroa Jhikargaccha, Navaron, , Stkhira and Vetkhali	DFID Rest House, Khulna	do	We started early in the morning due to general strike in the Jessore town. Data collection was disrupted by a torrential storm and heavy rain at 1100 h but weather was good in the afternoon.
05/02/98	Khulna, Jessore Keshobpur, Dumuria Monirampur, and Paikgaccha thana	DFID Rest House, Khulna	do	Road construction in Monirampur thana slows down our progress.
06/02/98	Khulna Bagerhat, Rampal, Mongla, and Morrelganj,	CARE guest house, Bagerhat	do	It was possible to go up to Sundarbans in Morrelganj thana, Bagerhat.
07/02/98	Bagerhat, Fakirhat, Mollarhat and Gopalganj	Return to DFID Rest House, Dhaka	do	Had to wait for whole night at the Ferry ghat due to traffic.
17/02/98 to 20/02/98	Khulna DFO office, Khulna University, Bagerhat, Dumuria, Rampal, Mongla, forest office in the Sundarbans	DFID Rest House, Khulna	Hired Motor bike	It was possible to go to the remote places with the guide of a local man who run the motor bike.
21/02/98 to 2/03/98	Went to Different Government and NGO offices in Dhaka	Dhaka	Bus, Taxi Rikshaw	Collected a range of data during this time.
29/01/99 to 30/01/99	In side Sundarbans up to Koitka	On board ship	Hired Launch	It was possible to verify the mangrove image and land use in side the Sundarbans.
31/01/99	Rampal, Kochua, Chitalmari and Mollarhat	Hotel in Khulna	Hired Micro-bus	Remote area, road construction almost stopped our journey.
01/02/99	Terokhada and Kalia thana	Hotel in Khulna	Hired Micro-bus	Mostly prawn culture area, met with some farmers.
02/02/99	Satkhira, Asasuni and Debhata	Hotel in Satkhira	Hired Micro-bus	Real shrimp culture area, met with some farmers.
03/02/99	Satkhira DFO office, Kolaroa, Jerrore	Return to Dhaka DFID Rest House	Hired Micro-bus and by air	Some of ox-bow lakes were visited which are seen in the image.
4/02/99 to 11/02/99	Went to Different Government and NGO offices in Dhaka	Dhaka	Bus, Taxi Rikshaw	Collected a range of data during this time.

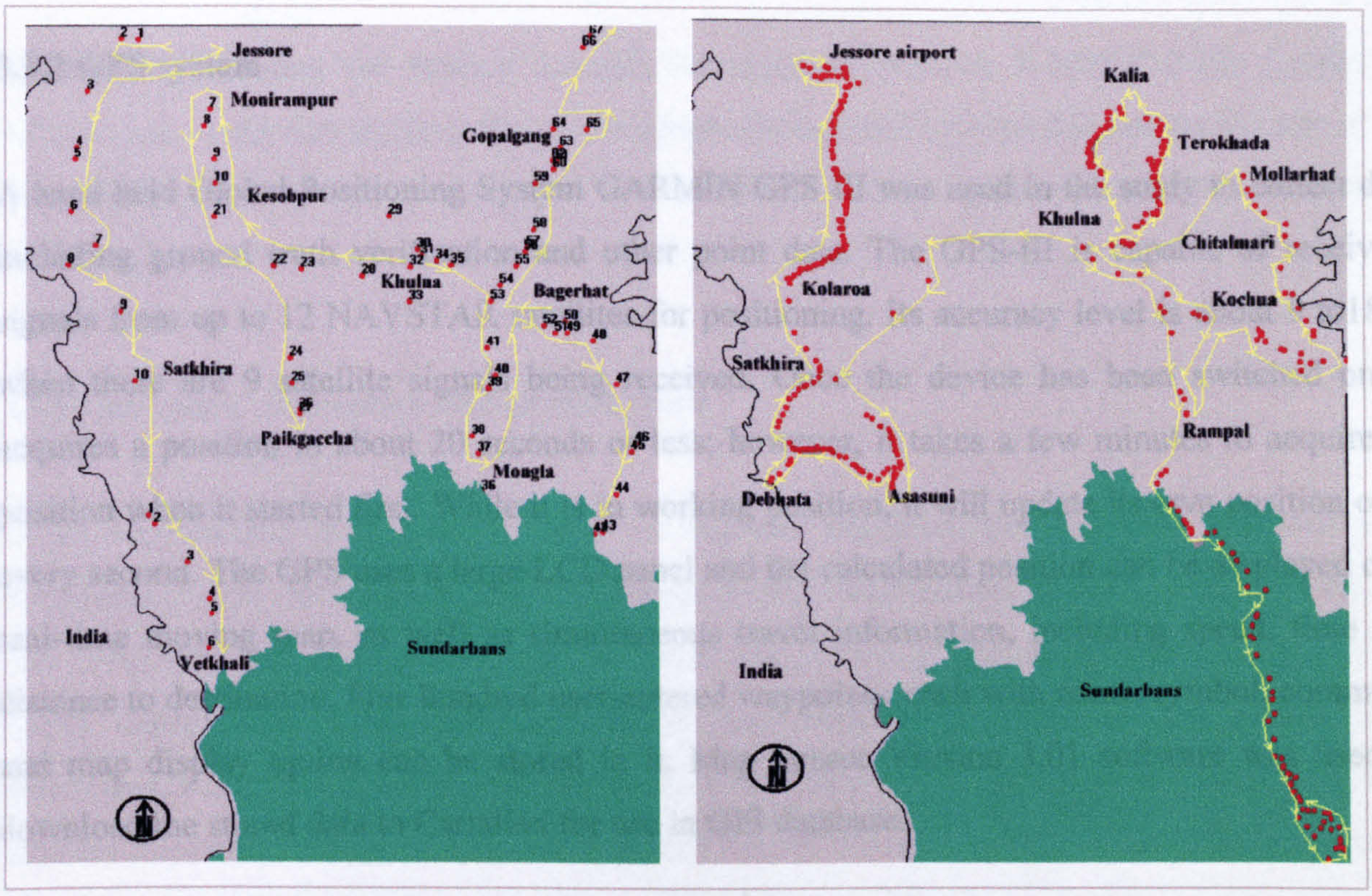

Figure 3.7. The field visit routes in 1998 left and 1999 right in the Khulna region.

Several types of field data were collected ranging from observations of land-use types, vegetation cover, water and soil properties and other parameters. These needed to be stored in an organised way for subsequent integration into the GIS database and the collected field data was processed as quickly as possible to minimise the error in the modelling process. Collected data broadly fell into two categories. The first category was natural resources (e.g. water quality, water availability, soils, climate, topography, and land use), whilst the second category comprised the socio-economic factors (e.g. infrastructure, fish markets, inputs, natural seed availability, population density and agglomeration).

The field trip in 1998 was guided by administrative maps of 1:250,000 scale of Khulna division prepared by US Army (1955), which was supplemented by printed Landsat TM colour composite images produced using the WINDOW module. However, for the 1999 field trip, navigation through the area was made with the help of 50,000 topographic maps, GPS and backdrop bitmap image loaded in the portable computer.

3.3.2 GPS system

A hand held Global Positioning System GARMIN GPS III was used in the study to collect data including ground truth verification and other point data. The GPS-III is capable of receiving signals from up to 12 NAVSTAR satellites for positioning. Its accuracy level is about 9 to18 m when there are 9 satellite signals being received. Once the device has been switched on, it acquires a position in about 20 seconds or less; however, it takes a few minutes to acquire its position when it started first. While it is in working position, it will update its own position once every second. The GPS uses a large LCD panel and the calculated position can be displayed on a real-time moving map, as well as simultaneous travel information, including speed, time and distance to destination. Five hundred user-entered waypoints, each with name, symbol, comment, and map display option can be stored in it. Map Source Version 3.01 software was used to download the stored data to Cartalinx for use in GIS database.

A second GPS the Garmin GPS SRVY II, which is capable of receiving signals from up to 8 satellites was used for navigating with the vehicle during the February 1998 field trip. Only the Germin III was used in 1999.

3.3.3 Sampling of soils

During data collection, some tests were done on soils in the field. The samples were collected using a hand trowel. Collected soil samples were used to perform plasticity, stickiness, pH and soil texture test in the field according to Coche, 1985 (**Appendix 3.3**).

3.3.4 Measurement of pH, salinity and temperature in the field

Part of the collected soil samples were used to measure pH and salinity using a pH meter and hand held refractometer respectively. Prior to measuring pH and salinity with the collected soil samples, the soil was diluted in a conical flask using distilled water and kept in the flask until the soil particles had settled. The supernatant was then decanted into another flask in order to make this measurement. Before carrying out the pH test, the pH measurement was calibrated using buffer 7 solution. A drop of water was poured into the hand-held refractometer and the salinity determined by noting the reading through the eyepiece (scale = 1-100‰; 0.1‰ precision). Salinity was found zero in most of the soil samples tested, due to torrential rain on the day of the field works. Air and water temperatures were recorded simultaneously with other data collecting activities.

3.3.5 Land uses verification and ground truth

Direct observations were made of land use and soil characteristics and GPS positions were recorded for each site visited. This was important for classification of the Landsat TM image. The (246) land use verification sites and routes are shown in **Figure 3.7** for 1998 and 1999. Points collected by GPS serve as reference and verification points for the classification procedures. From one hundred stratified random sampling points generated in IDRISI that were selected to perform the field visit, thirty-six fell outside the area in 1998. Some points had to be discarded either because there were no good road links, rail track or river transport systems or because they were in a water body or in the middle of an irrigated rice field and hence inaccessible.

Land use was recorded (photograph) where the GPS reading was taken for an area determined by the pixel size (30m x 30m) but also its near surroundings. Additional waypoints were plotted while moving one sampling point to another along with the land use pattern.

3.3.6 Selection of Factors for GIS studies in Aquaculture

Land resources are of considerable importance in the world, especially in the developing countries and in order to make use of the available land it is of greatest importance to assemble complete and accurate information about this resource (Wang *et al.* 1990). Aquaculture, like any other economic activity, involves a wide range of interacting factors, which between them describe and affect a specific function. These factors are sometimes called production function (Meaden and Kapetsky, 1991) or criteria (Eastman, 1995). These criteria are of two kinds: factors and constraints (Eastman, 1995). A factor enhances, or detracts from, the suitability of a specific alternative under consideration. It is therefore measured on a continuous scale. Factors are also known as decision variables or structural variables. On the other hand, a constraint serves to limit the alternatives under consideration. A good example of a constraint would be the exclusion from development of areas designated as mangrove or wildlife reserves. In most cases constraints are expressed in the form of a Boolean map, for example areas excluded from consideration being coded with 0 and those open for consideration with 1.

The selection of factors and constraints involved in a GIS is very important since they are the basis of the evaluation. **Table 3.6** shows the features used in aquaculture studies carried out by different authors using GIS to date. There have varied in nature, because aquaculture is a very complex activity (Meaden and Kapetsky, 1991). Most previous studies have principally incorporated environmental factors although socio-economic aspects were reviewed and incorporated on a simple level. Only Gutierrez-Garcia (1995) has entirely focused on socio-economic factors. Overall, some common factors can be identified such as water resources, water quality, soils, land use and infrastructure. The final choice of relevant production functions will depend on the circumstances of the study (Meaden and Kapetsky, 1991). The common objective must be the explanation of the particular advantages of a given site in a sustainable manner, whilst protecting the environment and to achieve the most cost-effective production conditions, taking into account the requirements of both stock and the farmer. Databases for this GIS study were developed by consulting with the literature and the author's own aquaculture based knowledge. For example, winter rain was incorporated as risk factors for brackish water aquaculture as salinity level in the region is not as much as in the other coastal region of the world. In the preliminary stage data were collected and build up the primary databases for the GIS modelling according to their availability in the region without knowing their number. Later on considering the ranges of environmental and socio-economic factors used in the GIS modelling process by several authors in their works around the world, 36 primary criteria were used in the present study.

Table 3.6. Criteria used by different authors in GIS studies for aquaculture developments in 1987-1999.

Year	Country	Authors	Number of Criteria	Criteria used in the study
1987	England, U.K	Meaden	14	Water quality, water temperature, water quantity, groundwater, relief, rainfall, waterway, agglomeration, land costs, road, markets, trout farms
1987	Gulf of Nicoya Costa Rica	Kapetsky *et al.*	23	Fresh and salt water, salinity, soils, infrastructure, (villages, roads, ferries, processor, electric service), land uses (water, coniferous forest, deciduous forest, range, pasture, marsh, cropland, shrimp ponds, salt ponds, mangrove), bathymetry, shrimp post larvae, shelter and security.
1988	Louisiana State, USA	Kapetsky *et al.*	5	Soil suitability for ponds and levees, commercial building, roads and heavy equipment.
1989	Johor-State Malaysia	Kapetsky	21	Water quality (Amoniacal nitrogen, BOD, pH), annual rainfall, soils (hydrogen ion concentration, texture), infrastructure (primary roads, secondary roads, cities and towns), land use (agriculture, urban, mining, district, drainage basin), shrimp farms, cages, bathymetry (mud-banks, contours), shelter, currents.
1990	Louisiana State, U.S.A.	Kapetsky *et al.*	14	National and state parks and wild life refuges, urban areas, inland water bodies, parish boundaries, soils distributions and topography, soil suitability, soil characteristics, length of growing season, yields and surface area of catfish, rice and sorghum farming.
1990	Yucatan State Mexico	Nava	12	Freshwater lakes, sinkholes, clogged sinkholes, seasonal ponds, gravel queries, precipitation, land elevation, soils, agriculture, population centers, villages and roads.
1990	Yaldad Bay, Chile	Krieger and Muslow	7	Bathymetry, bottom salinity, sediment type, organic content, percent shells in sediment, number of species and density of macro fauna.
1990	Ghana	Kapetsky *et al.*	15	Water (annual rainfall, evaporation), land (water surface of lake Volta and lagoons, soils, forestry-reserved areas), inputs (cattle, pig, poultry and rice bran), markets, welfare, extension services, agglomeration and development of roads.
1991	Pakistan	Ali, *et al*	9	Surface water availability, rainfall, groundwater, air temperature, soil type, slope, fish seed, markets and roads.
1991	Norway	Ibrekk *et al.*	32	Environment (wave exposure, shallow areas, critical temperatures, icing conditions, salinity, pollution), tidal range, water exchange, current utilization (housing, outdoor recreation, traditional fishing), infrastructure (road, electricity, feed manufacture, slaughtering facilities, waste disposal facilities), special area (existing fish farms, protection zones for salmonids, nature conservation areas, defense areas, areas earmarked by local authorities), existing loading capacity (sewage, agriculture, industry, precipitation, agriculture, forests, mountains, moorlands), aquaculture permits, open coastal areas and fjords.

Continued Table 3.6.

Year	Country	Authors	Number of Criteria	Criteria used in the study
1992	Nepal	Karki	9	Annual precipitation, climate, soil, irrigation, relief, agriculture, communications, population density and irrigated land.
1992	Prince Edward Island, Canada	Legault	13	Shellfish leases, lease owner, coastline, river systems, roads, country divisions, shellfish closure zones, shellfish approved zones, land-based pollution sources (e.g., waste water outfalls), Agriculture activities, known and potential pollution sources and waste disposal sites.
1993	Tabasco State Mexico	Manjarez and Ross	22	Lakes, rivers, streams, groundwater, rainfall, evaporation, climate, oil wells, pipelines, factories and buildings, soils, relief, topography, agriculture, vegetation, livestock rearing, forestry, roads and cities, population density and agglomeration.
1993	Camas Bruaich Scotland	Ross *et al.*	5	Site, salinity, currents, wave height and bathymetry
1994	Africa	Kapetsky	9	Water temperature, annual rainfall, streams and rivers, soil texture, slope, market, agricultural by products and road infrastructure.
1994	Philippines	Paw *et al.*	20	Soil texture, physiography (tidal flats, beaches, alluvial areas), elevation, land use (grasslands, swamps, coconut plantations, unproductive agricultural land, degraded mangrove areas, national parks, paddy fields, settlements) roads (private, provisional or national), water sources (seashore, rivers), eco-zones (buffer zone from river and shoreline).
1994	Maryland's Chesapeake Bay	Smith *et al.*	19	Spatfall, mortality, population size structure, disease prevalence and intensity, locations and extent of all charted oyster bars, bottom characteristics, geographic boundaries and features, bathymetry, salinity, temperature, shell and seed planting, seed movement, harvest, lease boundaries and boundaries of special management areas.
1994	Camas Bruaich Scotland	Beveridge *et al.*	7	Site, salinity, currents, wave height, bathymetry, dispersion of dichlorvos from cages and dispersion of solid wastes around cages.
1995	Sinaloa State Mexico	Manjarez and Ross	30	Lagoons, rivers, streams, groundwater, rainfall, evaporation, lakes, dams, temperature, soils, topography, agriculture, irrigation, livestock rearing, forestry, shrimp farms, natural post larvae, mangroves, population density, industries, sugar factories, domestic pollution, cities, towns, villages, paved roads, gravel roads, railways, dirt roads and conservation areas.

Continued Table 3.6.

Year	Country	Authors	Number of Criteria	Criteria used in the study
1995	Tabasco State Mexico	Guiterrez Garcia	15	Potential jobs, entrepreneurial tendencies, fishing, rural co-operation, activity conflicts, road system and transport type, farms, hatcheries, agglomeration, related industry, communications, disposable income, consumption per capita and population density.
1996	Vietnam	Thu and Demaine	5	Water depth, inputs (garden waste), rice (surplus), night soil (human excreta) and brewery waste (waste from beer industry).
1997	Bangladesh	Hoque *et al.*	7	Soil salinity, soil pH, water salinity, water pH, soil type, elevation, and electricity.
1997	Latin America	Kapetsky and Nath	16	Urban market size, proximity to town, population density (farm gate sale), soil texture, slope, depth of soil, salinity, pH, catclays, gypsum, evaporation, rainfall, air temperature, seepage, water loss, agricultural by products and fertilizer.
1998	Sepetiba Bay, Brazil	Sergio Cansado	15	Water and air temperature, salinity, dissolved oxygen, food availability, seed supply, exposure to wind, currents, bottom characteristics, towns (as a market facilities), roads, fishermen locations, conflicts, restricted areas and pollution.
1998	Africa	Manjarez and Nath	19	Water requirement, urban market size (major cities), proximity to town, soil texture, slope, potential evaporation, precipitation, minimum and maximum air temperature, seepage, agricultural by products, livestock wastes, population density (farm gate sale), constraints, roads, mean annual wind velocity, and fertilizer.
1999	Sepetiba Bay, Brazil	Scott and Ross	22	Water temperature, salinity, dissolved oxygen, Chlorophyll-a, fecal coliforms, natural indicators, technical support, road network, fishermen locations, seed sources, shelter, currents, bathymetry, population center, buying power, fish consumption, port distance, fishing areas, polluted areas, navigation areas, military areas, and wrong bathymetry.
1999	Bangladesh	Salam and Ross	35	Flood, land use, market, weekly village markets, mangrove, town and cities, roads and rails, soil pH, sub soil pH (< 75 cm) water pH, shrimp fry availability (nature and hatchery), soil salinity, water salinity, water temperature, dissolved oxygen, inputs (agricultural by products), animal wastes (cattle and poultry), government support, support from research stations, support from University, support from NGO, evaporation, winter rainfall (as a risk factors), pollution from industry, pollution from city development, rainfall, distance from processing plants, population density, underground water, disease, drought and cyclones.

Chapter 4

Remote Sensing and Land Use Classification

4.1 Introduction

Remote sensing of land cover types has a long and complex history. Interpretation of aerial photographs allows terrain and vegetation type to be determined by experts fairly accurately, but photographic coverage is patchy and spasmodic (Rogers, 1999). Earth orbiting satellites of the Landsat and SPOT series provide multi-spectral data and resolutions down to 30 m, and panchromatic coverage is down to 10 m. This imagery has found wide application in the production of base maps and predictions of land-cover-types through both unsupervised and supervised classification methods (Lillesand and Kieffer, 1994). The purpose of this study is to generate a limited category land cover map of the Khulna region. This study evaluates the effectiveness of digital image analysis in the production of land cover maps, which were later incorporated with the GIS databases.

The satellite data used for this project was obtained from Landsat 5's Thematic Mapper (TM) sensor acquired in February 1996 (dry season). Satellite data are potentially very useful for the land and water use in GIS, especially in Bangladesh where the large-scale maps are from the mid 1970's and by now well outdated in terms of information on the land uses and infrastructure. The most useful aspects of satellite data are that they are up to date and more detailed than the survey maps. Some of the information most useful to assess site suitability is land cover and land uses. Further, land uses adjacent to the aquaculture site will indicate dangers from pesticide and agro-chemical pollution (e.g., from nearby paddy fields) and other possible water quality problems from domestic or industrial waste (Kapetsky, 1989). Apart from aquaculture development, satellite imagery can be used to inventory and monitor aquaculture, fishery resources and small water bodies (Kapetsky, 1989; Rao *et al.* 1998). For example, individual ponds on a large shrimp culture site could be readily identified in Khulna region (Shahid *et al.* 1992). Thus, used in the combination with other information in a GIS, satellite data can be a tool for aquaculture management as well as for development.

Using satellite imagery as the primary information base has four advantages (Green, 1992). They are as follows:

i) Substantially less time and cost is needed to produce the GIS layers. Aerial photography has long been used to delineate and classify forest vegetation and land use type. To turn it into a GIS layer, however, this information must be transferred to a planimetric base and entered into a computer. These four steps, (a) classification, (b) delineation, (c) transfer, and (d) data entry can be extremely time intensive and costly.

ii) A much richer GIS layer is produced because it can contain both traditional land use/ land cover polygon labels and information about each unit (i.e., pixel) in the satellite imagery.

iii) Landsat TM satellite data are captured for the same ground area every 16 days. Thus, fast and inexpensive updating is possible, because satellite images used to create the landscape delineation can be directly compared with those taken at a later date.

The pressure of population on the land and its resources is a major factor affecting sustainable development in Bangladesh (Giri and Sherestha, 1996). Whether by over-exploitation or mismanagement, changes in land use, and therefore in land cover, are taking place at an unprecedented rate. The increased awareness of environmental issues and the need to strive for sustainable management of natural resources has focused attention on the need to map and monitor changes in land cover at different temporal spatial scales.

The Sundarbans is composed of naturally grown halophytic plants, commonly referred as mangroves. Its tidal forest is divided into low mangrove forests, tree mangrove forests, salt water *Heritiera* (Sundari) forests, and freshwater *Heritiera* forests. On the other hand, based on productivity of the forests, foresters have classified the Sundarbans into three major zones, each of which coincides with a varying range of salinity (**Figure 4.1**). However, due to its relatively low, flat profile, the Sundarbans vegetation is best seen as mosaic and the zone concept is only applicable on a very broad scale (**Figure 4.3**).

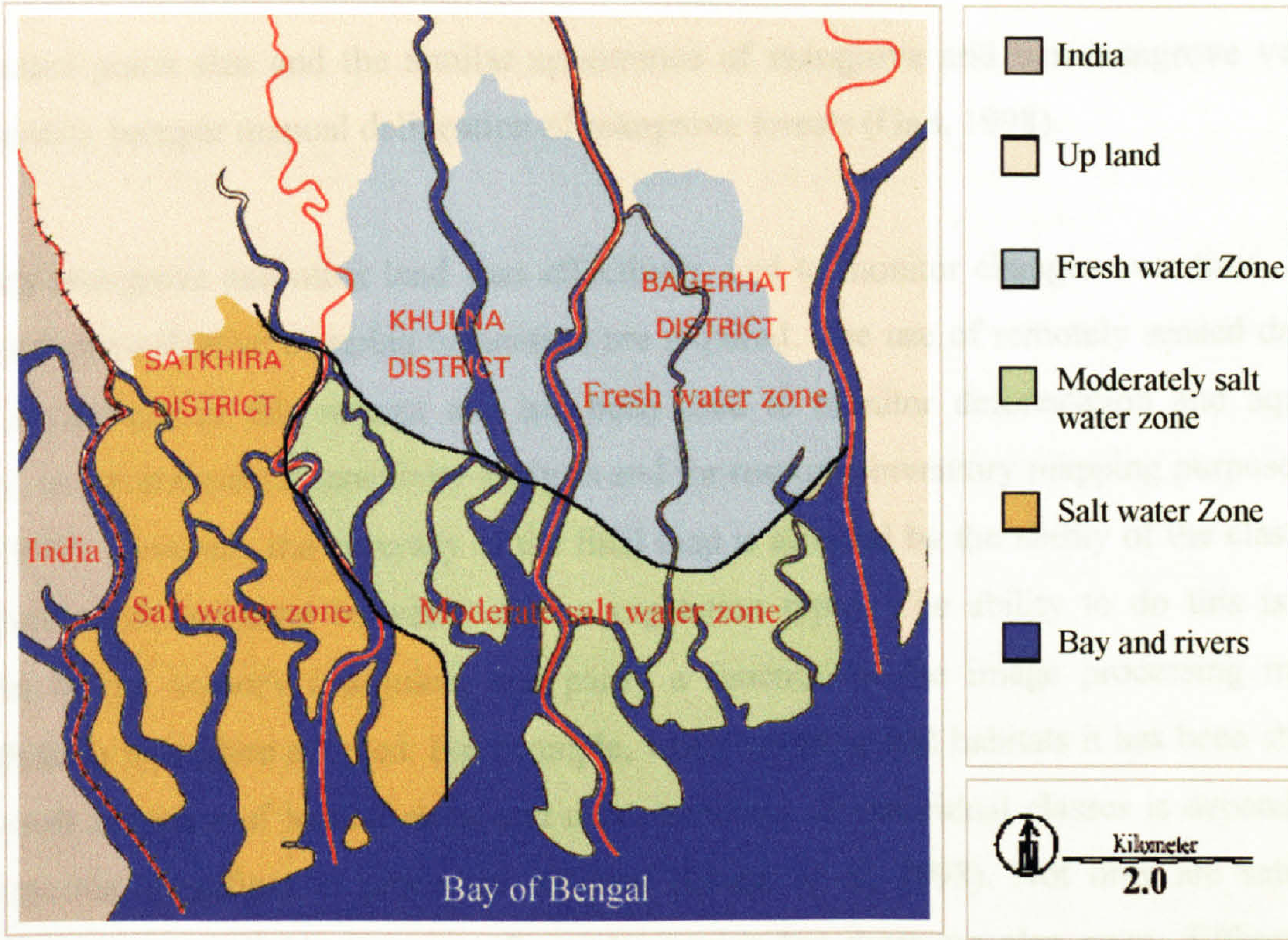

Figure 4.1. Illustrates three salinity zones in the Sundarbans mangrove forest (modified after Rahman, 1998).

The importance of mangroves as coastal resources is well established. Mangrove forests are used throughout the tropics as fishing areas, wildlife reserves, for recreation, human habitation and aquaculture. Mangrove vegetation itself is harvested directly as feed supplement and for timber products (Long and Skewes, 1996; Wafar *et al.* 1997; Wong and Tam, 1995). Mangroves are also important nursery areas for the juveniles of many commercial fish and crustacean species (Robertson and Duke 1987; Wong and Tam, 1995) and play important roles in coastal protection and water quality (Kapetsky, 1985). This importance is reflected in the economic value of mangroves which lies in the range of US $ 100-277,000 /km^2 depending on use (Stevenson, 1997). **Figure 1.4** illustrates the relationship among the coastal protection, artisanal fisheries and aquaculture.

The vegetation communities in coastal areas next to mangrove habitats complicate the machine-based automatic separation of mangrove forests from other vegetation covers because of the similarity in their spectral reflectances. The accurate differentiation between mangrove and non-mangrove vegetation is exacerbated in climatically marginal zones where mangrove condition, such as their density and physical appearance, varies enormously. Consequently, their highly fragmented patch size and the similar appearance of mangrove and non-mangrove vegetation considerably hamper manual delineation of mangrove forests (Gao, 1998).

To study mangrove and other land uses effectively, and to monitor changes over time, accurate, rapid and cost-effective mapping techniques are required. The use of remotely sensed data offers many advantages in this respect and has been used to monitor deforestation and aquaculture activity, in environmental sensitivity analysis and for resource inventory mapping purposes (Green *et al.* 1996). However, the accuracy of the final map is affected by the ability of the classification procedure to discriminate between various vegetation types. The ability to do this is partly a function of the sensor's resolution, and partly a function of the image processing method or classification procedure adopted. For example, when mapping real habitats it has been shown that the overall accuracy of habitat maps and user's accuracy of individual classes is dependent upon the particular classification procedure adopted (Green *et al.* 1998). Not only are satellite and airborne systems available to users of remote sensing but there are also many different image-processing techniques. The choice of an appropriate system and technique depends on the objectives of the study and size of the budget but few, if any, guidelines exist to facilitate this selection process. **Table 4.1** shows different classification techniques adopted by various authors for mangrove and coastal land use classification.

For the purpose of image classification, supplementary data were collected from field visit in an extensive data collection program. The data were collected from various institutions and organisations in Bangladesh, and also from literature review. **Figure 4.2** shows the image processing techniques adopted in the study.

4.1.2 Image Enhancements

Landsat TM images path 137 and 138 and row 44 were provided by NPA a satellite Imaging Groups in London. These images represented dry season vegetation growth (February, 1996), when the majority of the agricultural crops were ripe and part of them were harvested and most of the fields were dry except irrigated rice. Moreover irrigated rice was just planted and were similar to the shrimp ponds, which were in drying condition. It was felt that a spring (April-May) image was representative of optimal vegetation growth when rice would have been in full growing condition and shrimp ponds full of water. However, funds were a constraint.

Table 4.1. Summary of mangrove image processing techniques used by various authors.

Processing method	Sensor	Validation	Accuracy	Level of discrimination achieved
I. Visual interpretation				
Gang and Agatsiva (1992)	SPOT XS	Field data	No	Five classes (labelled after dominant species or associations of species).
Roy (1989)	MK6	Field data	No	Seven classes (labelled after dominant species or associations of species).
Paterson and Rehder (1985)	KATE-140 Aerial photos	Field data		Four classes (fringing, black, mixed and riverine mangrove).
Untawale *et al.* (1982)	Aerial photos	Field data		Ten classes (labelled by species or genera).
II. Vegetation index image				
Blasco (1986)	SPOT*	Aerial photograph	No	Two class (fringing and cleared mangrove).
Jensen *et al.* (1991)	SPOT XS	Field data	No	Percentage canopy closure.
Chaudhury (1990)	Landsat TM	Aerial photograph	No	Two classes (labelled according to dominant species).
III. Unsupervised classification				
Vits and Tack (1995)	SPOT XS Landsat TM	Field data	95% 97%	Four classes (2 fringing, mixed, shrub and logged mangrove).
Loo *et al.* (1992)	Landsat TM	Field data	No	Three classes (dense, less dense and cleared coastal vegetation).
Woodfine (1991)	SPOT XS Landsat TM	Field data	N/A	Failed to distinguish mangrove and forest satisfactorily.
Chaudhury (1990)	SPOT XS	Aerial photos	No	Four classes (Labelled according to dominant species).
IV. Supervised classification				Four classes (2 fringing, mixed, shrub
Dutrieux *et al.* (1990)	SPOT XS	Field data	No	Four qualitative densities class (dense and medium, low and very low density).
Vits and Tack (1995)	SPOT XS	Field data	91%	Two classes of wetland vegetation.
Aschbacher *et al.* (1995)	SPOT XS Landsat TM MOS-1, MESSR JERS-1 ERS-1 SAR	Field data and maps	No	Three classes (2 labelled according to dominant species, cleared mangrove)
Mohamed *et al.* (1992)	Landsat-MSS	Field data	No	Two classes (primary and secondary mangrove)
Eong *et al.* (1992)	Landsat TM	Field data	No	Three classes (2 labelled according to dominant species and one cleared mangrove)

Continued Table 4.1.

Processing method	Sensor's	Validation	Accuracy	Level of discrimination achieved
Palaganas (1992)	SPOT XS	Field data	81%	Mangrove (as separate from non-mangrove vegetation)
Vibulsresth *et al.* (1990)	Landsat TM	Aerial photograph	No	Six classes (4 labelled according to dominant species, 2 mixed mangrove)
Bina *et al.* (1980)	SPOT XP Landsat-MSS MOS-1 MESSR	Field data, aerial photos, maps	85%	Mangrove (as separate from non-mangrove vegetation)
Lorenzo *et al.* (1979)	Landsat-MSS	Field data	No	Mangrove (as separate from non-mangrove vegetation)
Green *et al.* (1998)	CASI	Field data	78%	Six classes (defined from hierarchical cluster analysis of field data)
Woodfine (1991)	Landsat TM	Field data	No	Five classes (Mixed community, complex community, transitional to freshwater, transitional to upland vegetation, cleared mangrove with secondary invasion)
V. Band ratio-ing				
Gray *et al.* (1990)	Landsat TM	Landsat TM	No	Three height classes (tall [>10m], medium [4-10m] and dwarf [<4m] mangrove)
Kay *et al.* (1991)	Landsat TM	Landsat TM	N/A	Mangrove (as separate from non-mangrove vegetation)
Long *et al.* (1994)	Landsat TM	Aerial photos	No	Mangrove (as separate from non-mangrove vegetation)
Populus and Lantieri (1991)	Landsat TM SPOT XS	Landsat TM	No	Two classes (high density, mature mangrove, and low density young)
Ranganath *et al.* (1989)	Landsat TM	Landsat TM	No	Mangrove (as separate from non-mangrove vegetation)

The images were subjected to preliminary digital enhancements in order to enable their interpretation. A false colour composite using the Landsat TM bands 2, 4 and 3 (visible green, near infrared and visible red respectively), was found to give a clear visual discrimination of the mangrove and non-mangrove boundary (Gray *et al.* 1990; Trolier and Philipson, 1986). An associated contrast stretch of 5% was also applied to give a better visual representation (**Figure 4.3**). The middle infrared Band 5 of Landsat TM, which was not available in the study, would improve the classification accuracy since it has been shown to be useful for mapping mangroves (Kay and Hick, 1988).

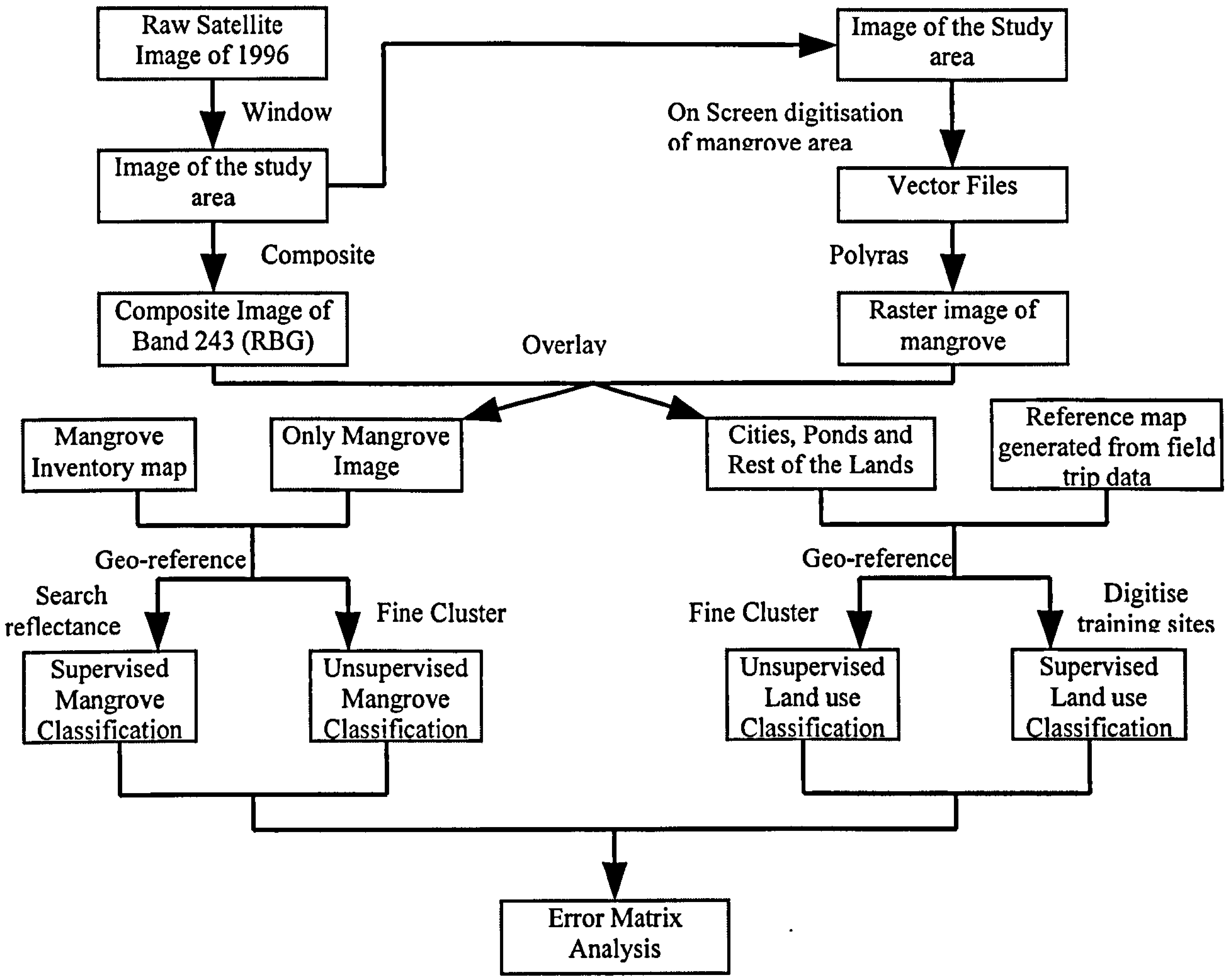

Figure 4.2. Schematic diagram of image processing techniques used for remote sensing image.

4.1.3 Masking

The mangrove area separated from the other inland vegetation and water bodies prior to image classification. Young mangrove trees gave the same reflectance as palm trees farther inland and apparent scattered mangroves were observed far away from the mangroves mixed with inland trees (Aschbacher *et al.*1995; Chuvieco and Congalton, 1988; Green *at al.* 1998; Yusof, 1998). Moreover, irrigated boro rice and marshland in the mangrove also gave the same reflectance, which was difficult to separate. Furthermore, the image was taken during the time of an intermediate stage for shrimp culture and agricultural crops. Ponds were drying or had been left with very shallow water, which gives a similar reflectance to irrigated rice. Not only that, bare-land also gives a similar reflectance to the cities.

To overcome these problems, mangroves, ponds and cities were separated from image using masks, which were developed using on screen digitisation facilities in IDRISI. The vector files were then rasterized and applied as masks to the colour composite image using OVERLAY module.

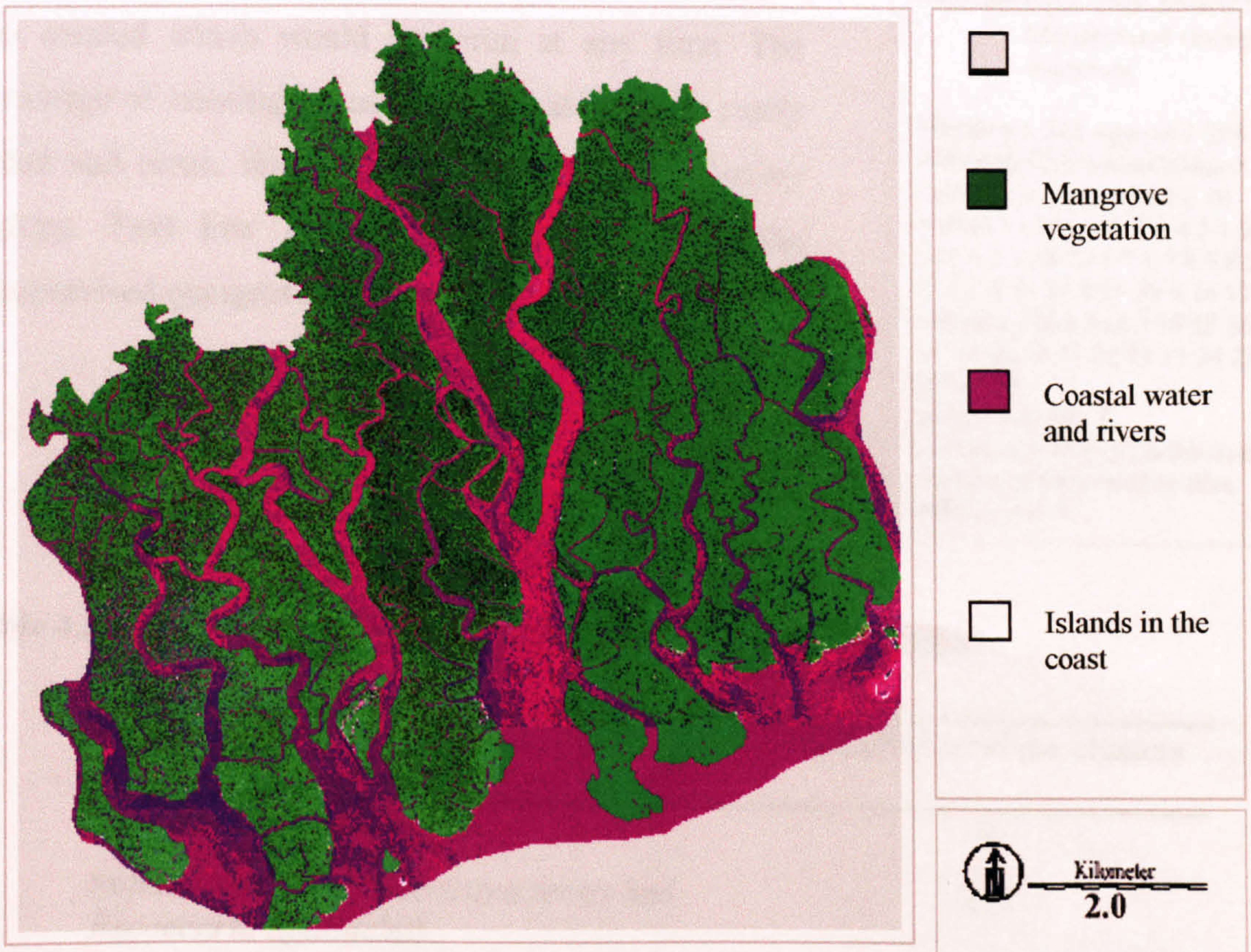

Figure 4.3. A false colour composite image using the Landsat TM bands 2, 4 and 3 to give a clear visual discrimination of the mangrove vegetation.

4.2 Unsupervised Mangrove Classification

The logic by which unsupervised classification works is known as cluster analysis and this is provided in IDRISI by the CLUSTER module. This module groups together features with similar reflectance patterns. The module was used to produce an unsupervised classification from the colour composite image and this provides an interpretation of the number of spectral classes in the raw data. This was conducted in several steps. Cluster was used with the option of user selecting the number of classes for the final image. The module then classifies the image into discrete categories. This process was conducted using 30 fine clusters. Following the cluster, a 3 x 3 mode FILTER was carried out to eliminate small clusters with less than 3 pixels. The clusters were then identified and further reclassified into nine forest cover classes based on the forest inventory map, supplemented by the colour composite Landsat TM image and field visit data. **Table 4.2** shows the groupings of forest categories from the cluster analysis.

Once the classification had been achieved, a macro file was created which would be rerun at any time. The advantage of creating a macro file is that it can be easily edited and rerun, thus all major investigation of many options. **Text box 1** shows the macro file for the unsupervised mangrove classification.

Text box 4.1. IML macro file for unsupervised classification of mangrove

```
Window x 243 mgrove 1 994 2439
3959 5666 0 D:\salam\salam3
cluster x mgrove inta 2 2 30
reclass x i inta intb 2 1 4 5 1 9 10 1 13
14 4 6 7 5 18 19 6 7 8 7 8 9 8 21 22 8
17 18  8 14 15 8 27 28 9 16 17  -9999
reclass x i intb intd 2 10 15 16 10 11
13  11 19 21 11 22 23 11 24 25  0 12
999 -9999
filter x intd inte 3
overlay x 3  inte mask-mv m-unsup
deleting all intermediate files
delete x int*.*
```

Table 4.2. Groups formed by the fine cluster analysis with 30 cluster.

Name of the tree species	Reflectance of the clusters
Sundari (*Heritiera fomes)*	3
Sundari and Gewa *(Heritiera fomes* and *Excoecaria agallocha)*	2, 7
Gewa *(Excoecaria agallocha)*	8
Gewa and others *(Excoecaria agallocha)*	5
Goran *(Ceriops decandra)*	16
Goran-and others *(Ceriops decandra)*	11, 12, 15
Kewra *(Sonneratia apalata)*	7
Grass/ Bare land/ Beaches	14, 17, 21, 27
Water	4, 9, 13, 14, 17, 18, 19, 20, 21, 22, 24, 25, 26, 27

4.3 Supervised Mangrove Classification

Supervised Classification is a technique for the computer-assisted interpretation of remotely sensed imagery. The operator trains the computer to look for surface features with similar reflectances to a set of examples of known interpretation within the image. These areas are known as training sites. For the spectral supervised classification, signatures for groups shown in **Table 4.3** were developed based on the three bands of raw Landsat TM data.

Supervised classification begins with digitizing of polygons thought to be representative of the intended spectral or textural classes. Digitizing was conducted, using the on screen digitizing facilities and windowing and vector drawing features in IDRISI. Each polygon was assigned a group number. The MAKESIG module was then used to process the polygons into spectral signatures representative of the intended classes.

The SIGCOMP module was then used to evaluate the quality of the signatures, and allows the user to compare the signatures for each of the bands of raw data as line graphs. The greater the degree of spectral separation between each signature, the better the final classified image is expected to be. The SCATTER module was also used to evaluate the quality of the signatures in the raw data and MINDIST module was used to process the raw data for supervised mangrove classification. The full process is summarized in the macro file shown in **Text box 4.2.**

Text box 4.2. ILM macro file for supervised classification of mangrove as reflectance.

```
rem: creating a blank image
initial x int-a 1 1 0 1 winover m
rem: creating mangrove mask image
polyras x m-mask int-a
overlay x 3 band2 int-a m-band2
overlay x 3 band3 int-a m-band3
overlay x 3 band4 int-a m-band4
makesig x v trsites 3 band2 band3 band4 sun s-gw gw gw-othrs gw-gor gor g-othrs kwr gr/bl wat
sigcomp x 1 9 sun s-gw gw gw-othrs gw-gor gor g-othrs kwr gr/bl wat
scatter x band3 band4 scat34 1
mindist x 9 int-b 2 0 trainsig
filter x intb intc 3
overlay x 3 m- mask int-c m-sup
rem: deleting all intermediate files
delete x int*.*
```

Note: S-gw= Sundari and Gewa, gw= Gewa, Gor= Goran, gw-othrs= Gewa and others, gw-gor= Gewa and Goran, kwr= Kawra, gr/bl= grass or bareland and wat= water bodies.

4.4 Land Use Classification

As for mangrove classification, land use was also classified using both unsupervised and supervised procedures. Land use was classified according to the classes shown in **Table 4.3.**

Table 4.3. Illustrates land use categories groups formed by the fine cluster analysis.

Name of the Land use category	Reflectance of the clusters
Water bodies: rivers, lakes, canals, natural depressions,	1 23-24 and 28
Homestead trees: deciduous forest, evergreen forest, mixed forests	2, 3, 5 and 18
Agricultural crops: wheat, lentils, oil seeds, chick peas, mixed crops	11, 14 and 15
Irrigated rice fields	4, 8, 9, 12, 19, 22, 26 and 27
Shrimp ponds: extensive, semi-intensive	16 and 17
Cities: build up areas, roads, ports, residential areas	10
Stubble /bare lands: harvested rice and other crop fields sand and muddy flats.	6, 7, 13, 20, 21 and 25.

4.4.1 Unsupervised Land Use Classification

The Cluster module is also used to produce an unsupervised land use classification from the colour composite image. Thirty clusters were produced using the fine cluster module. The clusters were then identified and further reclassified into seven land cover classes based on the land use and a topographic map, which is supplemented by colour composite Landsat TM image and field visits data. After classification, a 3 x 3 mode FILTER was carried out to eliminate the small clusters less than 3 pixels. The classification procedure is summarised in the macro file shown in **Text box 4.3.**

4.4.2 Supervised Land Use Classification

4.4.2.1 Selecting Training Sites

In supervised image classification, training sites are those areas which the analyst identifies that exemplify each land-cover type in the image to be classified. These sites are used to "train" the software classifier to recognise each cover type so that all pixels in the image may be assigned to their appropriate cover classes (Eastman, 1997). The success of supervised land use classification depends on how well the training sites are picked up.

The acquisition of land use reference data (training sites) involved the collecting of qualitative and quantitative observations of water bodies, agricultural crop pattern, villages and cities and vegetation on the ground. The reference data aided in the analysis and interpretation of remotely sensed data, i.e., it established a link between variation on the ground and variation in the image. This link was pertinent for assigning image spectral classes to land cover classes in the image classification process. Training sites are also important in assessing the accuracy of the classified image.

Text box 4.3. IML macro file for unsupervised classification of land use except river and mangrove.

```
rem :unsupervised classification for land use
initial x inta 1 1 0 1 winover m
polyras x city inta
polyras x pond inta
polyras x mgrove inta
reclass x i river2 int-riv 2 0 1 2 1 0 1 -9999
reclass x i inta intb 2 0 1 9 1 0 1  -9999
overlay x 3 intb winover int-c
overlay x 3 intc int-riv int-land
cluster x int-land intd 2 2 30
reclass x i intd inte 2 1 23 25 2 3 4 2 5 6 2 18 19 3 14 16 4 8 11 4 12 13 4
17 18 4 26 28 7 13 14 7 20 22 7 25 26 -9999
reclass x i inte land-uns 2 1 0 1 4 19 20 4 22 23 1 28 29 3 11 12 7 6 7 0 8
999  -9999
rem: unsupervised classification of shrimp ponds
reclass x i inta intf 2 1 1 9 -9999
overlay x 3 intf winover int-pond
cluster x int-pond intf 2 2 30
reclass x i intf intg2 1 4 5 6 2 3 6 5 6 1 10 11 1 12 13  2 25 26 2 21 22 6
11 12 6 7 10 6 13 14 6 3 4 6 26 27 3 15 16 -9999
reclass x i intg pond-uns 2 7 16 17 6 14 15 6 17 20  6 22 23 3 23 25 7 20
21 -9999
rem: Unsupervised classification of city
reclass x i inta inti 2 1 1 9 -9999
overlay x 3 inti winover int-city
reclass x i int-city intj 2 1 21 25 2  8 9 2 20 21 2 28 29 3 4 6  3 11 12 3
13 14 3 15 16 3 19 20 3 25 26 4 9 10 4 17 18 -9999
reclass x i intj city-uns 2 4 29 31 5  6 8 5 10 11 5 12 13 5 14 15 5 16 17
5 18 19 5 20 21 5 26 27 0 8 999  -9999
rem: joining city, pond and lands together
overlay x 1 land-uns pond-uns intk
overlay x 1 intk city-uns int-lpc
filter x int-lpc intl 3
overlay x 1 intl river2 luns2000
reclass x i WAY9CPL intm 2 1 1 8  -9999
overlay x 3  intm Luns2000 intn
errmat x WAY9CPL intn
rem deleting all intermediate files
```

The training sites were representative examples of land cover types habitat could be interpreted both on the ground and in the TM image. The number of training sites needed for a thorough classification depends largely on how many land-use categories that the operator is trying to distinguish. For this classification 7 different classes were attempted. A diverse set of training site data was collected to cover all classes in the classification scheme and the spectral variation in the image. Due to the fact that slope aspect, plant vigor, plant density and many other factors may affect reflectances, multiple training sites per class were recorded. A total of 246 points were collected, which are shown in **Figure 4.4.**

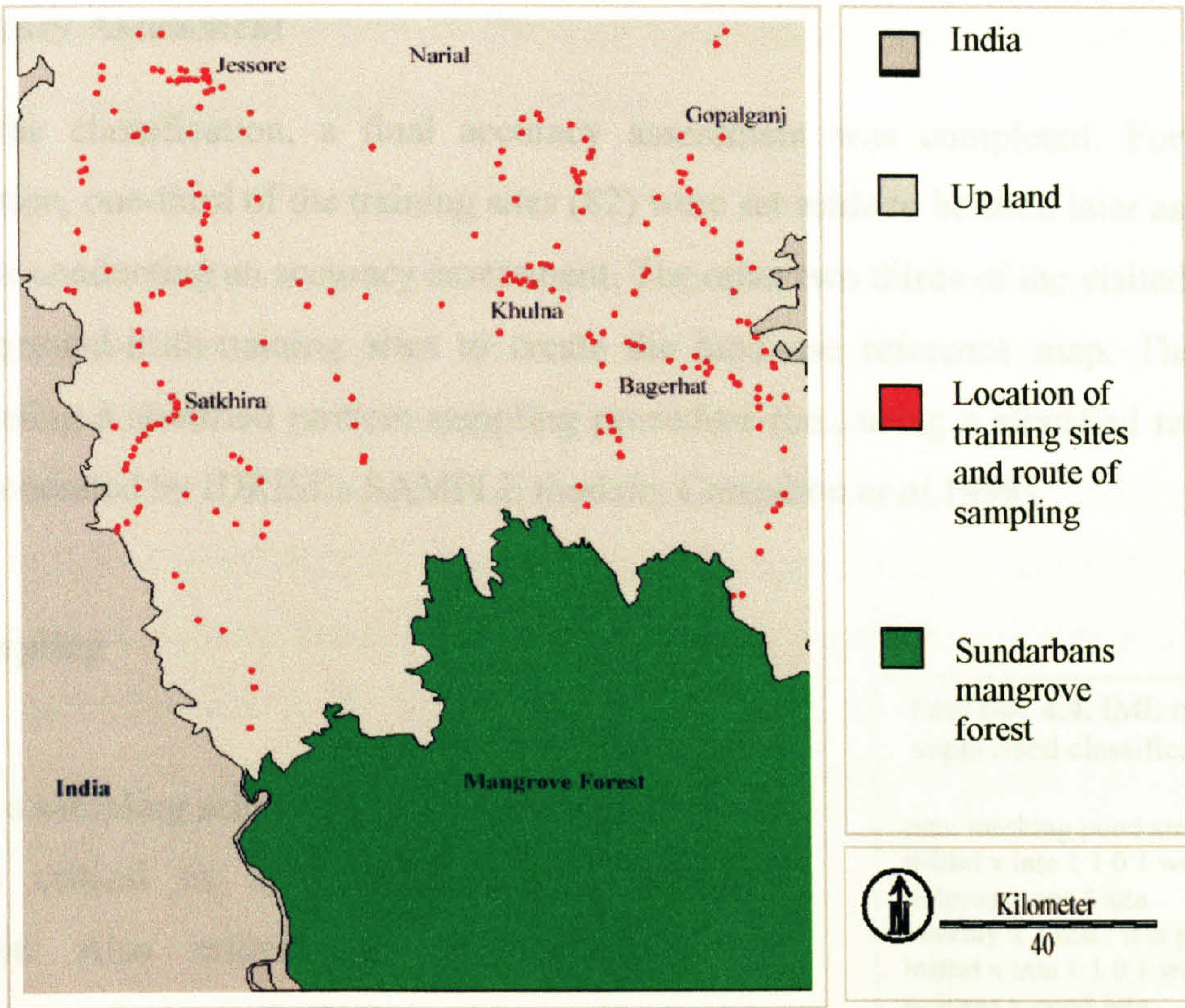

Figure 4.4. Schematic diagram of location of training sites used in supervised land use classification.

The training sites were located based principally upon the following criteria:

i) the sites were homogenous with regard to vegetation/natural phenomena (e.g., agricultural crops must have at least 75% crown closure in the crops category, Congalton *et al*. 1998);

ii) delineate many training sites occurring at different aspects, as mixed land use;

iii) training sites were to be located near to roads so that field time was efficiently used;

iv) a print out of composite image was used in the field to maximise efficiently;

v) the chosen training site was large enough to be seen by the remote sensor but small enough to exclude interference by other natural phenomena near the site;

vi) a set of pre-determined labels were used for different land use types such as water, trees, crops, rice, ponds, cities and stubble.

4.5 Accuracy Assessment

To test the classification, a final accuracy assessment was completed. For this particular classification, one-third of the training sites (82) were set aside to be used later as an independent sample for conducting an accuracy assessment. The other two thirds of the visited site (164) were used as ground-truth-training sites to create the land use reference map. These fields were selected using a stratified random sampling procedure (i.e., using a stratified random sampling number generated by IDRISI's SAMPLE module, Congalton *et al.*1998).

4.5.1 Sampling

Selecting a sampling scheme, which is appropriate to the study, is critical to the validity of the accuracy assessment. Also critical in this regard is the establishment of criteria for how many sampling points are to be used. For this project the stratified random sampling technique was used. In the stratified random sampling procedure, ground observation locations are allocated to the categories of the final map in proportion to the size of the classes. The locations of the sampling points are then assigned randomly. This procedure assures that a certain number of sampling points are assigned to each class while maintaining a random element. Congalton *et al.* (1998) noted that the random sampling technique performs adequately, but that the stratified random sampling procedure should be used to ensure that all of the classes are sampled. Two hundred and seventy two sampling locations are selected for the mangrove spectral classification on the Forest Inventory map, and two hundred and one for the land use classification map, utilizing the IDRISI's SAMPLE module. An attempt was made to visit each of the sampling locations to determine the observed class for the location. Inaccessible sampling locations are evaluated based on interviews with the people of that area and looking at the land use map. Classification accuracy

Text box 4.4. IML macro file for supervised classification of land use.

```
rem: masking pond area for all 3 bands
initial x inta 1 1 0 1 winover m
polyras x pond inta
overlay x 3 test1 inta pband2
initial x inta 1 1 0 1 winover m
polyras x pond inta
overlay x 3 test2 inta pband3
initial x inta 1 1 0 1 winover m
polyras x pond inta
overlay x 3 test3 inta pband4
initial x inta 1 1 0 1 winover m
polyras x pond inta
overlay x 3 winover inta pcomp
makesig x v trsites 3 pband2 pband3
pband4 wat tr agcrop rice ponds cities
st/bare
sigcomp x 1 9 wat tr agcrop rice ponds
cities st/bare
scatter x band3 band4 scat34 1
mindist x 9 intb 2 0 trainsig
overlay x 3 mask- rcl  intb pond-sup

note: city and rest of the land classified
using the same procedure and then joined
them together.

rem: joining cities, ponds and lands to
have one complete land use map
overlay x 1 pond-sup city-sup intc
overlay x 1 intc land-sup intd
overlay x 3 intd mask-rcl inte
overlay x 1 inte river2 intf
filter x intf lsup2000 3
```

is based upon a statistical analysis of the final ground truth data using the cross tabulation technique and computation of the Kappa Coefficient.

Polygons for the land use classes were digitized using on screen digitizing facilities based on field trip data, land use map, and the false color composite image and knowledge of the study area. Signature files were created using MAKESIG and then evaluated in the SIGCOMP and SCATTER modules, which helped to refine signature characteristics. SIGCOMP compares signatures created with MAKESIG. It graphs up to 9 signatures over all bands simultaneously either as a spectral response pattern of mean reflectances, or as a box plot illustrating minimum and maximum reflectance's. In **Figure 4.5**, which is a SCATTER diagram showed that reflectances from cities and irrigated rice and agricultural crops and inland trees has overlapped means separation among these were not done properly.

The MINDIST module was then used to classify the land use raw data. When classification was completed, a 3 x 3 mode FILTER was carried out to eliminate the small clusters less than 3 pixels with both of the mangrove and land use supervised images. The full process is summarized in **Text box 4.4**, which shows the macro file for the supervised land use classification.

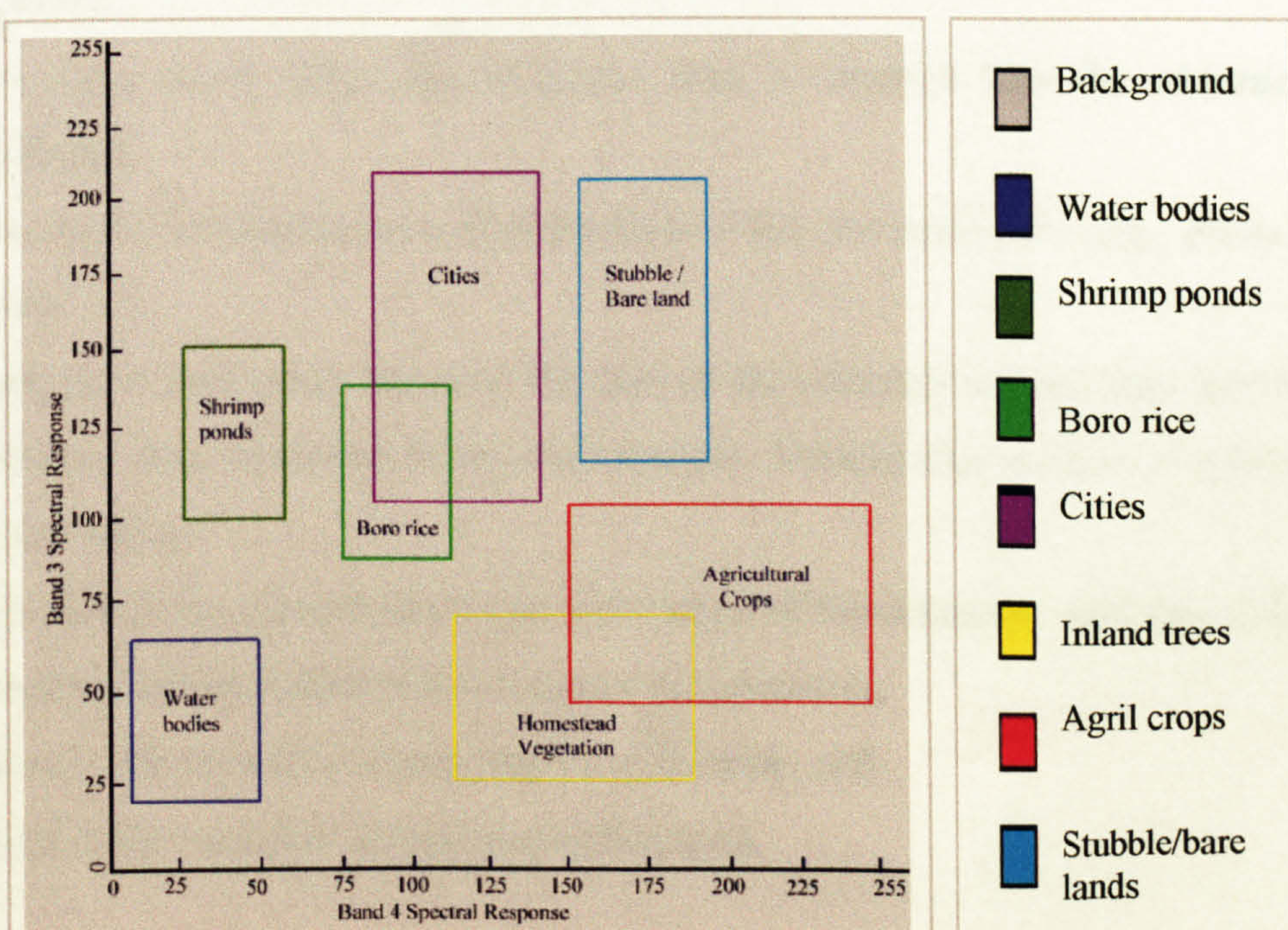

Figure 4.5. SCATTER diagram between band 3 and band 4 to compare the mean reflectance values of land use categories.

4.6 Error Matrix Generation

An error matrix is a square array of numbers set out in rows and columns which expresses the number of sample units (i.e., pixels, clusters of pixels, or polygons) assigned to a particular category relative to the actual category as verified by some reference data. The columns usually represent the reference data while the rows indicate the classification generated from remotely sensed data. In other words, an error matrix is a comparison between sampled areas on the map generated from the remotely sensed data and those same areas as determined by some reference data (**Table 4.4**). The reference data are typically ground visits or large-scale photographs. The object then of the error matrix is to represent the accuracy of the remotely sensed image classification (i.e., the error in the map). An assumption made here is that all differences between the remotely sensed image classification and the reference data are due to classification or delineation error. However, there are many other sources of confusion between the remotely sensed image classification and the reference data that must also be considered (**Figure 4.6**). They include:

i) registration differences (geo-reference difference) between the reference data and the remotely sensed map classification;

ii) delineation error encountered when the sites chosen for accuracy assessment are digitised;

iii) data entry error when the reference data is entered into the accuracy assessment databases;

iv) error in the interpretation and delineation of the reference data (e.g., photo interpretation error);

v) changes in land cover between the date of the remotely sensed data and the date of the reference data (temporal error), for example, changes due to fires or urban development or harvesting;

vi) variation in the classification and delineation of the reference data due to inconsistencies in human interpretation of heterogeneous vegetation;

vii) errors in the remotely sensed map classification, and

viii) errors in the remotely sensed map delineation.

Table 4.4. A typical Error matrix generation table (modified after Congalton *et al.* 1998).

CLASSIFIED MAP	Class 1	Class 2	Class 3	Class 4	Row MARGINALS
Class 1	✔	O			RT
Class 2	C	✔	C	C	RT
Class 3		O	✔		RT
Class 4		O		✔	RT
COLUMN MARGINALS	CT	CT	CT	CT	Σ

(REFERENCE DATA: Class 1 – Class 4)

RT, CT Sum of Row or Column Entries
Σ Number of Total Sampled Observations
✔ Total Diagonals Entries = Correctly Classified Units
C, O Number of Row Commission and Number of Column Omission Errors

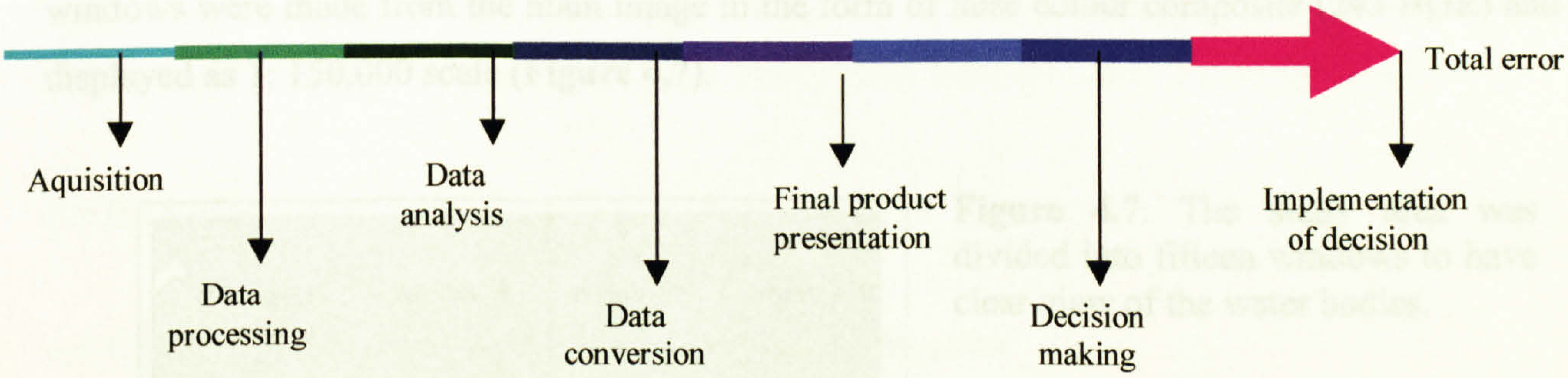

Figure 4.6. The accumulation of errors in typical remote-sensing and image processing techniques (after Lunetta *et al.* 1991).

4.7 Resampling Image

When comparing two or more images, spatial registration is a crucial step for the purpose of accuracy assessment. This is because the process of looking at the image to be classified and the reference image is typically done by examining the differences in the values of corresponding cells in the multiple images. This process will only make sense provided that the corresponding pixels of each image actually describe the same location on the ground. Geo-registration procedure is described in **Chapter 3**.

4.8 Small Water Body Inventory

The study is based on the visual analysis of two Landsat Thematic Mapper images of Southwest part of Bangladesh, where most of the shrimp farms are located. The images were captured during the dry season (9 February and 16 February 1996). A window was cut out from these images for this purpose. The study is supported by 1:50,000 topographic map produce by Survey Bangladesh during 1972-1975. Thematic mapper has 7 spectral bands, which individually or in combination, can be used to identify and extract various land cover and water features. This enables not only identification of the water bodies, but also their recognition in the context of land forms and land uses in which they occur. A colour composite image of bands 2 (water turbidity), 4 (water) and 3 (terrestrial vegetation), was made. In order to facilitate location and identification of water bodies alone, a separate image was prepared using only band 4. Fifteen windows were made from the main image in the form of false colour composite (243 BGR) and displayed as 1: 150,000 scale (**Figure 4.7**).

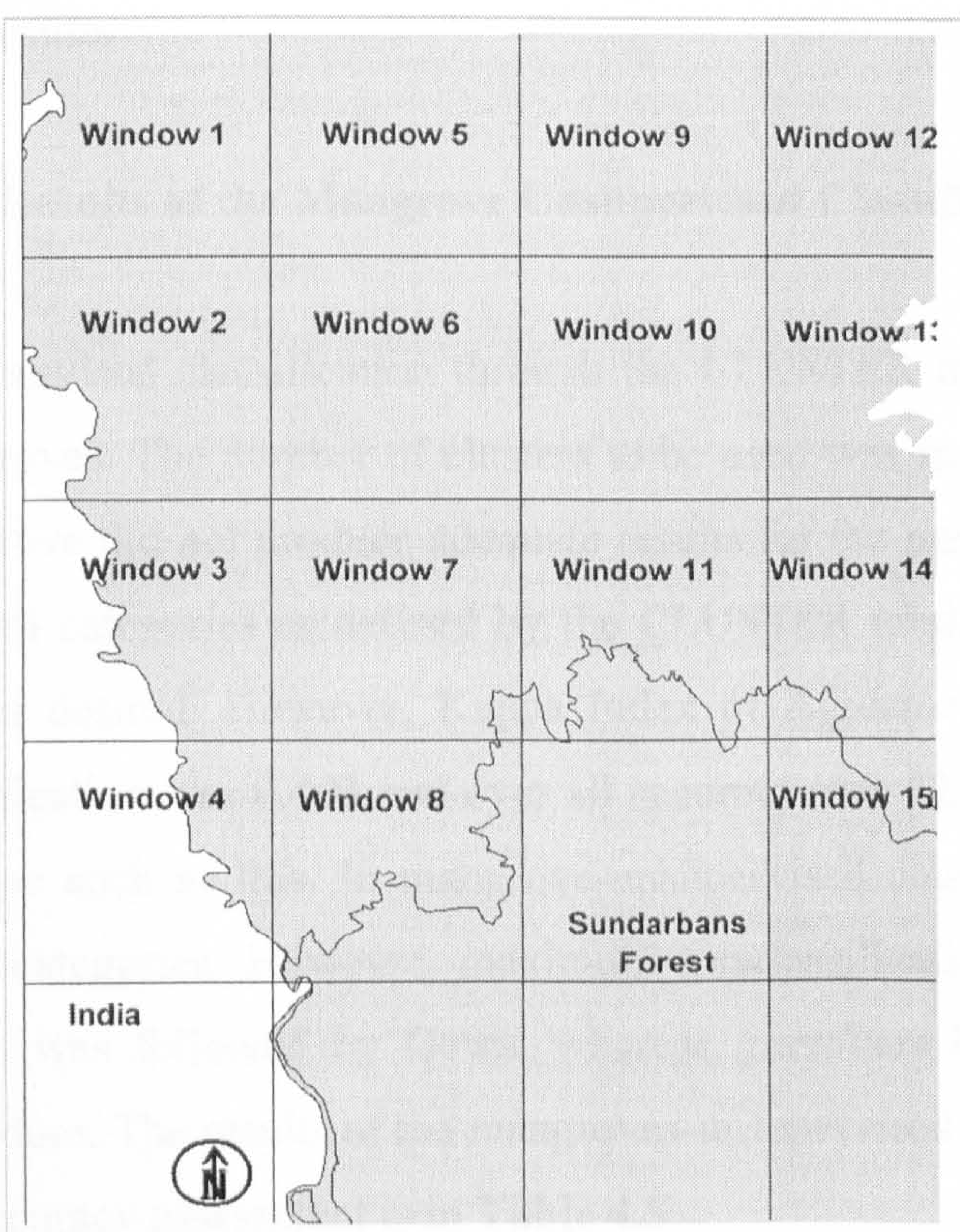

Figure 4.7. The study area was divided into fifteen windows to have clear view of the water bodies.

A complete inventory was made of the water bodies in the image. Water bodies were identified and digitised onscreen as polygons. A further zoom was applied to verify many of the small

water bodies. These polygons were overlaid on to the band 4 image and these water bodies which were not identified in the colour composite image were located and digitised.
Using the topographic maps of 1972-1975 as the baseline, water bodies were delineated separately to compare with the water bodies extracted from the image. Finally, the water bodies were tabulated.

During sampling, the hue of the water body was noted which gives an indication of the state of turbidity, which in turn, may suggest levels of aquatic productivity. Judgement about turbidity based on colour of the water bodies are that as particle size increases there is a colour shift from blue to green to yellowish to green irrespective of wavelength until the colour of the water becomes that of the natural colour of the particles causing the turbidity (Kapetsky, 1987). The hue also can be influenced by life forms, and the spectral response of the predominant life form will determine the water colour. However, in shallow waters, such as ponds, the bottom can be detected and water colour would thus be altered towards bottom colour (Kapetsky, 1987).

4.9 Results

4.9.1 Results of the Mangrove Unsupervised Classification

Unsupervised classification through the CLUSTER module was conducted on the raw data of mangroves. The number of clusters to be used was specified as thirty. The classification for the mangrove did not produce adequate results for the purposes of the study. Most of the cases, the spectral categories as defined by the CLUSTER module did not correspond to the information classes desired. However, Kappa Index of Agreement (KIA) for the mangrove-unsupervised classification was 0.403 and over all accuracy was 52.21%, which was judged fair for modeling purpose such as this. In mangrove-unsupervised classification the water separated better than other categories. However, maximum misclassification was observed with Gewa and others, which was followed by Gewa, whereas grass/bare-lands category was totally wrong in this procedure. The results of the mangroves-unsupervised classification are shown in **Figure 4.8** and the accuracy assessment is in **Table 4.5**.

The error matrix module generates the KIA, which is particularly important as it is used to determine the degree of agreement between the two images (Eastman *et al.*1995). Kappa ranges in value from -1 to 1. A value of 1 indicates that the two images are in perfect agreement (no change occurred), whereas if the two images are completely different from one another, then the Kappa value is -1. If all the change that occurred could be accounted for by chance, then Kappa is 0.

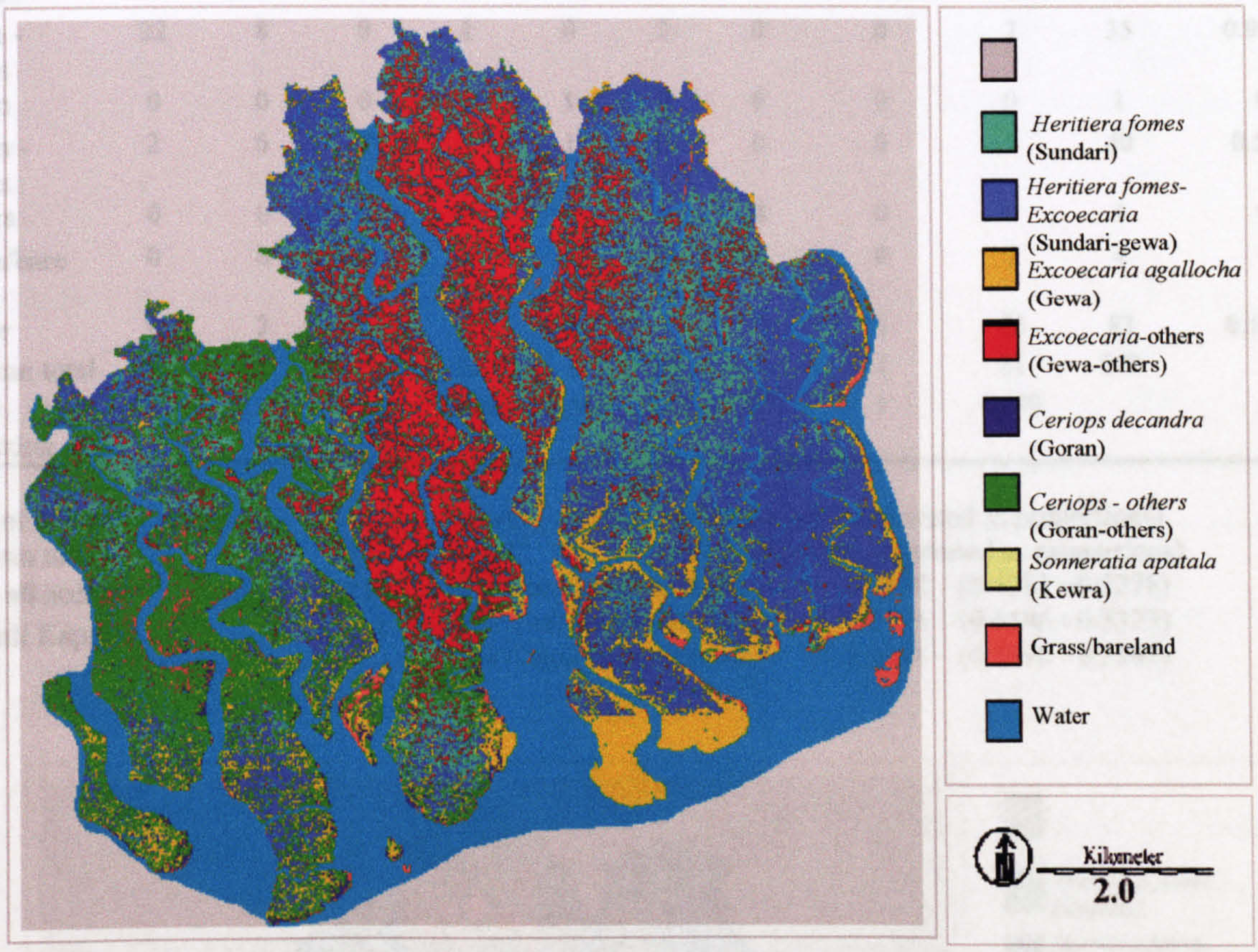

Figure 4.8. The result of unsupervised mangrove classification.

4.9.2 Results of the Supervised Mangrove Classification

The SAMPLE module for the accuracy assessment selected two hundred and seventy two sampling points over Forest Inventory map of mangroves of 1985. The results of the accuracy assessment of supervised mangrove classification (**Figure 4.9** and **Table 4.6**) indicate that the methodology produced fair results, with an overall percentage correct pixels of 54.41% and KIA of 0.433, which is slightly better than the unsupervised classification.

Table 4.5. Error Matrix Analysis of mangrove unsupervised classification (columns) against mangrove inventory maps (rows).

	Sundari	Sundari Gewa	Gewa	Gewa-others	Goran	Goran others	Kewra	Grass/ Bare land	Water	Row total	Error Commission
Sundari	**14**	12	1	4	0	3	0	0	0	34	0.5882
Sundari-Gewa	12	**29**	1	12	0	7	0	0	3	64	0.5469
Gewa	0	3	**1**	2	0	1	1	0	0	8	0.875
Gewa - others	22	8	0	**1**	0	2	0	0	2	35	0.9714
Goran	0	0	0	0	**1**	0	0	0	0	1	0
Goran - others	2	6	2	9	1	**19**	0	0	1	40	0.525
Kewra	0	0	0	0	0	0	**4**	0	0	4	0
Grass/bare land	0	0	0	1	0	1	0	**0**	2	4	1
Water	0	2	1	3	0	2	0	1	**73**	82	0.1098
Column total	50	60	6	32	2	35	5	1	81	272	
Error Omission	0.72	0.517	0.833	0.969	0.50	0.46	0.2	1	0.099		

Sum of the major diagonal	142	ErrorO = Errors of Omission (expressed as proportions)	
Column total	272	ErrorC = Errors of Commission (expressed as proportions)	
Over all accuracy	52.21%	90% Confidence Interval = +/- 0.0498	(0.4281 - 0.5278)
Overall Kappa	0.403	95% Confidence Interval = +/- 0.0594	(0.4186 - 0.5373)
		99% Confidence Interval = +/- 0.0781	(0.3998 - 0.5561)

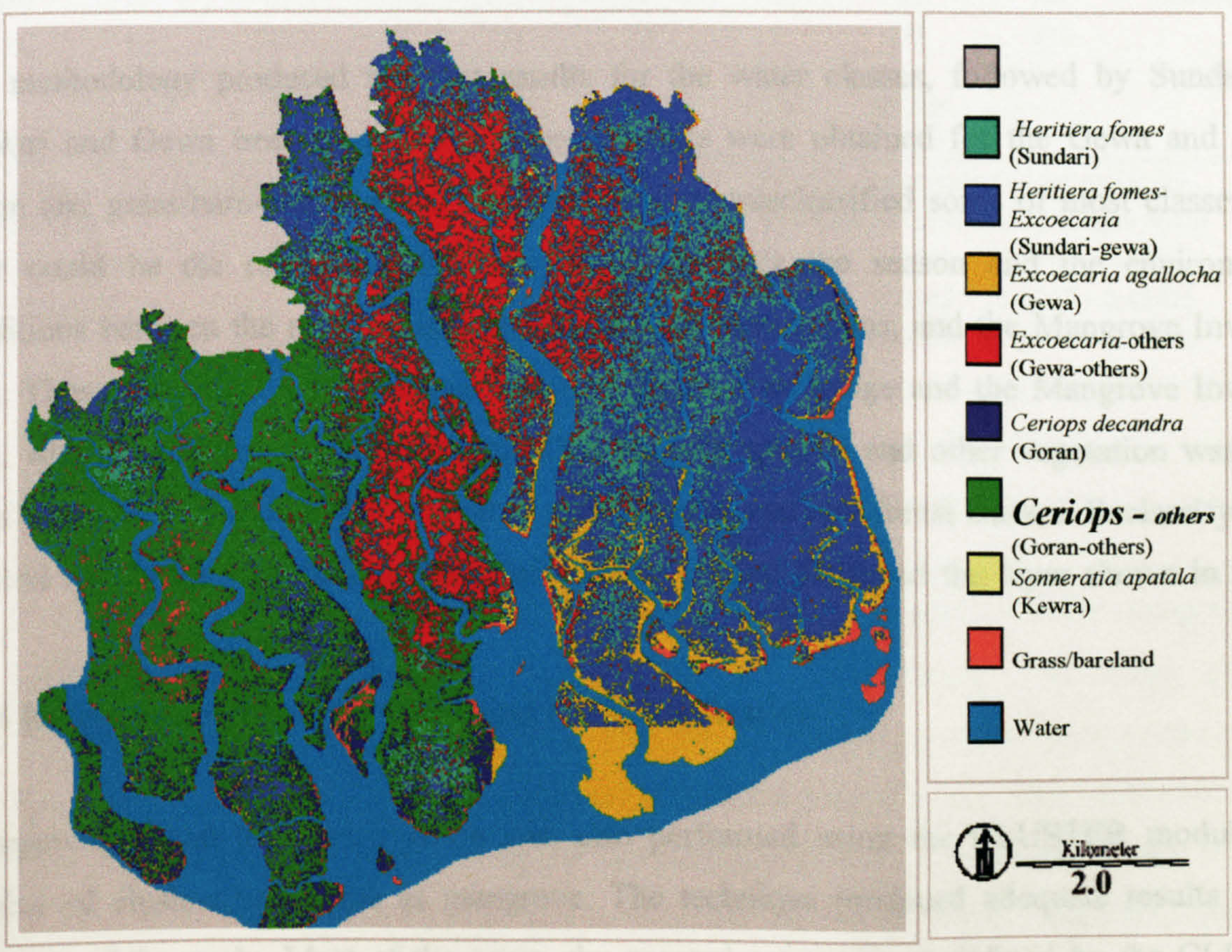

Figure 4.9. Result of the spectral supervised classification of the Sundarbans mangroves.

Table 4.6. Error Matrix Analysis of supervised mangrove classification (columns) against mangrove inventory map (rows).

	Sundari	Sundari-Gewa	Gewa	Gewa-others	Goran	Goran others	Kewra	Grass/ Bareland	Water	Row total	Error Commission
Sundari	14	8	0	2	0	1	0	0	0	25	0.44
Sundari-Gewa	12	28	1	10	0	3	0	0	3	57	0.5088
Gewa	0	1	1	1	0	0	0	0	0	3	0.6667
Gewa - others	22	8	0	1	0	0	0	0	2	33	0.9697
Goran	0	1	0	0	1	1	1	0	0	4	0.75
Goran - others	2	12	3	14	1	26	0	0	1	59	0.5593
Kewra	0	0	0	0	0	0	4	0	0	4	0
Grass/bare land	0	0	0	1	0	2	0	0	2	5	1
Water	0	2	1	3	0	2	0	1	73	82	0.1098
Column total	50	60	6	32	2	35	5	1	81	272	
Error Omission	0.72	0.5333	0.833	0.9688	0.5	0.2571	0.2	1	0.0988		

Sum of the major diagonal	148	ErrorO = Errors of Omission (expressed as proportions)
Column total	272	ErrorC = Errors of Commission (expressed as proportions)
Over all accuracy	54.41%	90% Confidence Interval = +/- 0.0498 (0.4281 - 0.5278)
Overall Kappa	0.4331	95% Confidence Interval = +/- 0.0594 (0.4186 - 0.5373)
		99% Confidence Interval = +/- 0.0781 (0.3998 - 0.5561)

The methodology produced the best results for the water classes, followed by Sundari and Sundari and Gewa tree species. The poorest results were obtained for the Gewa and others, Goran and grass/bare-land classes. The methodology misclassified some of most classes. This error could be the related to the reference map, since the season and the environmental conditions between the raw Landsat data, the visual observations, and the Mangrove Inventory map. There was also an 11-year gap between the Landsat image and the Mangrove Inventory map, which could be crucial. Discrimination between grasses and other vegetation was good; grass pixels were misclassified into other grass classes, and into forest classes. Reclassifying the spectral categories into the nine final information classes produced the layer shown in **Figure 4.9.**

4.9.3 Results of the Unsupervised Land Use Classification

Unsupervised land use classification was also performed using the CLUSTER module. The number of clusters was same as mangrove. The technique produced adequate results for the purposes of the study. Most of the cases, the spectral categories as defined by the CLUSTER module, correspond fairly with the information classes. However, KIA for the land use unsupervised classification was 0.505 and over all accuracy was 60.81%, which was judged adequate for the modelling purpose in a large area. In land unsupervised classification, water separated better than other categories. However, maximum misclassification was observed with irrigated rice followed by winter crops. On the other hand, winter crops were classified as irrigated rice and stubble and irrigated rice was misclassified with stubble. The result of the land use unsupervised classification is shown in **Figure 4.10** and the accuracy assessment is in **Table 4.7.**

Table 4.7 Error Matrix Analysis of field visit data (columns) against unsupervised land use classification maps (rows).

	water	Trees	Crops	Rice	Cities	Ponds	Stubble	Row total	Error Commission
water	**10**	1	1	1	0	2	0	15	0.3333
Tree	0	**16**	4	3	0	0	0	23	0.3043
Crops	0	1	**23**	6	1	0	4	35	0.3429
Rice	2	8	15	**43**	3	0	16	87	0.5057
City	0	0	0	0	**6**	0	2	8	0.25
Ponds	0	0	0	3	0	**5**	2	10	0.5
Stubble	0	0	7	3	1	0	**32**	43	0.2558
Column total	12	26	50	59	11	7	57	222	
Error Omission	0.1667	0.3846	0.54	0.2712	0.4545	0.2857	0.4386		

Sum of the major diagonal	135	ErrorO = Errors of Omission (expressed as proportions)
Column total	222	ErrorC = Errors of Commission (expressed as proportions)
Over all accuracy	60.81	90% Confidence Interval = +/- 0.0539 (0.3380 - 0.4458)
Overall Kappa	0.505	95% Confidence Interval = +/- 0.0642 (0.3277 - 0.4561)
		99% Confidence Interval = +/- 0.0845 (0.3074 - 0.4764)

4.9.4 Results of the Supervised Land Use Classification

For the supervised land use classification, the same procedure was applied as for mangrove. The MINDIST module of classification was used to classify the image. The image exhibited systematic misclassification of pixels where land met water and bare land pixels misclassified with the city. Irrigated rice was also misclassified with the shrimp ponds when the whole image was used **(Figure 4.11)**. To compensate for this misclassification, a water mask, city mask and shrimp pond mask was applied and the data reclassified separately. These masks were then used as an overlay to mask out the cities, ponds and water pixels. This technique removed many of the misclassified pixels. However, natural water logged areas near Bagerhat and Gopalganj district lacked the spatial definition to be masked out. These water bodies are incorrectly classified as trees due to presence of dense submerged and floating aquatic vegetation. **Figure 4.12** shows the supervised classification of land use when done separately and subsequently joined together.

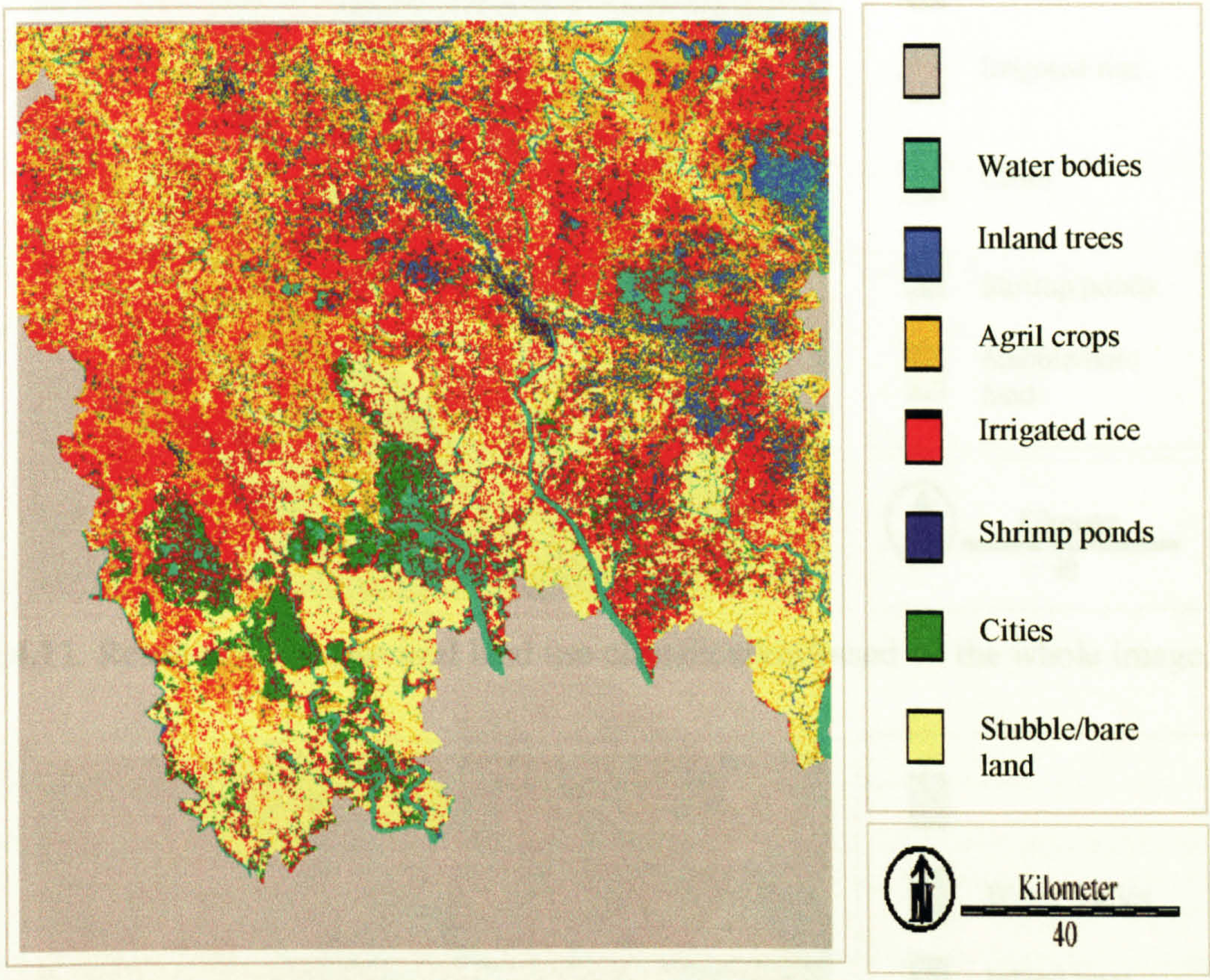

Figure 4.10. The result of the unsupervised land use classification.

The SAMPLE module selected 82 sampling points for the accuracy assessment of supervised land use classification. Ground truthing was conducted via a survey of the accessible points and evaluation of interviews for the inaccessible areas. The results of the accuracy assessment (**Table 4.8**) indicate that the classification methodology produced satisfactory results, with an overall percentage correct of 64.41% and KIA of 0.554 when shrimp ponds, cities and land were classified separately and then joined together. However, the methodology did not produce satisfactory results, when the whole image was classified, the classification accuracy being only 41.1% and KIA 0.41 only.

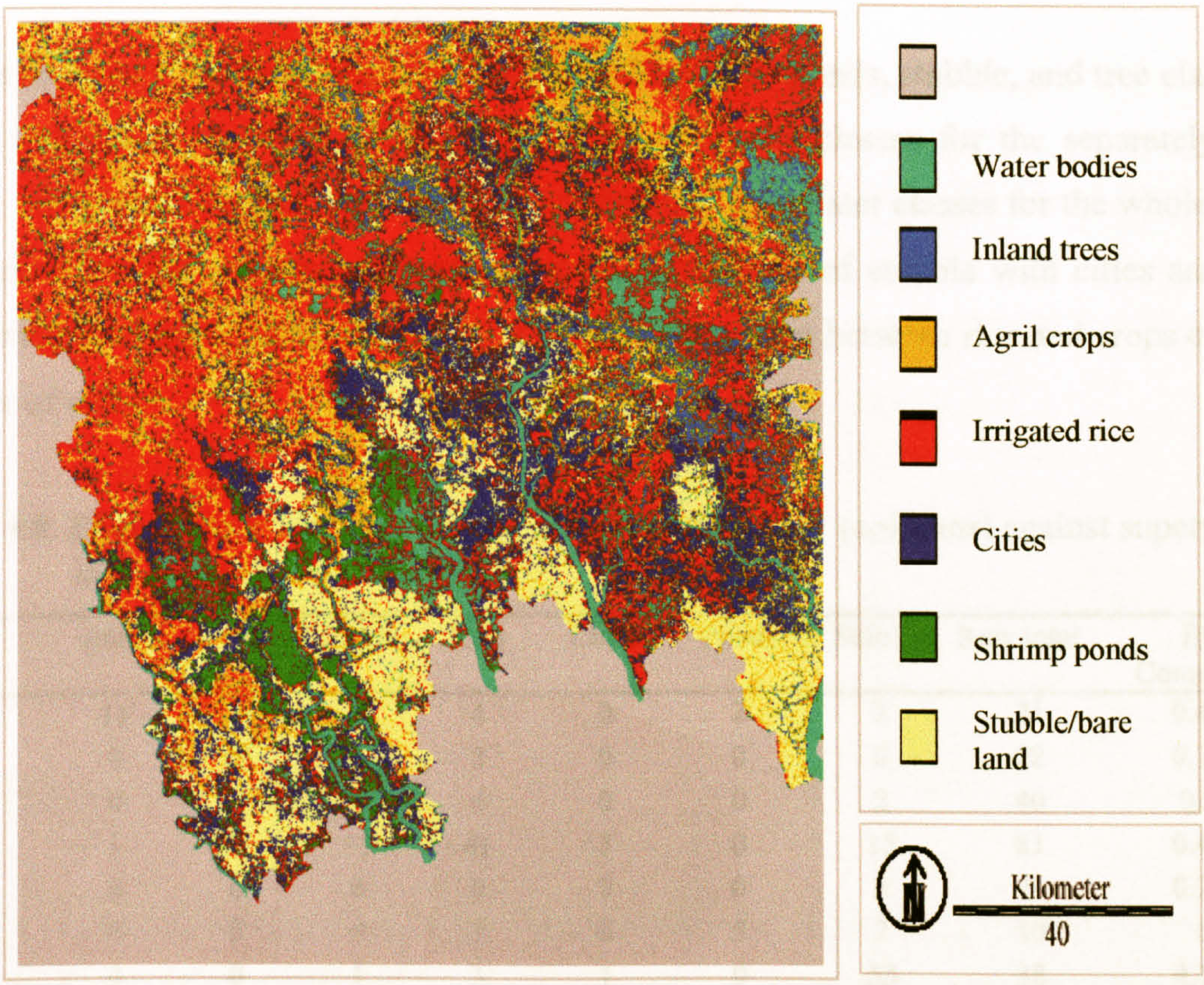

Figure 4.11. Result of the supervised land use classification based on the whole image.

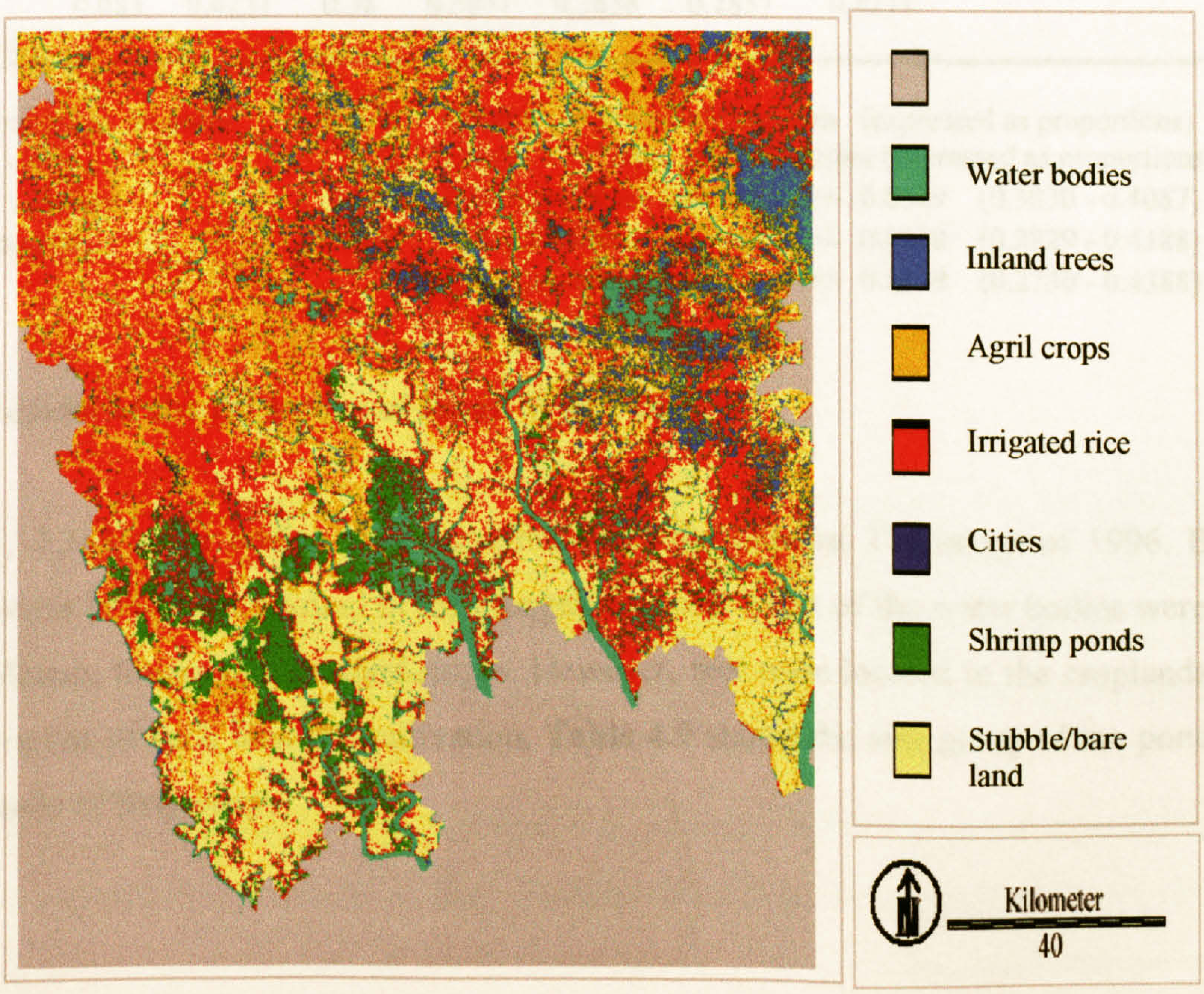

Figure 4.12. Result of the supervised land use classification when separately classified and subsequently joint together.

The methodology produced the best results for the shrimp ponds, stubble, and tree classes for the whole image and shrimp ponds, stubble, cities and crop classes for the separately classified image. The poorest results were obtained for the cities and water classes for the whole image and water class for the separately classified image. Confusion of stubble with cities and rice with crops were the largest sources of error. Also, discrimination between rice and crops classes were sources of error.

Table 4.8. Error Matrix Analysis of field visit reference data (columns) against supervised land use classified data (rows).

	water	Trees	Crops	Rice	Cities	Ponds	Stubble	Row total	Error Commission
water	**11**	2	0	4	0	2	2	21	0.4762
Tree	0	**15**	5	2	0	0	0	22	0.3182
Crops	0	1	**31**	6	0	0	2	40	0.225
Rice	1	8	13	**41**	3	0	15	81	0.4938
City	0	0	0	0	**7**	0	2	9	0.2222
Ponds	0	0	0	3	0	**5**	2	10	0.5
Stubble	0	0	1	3	1	0	**33**	38	0.1316
Column total	12	26	50	59	11	7	57	222	
Error Omission	0.083	0.4231	0.38	0.3051	0.3636	0.2857	0.4211		

Sum of the major diagonal	143	ErrorO = Errors of Omission (expressed as proportions)
Column total	222	ErrorC = Errors of Commission (expressed as proportions)
Over all accuracy	64.41	90% Confidence Interval = +/- 0.0529 (0.3030 - 0.4087)
Overall Kappa	0.5543	95% Confidence Interval = +/- 0.0630 (0.2929 - 0.4188)
		99% Confidence Interval = +/- 0.0829 (0.2730 - 0.4388)

4.9.5 Results of the Inventory of Small Water Bodies

In total, 2,354 water bodies were identified from the Landsat TM image of 1996. By contrast, 1,566 water bodies were found in the topographic map. Most of the water bodies were associated with villages, towns and elevated ridges. However, few were located in the croplands due to the intensive use of such land for cultivation. **Table 4.9** shows the size group of the ponds and their occurrence of frequency.

Table 4.9. The number of water bodies identified in the Landsat image and in the topographic map.

Number of pixels occupied by water bodies	Average area in hectare	Number of water bodies located in the image	Number of water bodies recognize in the map
<10	<0.09	1904	1319
11-50	0.99-4.5	296	151
51-100	4.59-9	57	36
101-500	9.09-45	79	41
>500	>45	18	19

4.9.6 Water colour

In practice, only the colour of the larger water bodies, i.e. those in the third to fifth size category and larger than 51 pixels, could be discerned with visual methods. Of the 154 water bodies in these categories, 21 were black indicating a minimum of turbidity or productivity, 26 were dark grey suggesting some small quantity of turbidity and very small productivity. However, 96 were pink in colour indicating a relatively high inorganic turbidity (i.e., silt and suspended particles) and 11 were light blue suggesting relatively high levels of organic turbidity (i. e., phytoplankton). **Figure 4.13** shows the water bodies, which are visible in the image.

4.10 Discussion

The results of the mangrove and land use classification and inventory of small water bodies show that the satellite remote sensing image can be a valuable tool to classify and update the thematic maps and to locate and inventory small water bodies for fishery and aquaculture development. However, the advantages and limitations of the techniques also need to be fully understood.

There is 11 years gap between the TM image acquisition (1996) and the preparation of mangrove inventory map (1985). Which means, changes could happen in these areas especially due to erosion and accretion because of the dynamic nature of the rivers and regeneration of mangrove forests. In addition cyclones have caused some damage in the forest since 1996. **Figure 4.14** shows an example of the extensive damage of mangrove forest caused by cyclone in 1998.

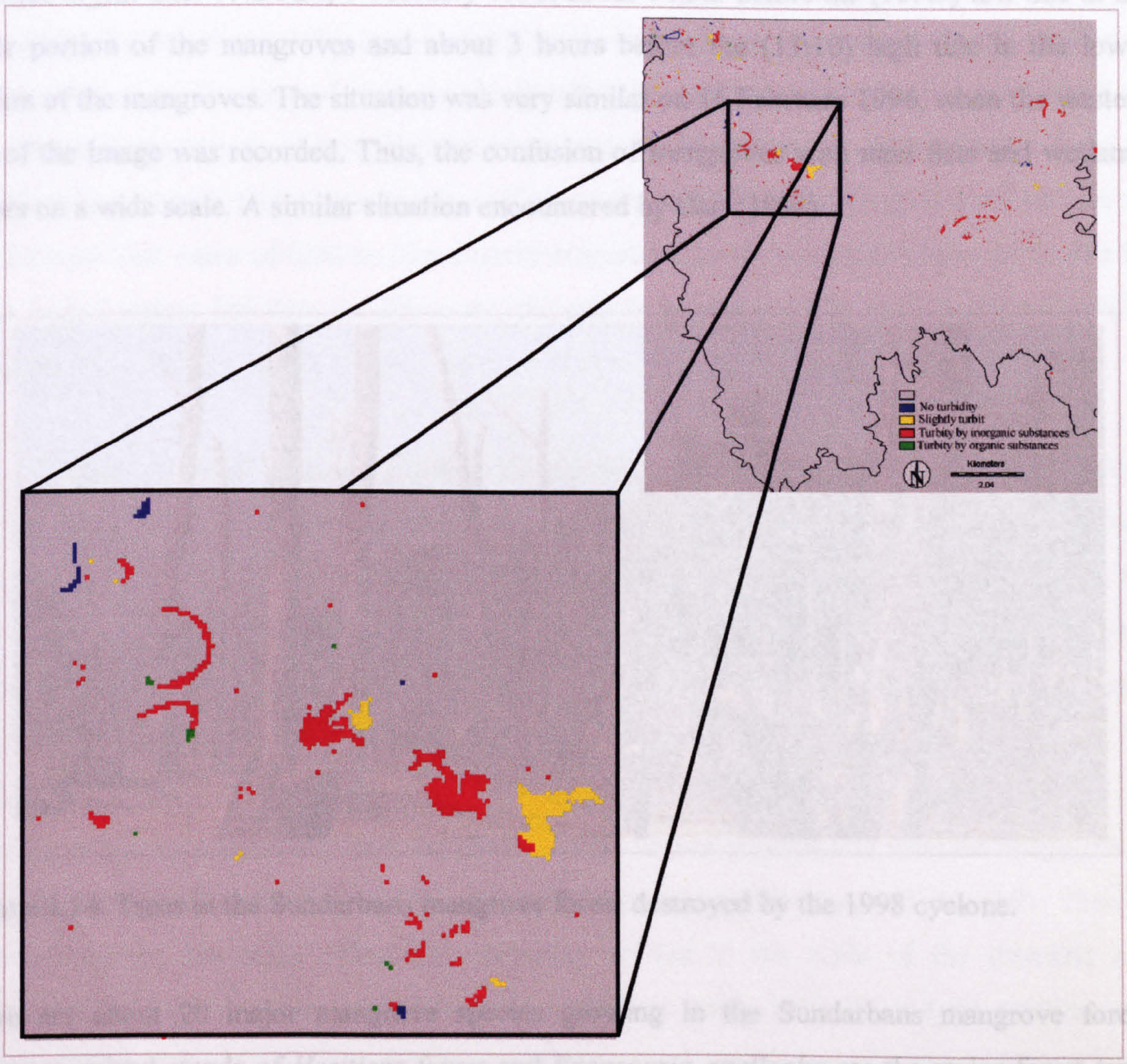

Figure 4.13. Small water bodies identified from the image by visual interpretation and on screen digitisation.

Tidal height at the time of imaging can affect the mapping accuracy of the mangrove forest as well as in lands. Mangroves, which are located in the flat, shallow inter-tidal zone, have a spatial extent and spectral features that are highly vulnerable to fluctuation in tidal height. A high tide causes muddy ground and even some of the shorter mangroves to be totally submerged, whereas a low tide exposes them and the muddy ground. In the former case, the disappearance of bare muddy ground drastically reduces the confusion of mangroves with mud flats, and to lesser degree, with bare land. Although the area classified as mangrove is reduced, the mapping accuracy is higher due to decreased confusion. On the other hand, the mapped mangroves may have a broader spatial limit at a low tide; such an expanded extent being a consequence of larger errors of commission. The Landsat TM data used in the eastern section of the image were recorded at just after 9:42 AM, 9 February 1996, about 1 hour before the (10:49) low tide in the upper portion of the mangroves and about 3 hours before the (13:10) high tide in the lower portion of the mangroves. The situation was very similar on 16 February 1996, when the western part of the image was recorded. Thus, the confusion of mangroves with mud flats and wetlands occurs on a wide scale. A similar situation encountered by Gao (1998).

Figure 4.14. Trees in the Sundarbans mangrove forest destroyed by the 1998 cyclone.

There are about 20 major mangrove species growing in the Sundarbans mangrove forest. However, mixed stands of *Heritiera fomes* and *Excoecaria agallocha* are the major forest types and constitute over 70% of the forests. In this study, 7 forest types and grass or bare land and water bodies were discerned with a classification accuracy of 53%. In a similar study using Landsat TM sense, Chaudhury (1990) mentioned that it would not be possible to perfectly classify mixed forests, like the Sundarbans.

Land cover is a dynamic feature that can change rapidly across the landscape, which adds to the difficulty of making generalisations and extensions of sparse data over a large area. In lands, forest regeneration, dry shrimp ponds and newly planted rice fields were difficult to distinguish using automated classification techniques and limited ground truth input. It was difficult to separate cities, stubble and water bodies while working with the whole image. Discrimination between stubble and cities and rice with crops were the largest source of error in the classification procedure.

Generally the accuracy of the image classification depends on the purpose of the project and extent of the area. For example, in a simple classification scheme the required level of detail may be only to distinguish residential from commercial areas. For this type of classification, accuracy could be less than a forest classification. Cihlar *et al.* (1997) achieved an overall accuracy of 66.6% and khat value of 0.56 in a land cover classification of the Boreas region of 9, 850 km^2 area from Landsat TM data. In this study, the area is greater (14,000 km^2), and for modelling purpose achieves results that are considered sufficient.

Some pixels in natural water bodies near Gopalganj were designated as homestead trees due to the presence of dense aquatic vegetation, which have similar reflectance to trees. This confusion is difficult to remove from the supervised classification procedure unless sufficient training sites are taken in those areas. An improved classification was achieved when water bodies were masked out prior to classification. Trolier and Philipson (1986) encountered a similar situation, in a visual analysis of Landsat TM image.

A comparison of small water bodies identified from thematic maps and satellite image showed that the water bodies are fewer in the thematic maps than in the image (**Table 4.9**). There are several reasons for these differences, probably related to the scale of the thematic maps (1:50,000) and the time elapsed between production of maps (1972-75) and the satellite image (1996). Most of the small size water bodies can be seen in the image after zooming into it but a zoom factor cannot be applied to the maps. Another very likely cause for differences is the season during which the thematic maps were produced. Finally, with the satellite image there is a possibility for misidentification. For example, shallowly flooded fields and newly planted irrigated rice are very similar to small water bodies in a satellite image (Kapetsky, 1987).

Colour composites of bands 2, 3, and 4, and band 4 were used singly in this study and gave satisfactory results for water body identification. However, other combinations such as bands 1, 2 and 3 and 3, 4 and 5 of Landsat TM have also been shown to be useful for inventory of water bodies (Kapetsky, 1987; Trolier and Philipson, 1986). Bands 4 to 7 have also been individually used successfully, whereas, water body identification was only marginal using bands 1, 2 and 3 singly (Kapetsky, 1987).

One advantage of visual processing is that it is much more accessible than computer automated processing. Good results have been obtained by visual analysis of Thematic Mapper images for hydrological inventory including water bodies and wetlands (Trolier and Philipson, 1986). Computer processing of the imagery in contrast to visual analysis provides for more efficient use of time and for more comprehensive analysis. However, computer-processing results were not included in the study due to patchiness of the land use in the study area, which includes the irrigated and moist crop fields in the results.

Registration differences occurred while scanning the forest inventory map of 1:50,000 scale to 1:20,00,000 to put into error matrix. This was revealed following visual inspection of the colour composite image and the inventory maps. Other problems were that the size class (i.e., diameter of the trees, shape and size of the water bodies) can change between the time of the inventory map and remotely sensed data acquisitions, especially in a fast growing area such as the Sundarbans mangrove forest. Moreover, inconsistencies in human interpretation, especially for heterogeneous areas, can be a very difficult factor to control. Measures of variation in interpretation need to be further developed that can test the validity of class boundaries while at the same time provide for allowable variances in the accuracy assessment (Congalton and Green, 1993; Lunetta *et al.* 1991).

Brisco and Brown (1995), Congalton *et al.* (1998), Kapetsky (1987 and 1989), and others have shown that digital processing of satellite imagery, combined with field visits and aerial photography as ancillary data, can accurately produce both detailed and broad GIS coverage of vegetation / land cover type.

Chapter 5

Classification, Manipulation and Integration of Primary Criteria

A Schematic diagram of the procedures involved in classification, manipulation and integration of primary criteria in the GIS study is shown in **Figure 5.1.**

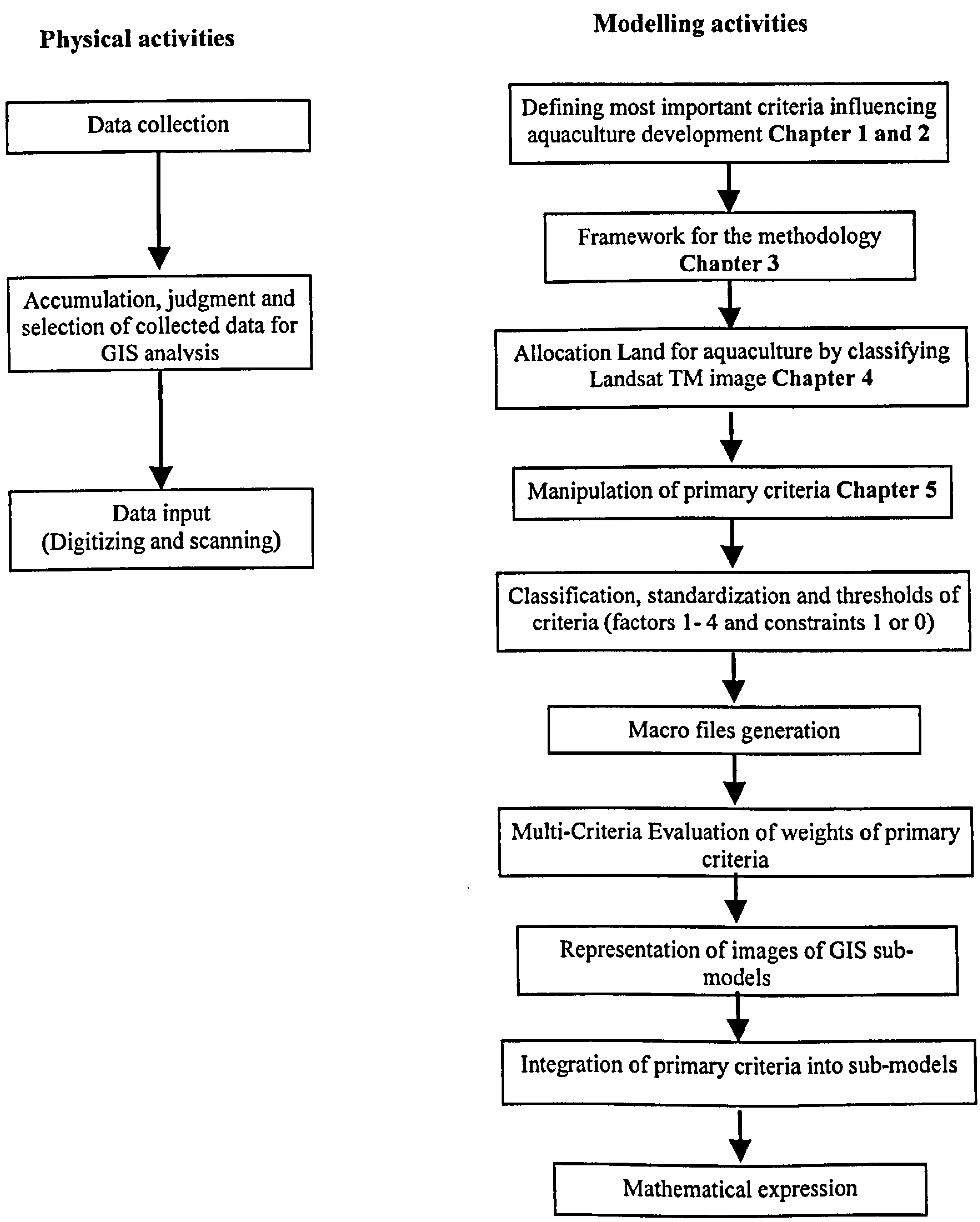

Figure 5.1. Schematic diagram of the procedures which were involved in classification, manipulation and integration of primary criteria in the GIS study.

5.1. Spatial manipulation of factors

In order to prepare data for spatial modelling, and depending on the origin of the data, the primary data layers could be manipulated in different ways:

1. spatial evaluation in IDRISI all factors must be scored positively with respect to suitability, meaning appropriateness according to predetermined conditions, requirements or circumstances. This is a common term in decision making or allocation situations where tracts of land are to be allocated according to their suitability for one or more purposes. Suitability for a purpose is determined by whether or not certain criteria are met by the piece of land under consideration. The results of such an assessment can be presented in the form of a suitability map.

2. most of the factors were reclassified using the RECLASS or ASSIGN module according to the requirement. For example, land use maps which were already classified according to agricultural crops, could be reclassified in terms of aquaculture suitability where highly intensive agriculture land would have a low score for aquaculture because these sites would be likely to have pollution problems from pesticides or herbicides (Kapetsky, 1989).

3. some data were only available in statistical form and these were incorporated as choropleth maps at a Thana level (map which depicts average values per unit of area over an administrative unit), since the Thana is the smallest administrative unit from which the data are reported.

4. in some cases a distance range was created using the DISTANCE module. This was applied to factors such as fish processing plants or rivers that are commonly represented spatially as either points or lines. For example, to evaluate water availability from a river, a buffer zone was created using the DISTANCE module in IDRISI. Therefore, a range of values was created (1 – 4). Those closest to the river were given a score of 4 and the furthest away a score of 1. Moreover, DISTANCE module was also used to represent distances from pollution sources, such as distances from industries or urban developments in order to avoid or alleviate possible pollution problems.

5. many factors were used in both the environmental as well as infrastructure evaluation. For example, the urban development factor was considered as having a positive effect in the market potential evaluation, but a negative effect in the environmental evaluation.

5.2 Standardisation and thresholds

Raw data were measured on different scales which needed a standard classification method (Eastman *et al.* 1995). The GIS database was prepared by giving each factor a physical score from 1 to 4 according to Kapetsky (1994), as follows:

- Very suitable = 4
- Moderately suitable = 3
- Marginally suitable = 2
- Currently unsuitable = 1.

This classification was proved to be appropriate as it was found that most thematic maps were classified within a range of four values, matching Kapetsky's classification in terms of suitability of land for defined uses. The thresholds were identified from the literature and using guidance from the expert panels at the Institute of Aquaculture, Stirling University. Based on these combined inputs, it was possible to make sound judgements between suitability classes.

5.3 Weighting procedure

After standardising all the primary data sources to a common scoring system, it was necessary to establish the relative importance between the factors by developing weights. Relative importance is usually judged according to several criteria. Although a variety of weighting techniques exists, the pair-wise comparison developed by Saaty (1977) known as the Analytical Hierarchy Process (AHP), was used to develop a set of relative weights for a group of factors in a multi-criteria evaluation. Providing a series of pair-wise comparisons of the relative importance of factors to the suitability of image pixels for the activity being evaluated develops the weights. These pair-wise comparisons are then analysed to produce a set of weights that sum to 1. The factors and their resulting weights can then be used as input for the multi criteria evaluation (MCE) module by either weighted linear combination (WLC) or ordered weighted average (OWA).

Alternatively, the feature and weighting can be used directly in the SCALAR or OVERLAY modules.

The relative rating of pair of factors are systematically scored on a 17 point continuous scale from 1/9 (least important) to 9 (most important) as in **Tables 5.1** and **5.2.**

Table 5.1. Scale for the relative importance of criteria (according to: Saaty, 1977).

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**						→	

Table 5.2. The continuous rating scale and its description (according to: Saaty, 1977).

Intensity of importance	Definition	Explanation
9 8 7	extremely more important	The evidence favouring one activity over another is of the highest possible order of affirmation
6 5	strongly more important	An activity is strongly favoured and its dominance is demonstrated in practice
4 3 2	moderately more important	Experience and judgement moderately favour one activity over another
1	equally important	Two activities contribute equally to the objective
1/2 1/3 1/4	moderately less important	Experience and judgement moderately favour one activity less than another
1/5 1/6	strongly less important	An activity is strongly less favoured and this is demonstrated in practice
1/7 1/8 1/9	extremely less important	The evidence favouring one activity over another is of the lowest possible order of affirmation

To illustrate the approach, six factors were chosen to infer the relative risk for brackish water shrimp culture, drought (an important risk factor which caused ponds to dry in April-May period), disease (a frequently occurring disaster for the culture species), flood (another natural phenomena which more or less occurs every year in some parts of the area during wet season), winter rain (a very important risk factor which reduces the salinity in the water and causes death of culture species), pollution (this factor is less important) and elevation (the area is more or less near to the mean sea level (MSL) and during cyclones most farmers lose their crops). The procedure developed by Eastman (1995) is to enter all the data into a matrix and then compute a best-fit set of weightings. Since the weighting sums to one, a resulting suitability map would have a range of values that matched those of the standardised factor map (1- 4). In developing the weights, the decision-maker compares every possible pairing and enters the ratings into a pair-wise comparison matrix. As the matrix is symmetrical, only the lower half actually needs to be completed (**Table 5.3**). The procedure then requires that the pair-wise comparison matrix be computed to a best-fit weight. Table 5.4 which uses the authors weights has a consistency ratio (CR) of 0.09, well within the value of equal to or less than 0.10 recommended by Saaty (1977), signifying a small probability that the weightings were developed by chance.

Table 5.3. Weighting derived by the pair-wise comparison matrix for assessing risk to land based brackish water shrimp farming in south-western part of Bangladesh (numbers show the rating of the row factor relative to the column).

	Drought	Disease	Flood	Winter-rain	Pollution	Elevation	Weightings
Drought	1						0.2450
Disease	1/7	1					0.0523
Flood	1/5	3	1				0.0828
Winter-rain	3	3	4	1			0.3415
Pollution	1/6	1	1	1//4	1		0.0600
Elevation	2	4	2	1/2	3	1	0.2185
Sum							1.00

Consistency ratio (CR) =0.09

5.4. Constraints

Constraints were developed as Boolean maps where the image contained either 0 or 1. These were then applied to prevent or minimise the pollution impact or to exclude environmentally protected areas. The constraints for this study were combined in the following ways:

1. there are many areas, which are physically in use for different purposes in the area, which includes natural water bodies, cities and other permanent structures, like schools, colleges

and hospitals. One can not construct a pond in those areas and for these reasons, they are considered as a constraint. To protect environmentally sensitive places like the Sundarbans mangrove forest and natural water bodies, a pollution source proximity or distance constraint was first created using the DISTANCE module in the IDRISI and then reclassified using RECLASS to values of 0. For example, a 1-km buffer zone was created around the mangrove forest to minimise the possible pollution impact on it from aquaculture activities.

2. buffer zones were also created to protect conservation sites from the effluent of city development, industries and agricultural lands.

5.5 Sub-models

In a decision making process, the selected and scored criteria can be developed into a series of sub-models which can logically group certain factors within a general model. For example, some factors are grouped to form sub-models naturally, such as, a soil classification based on, soil texture, soil pH and soil salinity factors. Similarly, population density, fish processing plants and markets could be grouped to form a simple market potential sub-model. One reason for developing sub-models in a decision making process is that MCE can only easily handle a certain number of factors (usually less than ten factors, Ross, 1998) in a particular objective. When the number of factors is over10 the logic of the modelling for the MCE module becomes difficult. This process was first used by Aguilar (1992) and Aguilar and Ross (1995). Aguilar and Ross (1993) divided the sub-modelling into stages within the general model, such as, primary, secondary and tertiary, etc. According to those authors, the number of stages may vary with the application but the overall approach would remain same.

Model building is based on the following steps:

1. primary stage of a model is called its foundation and is represented by the original data sources. For example, thematic maps, statistical data, field trip data, interviews and data available in computer format and reclassified.

2. secondary stage of a model, where factors are grouped together naturally and non specifically. For example, lakes, rivers, and other water bodies would all be grouped into a water resources sub-model.

3. with the progress of a model, more sub-models are built up to suit the specific requirement of the users. For example, an aquaculture specific constraint sub-model was incorporated at the last stage in the modelling process.

4. at the final stage of the modelling process, groupings of sub-models can be applied to solve a specific problem.

To illustrate the approach, a schematic diagram of the hierarchical process of decision making for carps, tilapia, freshwater prawn, brackish water shrimp and crab culture in Khulna region, Bangladesh is shown in **Figure 5.2.**

5.6 Model Programming

1. **Mathematical expressions:** Once the factors have been standardised and the sub-models have been created (**Figure 5.2**), all these factors and sub-models can be assembled in a mathematical expression. For example, the soil pH sub-model was created with three primary data sources. These sources can be symbolised and used in a mathematical expression as follows:

   SpH = (SrpH X 0.3874) + (SbpH X 0.4434) + (FdSpH X 0.1692), where, **SpH** is the soil pH sub-model, **SrpH** is the surface soil pH, **SbpH** is the sub soil pH and **FdSpH** is the soil pH which were collected during the field visit in 1998. The factors are then multiplied with the weightings **(0.3874, 0.4434** and **0.1692)** derived from the WEIGHT module by pair-wise comparison matrices, for surface soil pH, sub soil pH and field visit soil pH respectively, to indicate the relative importance between those factors. Here, sub soil pH is given the highest weighting because surface soils are going to be removed when a pond is being dug.

2. **Command line module**: When an IDRISI module is being operated it will prompt the user to supply the information needed to run the module. However, data can be specified in a single command line for fully automatic operation. The following is the command line of MCE for the soil pH sub-model:
   MCE x 0 3 SpH SrpH 0.3874 SbpH 0.4434 FdSpH 0.1692

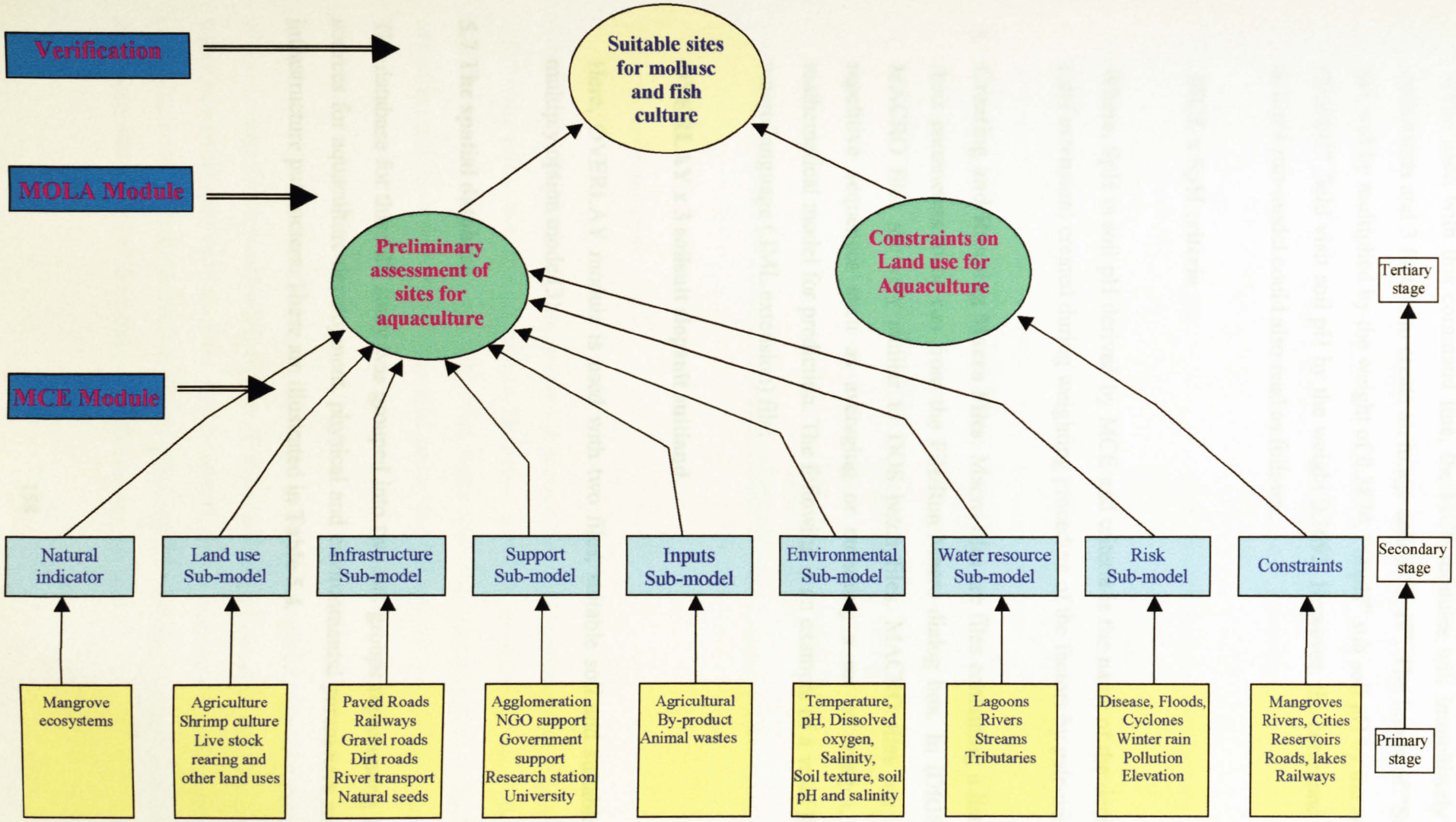

Figure 5.2. Schematic representation of decision making hierarchical process for carps, tilapia, fresh water prawn, brackish water shrimp and crab culture in Khulna region, Bangladesh (modified after: Aguilar and Ross, 1995; Gutierrez- Garcia, 1995).

When used with this command line, the MCE modules will immediately run, (x) using 0 constraints and 3 factors to create an image called "SpH". The image of "SrpH" surface soil pH will be multiplied by the weight of 0.3874, "SbpH" sub soil pH by the weight 0.4434 and "FdSpH" field visit soil pH by the weight 0.1692. However, the command line of MCE for soil pH sub-model could also read as follows:

MCE x SpH criteria

Where, SpH is soil pH derived by MCE and criteria is the name of the decision support file (.dsf extension) created during weighting procedure of the factors by pair-wise comparison.

3. **Creating and Running Macro Files:** Macro files are files containing a list of modules and their parameters to be run from the File/Run Macro dialog box. In IDRISI for Windows, MACRO files are very similar to DOS batch files. MACRO files are used to execute repetitive sequences such as averaging or summing a set of images, or to create a mathematical model for prediction. The following is an example of a valid line in an IDRISI macro language (.IML extension) file:

   OVERLAY x 3 soilsuit slopsuit suitland.

   Here, OVERLAY module is used with two files, suitable soil and suitable slope with the multiply option mode (3).

5.7 The spatial database

The database for this GIS study was grouped into two sub groups representing the primary data sources for aquaculture development, physical and environmental parameters and land uses and infrastructure parameters. These are illustrated in **Table 5.4.**

Table 5.4. Parameters for aquaculture development in Khulna region, Bangladesh.

Physical and Environmental Parameters	Land uses and infrastructure parameters
Water resources	Inputs
Proximity ranges to the sources of water (rivers and their tributaries)	Livestock wastes
	Agricultural by-products
Annual water balance	Land uses
Groundwater	
Monthly water balance	Road networks: Paved roads, Gravel roads, Dirt roads and Railway
Water chemistry	
Temperature	River transportation
Dissolved oxygen (DO)	Post larvae sources: for shrimp, crab, carp and prawn
pH	
Salinity for water	Market potential (population density of cities)
Soil	Processing plants
Soil texture (surface and sub soil)	Support: from NGO, Government office, Agglomeration, Universities and Research station.
Salinity for soil	
Soil pH(surface and sub soil) and soil pH (collected from the fields)	
	Risks factors: Drought, Winter rain, Diseases, Flood and cyclone and Elevation
	Pollution: Industries, Urban development
	Natural indicator
	Agriculture

5.7.1 Water resources

When evaluating a site for aquaculture potential, the total land and water resources of the site will be the prime determining factors. However, growing demands for water from an expanding aquaculture industry competes with other water users such as irrigation, industrial, navigation, drinking, and for meeting environmental needs day by day for this limited resources (Muir and Beveridge, 1987; Patricia, 1999; Phillips *et al.*1991).

Pond culture is the most common and extensive culture system for fresh water aquaculture. Water is supplied by collection of runoff from rainfall, or by pumping from wells or surface water accumulations such as reservoirs or streams. The amount of water used for aquaculture ponds includes the volume used to fill the pond initially and any amount needed to maintain the minimum water level of the pond during the culture period.

Evaporation and seepage cause most water loss from ponds. Rain falling directly on the pond surfaces or runoff from adjacent land, replaces some water lost during the year. Ponds with negligible seepage should be able to remain adequately full with average rainfalls. In dry years, makeup water would be required from either runoff or pumped water to maintain an adequate pond water level. On the other hand, during floods water needs to be drained out from the ponds but sometimes this is not possible and culture species are washed away during flooding. However, water loses from the brackish water ponds through evaporation and seepage can not be replaced by the rain due to the salinity problem and in fact rain water causes problems for the culture or species in brackish water ponds.

Surface water in the area is suitable for a diversity of aquaculture uses. Broadly there are three sources of water in the region; they are numerous freshwater streams flow into the Bay of Bengal, originating both inside and outside the area. Lakes are also a reasonable source of water, which can be use for aquaculture purposes. The Bay of Bengal and the estuaries that border it are natural resources that could provide opportunities for development of saltwater or brackish water aquaculture. It has been recognised that the water quality and abundant natural food in the coastal waters can be used for shellfish production in ways that will preserve the quality of the coastal areas. However, the aquaculture enterprises that have developed in the coastal areas of Khulna, are to date, all land based.

Three different factors were identified for evaluating the water availability in the region. They are (1) proximity ranges to the sources of water, (2) annual water balance and (3) monthly water balance.

5.7.2 Proximity ranges to the sources of water

Kapetsky *et al.* (1987), Aguilar (1996) and Haque *et al.* (1997) noted that proximity to the water sources, whether fresh or saline water, should be 1 km or less for easy transport to the ponds with minimal cost. So, a 1 km band can be generated either side of the water body to represent the area for both the fresh and salt water which could be moved by gravity or pumping wherever needed. Considering the abundance of rivers and tributaries in the area, a 500-m range was chosen as suitable for this study.

The DISTANCE module was used to create proximity ranges suitable for the different types of water sources as shown in **Text box 5.1.** In these proximity to lakes and rivers and their tributaries was given a sub-model, the higher priority than ground water. For brackish water shrimp culture, only tidal water resources were considered, but, for freshwater aquaculture, all three sources were included. Ground water sources are not considered as a source of water for brackish water aquaculture due to the absence of salinity. However, in other parts of the world freshwater is used to dilute higher saline water to maintain optimum salinity in the ponds. Furthermore, sites, which are closest to the water sources, are given highest score as water can be drawn with least cost and damage to the environment.

Text box 5.1. Scoring of proximity to water resources.

Interpretation		Score
Very suitable, environmental friendly and less cost to drain water up to pond.		4
Rivers and tributaries	250 m –750 m	
Lakes	250 m –750 m	
Ground waters	0-10 m	
Moderately suitable, environmental friendly and less cost to drain water up to pond.		3
Rivers and tributaries	750 m –1750 m	
Lakes	750 m –1750 m	
Ground waters	10 m –20 m	
Marginally suitable, less environmental friendly and high cost to drain water up to pond.		2
Rivers and tributaries	1750m - 4250m	
Lakes	1750m - 4250m	
Ground waters	20 m –40 m	
Unsuitable, high risk to environmental and high cost to drain water up to pond.		1
Rivers and tributaries	> 4250 m	
Lakes	> 4250 m	
Ground waters	> 40 m	

The development of the water resources sub-model uses overlay and MCE and is shown in **Figure 5.3** for brackish water and **Figure 5.4** for freshwater water culture systems, respectively.

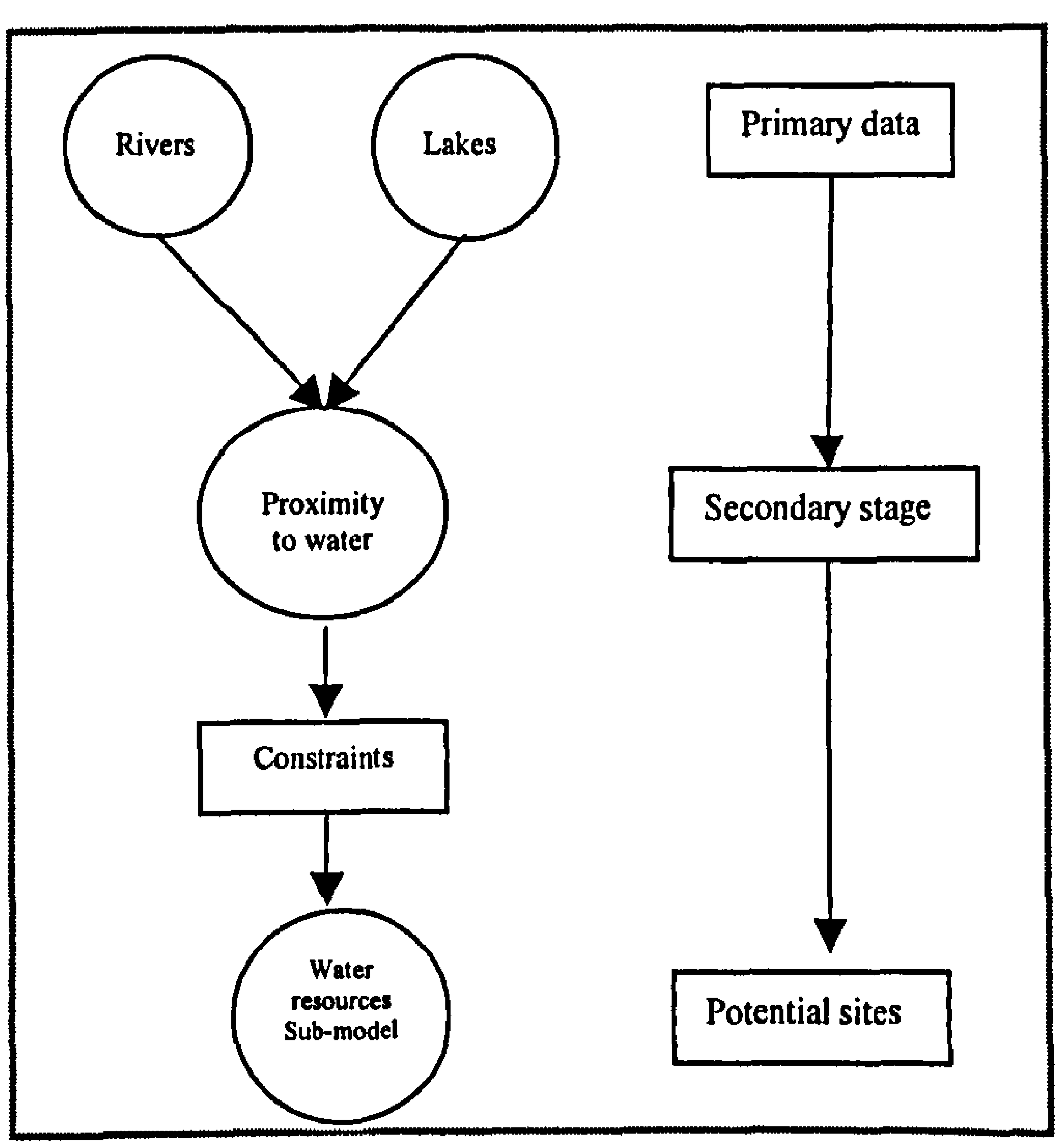

Figure 5.3. Schematic diagram of proximity to water resources sub-model for brackish water aquaculture.

Mathematical expression:
PW-SC = (Riv x 2) + Lak, where, PW-SC = water proximity to shrimp and crab culture, RIV= rivers and tributaries and Lak= Lakes.

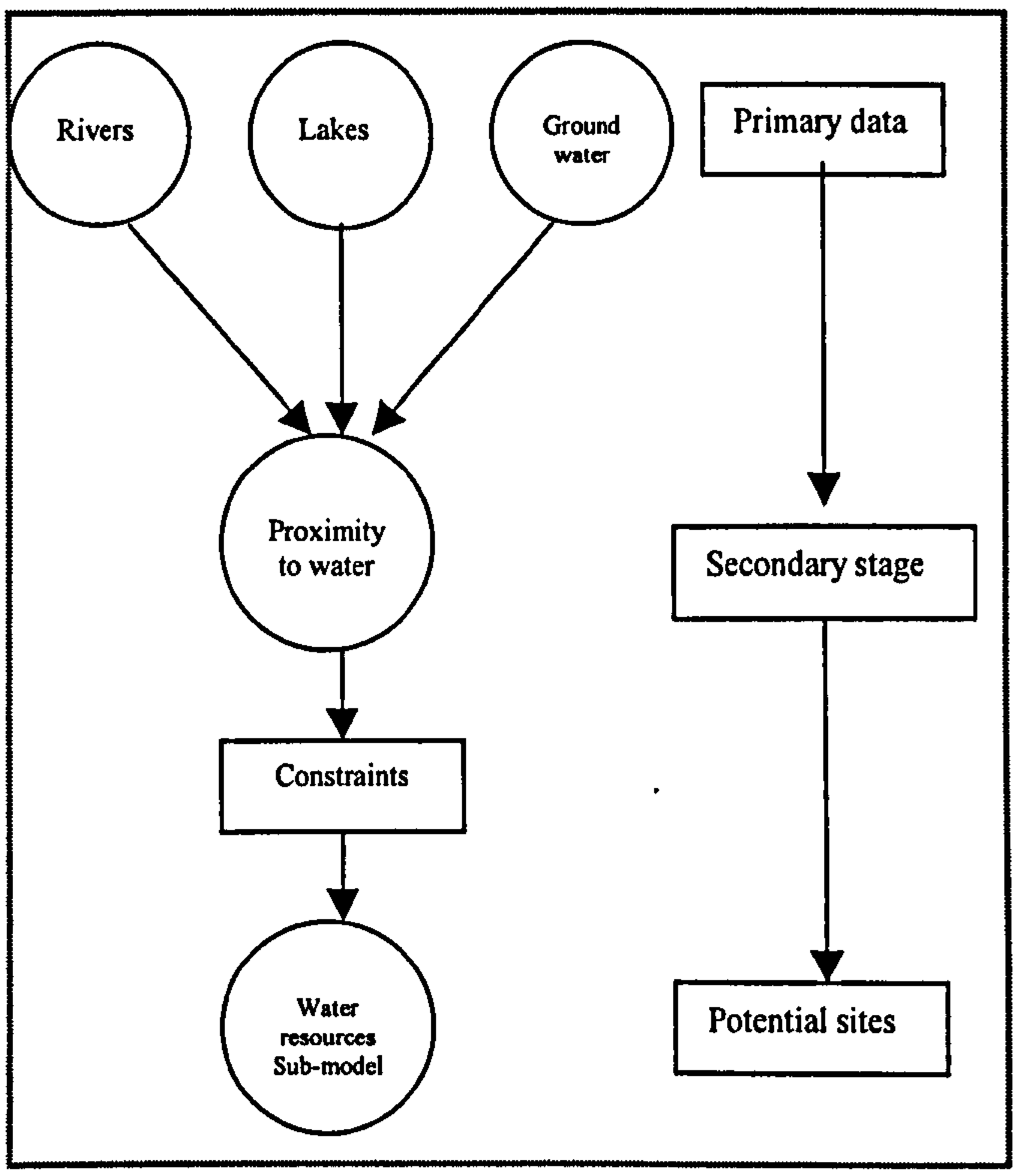

Figure 5.4. Schematic diagram of proximity to water resources sub-model for fresh water aquaculture.

Mathematical expression:

PW-PCT = (Riv x 0.7396) + (Lak x 0.166) + (GW x 0.0938) where, PW-PCT = water proximity to prawn, carps and tilapia culture, RIV= rivers and tributaries, Lak= Lakes and GW = ground water.

Figures 5.5 and **5.6** show the output of the proximity to water resources sub-model for brackish and freshwater water respectively. Very suitable sites were found for both cases in the southern and central part of the study area adjacent to the rivers and lakes. In the freshwater proximity sub-model, 32% of the land is very suitable, 68% of the land is moderately suitable and there is no unsuitable or marginally suitable land. However, in the brackish water proximity sub-model, 31% of the land is very suitable, 23% of the land is moderately suitable and 25 and 21% land are marginally or unsuitable, respectively.

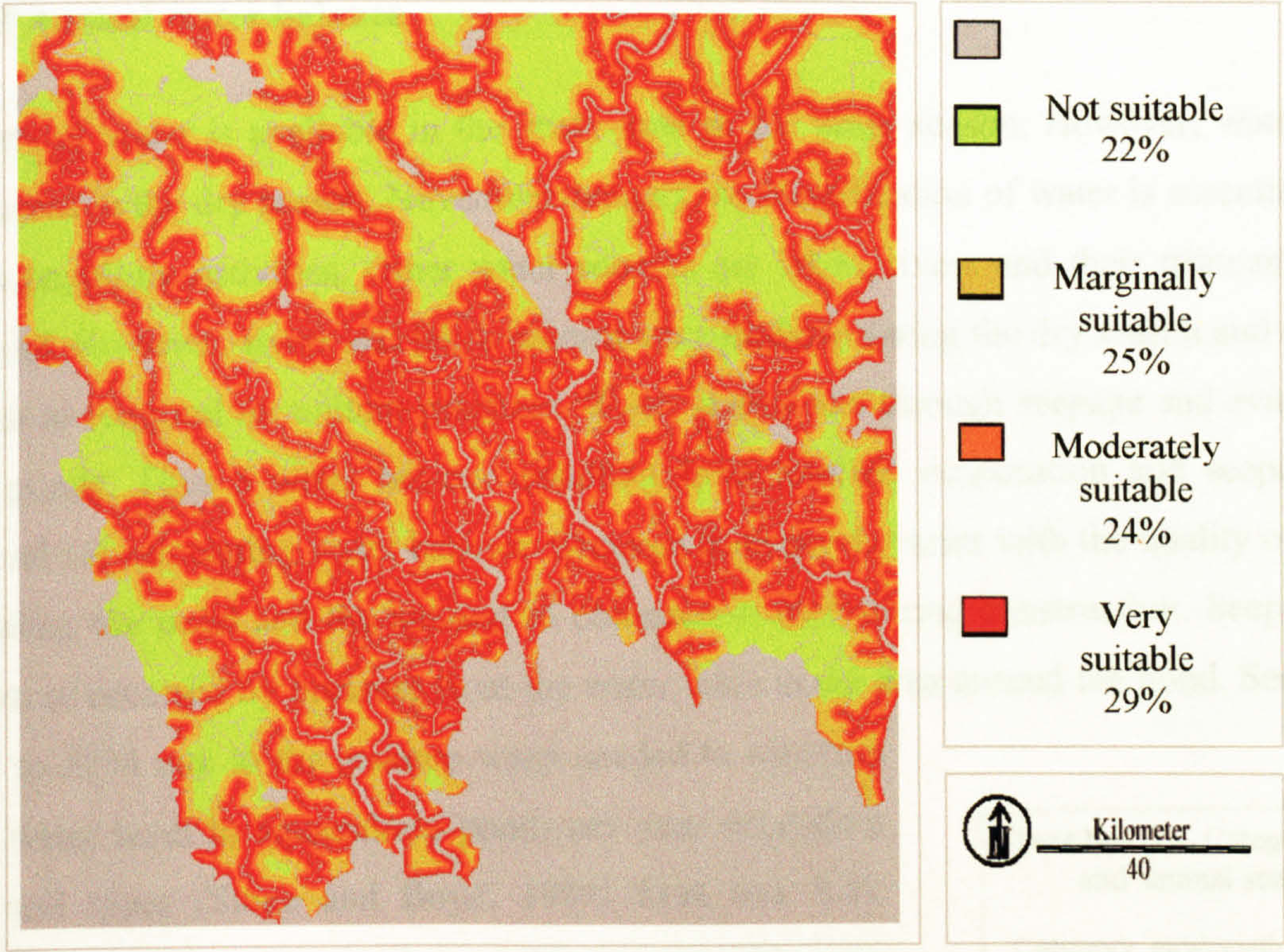

Figure 5.5 Proximity to water resources sub-model for brackish water aquaculture.

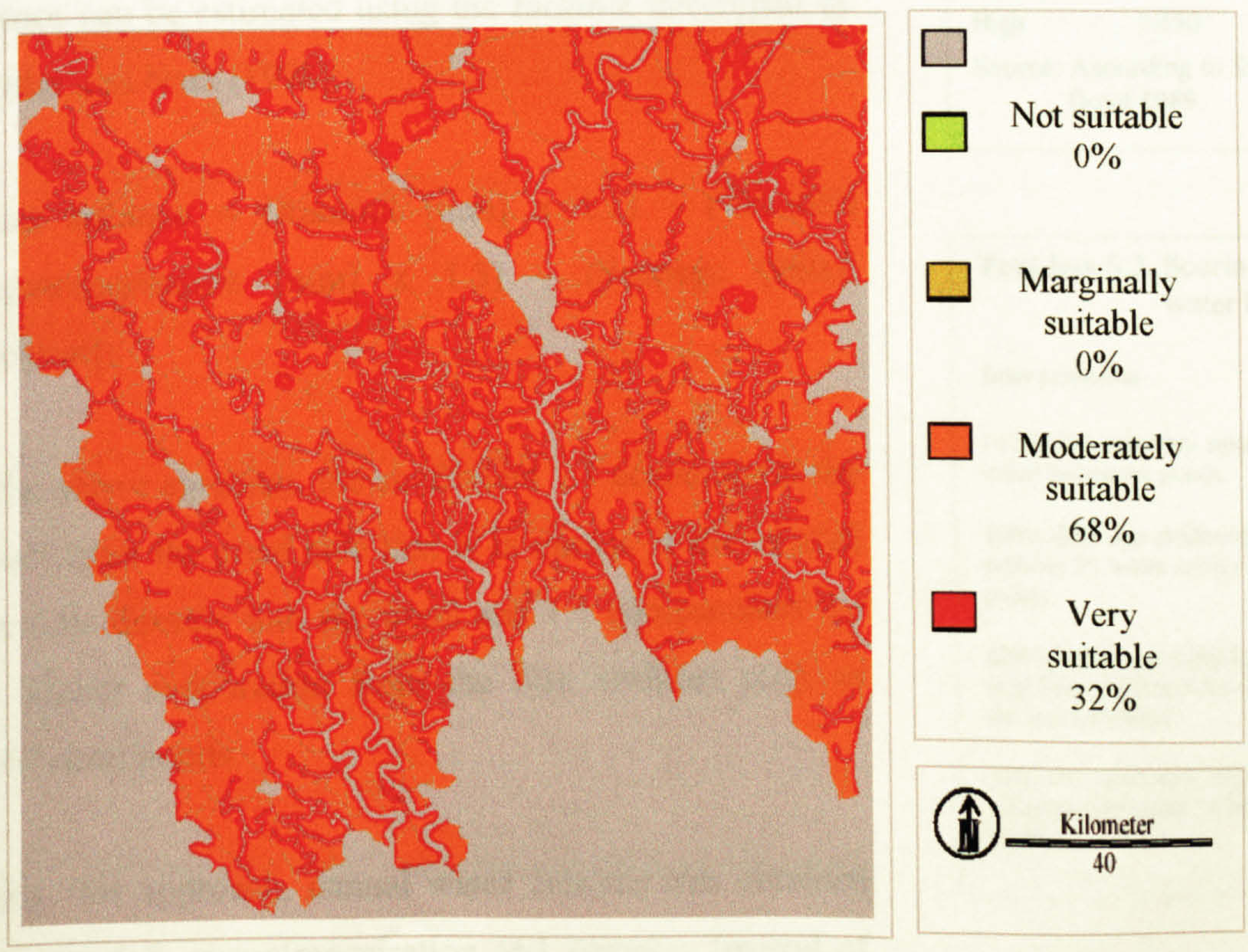

Figure 5.6 Proximity to water resources sub-model for freshwater aquaculture.

5.7.3 Annual water balance

Plenty of water is available in the study area in the rainy season. However, water deficit also occurred in the dry season, November-January, so classification of water is essential for any sort of aquaculture activities. Other water sources are lakes, rivers and their tributaries and under ground. However, rivers and lakes become very shallow during the dry season and cannot supply water as required for culture practices. Water is also lost through seepage and evaporation from the ponds. Thus a water balance resulting from rainfall, evaporation and seepage would be crucial for calculating water balance. Seepage from ponds varies with the quality of soil used for building the pond and the amount of compaction used during construction. Seepage is slowed down or reversed by pressure from the water table in the area around the pond. Seepage can add 457 to 2794 mm to the makeup water needed to maintain the water level in aquaculture ponds per year depending on soil types (Stone and Boyd, 1989, **Text box 5.2**). Therefore, the requirement for suitably impermeable soils at the site of pond construction is critical. Annual water balance can be estimated using the formula developed by Aguilar and Nath (1998):

Text box 5.2. Category of monthly and annual seepage rate.

Category	mm/month	mm/year
Low	0-15	0-180
Marginal	15-30	180-360
Moderate	30-90	360-1080
High	>450	>5600

Source: According to Stone and Boyd 1989.

Water balance = (Rainfall [mm] x 1.1) – (Potential evapotranspiration [mm] x 1.3) – (Seepage [960.0 mm/year]).

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 the free surfaces such as small open ponds.

Text box 5.3. Scoring of annual water balance.

Interpretation	Score
>1200 mm rain very suitable for water source for ponds.	4
1000-1200 mm moderately suitable for water source for ponds.	3
800-1000 mm marginally suitable may have problems for water in the culture ponds.	2
<800 mm unsuitable must have problems for water in the culture ponds.	1

Using this approach, annual water balance was obtained from rainfall, evapotranspiration and seepage. Instead of using real seepage data, an assumption was made at a seepage rate of 960 mm/y (Stone and Boyd, 1989). The score interpretations for annual water balance is shown in **Text box 5.3** and the resulting image in **Figure 5.7**.

Figure 5.7. Annual water balance image in the Khulna region for aquaculture development.

5.7.4 Monthly water balance

According to the annual water balance image, the whole region has plenty of water and there should be no water availability problem, but this is not the reality. In the dry season, evapotranspiration rate and seepage rate is higher than the annual mean. In addition, rainfall is not as frequent as during the wet season. Small rivers and their tributaries can also become dry during this time.

It was difficult to know which area has insufficient water during the dry season from the annual water balance image and so it was necessary to build up a monthly water balance to see the availability of water in dry season. A monthly water balance was calculated for the few meteorological stations in the region, using the equation:

Water requirement = (Rainfall [mm] x 1.1) – (Potential evapotranspiration [mm] x 1.3) – (Seepage [80.0 mm/month]).

The numerical values of evaporation and seepage were subtracted from rainfall. The score interpretation displays in **Text box 5.4** and **Figure 5.8** shows the monthly water balance in the region. It is clear from Figure 5.8 that the region has a negative water balance in the month of November to March for all four stations. However, the negative water balance could be over come either by pumping underground water or by increasing the depth of the ponds.

Text box 5.4. Scoring of monthly water balance.

Interpretation	**Score**
>4 continuous months with positive water balance.	4
3-4 continuous months with moderate water balance.	3
1-2 continuous months with marginal water balance.	2
No positive water balance in months. Scare supply of water.	1

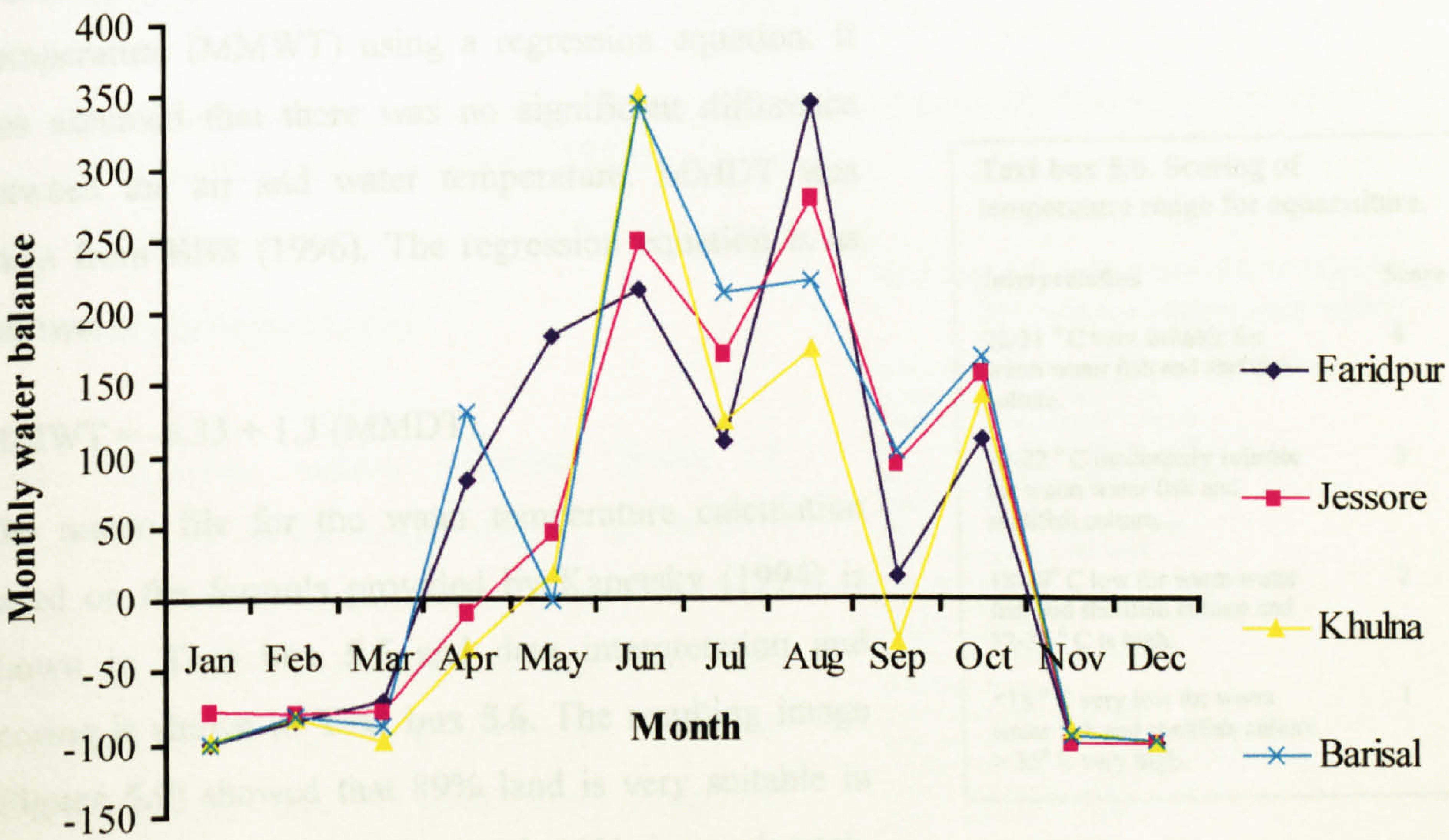

Figure 5.8. Monthly water balance in Khulna region for aquaculture development.

5.8 Water quality

5.8.1 Water Temperature

Water temperature has a major effect on the growth of aquatic species (Brett and Groves, 1979) and may be largely responsible for any differences in growth between sites. Water temperature is influenced by factors such as latitude, water depth, shelter and tidal exchange. Estuaries usually have a high average summer temperature but a wider daily and seasonal range (Kapetsky, 1994; Kapetsky and Nath, 1997). Water temperature is one of the single most important factors limiting shrimp culture world-wide (Deering *et al.* 1995; Jackson and Wang, 1998).

Text box 5.5. IML macro file for temperature calculation

Full expression is MMWT=-6.36+1.3 (MMDT).
part one : creating an image with value -6.35
initial x inta 2 1 -6.35 1 winover m
part two: multiplying MMDT by 1.3
scalar x MMDT intb 3 1.3
overlay x 1 inta intb intc
reclass x i intc wtcal 2 1 15 18 2 18 20 3 20 22 4 22 32 3 32 35 2 35 37 1 37 40 –9999
deleting all intermediate files
delete x int*.*

Water temperature data was not easily available for this study and so conversion of air temperature to water temperature was made according to Kapetsky (1994). In this procedure, Mean Monthly Day Temperature (MMDT) was converted to Mean Monthly Water Temperature (MMWT) using a regression equation. It was assumed that there was no significant difference between the air and water temperature. MMDT was taken from BBS (1996). The regression equation is as follows:

MMWT = -6.35 + 1.3 (MMDT).

Text box 5.6. Scoring of temperature range for aquaculture.

Interpretation	Score
22-31 ^{0}C very suitable for warm water fish and shellfish culture.	4
20-22 ^{0}C moderately suitable for warm water fish and shellfish culture.	3
18-20^0 C low for warm water fish and shellfish culture and 32-35 ^{0}C is high.	2
<18 ^{0}C very low for warm water fish and shellfish culture, > 35^0 C very high.	1

The macro file for the water temperature calculation based on the formula provided by Kapetsky (1994) is shown in **Text box 5.5** and data interpretation and scoring is shown in **Text box 5.6**. The resulting image **(Figure 5.9)** showed that 89% land is very suitable in terms of water temperature and 11% is moderately suitable for the temperature factors for variety of species. However, temperature is not a limiting factor in the region, even in the winter season, although in summer temperature could be the cause of water deficit in the ponds through evaporation.

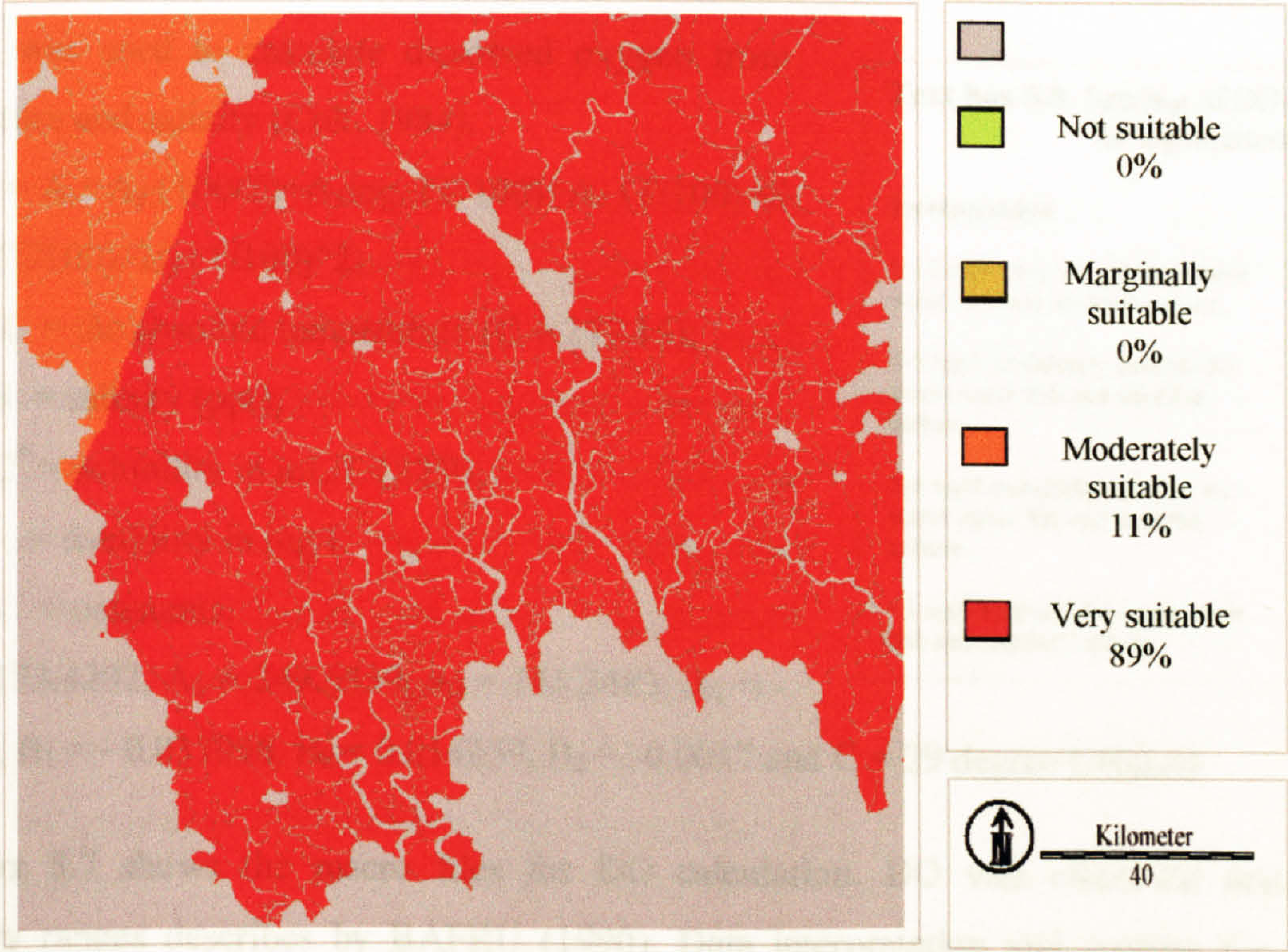

Figure 5.9. Manipulated water temperature image from air temperature through regression equation (source: Kapetsky, 1994).

5.8.2 Dissolved Oxygen (DO)

Aquatic organisms require sufficient levels of dissolved oxygen in the water column to survive. Dissolved oxygen for surface water ranges from 0 in extremely poor water conditions to a high of 15 mg/l in 0 degree Celsius water. The colder the water, the more oxygen it can hold. DO levels below 3 mg/l are stressful to most aquatic organisms, while DO levels below 1 mg/l would not support fishes. However, levels of 5-6 mg/l are usually required for most fishes and shellfish. DO for this study was computed from dissolved gas concentrations in water as functions of temperature, salinity, and pressure. The following

Text box 5.7. IML macro file to calculate DO from temperature and salinity.

```
rem: First, all temperatures are converted to degrees
absolute by multiplying 273.15
scalar x tempreal tempabs 3 273.15
rem: Set up a layer of one hundreds
initial x hundred 1 1 100 1 winover m
rem: part one
overlay x 4 hundred tempabs inta
scalar x inta part1 3 249.6339
rem: part two
scalar x tempabs intb 4 100
transfor x intb intc 2
scalar x intc part2 3 143.3483
rem: part three
scalar x intb part3 3 -21.8492
rem: part four
transfor x intb intd 6
scalar x intd inte 3 -0.0017
scalar x intb intf 3 0.014259
overlay x 1 inte intf intg
scalar x intg inth 1 -0.033096
overlay x 3 inth swmcsal part4
rem: finally calculating the result
overlay x 1 part1 part2 intk
overlay x 1 intk part3 intl
overlay x 1 intl part4 intm
scalar x intm intn 1 -173.4292
transfor x intn DO 1 3
scalar x do docalc 3 1.429
rem reclass do for suitability range
reclass x i docalc wdocal 2 1 2 3 2 3 4 3 4 5 4 5 10 3 10 12
2 12 13 1 13 14 0 0 2 0 14 999 -9999
update x wdocal 0 1632 1684 57 251 0 1474 1824 0 140 0
2912 3304 112 338
delete x int*.*
delete x part*.*
delete x tempabs.img
delete x hundred.img
```

formula was used to calculate dissolved oxygen from temperature and salinity (Colt, 1984).

$Log_e C_i^* = A_1 + A_2 (100/T) + A_3 log_e (T/100) + A_4 (T/100) + S (B_1 + B_2 (T/100) + B_3 (T/100)^2)$.

Where, T = the absolute temperature (C + 273.15);

S = salinity (ppt);

C^* = solubility in mL/L (STP);

= solubility in mg/l

A and B = constants.

(A_1= - 173.4292, A_2 = 249.6339, A_3 = 143.3483, A_4 = - 21.8492, B_1 = - 0.033096, B_2 = 0.014259, B_3 = -0.0017 and C = 29 degree Celsius).

Text box 5.8. Scoring of DO range for aquaculture.

Interpretation	Score
5-10 mg/l very suitable for warm water fish and shellfish culture.	4
4-5 mg/l moderately suitable for warm water fish and shellfish culture.	3
3-4 mg/l marginally suitable for warm water fish and shellfish culture.	2
<3 mg/l very low for warm water fish and shellfish culture.	1

Text box 5.7 shows the macro files for DO calculation. DO was classified according to suitability ranges describes by BAFRU (1990). Data interpretation and scoring for dissolved oxygen are presented in **Text box 5.8** and the resulting image is shown in **Figure 5.10**. Image interpretation showed that the whole area is suitable in terms of dissolved oxygen. There are no past records of major problems concerning DO in the region.

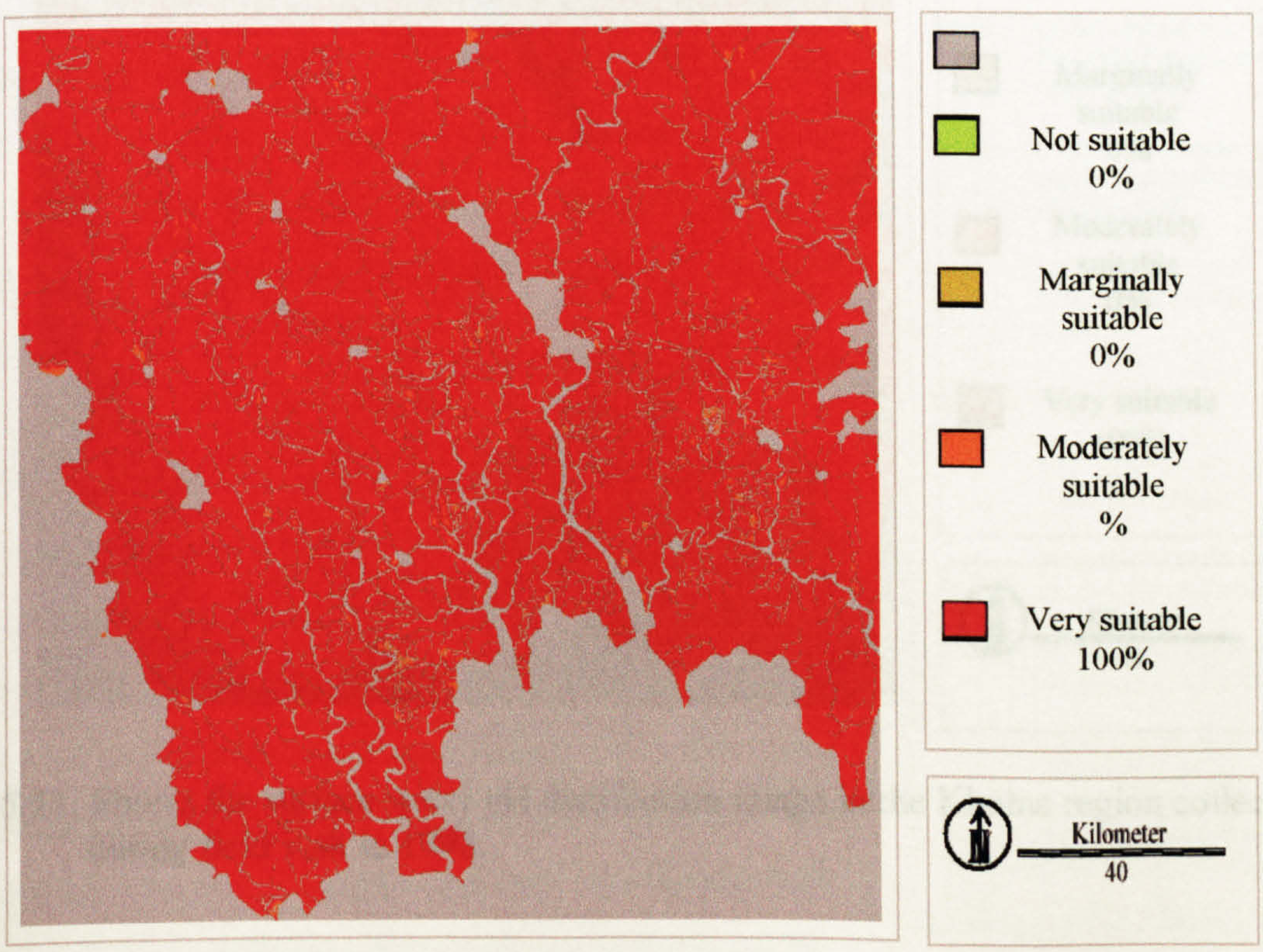

Figure 5.10. Dissolved oxygen concentration in water calculated from air temperature and salinity in the Khulna region for aquaculture development.

5.8.3 pH

The pH of water plays a crucial role in supporting aquatic life. Stream water usually ranges from pH 6.5 (slightly acidic) to a pH of 9 or over, an optimal range for most organisms. Rain water by contrast is naturally acidic at about 5.6. The pH of a stream affects the organisms living there. pH data for this study were collected during field visit in 1998 using a hand held pH meter. Data interpretation and score shows in **Text box 5.9 and Figure 5.11** illustrates the pH distribution in the region. Image interpretation showed that all the area is suitable for pH.

Text box 5.9. Scoring of pH range for aquaculture.

Interpretation	Score
6.5 - 9 very suitable for warm water fish and shellfish culture.	4
5.5-6.5 moderately suitable for warm water fish and shellfish culture.	3
4.5-5.5 marginally suitable for warm water fish and shellfish culture.	2
<4.5 very low for warm water fish and shellfish culture.	1

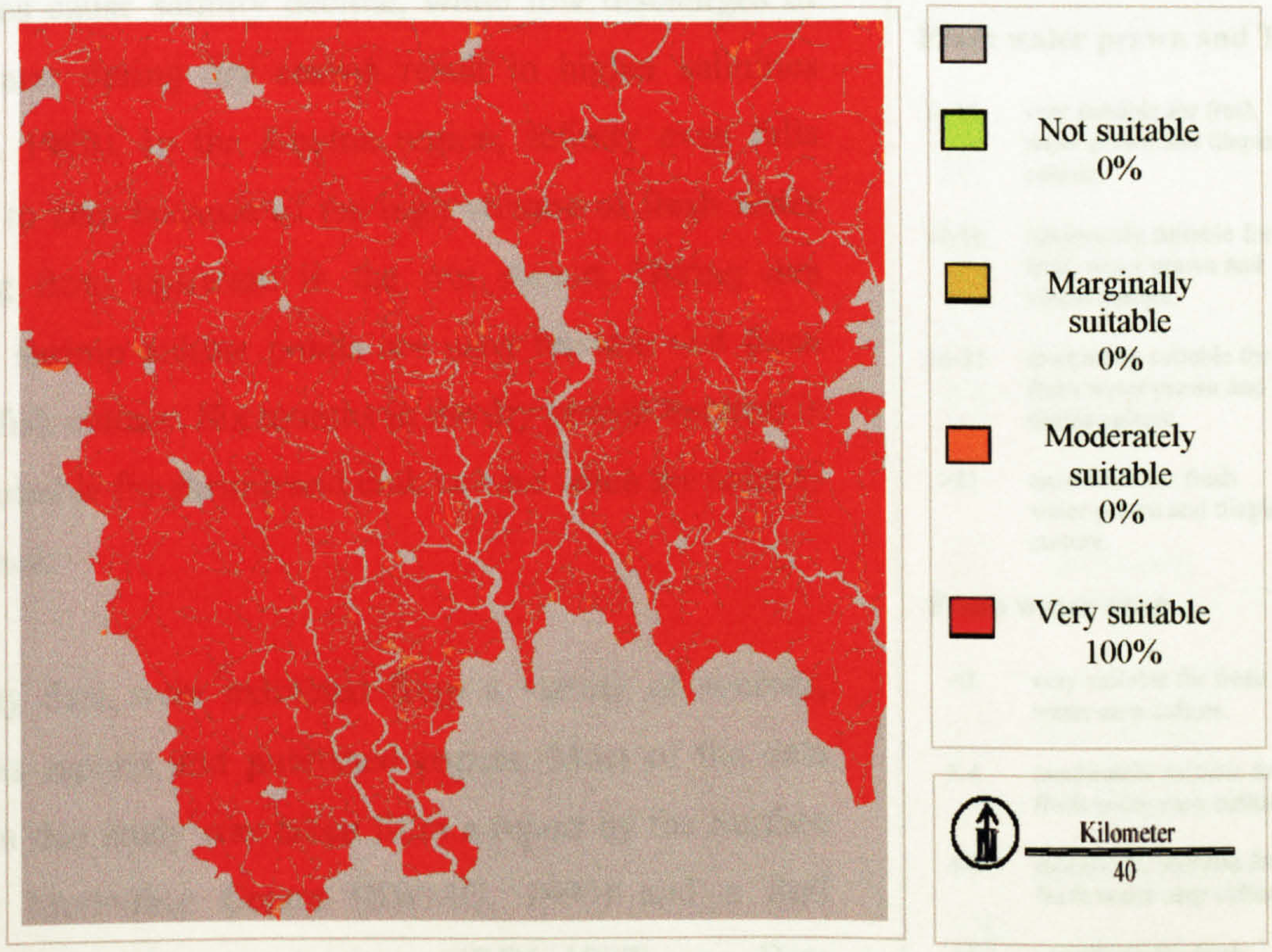

Figure 5.11. Shows the surface water pH distribution image in the Khulna region collected during field visit in 1998.

5.8.4 Salinity

Salinity is an important chemical criterion for all cultured animals. Too high or too low salinity affects growth and, if extreme, can be lethal. Low salinity can produce an off flavour in shrimp. The salinity of pond water in inland areas depends upon geologic and climatic factors. In humid areas, ponds usually have a salinity of 0.05‰, whereas, in arid regions ponds could have a salinity of 5 ‰ (Boyd, 1990).

In brackish water ponds, the salinity of water varies with the salinity of the estuaries, which serve as water supplies. During the wet season in tropical and sub-tropical regions, high discharges of freshwater from rivers into estuaries cause salinity decline, while low discharges of freshwater during dry season result in higher salinities (Boyd, 1990). In the Khulna region, salinity even falls nearly to zero because of the high volume of fresh water coming from upstream in the wet season. During this period shrimp culture ponds are used for rice and fresh water fish culture. Six months in the dry season the land is only suitable for shrimp and crab culture when the salinity increases.

Salinity data were extracted from a variety of sources, such as reports and published papers. Most of the data used in this study was taken from a report by the Surface Water Modelling Centre (SWMC, 1996) and a Soil Research Development Institute (SRDI, 1997) map. Data interpretation and scoring is shown in **Text box 5.10** and the salinity image for shrimp and crab in **Figure 5.12,** prawn and tilapia in **Figure 5.13** and carp in **Figure 5.14.**

Text box 5.10. Scoring salinity range for aquaculture.

Interpretation		Score
Brackish water shrimp and crab		
8 -26	very suitable for brackish water shrimp culture.	4
5-8 26-31	moderately suitable for brackish water shrimp culture.	3
3-5 31-36	marginally suitable for brackish water shrimp culture.	2
<3 >36	unsuitable for brackish water shrimp culture.	1
Fresh water prawn and Tilapia		
0 -11	very suitable for fresh water prawn and tilapia culture.	4
11-16	moderately suitable for fresh water prawn and tilapia culture.	3
16-21	marginally suitable for fresh water prawn and tilapia culture.	2
>21	unsuitable for fresh water prawn and tilapia culture.	1
Fresh water carp		
<2	very suitable for fresh water carp culture.	4
2-4	moderately suitable for fresh water carp culture.	3
4-6	marginally suitable for fresh water carp culture.	2
>6	unsuitable for fresh water carp culture.	1

Sources: Anon, 1997; Allan and Maguire, 1992; Deguara and Agius, 1997; Garg, 1996.

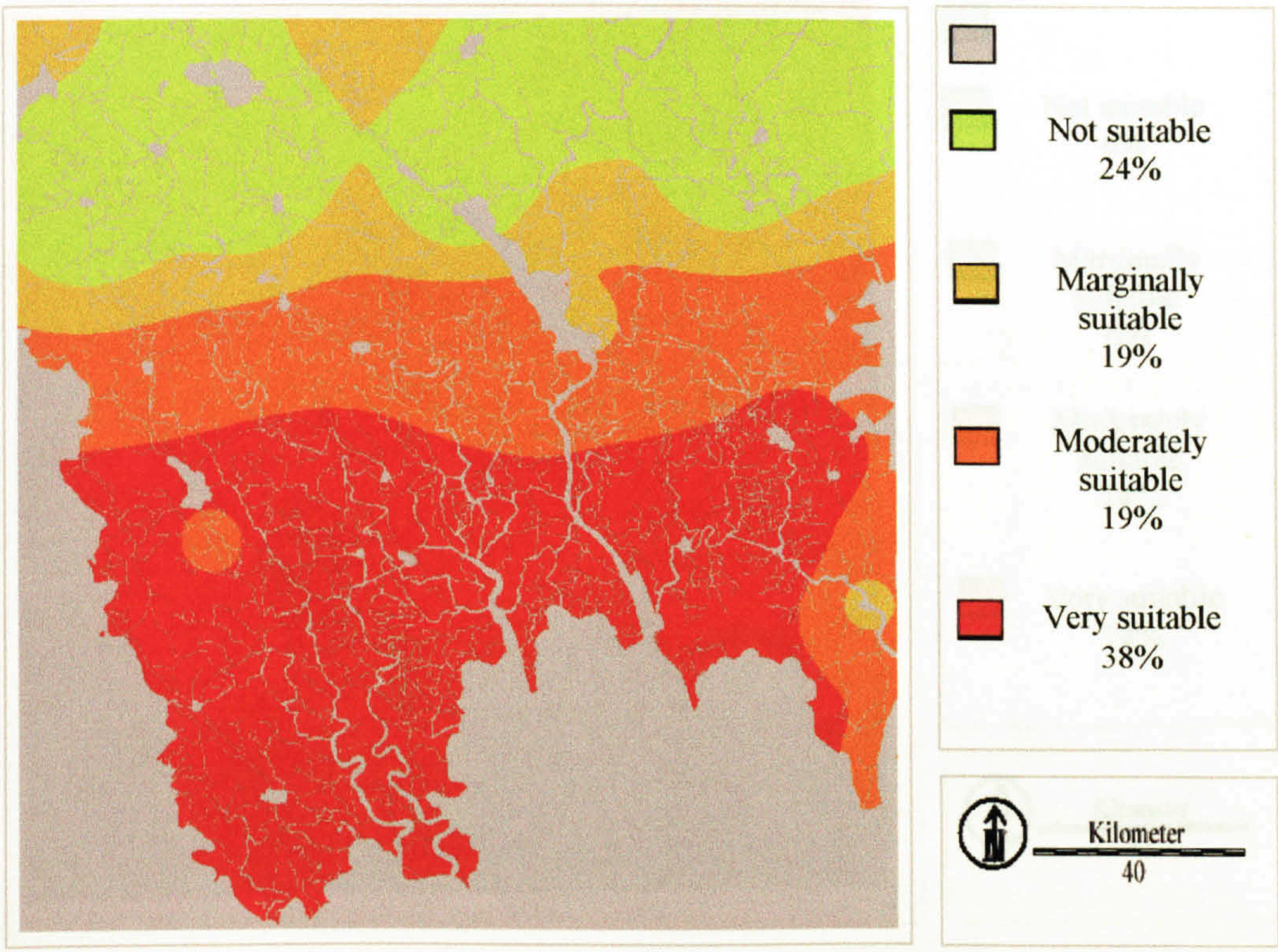

Figure 5.12. The reclassified salinity image for brackish water shrimp and crab culture in the Khulna region, Bangladesh.

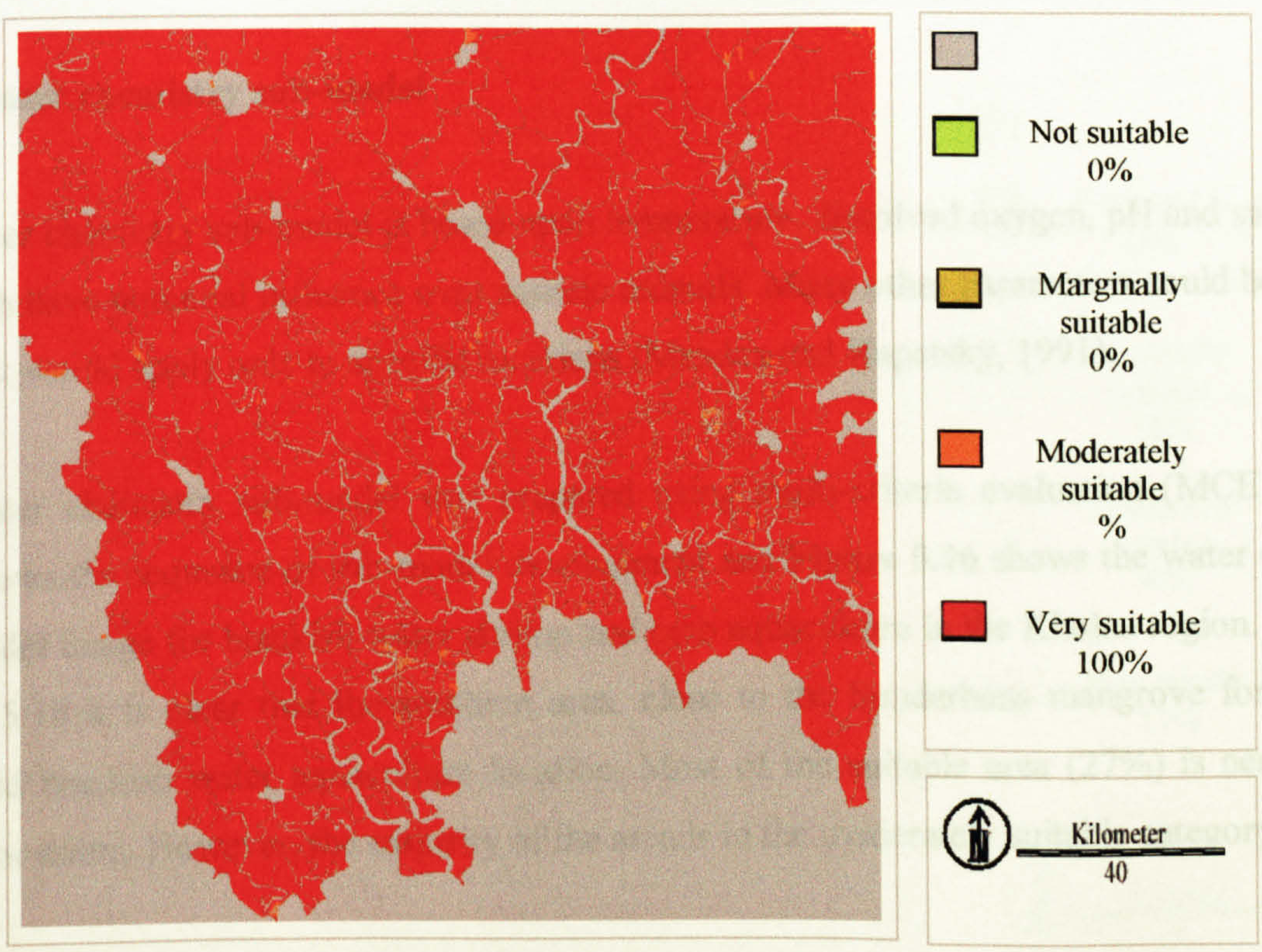

Figure 5.13. The reclassified salinity image for prawn and tilapia culture in the Khulna region, Bangladesh.

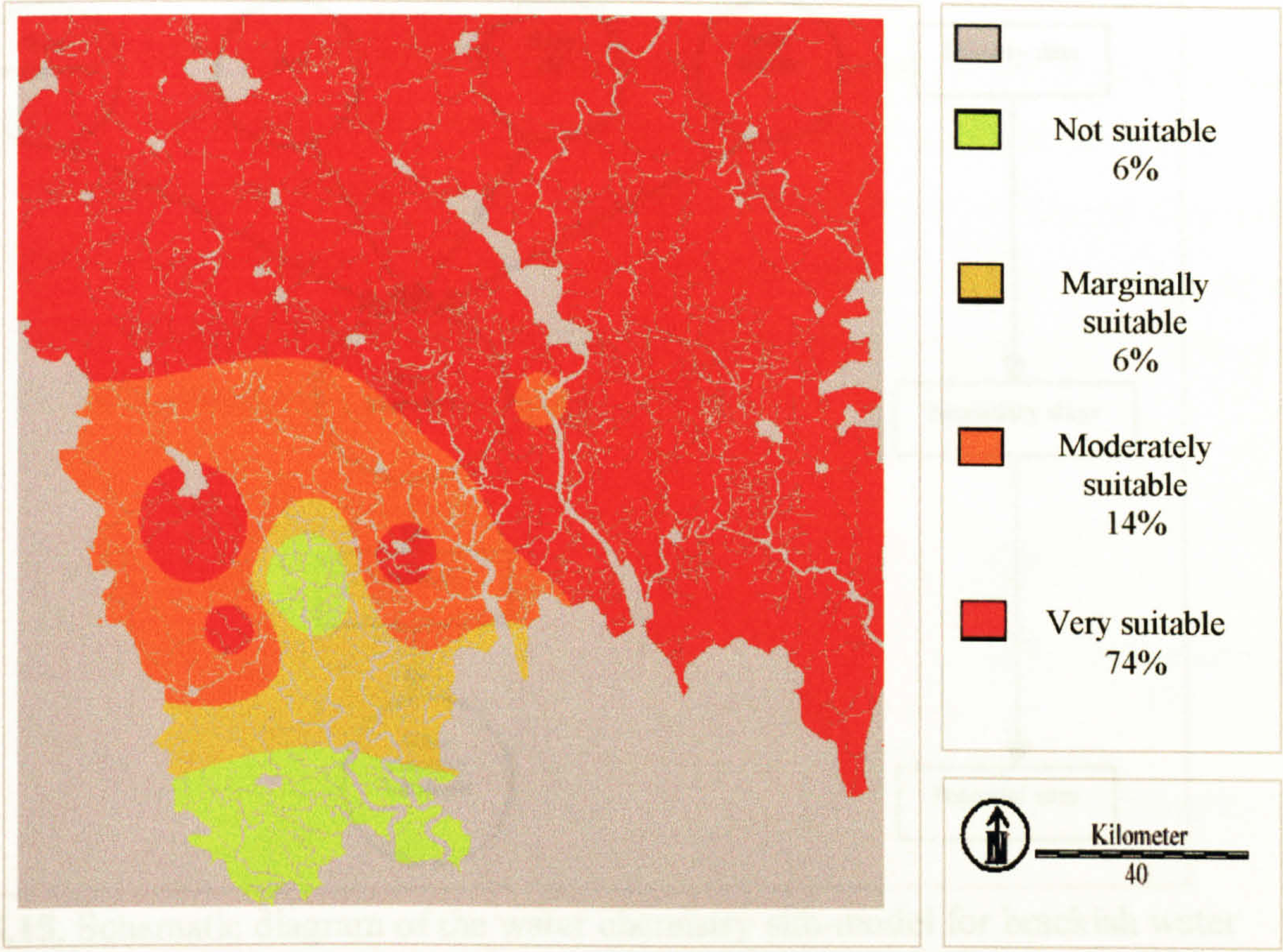

Figure 5.14. The reclassified salinity image for fresh water carp culture in the Khulna region, Bangladesh.

5.8.5 Water chemistry sub-model

The water chemistry sub-model is based upon temperature, dissolved oxygen, pH and salinity, all of which have potential influence over aquatic animals. Many other parameters could be defined but most would apply only to specific locations (Meaden and Kapetsky, 1991).

The water chemistry sub-model was prepared using multi-criteria evaluation (MCE). **Figure 5.15** shows the sequence of sub-model development and **Figure 5.16** shows the water chemistry sub-model image for brackish water shrimp and crab aquaculture in the Khulna region. From the Figure 5.16 it is clear that the southern area, close to the Sundarbans mangrove forest is the favoured brackish water aquaculture location. Most of the suitable area (27%) is near to tidal canals or rivers. However, the majority of the area is in the moderately suitable category (58%).

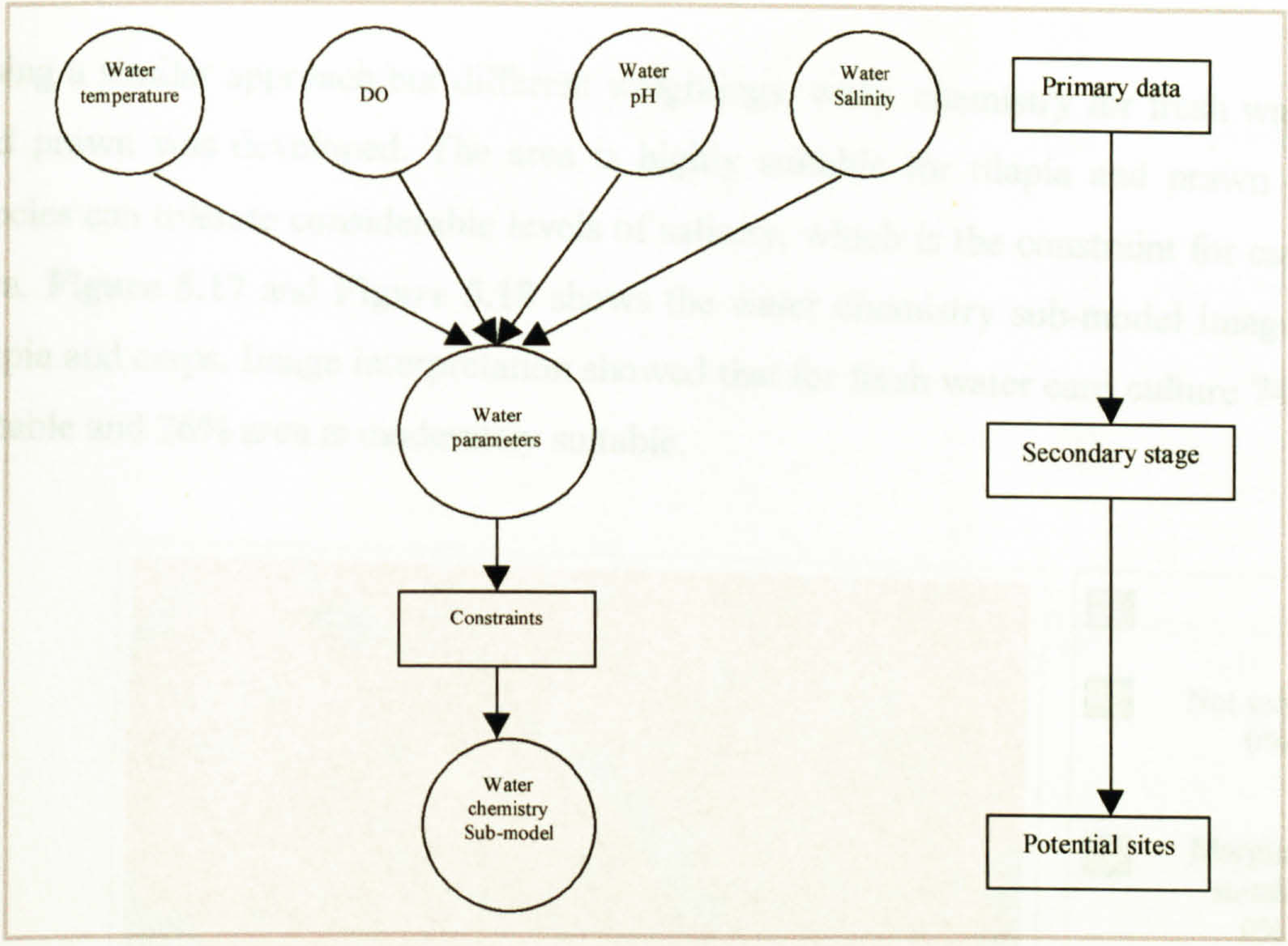

Figure 5.15. Schematic diagram of the water chemistry sub-model for brackish water aquaculture development in Khulna region, Bangladesh.

Mathematical expression:

WChSC = (WDO x 0.2166) + (WT x 0.3242) + (WpH x 0.0844) + (WSal x 0.3748). Where, WChSC = water chemistry for shrimp and crab culture. WDO = dissolved oxygen. WT = water temperature. WpH = water pH and WSal = water salinity respectively.

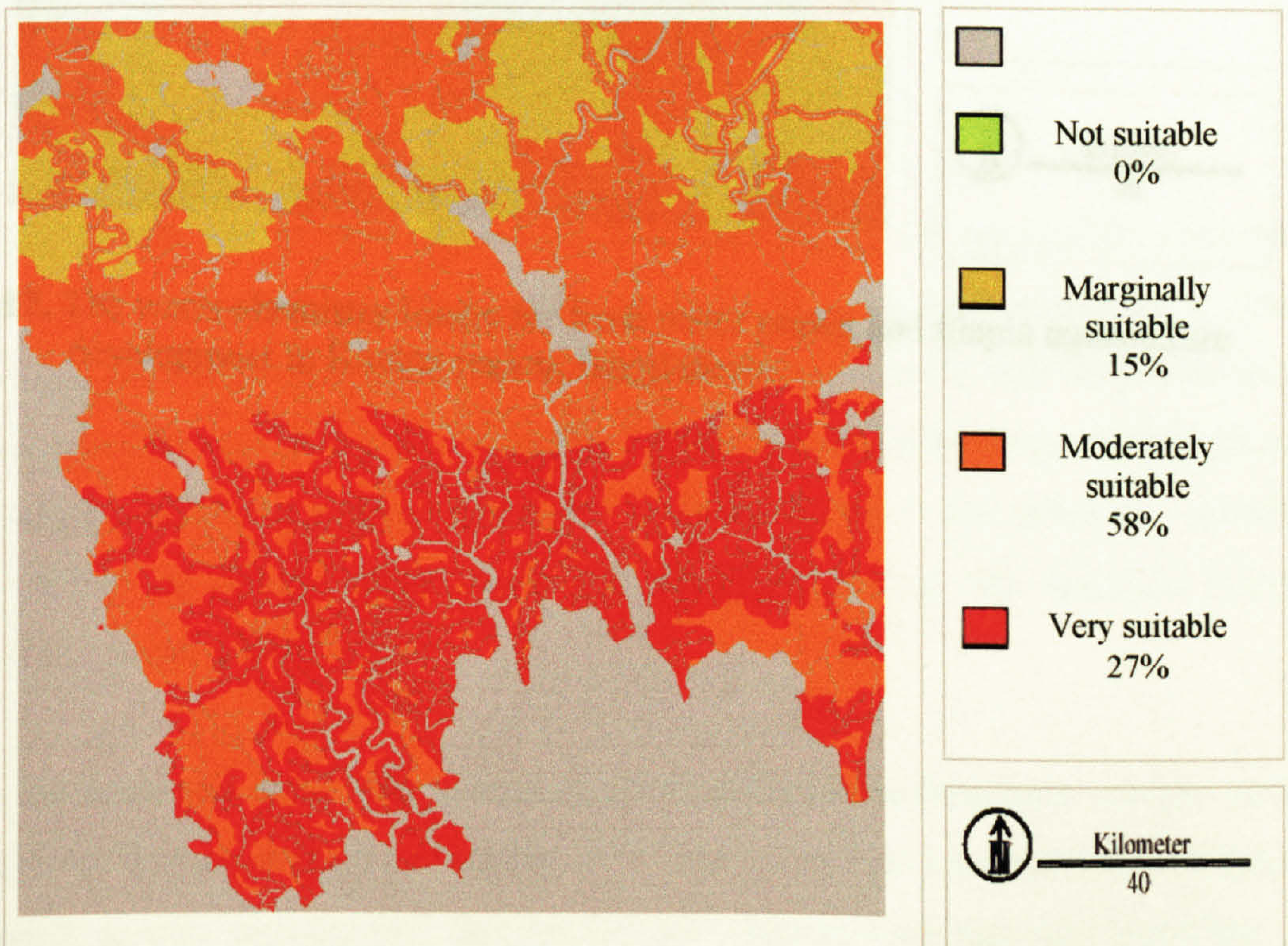

Figure 5.16. The water chemistry image for brackish water shrimp and crab aquaculture development in Khulna region, Bangladesh.

Using a similar approach but different weightings, water chemistry for fresh water carps, tilapia and prawn was developed. The area is highly suitable for tilapia and prawn culture as these species can tolerate considerable levels of salinity, which is the constraint for carp culture in the area. **Figure 5.17** and **Figure 5.18** shows the water chemistry sub-model image for prawn and tilapia and carps. Image interpretation showed that for fresh water carp culture 74% of the area is suitable and 26% area is moderately suitable.

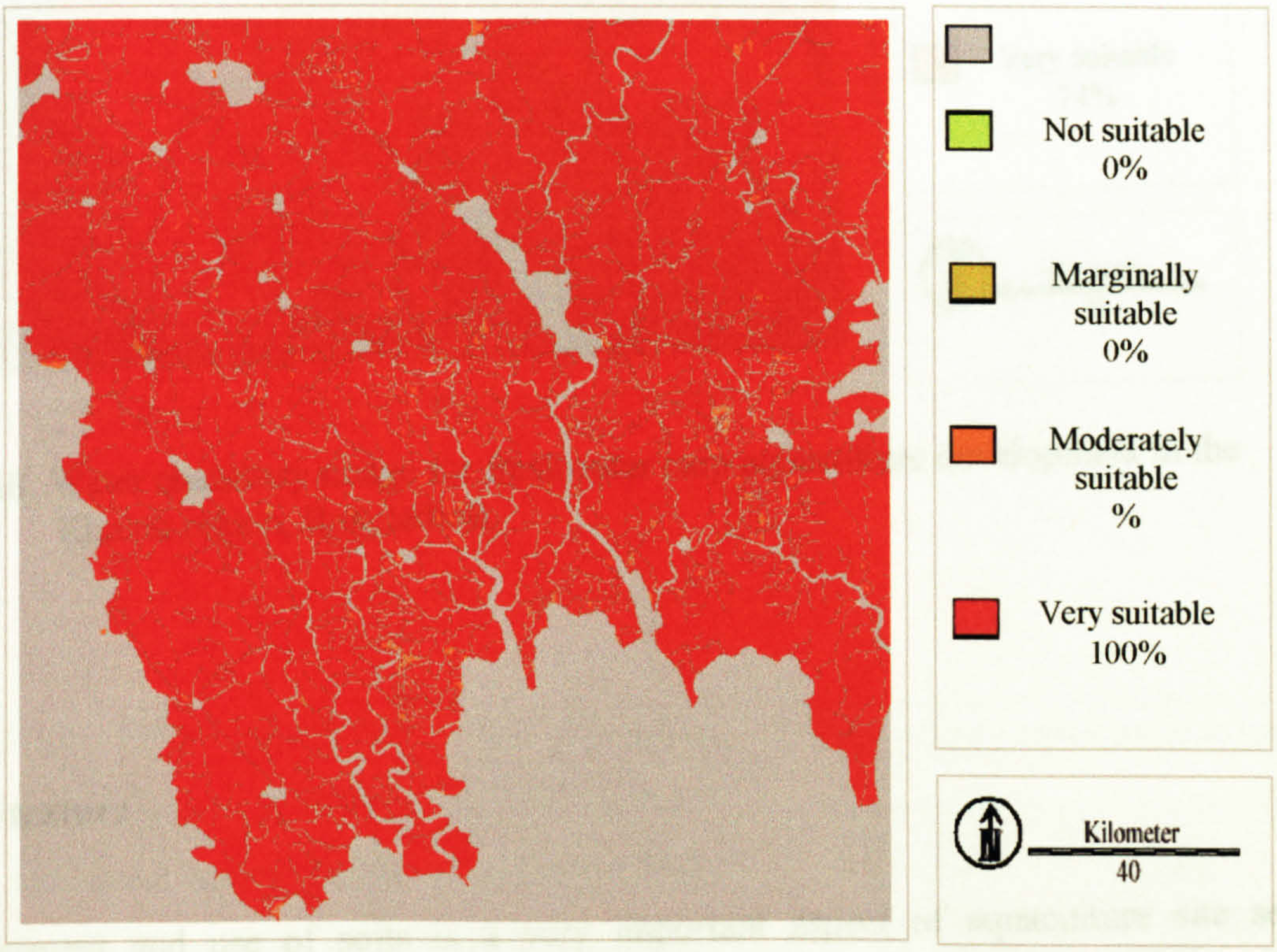

Figure 5.17. The water chemistry image for fresh water prawn and tilapia aquaculture development in Khulna region, Bangladesh.

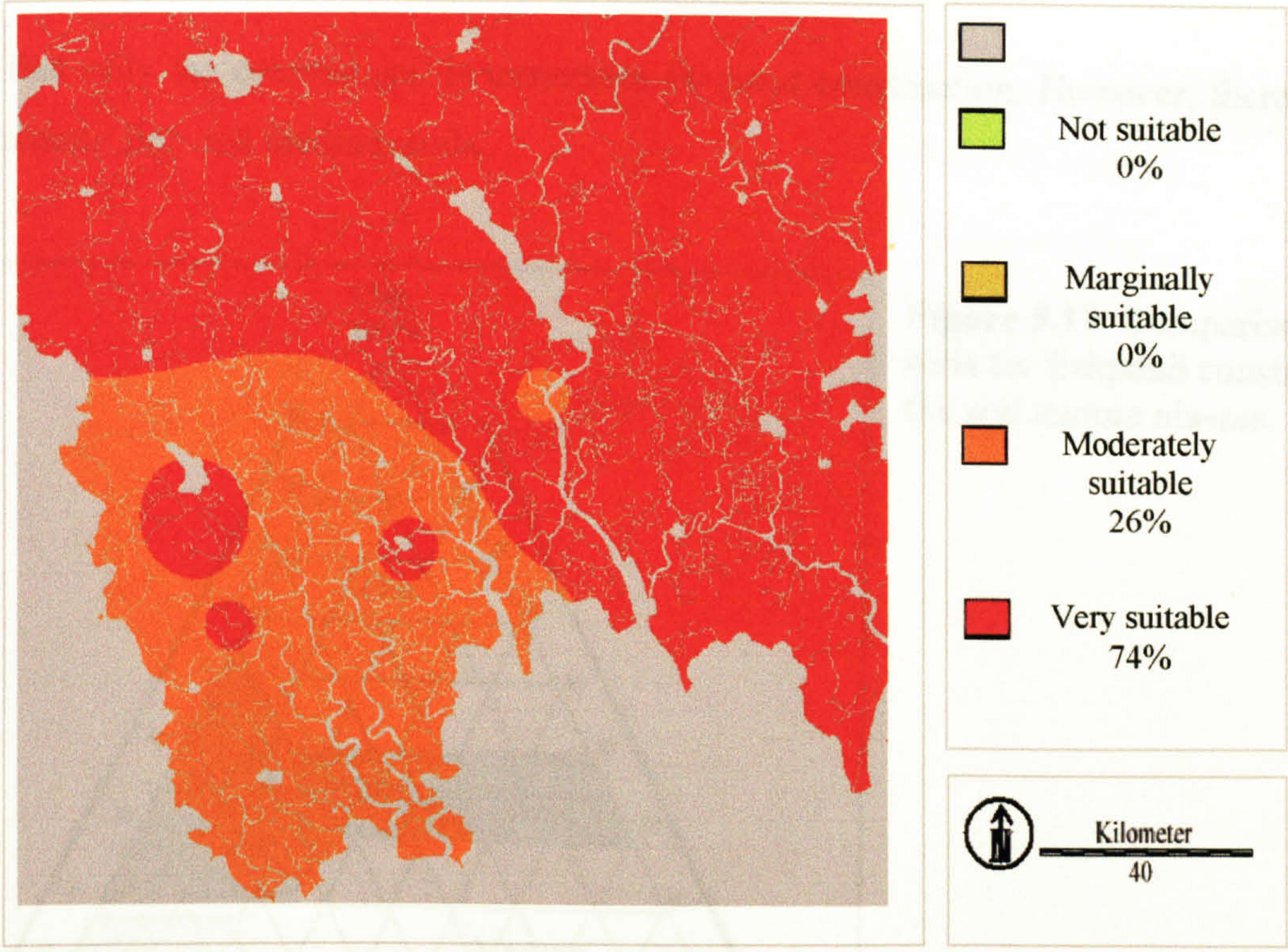

Figure 5.18. Water chemistry image for freshwater carp aquaculture development in the Khulna region, Bangladesh.

5.9 Soil

5.9.1 Soil texture

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 aquaculture, 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 additional 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; Boyd, 1990).

In order to identify areas suitable for construction of ponds, two criteria were chosen: surface soil texture (<20 cm) and sub-surface soil texture (>80 cm). Coche and Laughlin (1985) include three texture classes: coarse, medium and fine in their soil classification and they identified the best soils for fishpond construction in a soil texture triangle (**Figure 5.19**). From the triangle it is clear that only the coarsest soil is unsuitable for pond construction. However, there are suitable soils among fine and medium soils.

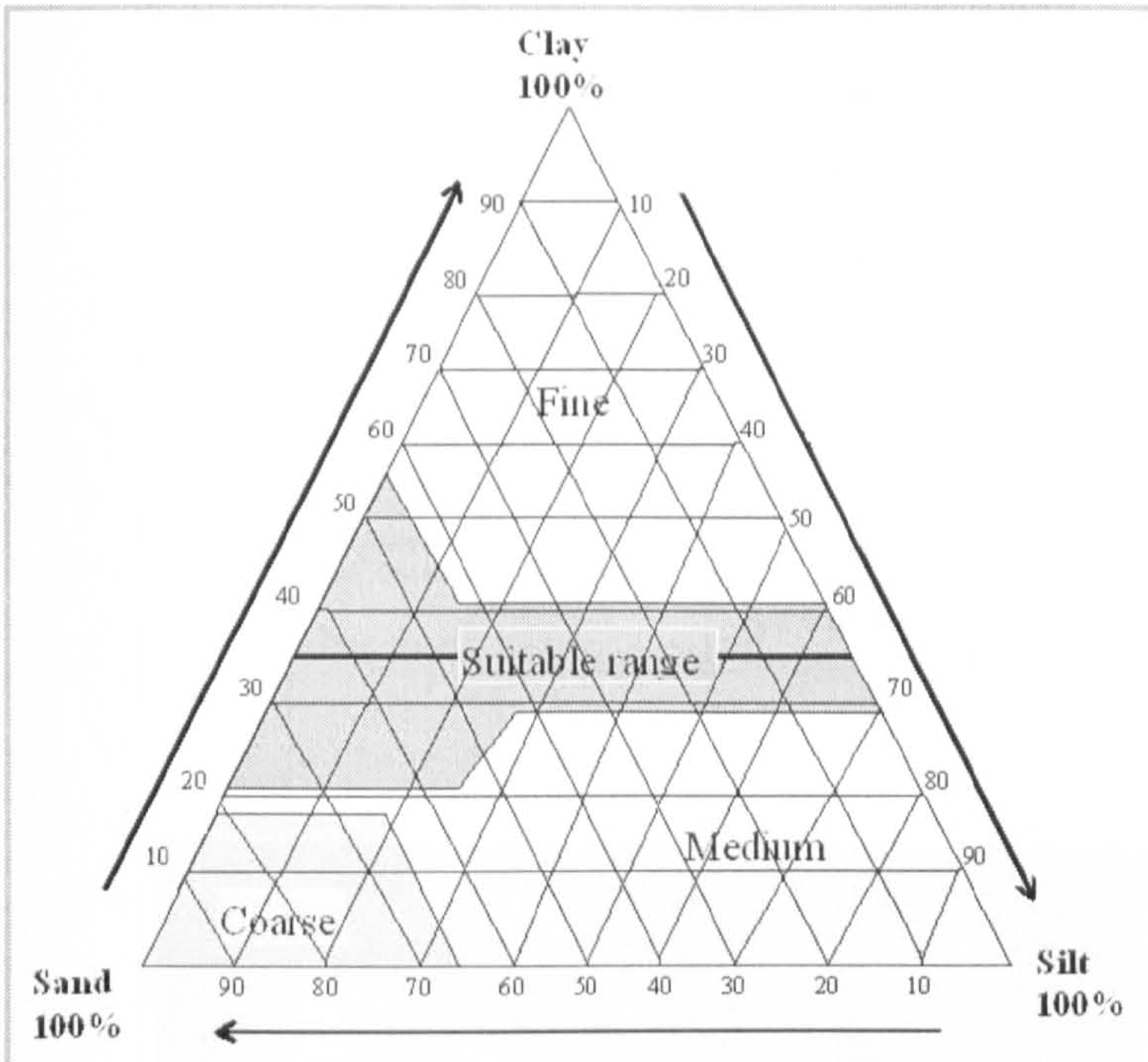

Figure 5.19: Comparison of the best soils for fishpond construction with the soil texture classes.

Soils from SRDI (1973-75) were classified according to Kapetsky (1994) for the textural classes and score interpretation is shown in **Text box 5.11**. The soil texture sub-model was prepared using MCE. **Figure 5.20** shows the sequence of soil texture and **Figure 5.21** illustrates soil distribution image in the region.

Text box 5.11. Scoring of soil texture.

Interpretation		Score
>75% fine 50-75% fine	Very suitable	4
>75% medium 50-75% medium	Moderately suitable	3
50-75% coarse <50% all	Marginally suitable	2
>75% coarse	unsuitable	1

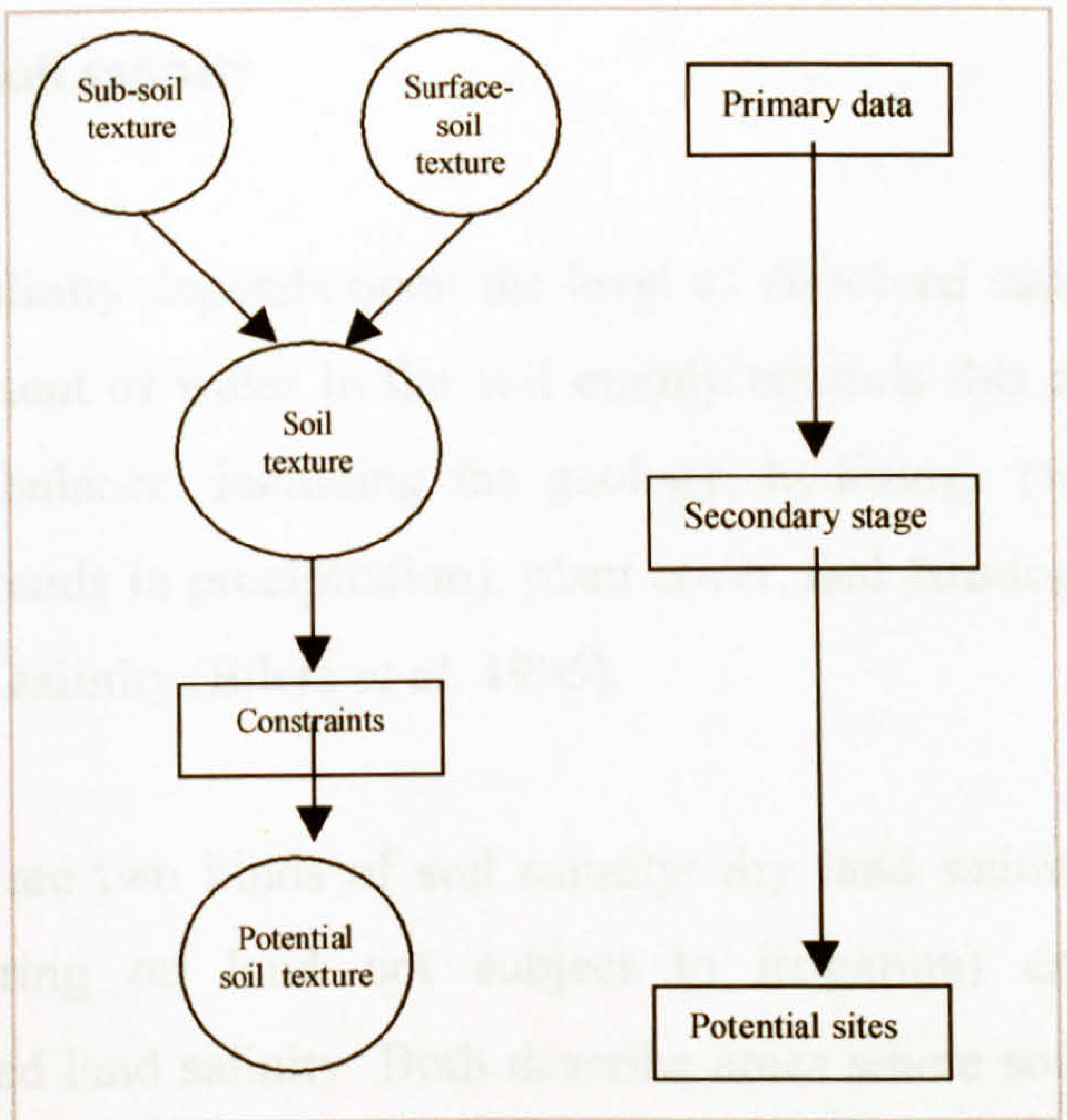

Figure 5.20. Soil texture sub-model for aquaculture development in Khulna, Bangladesh.

Mathematical expression:

STSM = (SrST x 0.25) + (SbST x 0.75). Where, STSM = soil texture sub-model, SrST = surface soil texture and SbST = sub soil texture.

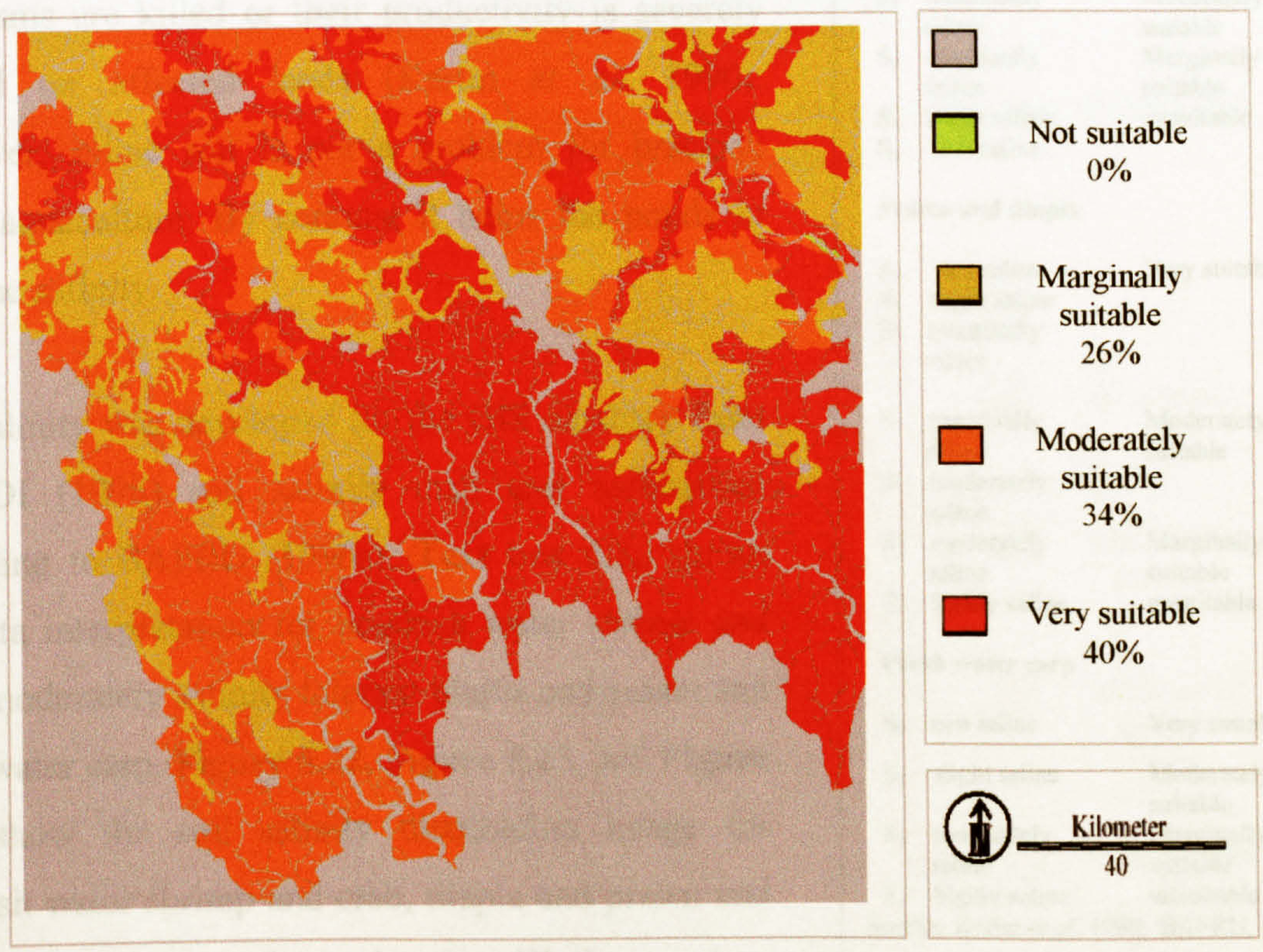

Figure 5.21. The reclassified soil texture distribution image in the Khulna region, Bangladesh.

5.9.2 Soil salinity

Soil salinity depends upon the level of dissolved salts in the plant root zone. The presence and movement of water in the soil mainly controls this condition. Any process that affects the soil water balance, including the geology, hydrology (water movement), climate (especially long term trends in precipitation), plant cover, and farming practices of an area may change the level of soil salinity (Eilers *et al.* 1995).

There are two kinds of soil salinity: dry land salinity (occurring on land not subject to irrigation) and irrigated land salinity. Both describe areas where soils contain high levels of salt. Usually, plants and soil organisms are killed or their productivity is severely limited on affected lands (Karim *et al.* 1990). However, saline soil is not a problem for brackish water aquaculture. By contrast it helps the ponds to hold the salinity.

Soil salinity was developed for the GIS database from a SRDI (1998) soil salinity map and reclassified according to BAFRU (1996a). **Text box 5.12** shows the data interpretation for brackish water shrimp and crab, moderately salinity tolerant tilapia and prawn and fresh water carp. **Figure 5.22, Figure 5.23,** and **Figure 5.24** show the soil salinity distribution image for brackish water shrimp and crab, tilapia and prawn and fresh water carp culture in the Khulna region, Bangladesh.

Text box 5.12. Scoring of soil salinity.

Interpretation of map data			Score
Brackish water shrimp and crab			
S_4	highly saline	Very suitable	4
S_3	moderately saline	Moderately suitable	3
S_2	marginally saline	Marginally suitable	2
S_1	slight saline	unsuitable	1
S_0	non saline		
Prawn and tilapia			
S_0	non saline	Very suitable	4
S_1	slight saline		
S_2	marginally saline		
S_2	marginally saline	Moderately suitable	3
S_3	moderately saline		
S_3	moderately saline	Marginally suitable	2
S_4	highly saline	unsuitable	1
Fresh water carp			
S_0	non saline	Very suitable	4
S_1	slight saline	Moderately suitable	3
S_3	moderately saline	Marginally suitable	2
S_4	highly saline	unsuitable	1

Source: Karim *et al.* 1990; BAFRU, 1996.

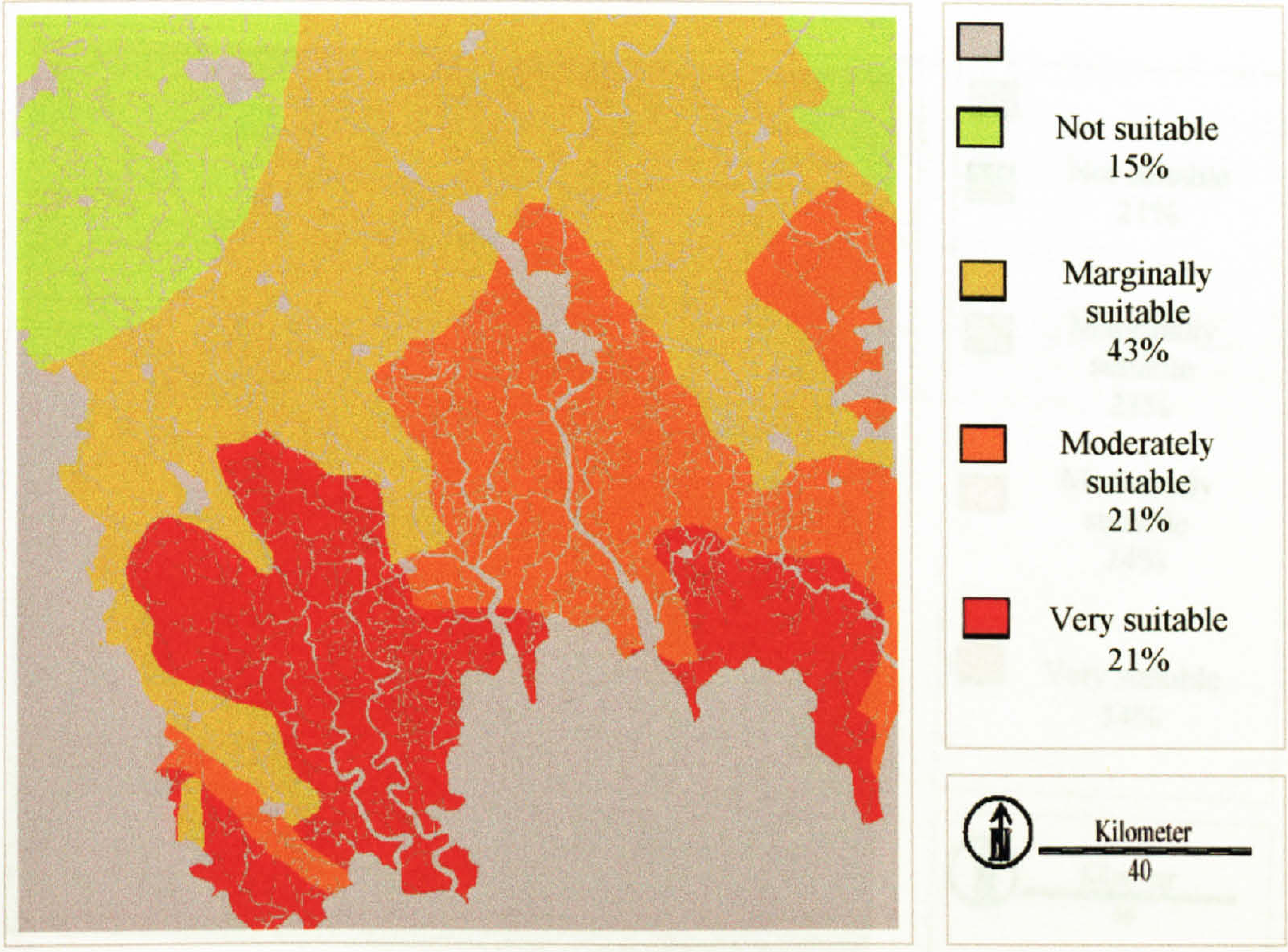

Figure 5.22. Reclassified soil salinity distribution image for brackish water shrimp and crab aquaculture in the Khulna region, Bangladesh.

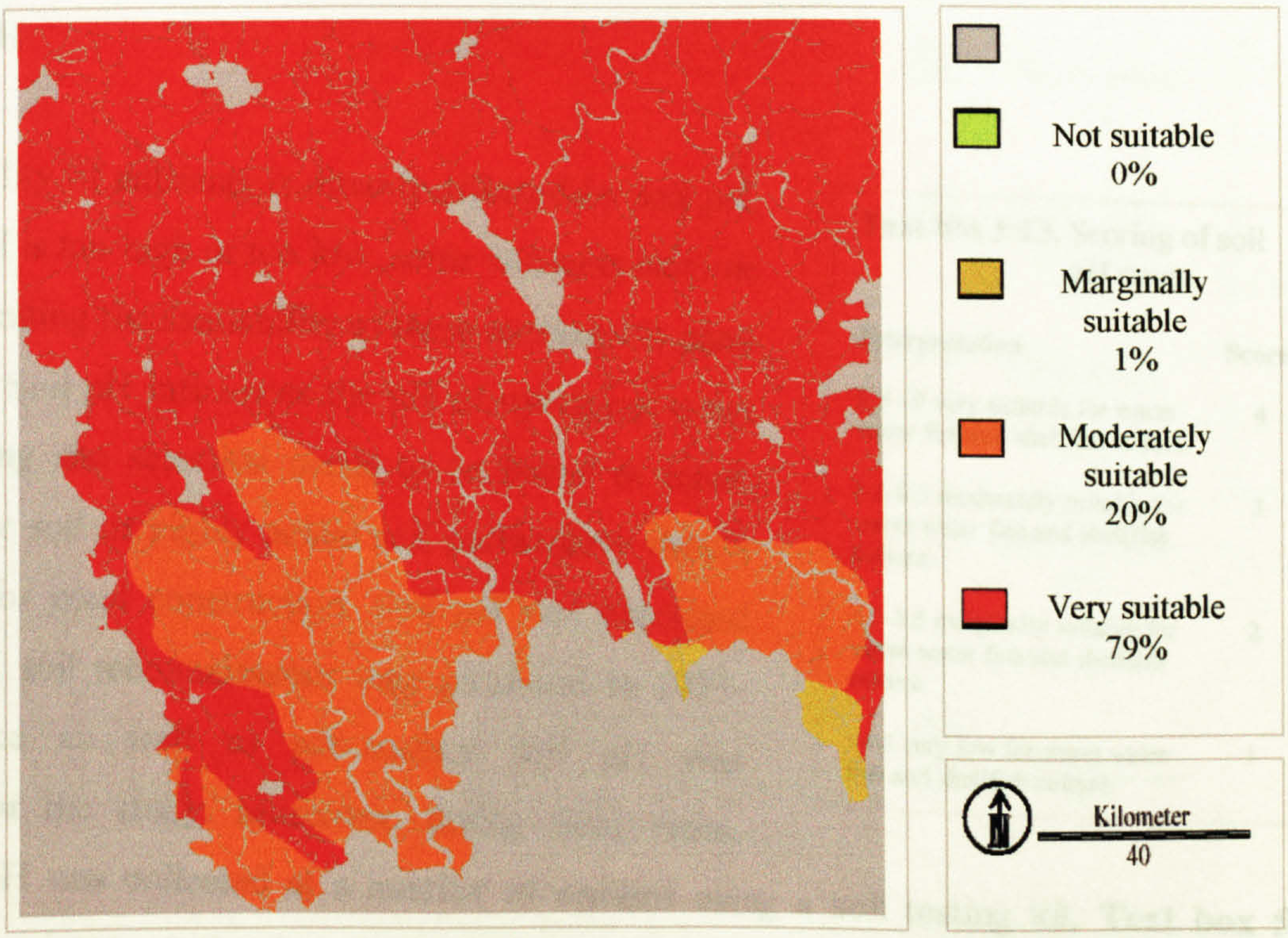

Figure 5.23. Reclassified soil salinity distribution image for prawn and tilapia aquaculture in the Khulna region, Bangladesh.

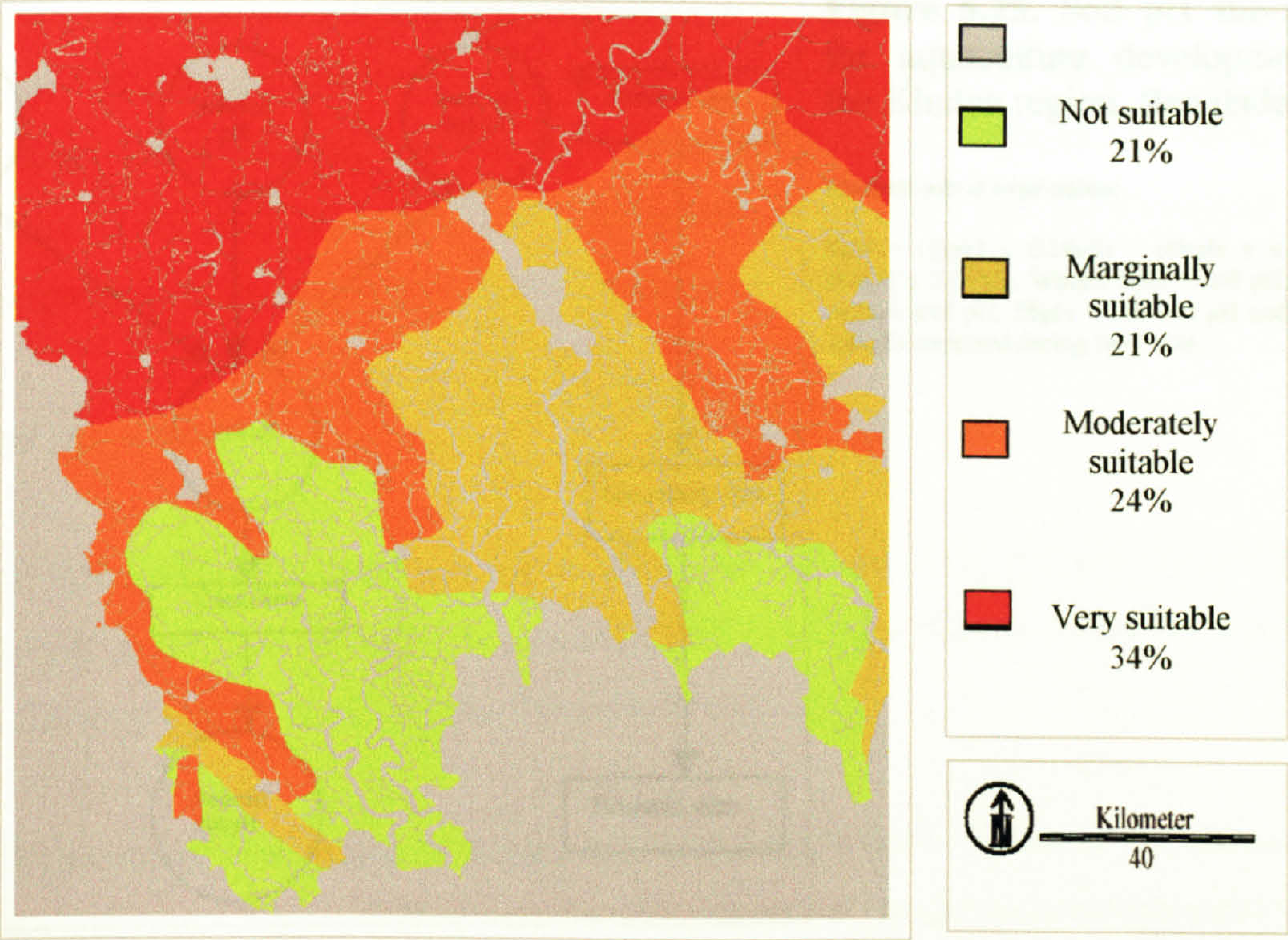

Figure 5.24. Reclassified soil salinity distribution image for fresh water carp culture in the Khulna region, Bangladesh.

5.9.3 Soil pH

The availability of nutrients is directly affected by soil pH. If the soil pH is too high or too low, some nutrients become insoluble, limiting the availability of these nutrients to plant root system. Soil pH influences the pH of overlying water and so, during site selection needs to be borne in mind. Acid sulphate soil or highly acidic soil particularly should be avoided for pond construction. Soil pH was extracted from a SRDI soil reconnaissance map produced in 1973-1975. Surface as well as sub-surface soil pH was considered for the study. Moreover, during field visits, surface soil pH was collected at a number of stations using a soil testing kit. **Text box 5.13** shows the score interpretation for soil pH. **Figure 5.25** illustrates the sequence of soil pH model development and **Figure 5.26** shows the reclassified soil pH distribution image in the region.

Text box 5.13. Scoring of soil pH range.

Interpretation	Score
6.5 - 9 very suitable for warm water fish and shellfish culture.	4
5.5-6.5 moderately suitable for warm water fish and shellfish culture.	3
4.5-5.5 marginally suitable for warm water fish and shellfish culture.	2
<4.5 very low for warm water fish and shellfish culture.	1

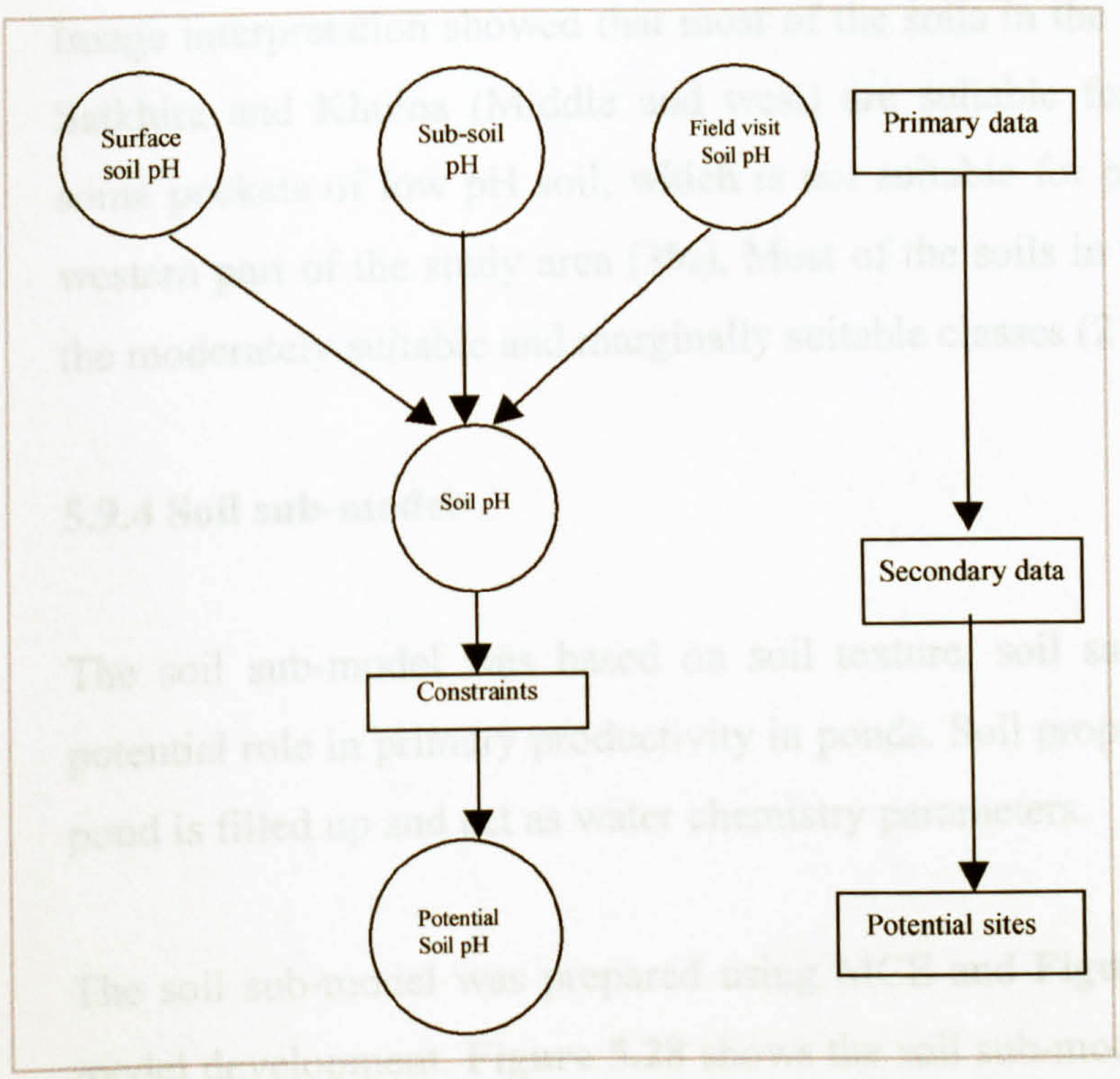

Figure 5.25. Soil pH sub-model for aquaculture development in the Khulna region, Bangladesh.

Mathematical expression:

SpH = (SrpH x 0.2969) + (SbpH x 0.6175) + (FdpH x 0.0856). Where, SpH = soil pH, SrpH = surface soil pH, SbpH = sub soil pH and FdpH = soil pH collected during field visit.

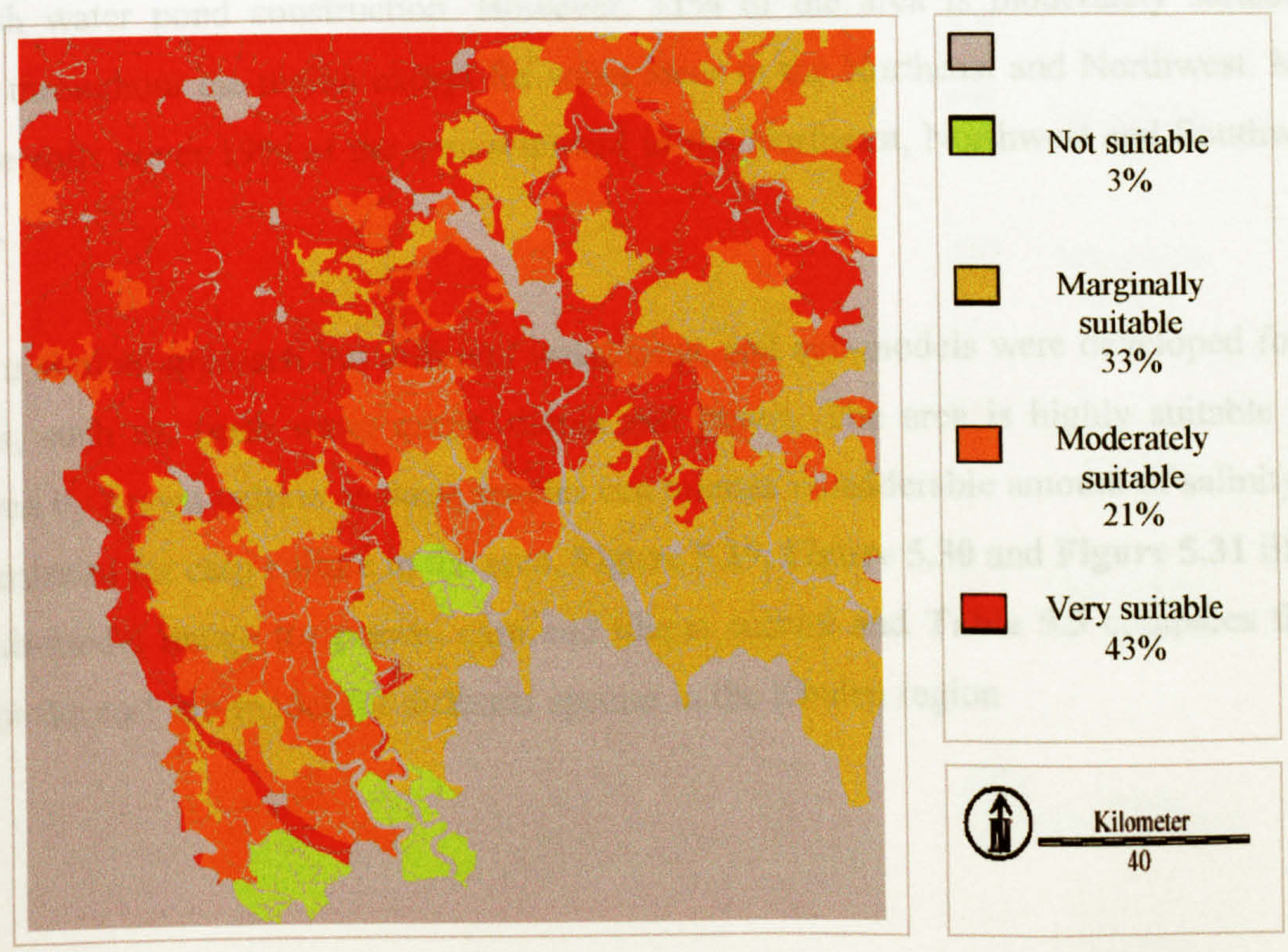

Figure 5.26. Reclassified soil pH distribution image for aquaculture development in the Khulna region, Bangladesh.

Image interpretation showed that most of the soils in the Jessore region (Northwest) and part of Satkhira and Khulna (Middle and west) are suitable for pond construction (43%). However, some pockets of low pH soil, which is not suitable for pond construction prevail in the South-western part of the study area (3%). Most of the soils in the Northeast and Southeast are within the moderately suitable and marginally suitable classes (21% and 33% respectively).

5.9.4 Soil sub-model

The soil sub-model was based on soil texture, soil salinity and soil pH, which also play a potential role in primary productivity in ponds. Soil properties directly affect the water while the pond is filled up and act as water chemistry parameters.

The soil sub-model was prepared using MCE and **Figure 5.27** illustrates the sequence of sub-model development. **Figure 5.28** shows the soil sub-model image for brackish water shrimp and crab aquaculture, in the Khulna region. It is clear that only 10% of the area is very suitable for brackish water pond construction. However, 71% of the area is moderately suitable, this is spread throughout the region except for some areas in the Northeast and Northwest. Marginally suitable soils cover 19% of the area scattered in the Northeast, Northwest and Southwest of the region.

Using a similar approach but different weightings, soil sub-models were developed for different species, such as, fresh water carps, tilapia and prawn. The area is highly suitable for tilapia followed by prawn culture as these species can tolerate considerable amount of salinity, which is the constraint for carp culture in the area. **Figure 5.29, Figure 5.30** and **Figure 5.31** illustrate the soil sub-model image for prawn, carp and tilapia culture and **Table 5.5** compares the suitable area for the soil sub-model for different species in the Khulna region

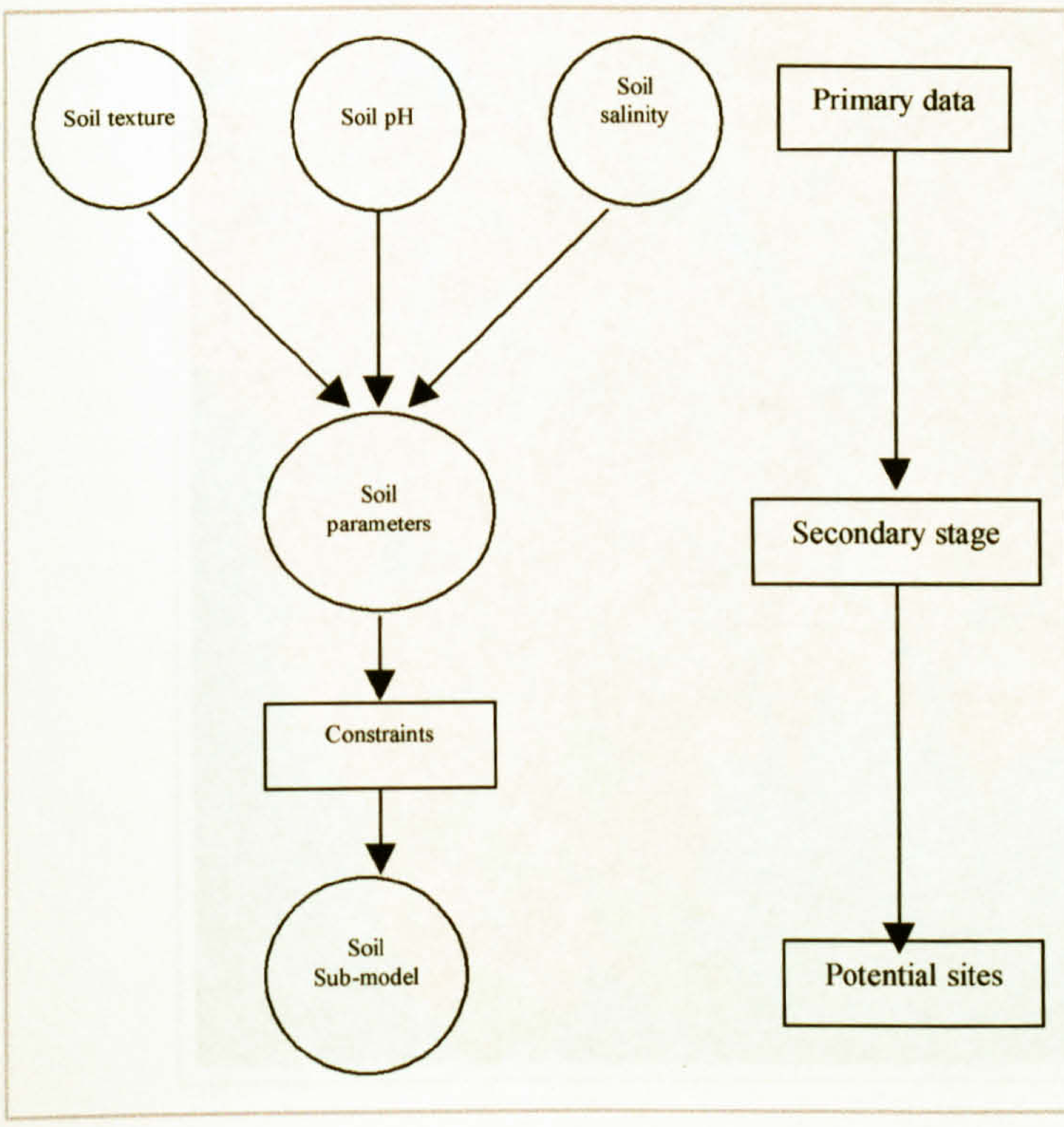

Figure 5.27. Schematic diagram of soil chemistry sub-model for brackish water aquaculture development in Khulna region, Bangladesh.

Mathematical expression:

SChSM = (ST x 0.1958) + (SpH x 0.3108) + (SSn x 0.4934). Where, SChSM = soil chemistry sub-model, ST = soil texture, SpH = soil pH and SSn = soil salinity.

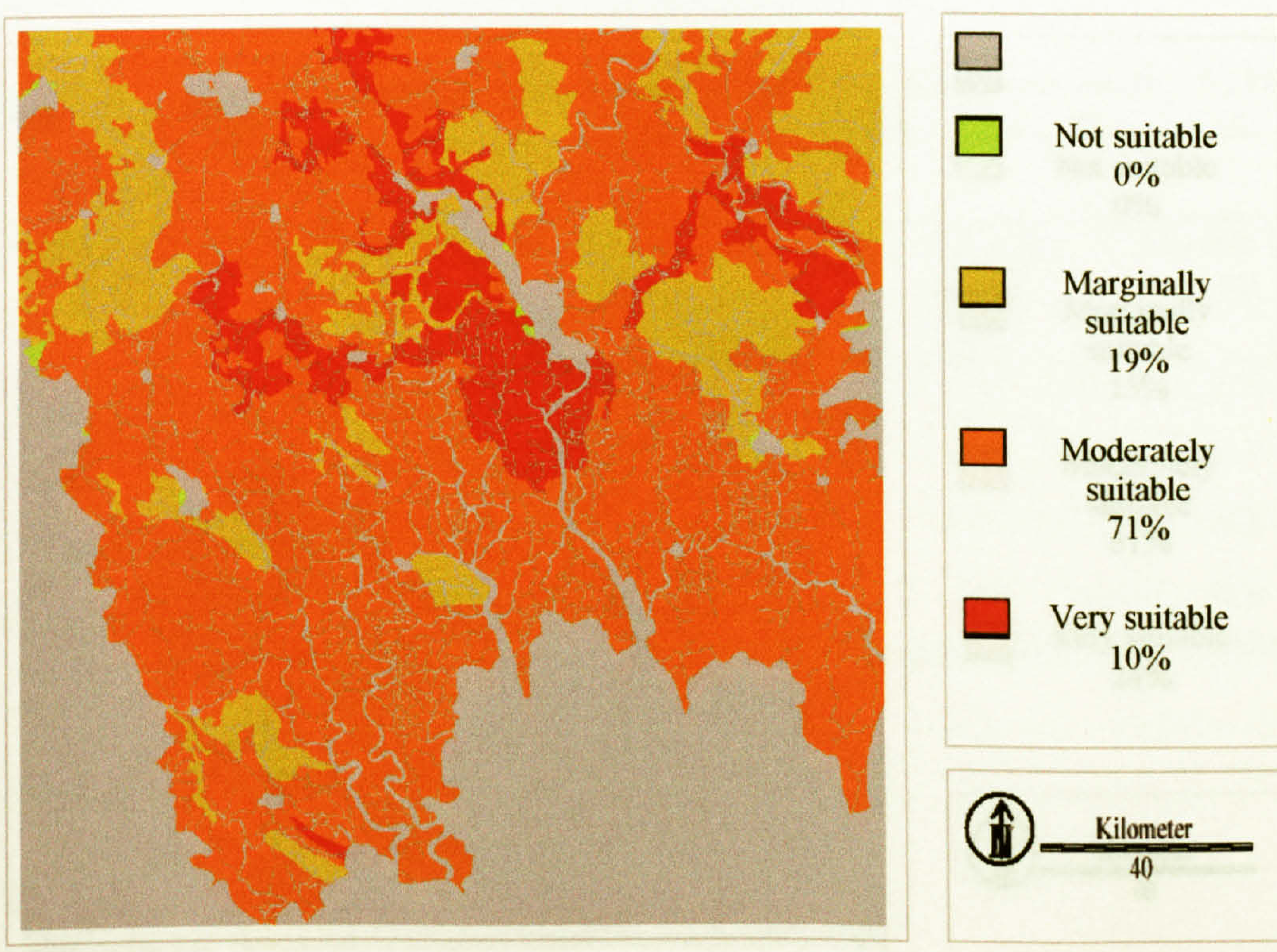

Figure 5.28. The soil sub-model image for brackish water shrimp and crab culture development in the Khulna region, Bangladesh.

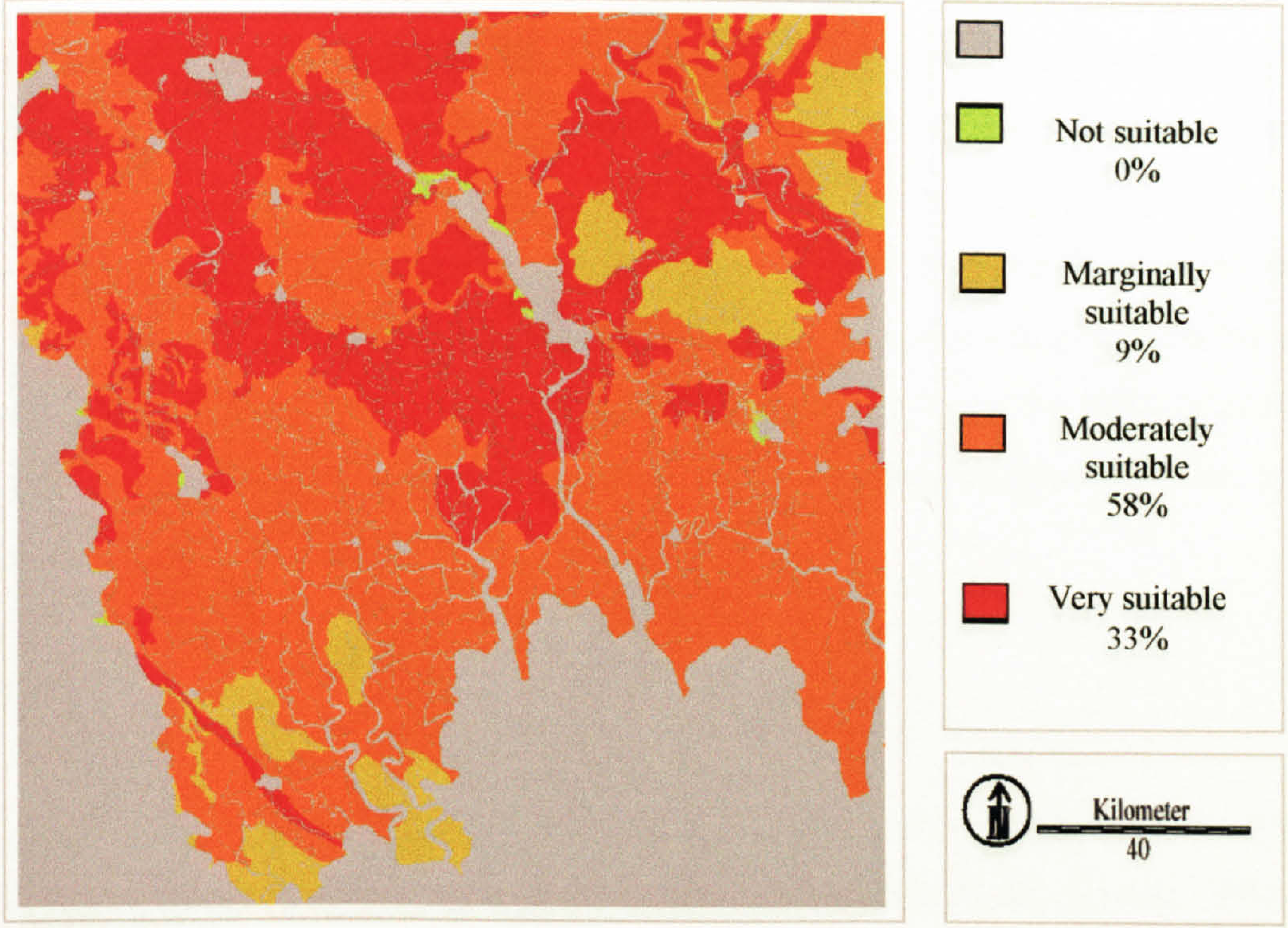

Figure 5.29. The soil sub-model image for prawn culture in the Khulna region, Bangladesh.

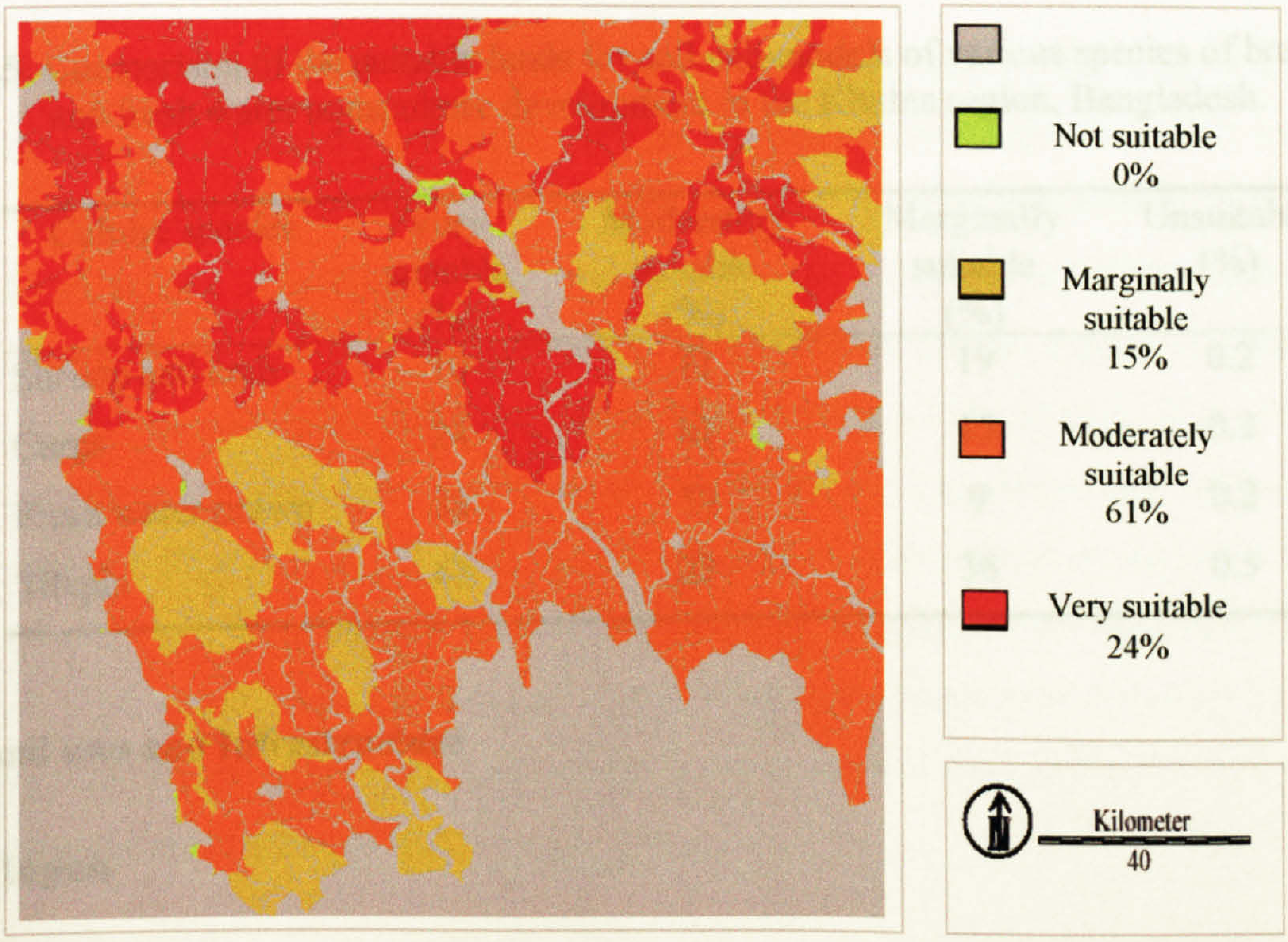

Figure 5.30. The soil sub-model image for fresh water carp culture in the Khulna region, Bangladesh.

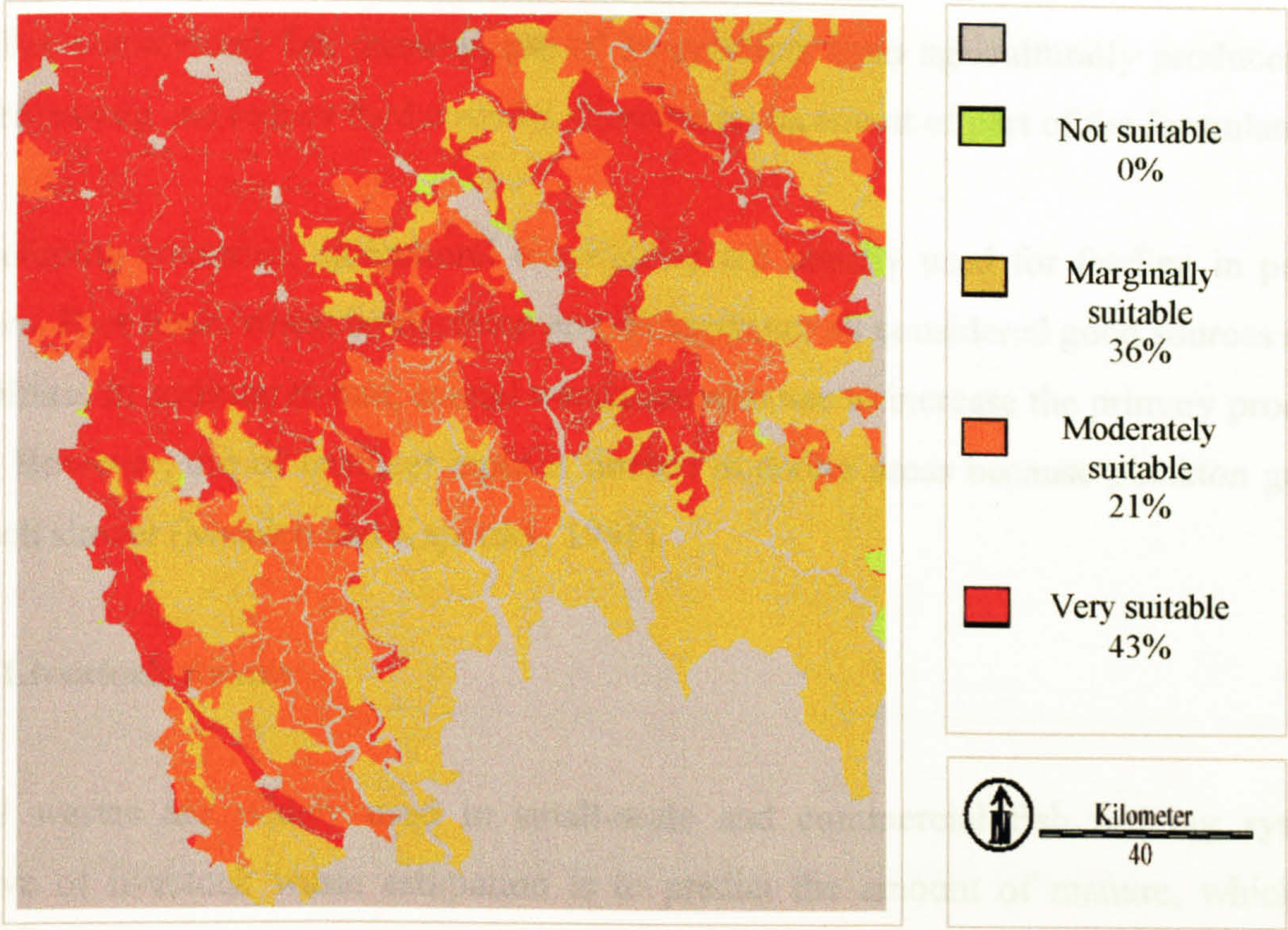

Figure 5.31. The soil sub-model image for tilapia culture in the Khulna region, Bangladesh.

Table 5.5. Comparison of the suitable lands for soil sub-models of various species of brackish and fresh water aquaculture development in the Khulna region, Bangladesh.

Culture species	Very suitable (%)	Moderately suitable (%)	Marginally suitable (%)	Unsuitable (%)
Shrimp and crab	10	71	19	0.2
Carps	24	61	15	0.2
Fresh water prawn	33	59	9	0.2
Tilapia	43	21	36	0.5

5.10 Land uses and Infrastructure

5.10.1. Inputs

The natural fertility of water body varies as a function of the complex interrelationships between a number of environmental factors. For example, photosynthesis depends upon available nutrients, water turbidity, depth of water etc. For small scale fish farming, agricultural by-products can stimulate higher yields than would be possible from the natural production of the pond. For commercial fish farming, use of by-products from agriculturally produced industrial food processing can reduce feed costs by allowing replacement of part of the formulated feeds.

In developing countries, agricultural by-products are usually used for feeding in pond culture practices. Rice husk, wheat bran, cotton and oil seeds are all considered good sources of inputs in aquaculture. In addition to that, animal wastes are also use to increase the primary productivity in ponds. However, use of fertiliser input is limited in cooler areas because plankton growth rates are much slower (Meaden and Kapetsky, 1991).

5.10.2 Livestock wastes

Animal wastes are widely used in small-scale and commercial fish farming systems. The objective of livestock waste estimation is to predict the amount of manure, which could be available for fishpond fertilisation in the region. Due to lack of manure data, livestock density is used as a surrogate measure of manure availability.

Data for production of cattle, sheep, goats, poultry and duck were collected from BBS (1997). The total amount of manure produced daily by various animals depends mainly on their live weight (LW). Sheep, 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 *et al.* 1998; Little and Muir, 1987). However, oxygen demand increases when organic matter is applied to ponds, for this reason the amount of organic matter to be used at one time should be limited. This safe amount is usually expressed in kilograms of dry matter per hectare per day, abbreviated as [kg.DM/ha/d]. FAO estimates (Coche *et al.* 1998) of daily production of farm animal wastes were used in this study (**Table 5.6**). The authors provided a range of weights, which correspond to typical livestock from which manure is obtained. These values are approximate estimates for this study, and they may change in time and with animal species, age and feed ration, type of confinement and method of manure handling.

Table 5.6. Livestock weight estimates and manure production per kilogram bio-mass per day (adapted from Coche *et al.*1998; Little and Muir, 1987).

Animal Type	Mean individual live weight (LW) [kg]	Total weight of waste* per day % LW	[kg]	Solid wastes per day [%]	Total fresh wastes* (Solids only) [kg/1000kg LW / day]
Cattle	210	6.2	13	69	60
Sheep	30	7	2.1	47	70
Goats	30	7	2.1	47	70
Poultry	2	4.8	0.048	0.02112	21
Ducks	2	4.8	0.056	0.02464	25

* Solid waste and urine

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

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

The total amount of manure potentially available was calculated by summing the amount of manure available for each livestock type:

Amount of manure available [tonnes] = ma_{cattle}[tonnes] + ma_{sheep}[tonnes]+ma_{goats}[tonnes]+ $ma_{poultry}$ [tonnes] + ma_{ducks}[tonnes], where, ma = manure available.

Text box 5.14. Scoring of available manure.

Interpretation		Score
Thousand tonnes/km²		
>10	very suitable	4
5- 10	moderately suitable	3
2-5	marginally suitable	2
<2	unsuitable	1

Detailed waste calculations are shown in **Appendix 5.1.** Data interpretation and scoring is shown in **Text box 5.14,** and the manure distribution in **Figure 5.32.** Image interpretation showed that only the Northwest region has sufficient manure to realistically boost aquaculture production. On the other hand, a patch of land lies in the mid Northern area is moderately suitable for availability of manure, while all other land to the South is only marginally suitable as fewer animals are found in that region.

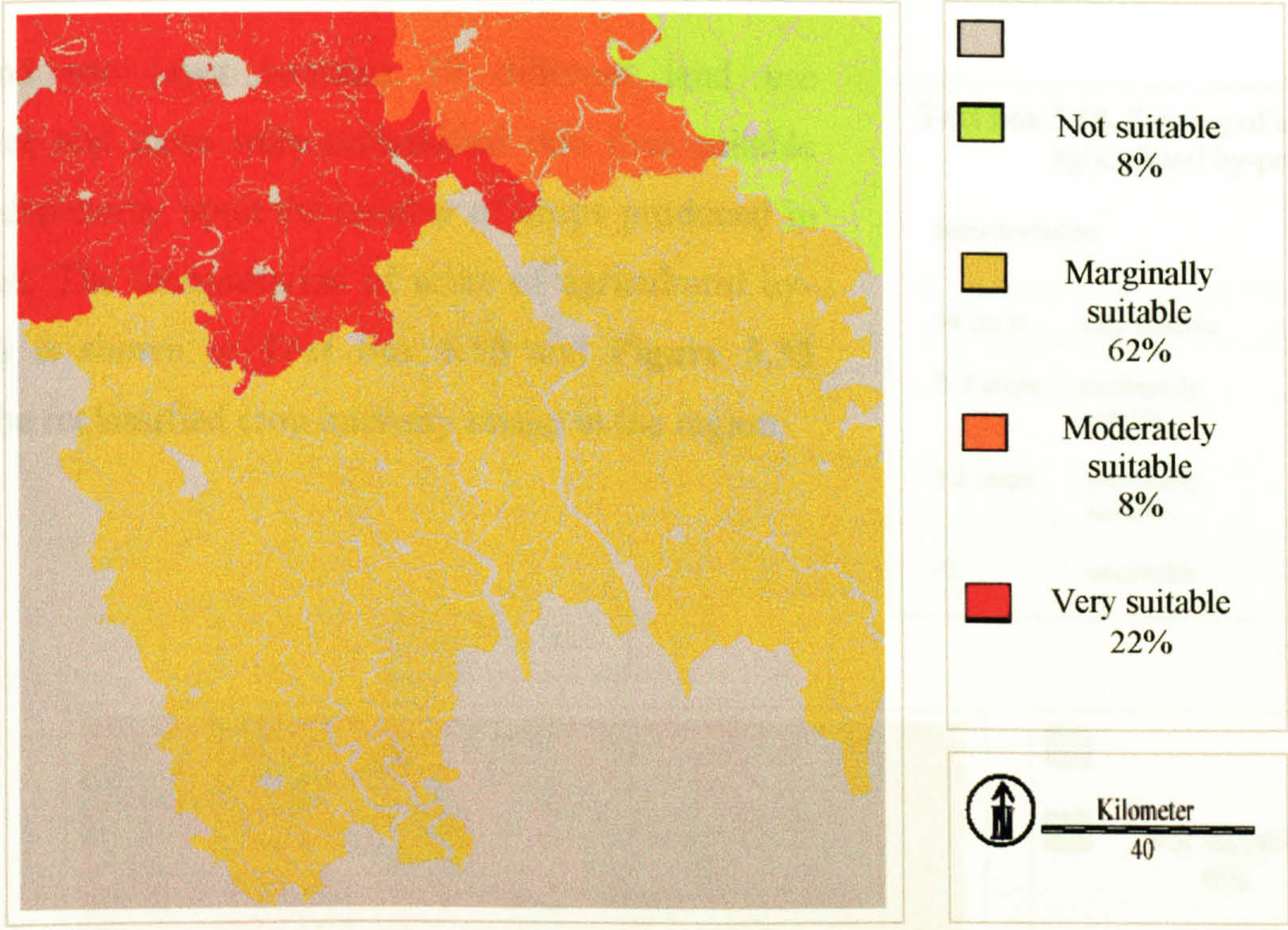

Figure 5.32. Animal waste distribution in the Khulna region, Bangladesh, reclassified in terms of aquaculture development.

5.10.3. 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 (Little and Muir, 1987). In Bangladesh, agriculture is the single most important economic activity and this is a good indicator of the potential for aquaculture development in the region. Kapetsky and Nath (1997) noted that 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 forces, villages or towns for essential supplies.
2. agriculture by-products can be a source of fish feed or fertiliser.

Crop data for this study were extracted from a land cover map produced by SRDI (1996). This land cover classification map does not distinguish among different crop types but does show crop intensity, which is an indicator of actual as opposed to predicted cropland area.

The land use layer contains 19 different land use categories and these were reclassified into four suitable classes depending upon the number of crops produced in each area. The interpretation of score of agricultural by-products is shown in **Text box 5.15** and **Figure 5.33** shows the reclassified crop intensity image in the region.

Text box 5.15. Scoring of available agricultural by-products.

Interpretation		Score
>4 crops	very suitable	4
2- 3 crops	moderately suitable	3
1-2 crops	marginally suitable	2
<1	unsuitable	1

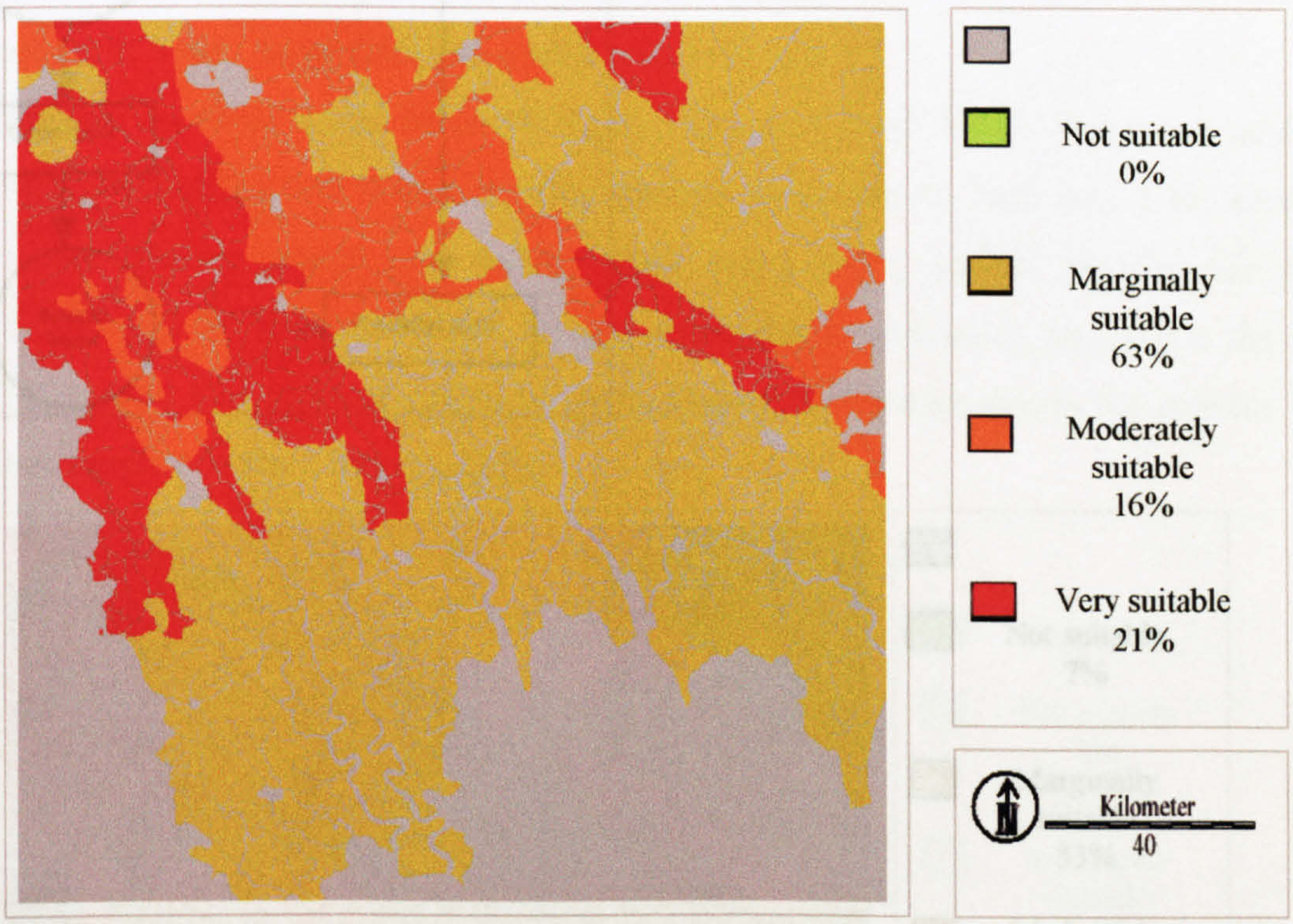

Figure 5.33. Reclassified crop intensity image in the Khulna region, Bangladesh.

5.10.4 Integration of inputs sub-model

It was considered that livestock manure was more important than agricultural by-products because small-scale fish farmers usually employ manure directly, but by-products are only used as a feed supplement. For example, most of the farms visited used cow manure for pond fertilisation. The sub-model was integrated by using MCE, which is illustrated in **Figure 5.34.** **Figure 5.35** shows the results of the inputs sub-model. From the image, it is clear that only 20% of land in the Northwest area are very suitable in terms of inputs. In addition, moderately suitable area also exists near the suitable land. Some areas in the Northeast corner are unsuitable, and rest of the areas is marginally suitable for inputs sub-model.

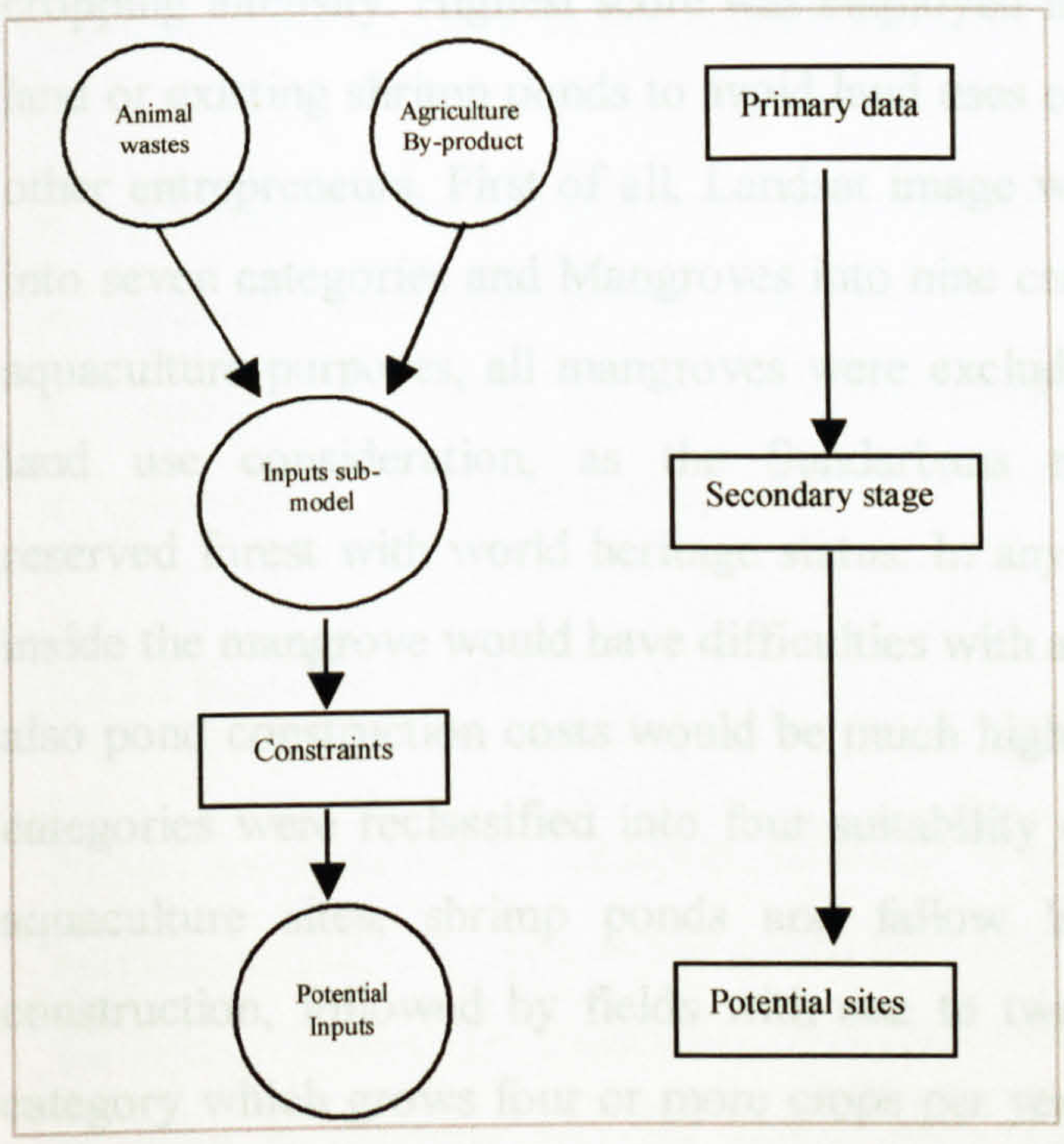

Figure 5.34. Schematic diagram of inputs sub-model for aquaculture development in the Khulna, Bangladesh.

Mathematical expression:

INPUTS = (WASTE x 0.6) + (AgByP x 0.4), Where, INPUTS = inputs from animal waste and agricultural by products, AgByP = agricultural by products.

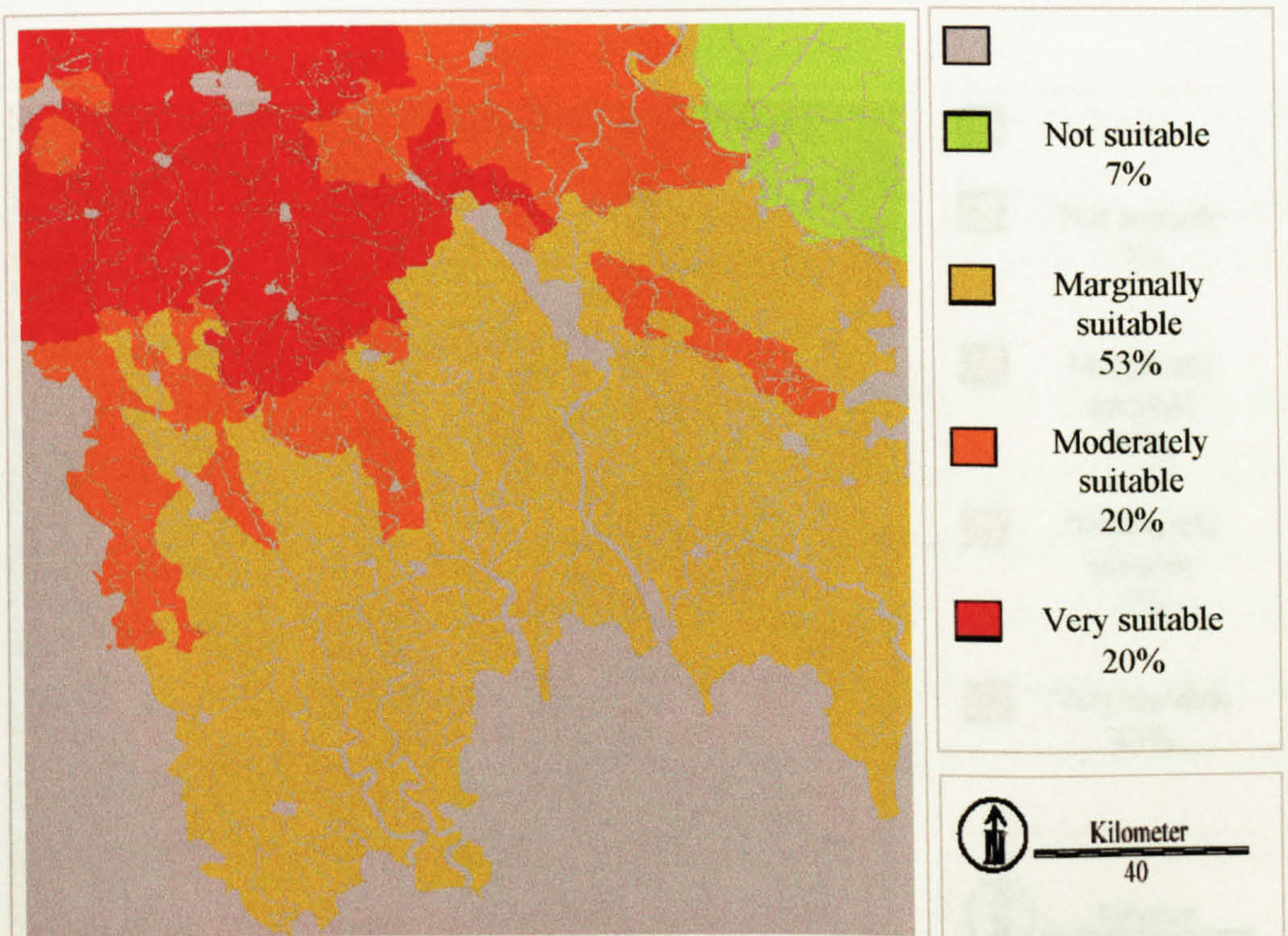

Figure 5.35. Agricultural inputs reclassified in terms of aquaculture development in the Khulna region, Bangladesh.

5.11 Land uses

Text box 5.16. Scoring of land use for aquaculture.

Interpretation		Score
<1 crops	very suitable	4
1-2 crops	marginally suitable	3
2- 3 crops	moderately suitable	2
>4	unsuitable	1

The classified land use image was reclassified according to the cropping intensity. Highest score was employed for the fallow land or existing shrimp ponds to avoid land uses conflicts with other entrepreneurs. First of all, Landsat image was classified into seven categories and Mangroves into nine categories. For aquaculture purposes, all mangroves were excluded from any land use consideration, as the Sundarbans mangrove is reserved forest with world heritage status. In any case, ponds inside the mangrove would have difficulties with acid soils and also pond construction costs would be much higher (Kapetsky *et al.* 1987). The seven land use categories were reclassified into four suitability classes, as shown in **Text box 5.16**. Existing aquaculture sites, shrimp ponds and fallow lands were given highest priority for pond construction, followed by fields with one to two crops and lowest score was given the land category which grows four or more crops per year. **Figure 5.36** demonstrates the suitable land for aquaculture purpose in the Khulna region

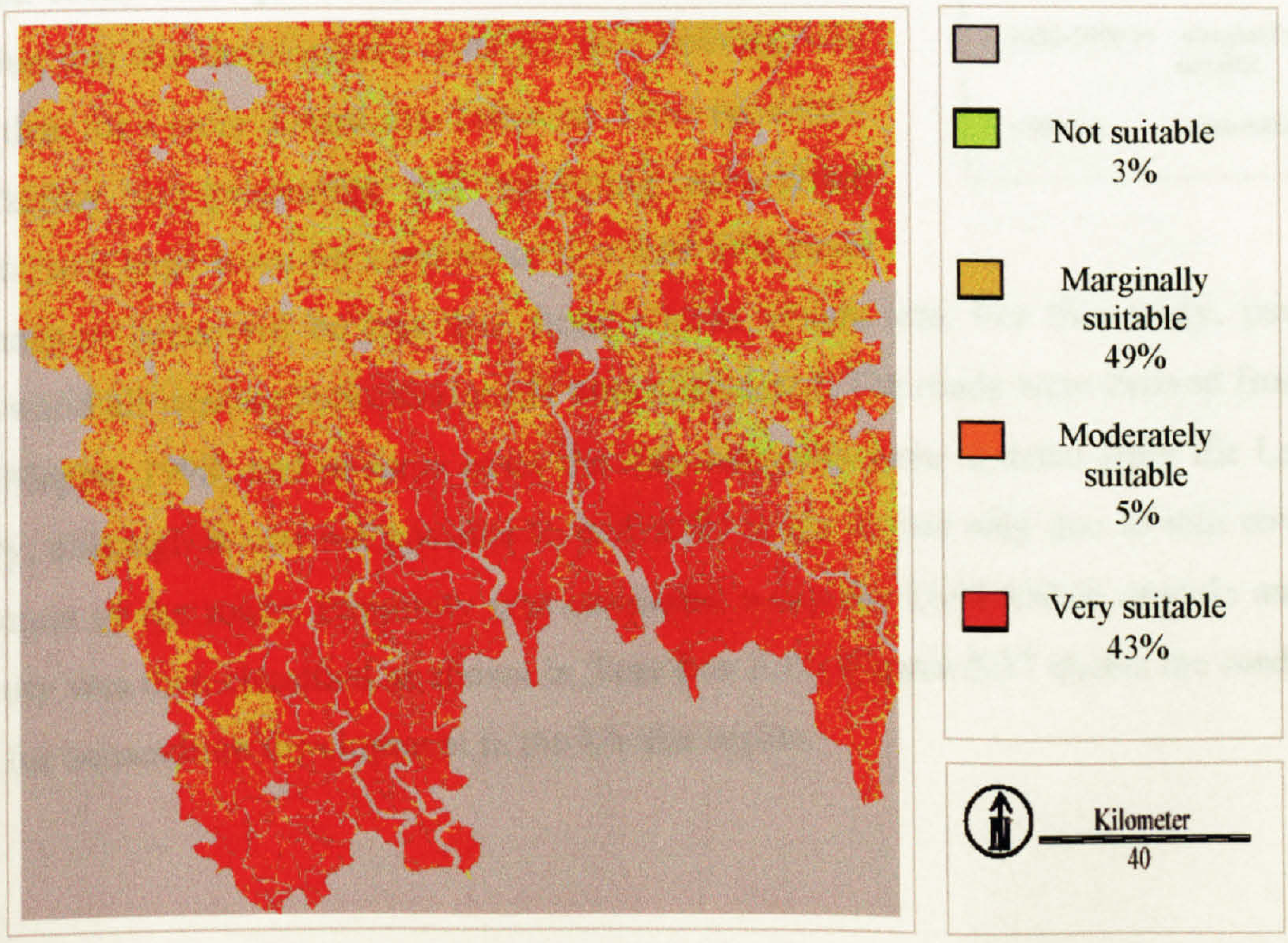

Figure 5.36. Opportunities for aquaculture in the Khulna region, Bangladesh, based on existing land use.

5.12 Infrastructure

Infrastructure is an important criterion for the development of aquaculture. For the purposes of this study, the major infrastructure factors were considered to be:

- the road and water transportation systems in the immediate vicinity of the area.
- available seeds for the culture species.
- market potential for fish, shrimp, crab, prawn and tilapia.
- processing plants for shrimp and prawn in the area.

5.12.1 Road networks

Roads are required to transport products to processors and markets and also to receive the goods and supplies necessary for culture operations. Especially important from a cost point of view is distance and the travel time. Proximities are important in two ways: site development costs and culture operation costs. Close proximity to a road or landing centre will mean that site development costs for road building will be less than for a more distant site. Likewise, close proximity to a facility for processing and marketing aquaculture products, to a large town for supplies or to a feed mill mean that transport costs will be less than from a more distant site. For this study, paved roads, railways and all weather motorable roads were considered. The roads were derived from the road maps (Mappa, 1998) and in some cases the road networks were updated from the Landsat TM imagery, although it was not possible to derive all roads in this way due to tree coverage and narrowness of the roads. Proximity was calculated using the DISTANCE module and the road proximity was then classified as shown in **Text box 5.17. Figure 5.37** shows the road proximity image for aquaculture development in the Khulna region.

Text box 5.17. Scoring of proximity to roads.

Interpretation		Score
60-2000 m	very suitable	4
2000-3000 m	moderately suitable	3
3000-5000 m	marginally suitable	2
>5000 m	unsuitable	1

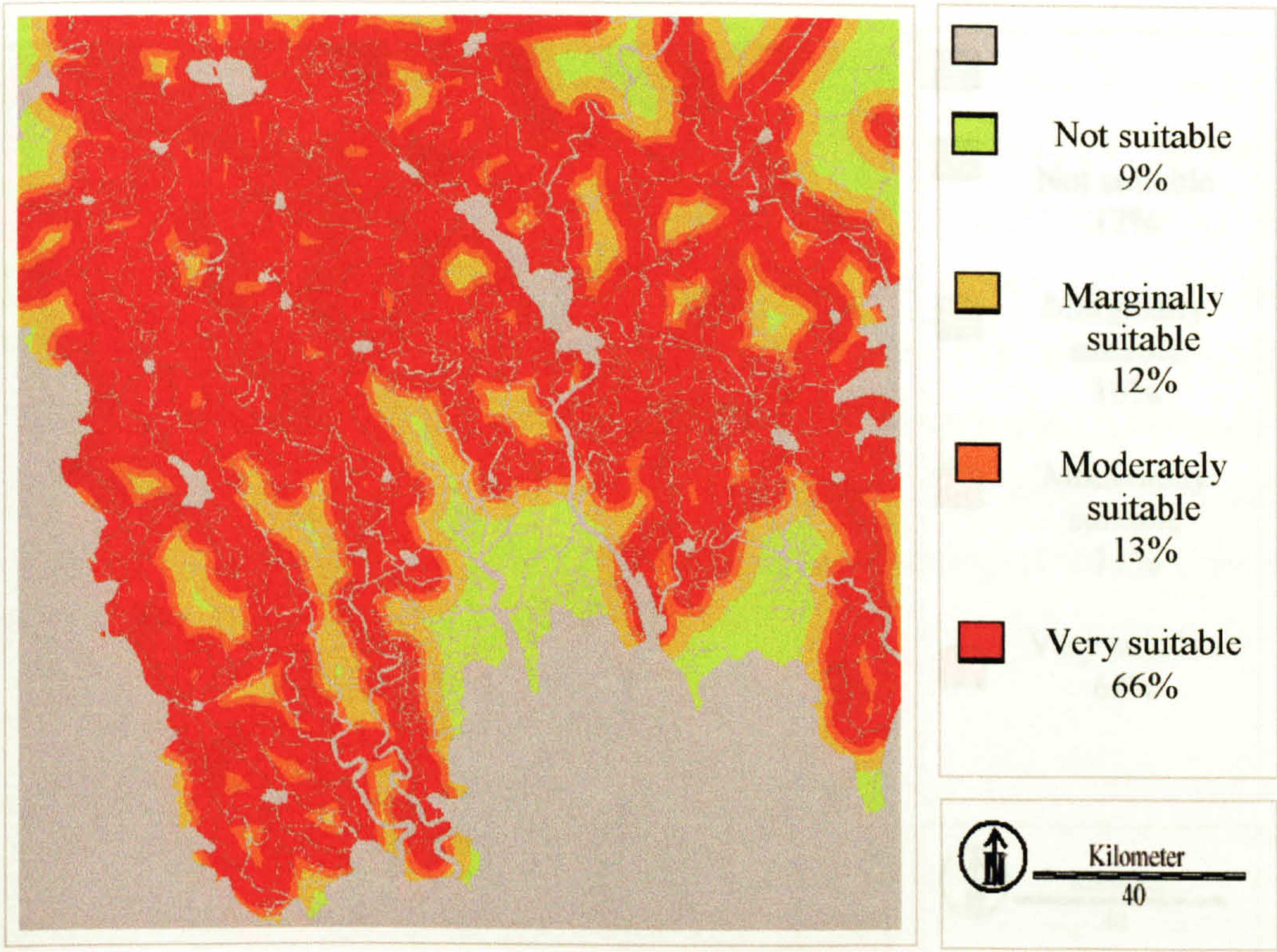

Figure 5.37. Proximity to road transportation in the Khulna region, Bangladesh for aquaculture development.

5.12.2 River transportation

Water transport is also very important as rivers play a vital role in the daily life of the people in the region. Transportation by water is comparatively cheaper than road transport in Bangladesh. Water bodies were derived from the Landsat image and water proximity was calculated using the DISTANCE module in IDRISI. The water proximity reclassified as shown in **Text box 5.18** and the resulting water proximity image is shown in **Figure 5.38.**

Text box 5.18. Scoring of proximity to rivers.

Interpretation		Score
<60-1000 m	very suitable	4
1000- 2 000 m	moderately suitable	3
2000-3000 m	marginally suitable	2
>3000 m	unsuitable	1

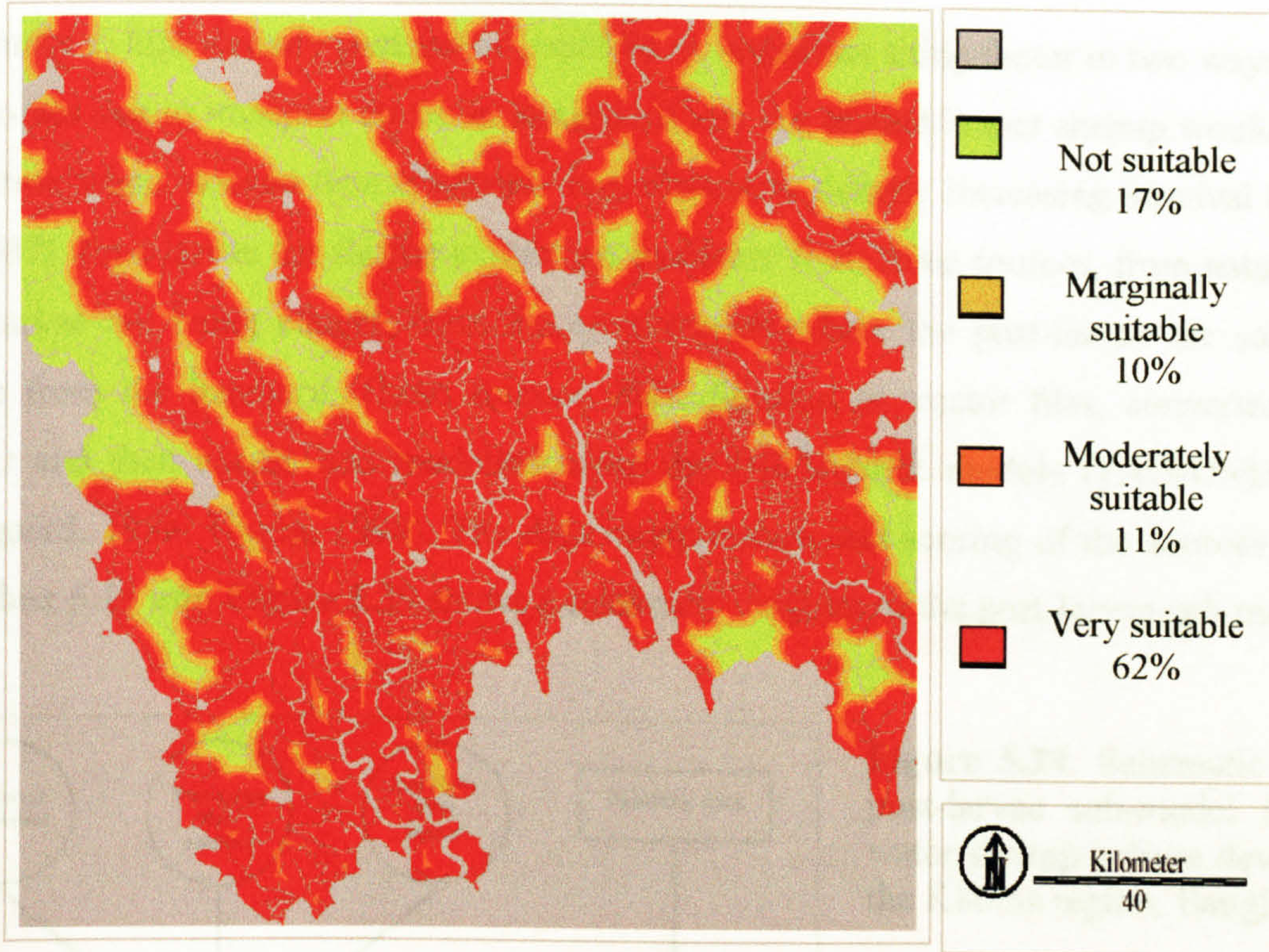

Figure 5.38. Suitable water proximity for transportation in Khulna region, Bangladesh for aquaculture development.

5.12.3 Sources of post-larvae

Shrimp post-larvae have to be available for successful culture as supplementary stocking is essential for higher productivity. If hatchery reared post-larvae are not available then the young stages must be collected from the wild. Thus, there is an advantage in knowing where post-larvae are most abundant so that they can be collected. In the Khulna region, most of these seed come from the environment, although a small number of hatcheries are in operation in the area. The farmers interviewed during the fieldwork have an impression that hatchery fry do not grow well so they prefer to use the natural fry in their ponds.

Text box 5.19. Scoring of sources of shrimp post-larvae and crab seed.

Interpretation		Score
Post-larvae from the hatchery		
<5 km	very suitable	4
5-10 km	moderately suitable	3
10-15 km	marginally suitable	2
>15 km	unsuitable	1
Post-larvae from the market		
<3 km	very suitable	4
3-7 km	moderately suitable	3
7-10 km	marginally suitable	2
>10 km	unsuitable	1
Post-larvae from the nature		
<3 km	very suitable	4
3-7 km	moderately suitable	3
7-12 km	marginally suitable	2
>12 km	unsuitable	1
Crab seed from the nature		
<10 km	very suitable	4
10-20 km	moderately suitable	3
20-30 km	marginally suitable	2
>30 km	unsuitable	1

Proximity to high-density post-larvae could be an important siting factor in two ways. The first is that losses due to transport could be minimised and the second is that shrimp would be in better condition when stocked than if carried long distances, thereby increasing survival (Kapetsky *et al.* 1987). Post-larvae for shrimp culture are available from three sources, from nature where the post-larvae are being caught, from the open market where the post-larvae are sold and post-larvae from the hatchery. These sources were digitised as vector files, converted into raster format and then access was modelled using the DISTANCE module (FAO-UNDP, 1994-95; Funegaard, 1986; Ubing, 1990). The data interpretation and scoring of the sources is shown in **Text box 5.19 and Figure 5.39** shows a schematic diagram of the post-larvae sub-model.

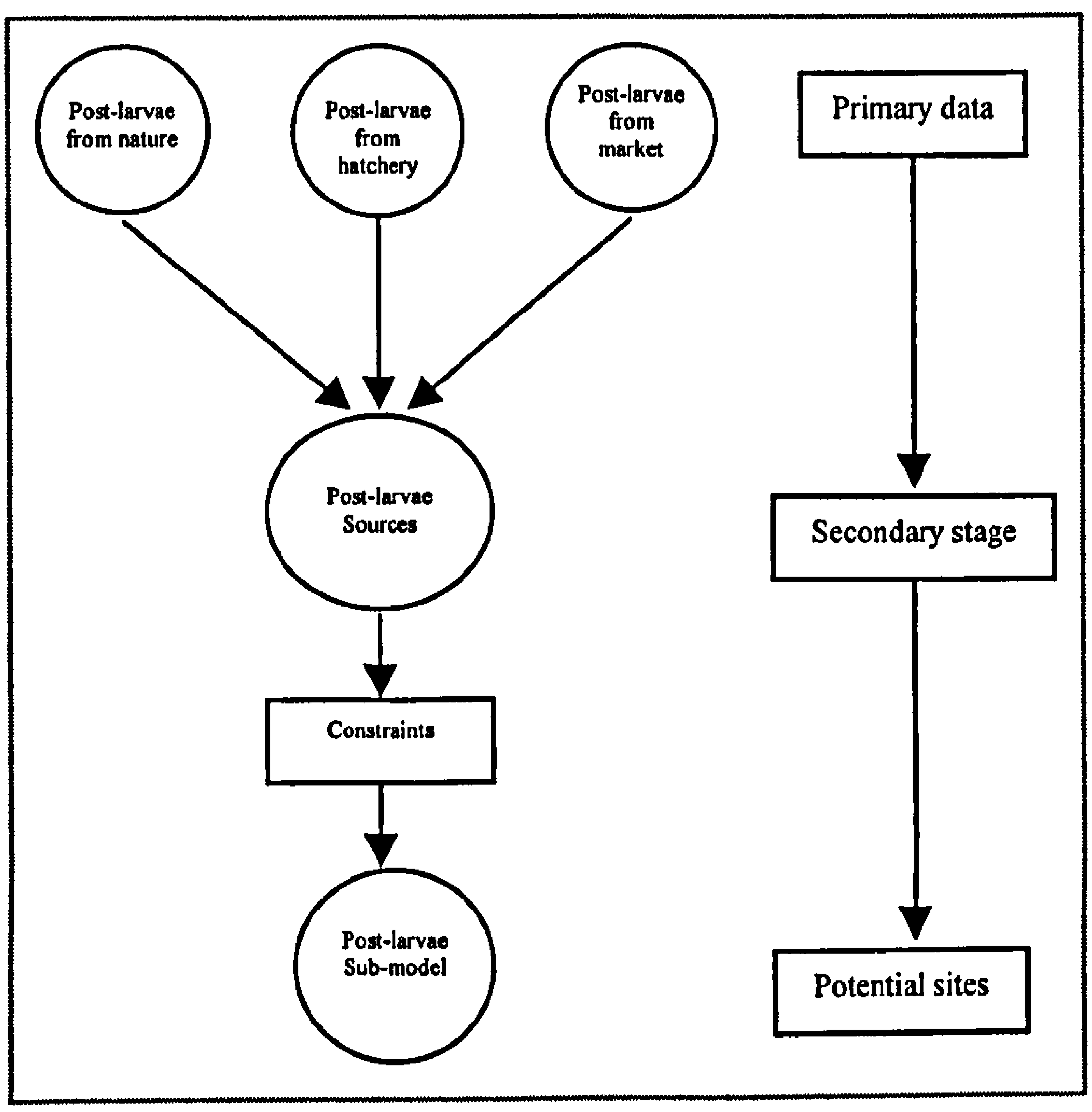

Figure 5.39. Schematic diagram of post-larvae sub-model for brackish water shrimp culture development in the Khulna region, Bangladesh.

Mathematical expression:

SSeedavl = (SSeedH x 0.3) + (SSeedN x 0.4) + (SSeedM x 0.3). Where, SSeedavl = shrimp seed availability, SSeedH = shrimp seed from hatchery, SSeedN = shrimp seed from nature and SSeedM =shrimp seed from market.

Figure 5.40 and **5.41** show the availability of shrimp post-larvae within the region. Image interpretation showed that none of the area is very suitable for shrimp post-larvae when the three different sources of post-larvae were used, whereas, plenty of post-larvae are being caught every year from the rivers and channels inside the Sundarbans mangrove forest and surounding it (Islam and Hossain, 1998). Moreover, the suitable area of post-larvae sub-model is reduced when three different sources of post-larvae were used. However, only the natural source of post-larvae makes a strong contribution to the suitable, moderately suitable and marginally suitable areas of the sub-model (**Figure 5.41**).

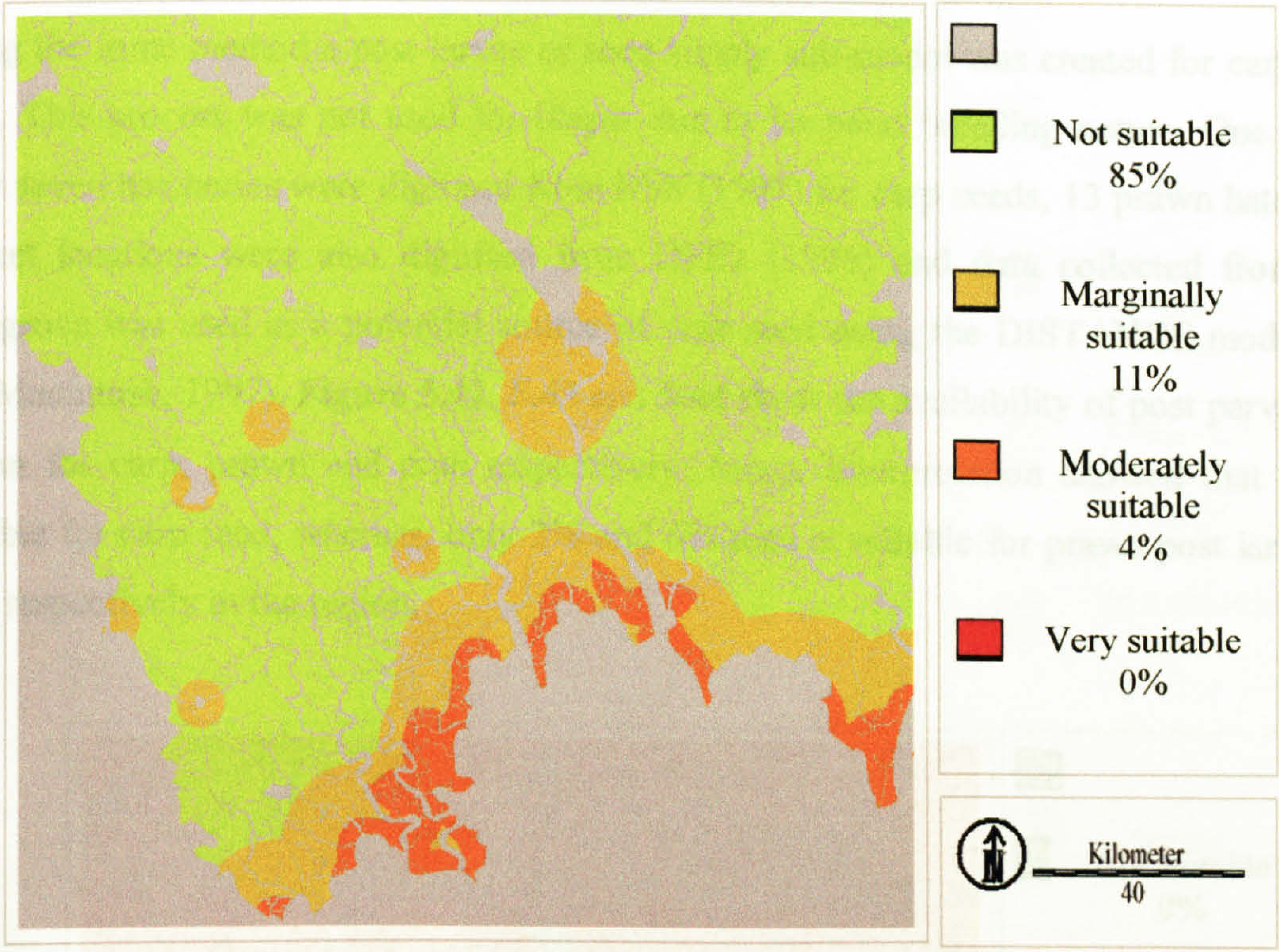

Figure 5.40. The distribution of shrimp post-larvae in the Khulna region when the three sources were used.

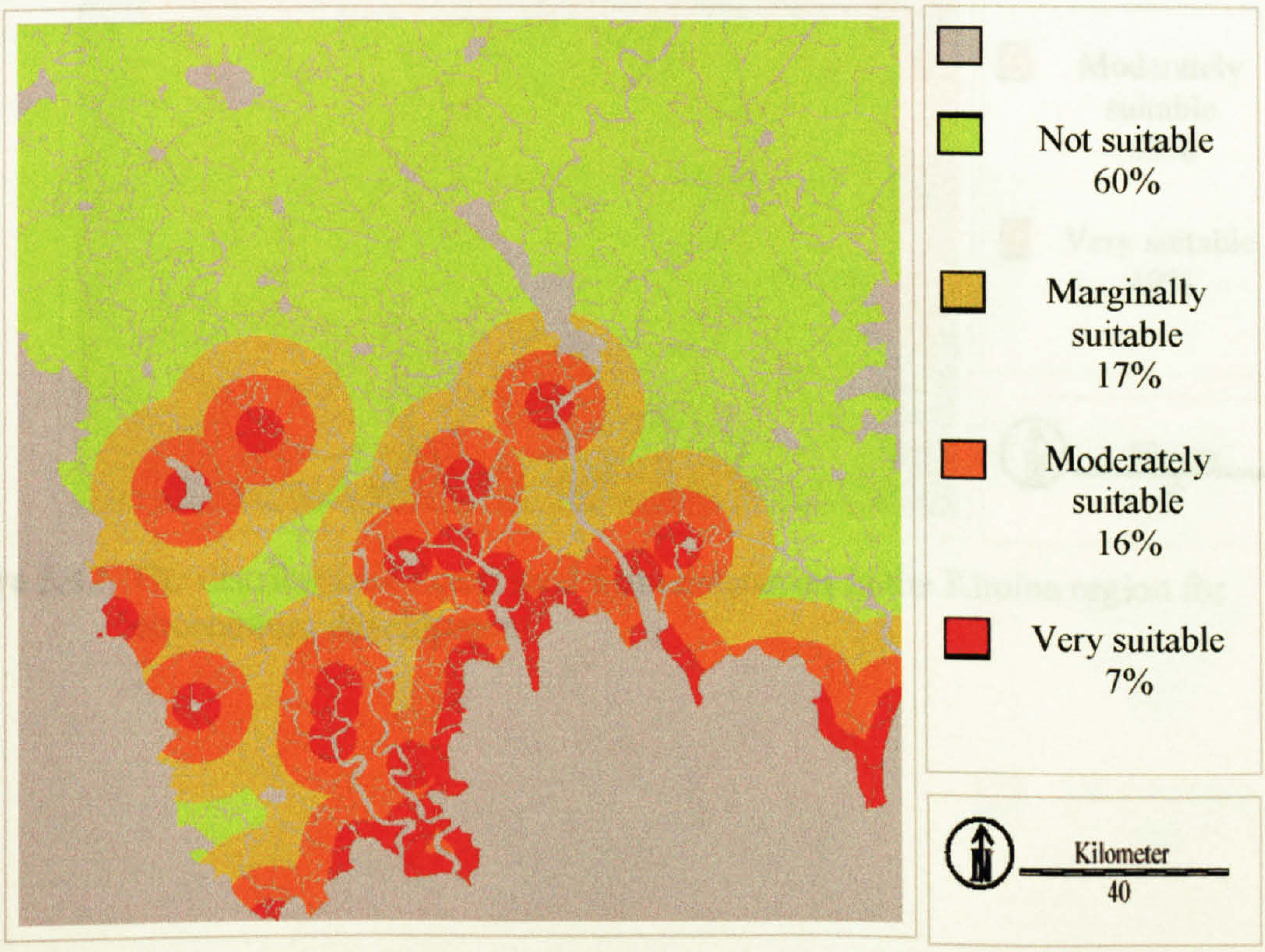

Figure 5.41. The distribution of post-larvae in the Khulna region when only natural source was used.

Using the same method a post-larvae or seed supply sub-model was created for carp, prawn and crab. This process was not used for tilapia due to its pond breeding nature. One hundred and sixty seven hatcheries were digitised from BSS (1997) for carp seeds, 13 prawn hatcheries and 9 market locations were also digitised from DFID (1996) and data collected from the fields. Mangrove was used as a potential source of crab seed using the DISTANCE module (Overton and Macintosh, 1997). **Figure 5.42, 5.43** and **5.44** show the availability of post parvae within the region for carp, prawn and crab respectively. Image interpretation showed that 49% area is suitable for carp seed, whereas, only 2% and 6% area is suitable for prawn post larvae and crab seed respectively in the region.

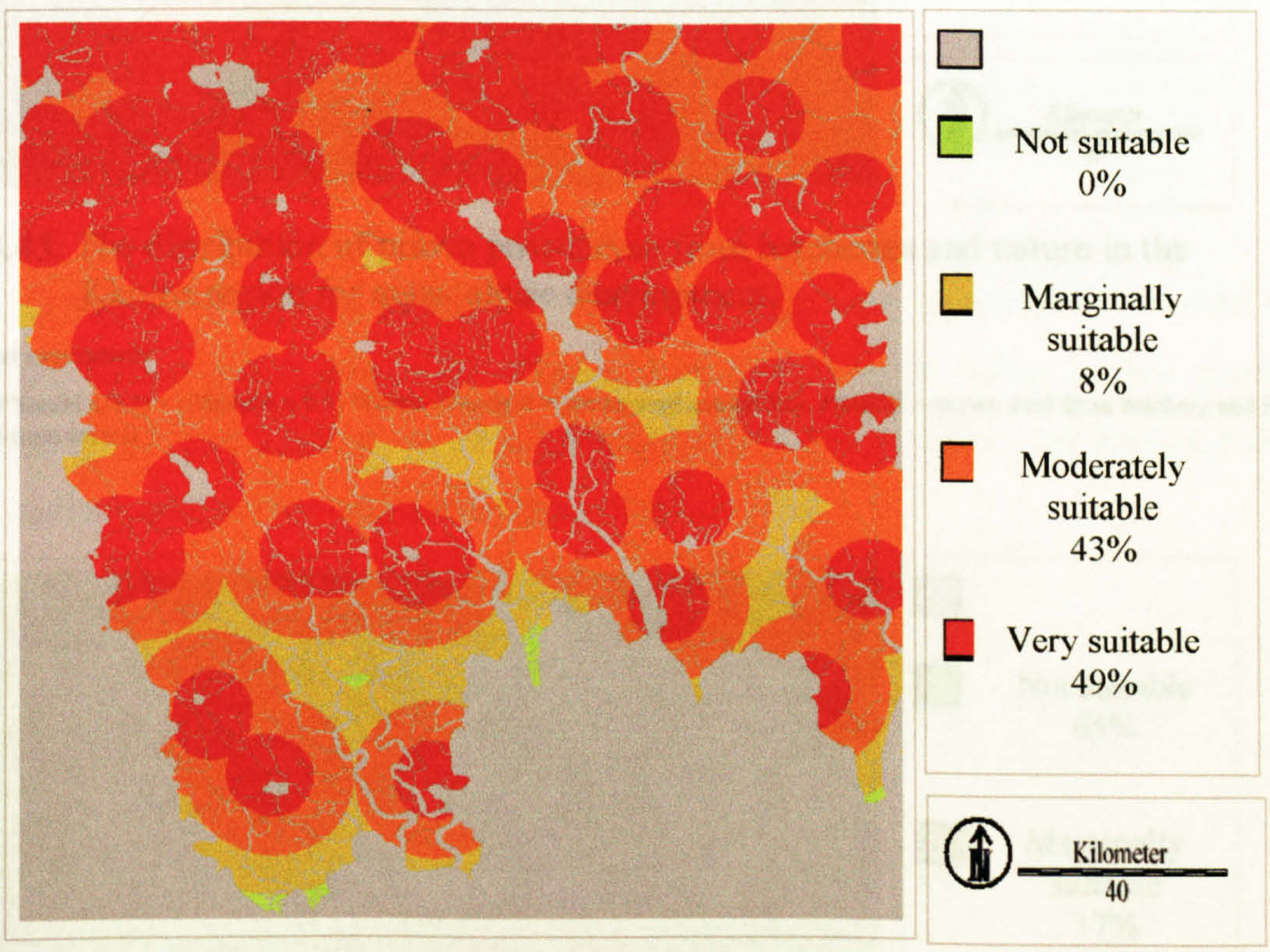

Figure 5.42. The distribution of carp seed from hatcheries in the Khulna region for aquaculture development.

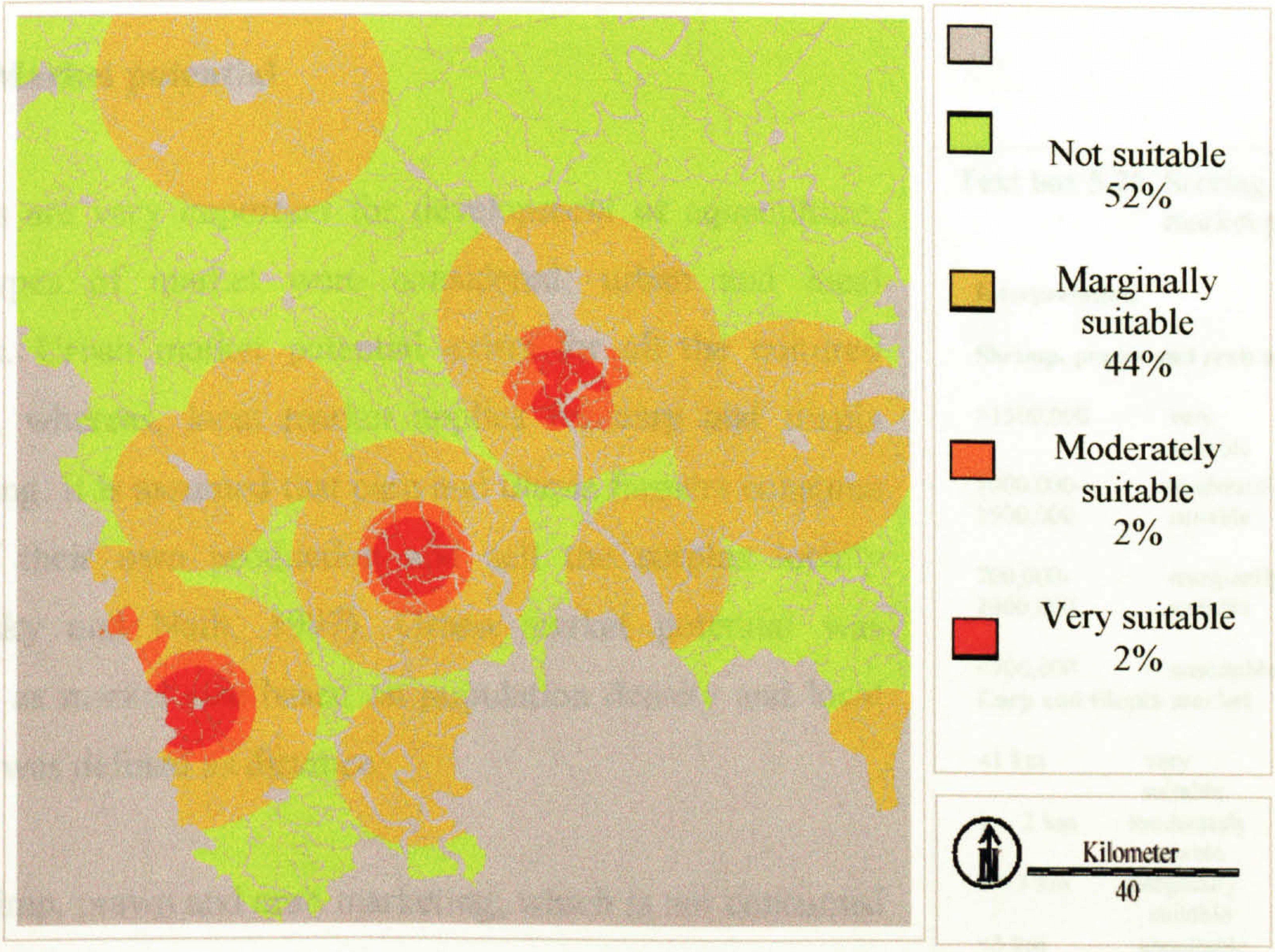

Figure 5.43. The distribution of prawn post-larvae from hatcheries and nature in the Khulna region for aquaculture development.

Mathematical expression:

PSeedavl = (PSeedH x 0.5) + (PSeedM x 0.5) Where, PSeedavl = prawn seed availability, PSeedH = prawn seed from hatchery and PSeedM = prawn seed from matket.

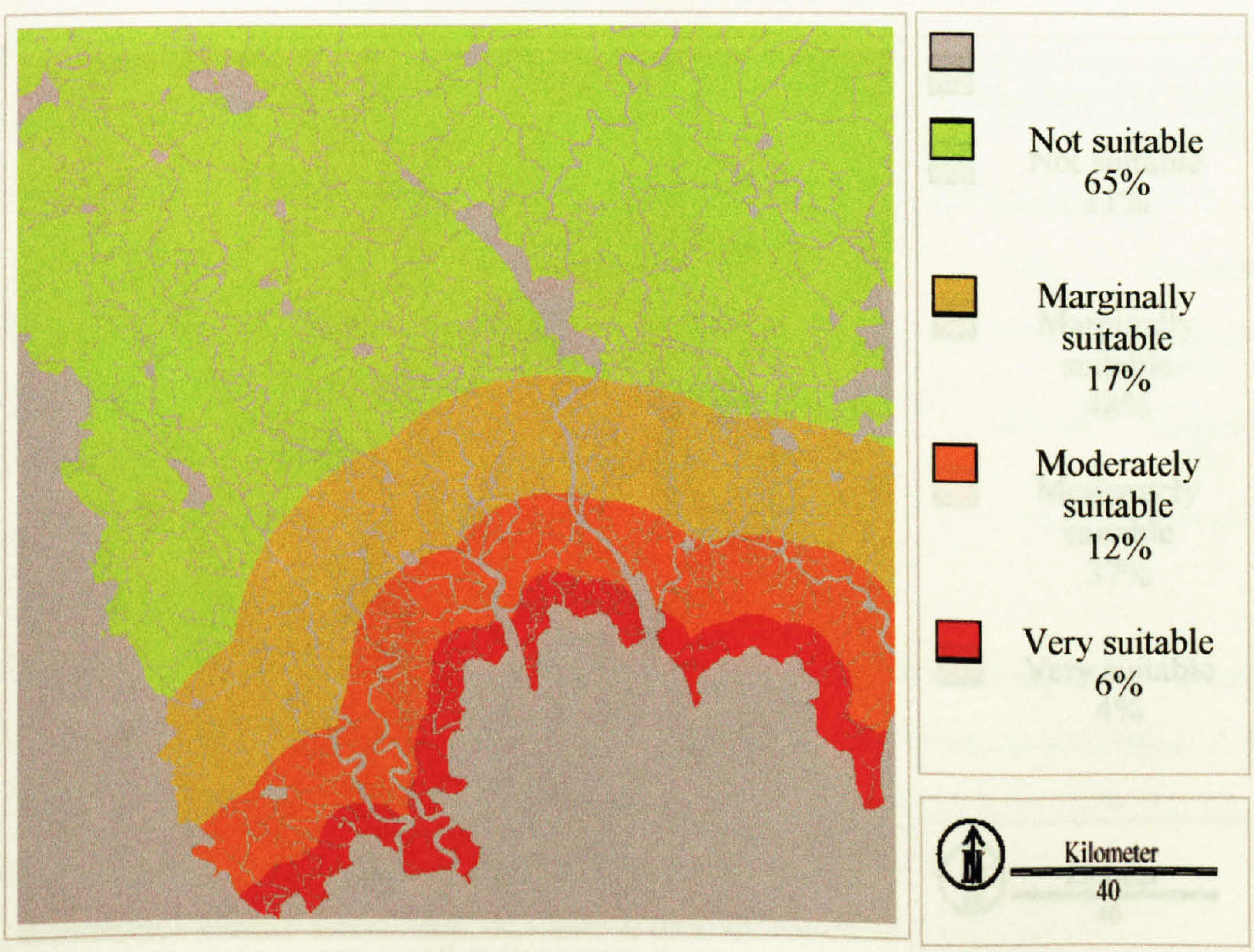

Figure 5.44. The suitable area range of crab seed in the Khulna region for aquaculture development.

5.12.4 Market potential

Markets are very important for development of aquaculture. Two types of market were considered: urban and local markets. Urban market potential exists for all the cultured species, whereas, local market applies for carp and tilapia marketing. It is assumed that carp and tilapia farmers consume part of their own production and sell the surplus locally (Kapetsky and Nath, 1997). Urban market potential was defined as market size based on population density and local market was defined as distance.

Text box 5.20. Scoring of market potential.

Interpretation		Score
Shrimp, prawn and crab market		
>1500,000	very suitable	4
1000,000-1500,000	moderately suitable	3
700,000-1000,000	marginally suitable	2
<700,000	unsuitable	1
Carp and tilapia market		
<1 km	very suitable	4
1 – 2 km	moderately suitable	3
2 – 3 km	marginally suitable	2
<3 km	unsuitable	1

For shrimp, prawn and crab marketing, which is not consumed locally, have market potential in big population centres, like Capital City and other regional cities. The population data were re-classified in order to make four suitable classes (**Text box 5.20**). **Figure 5.45** illustrates the urban market potential for shrimp, prawn and crab aquaculture development in the Khulna region and **Figure 5.46** shows the local market potential for carp and tilapia culture.

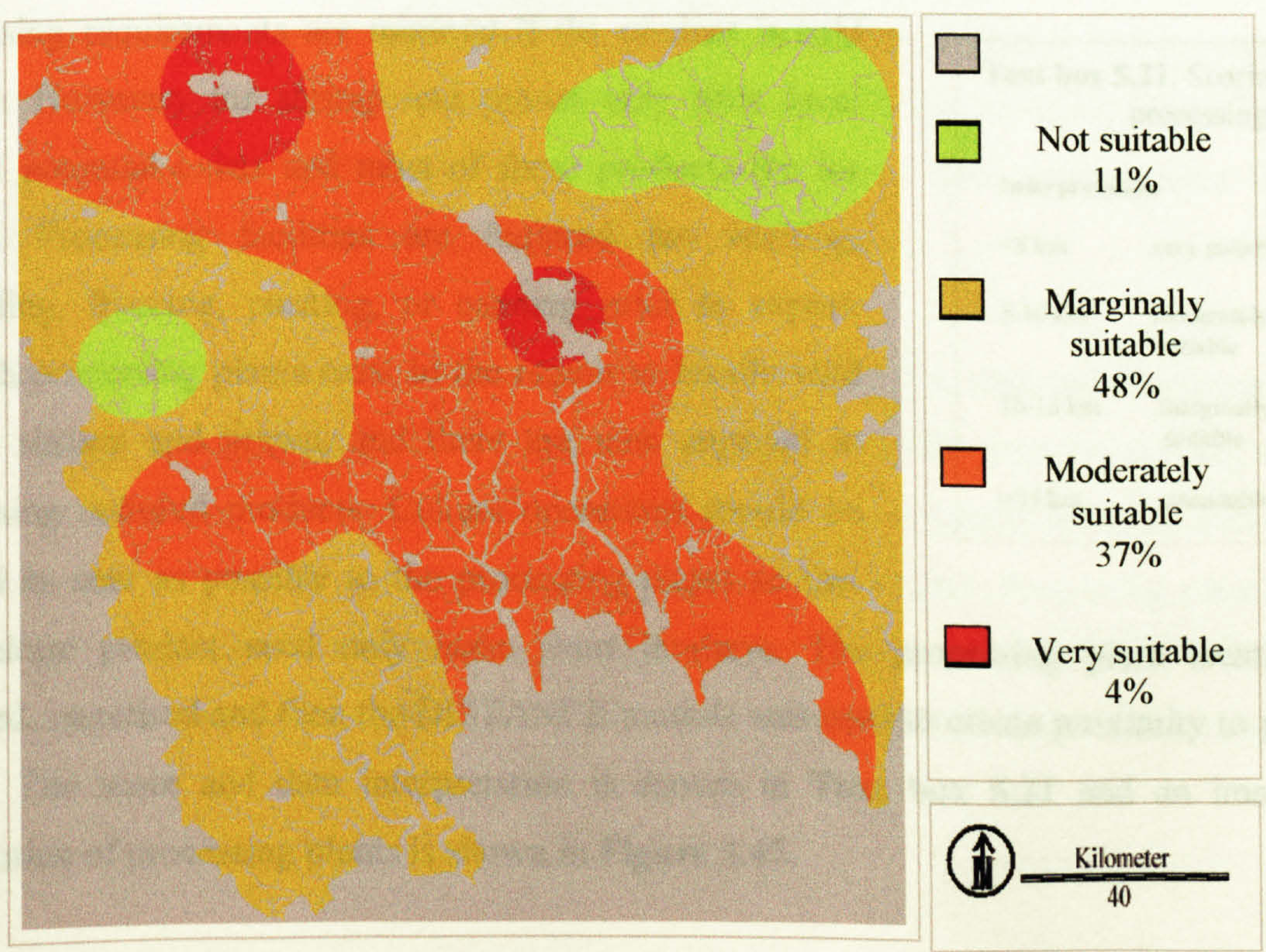

Figure 5.45. The urban market potential for shrimp, prawn and crab culture in the Khulna region, Bangladesh for aquaculture development.

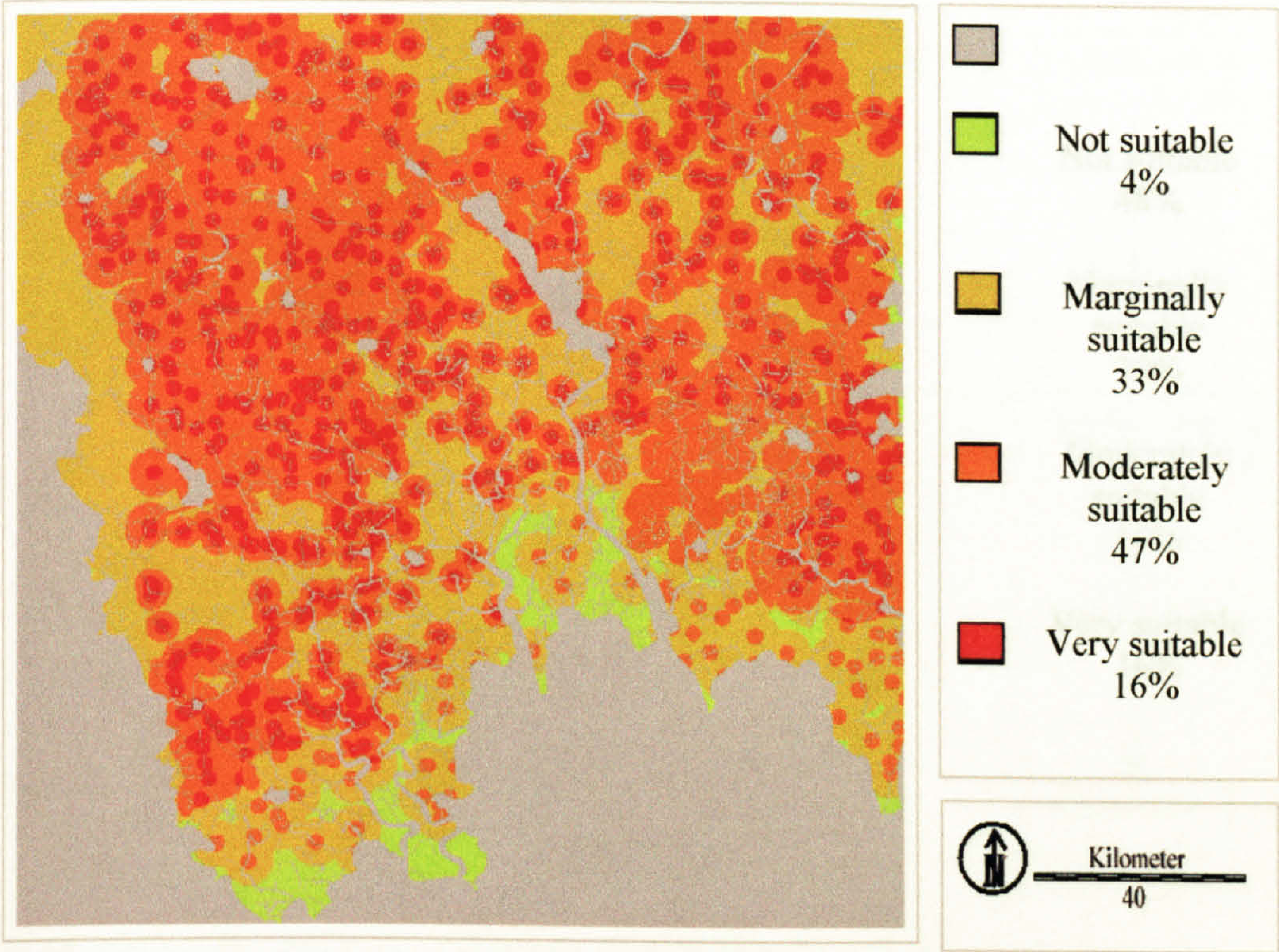

Figure 5.46. The local market potential for carp and tilapia culture in the Khulna region.

5.12.5 Processing plants

Processing requirements are minimal if the product is sold locally. However, for shrimp and prawn very little local market potential exists and most of these products are for export. Processing facilities are required for washing, beheading, freezing, packing, or canning prior to export. Enough processing plants exist in the region to handle wild caught shrimp and prawn, and there are now engaged in processing cultured products. Culture operations should be located as near as possible to the processing plants so that aquaculture product need only make short journeys. The processing plant locations were digitised, rasterised and then the DISTANCE module was used to create proximity to processing plants. The score and data interpretation is shown in **Text box 5.21** and an image of the distribution of processing plants is shown in **Figure 5.47.**

Text box 5.21. Scoring of processing plants.

Interpretation		Score
<5 km	very suitable	4
5-10 km	moderately suitable	3
10-15 km	marginally suitable	2
>15 km	unsuitable	1

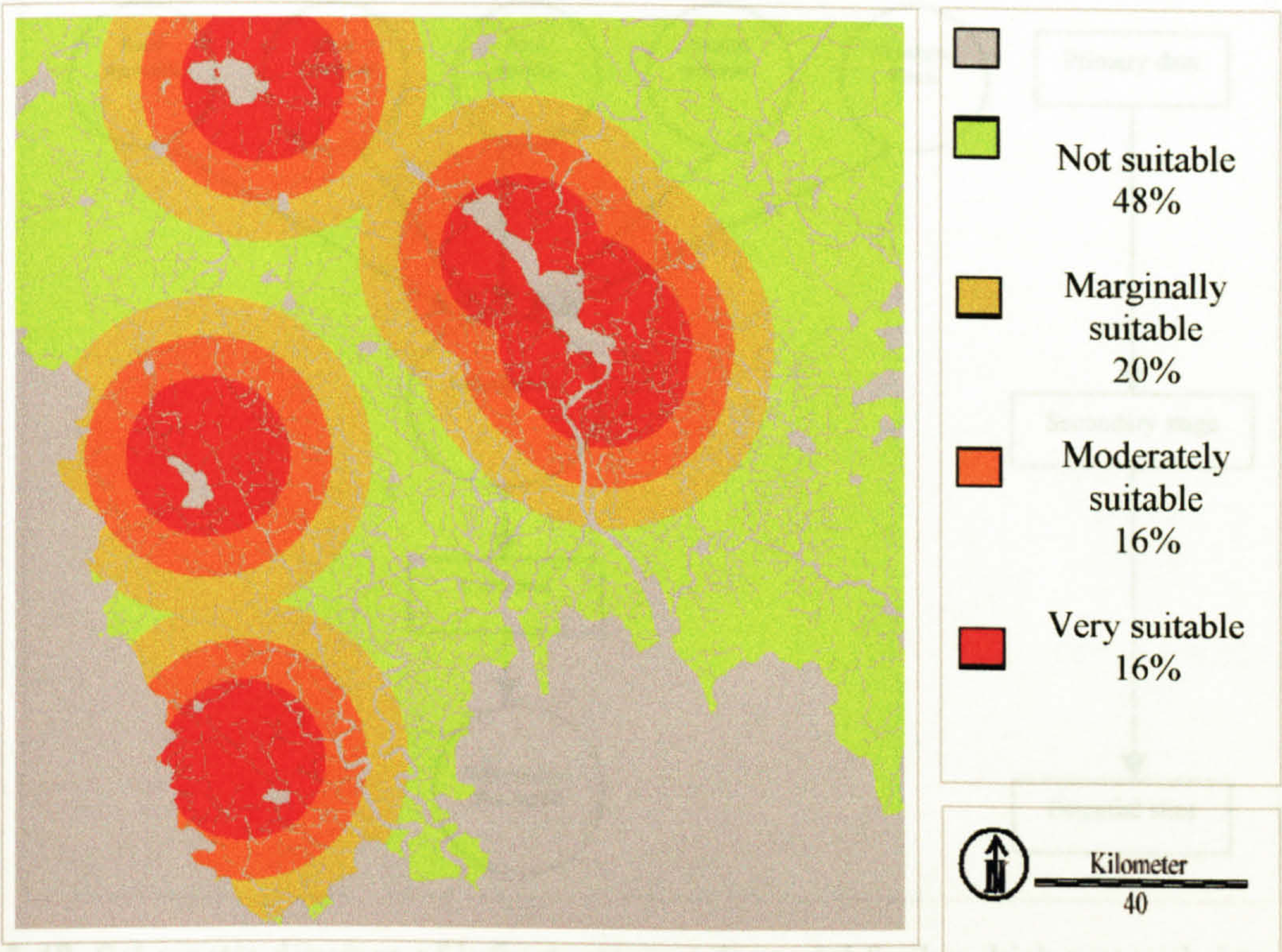

Figure 5.47. The proximity to processing plants for shrimp and prawn processing in the Khulna region, Bangladesh for aquaculture development.

5.12.6 Integration of Infrastructure sub-model

Road networks, river transportation, post-larvae sources, market potential and processing plants were combined into an infrastructure sub-model, which was prepared using MCE. **Figure 5.48** shows the sequence of sub-model development and **Figure 5.49** demonstrates the overall classification of infrastructure in the Khulna region, Bangladesh.

Similarly, an infrastructure sub-model was created for crab, prawn, carp and tilapia and these are shown in **Figures 5.50, 5.51**, **5.52** and **5.53**. The technique was the same but scoring for various species were different. For example, the crab infrastructure sub-model included available post-larvae, distance from roads and rivers for transportation and market. Processing plants were not included in this sub-model as crab is exported live using bamboo baskets. **Figure 5.54** shows a comparison of the suitable area of different infrastructure sub-models in the Khulna region.

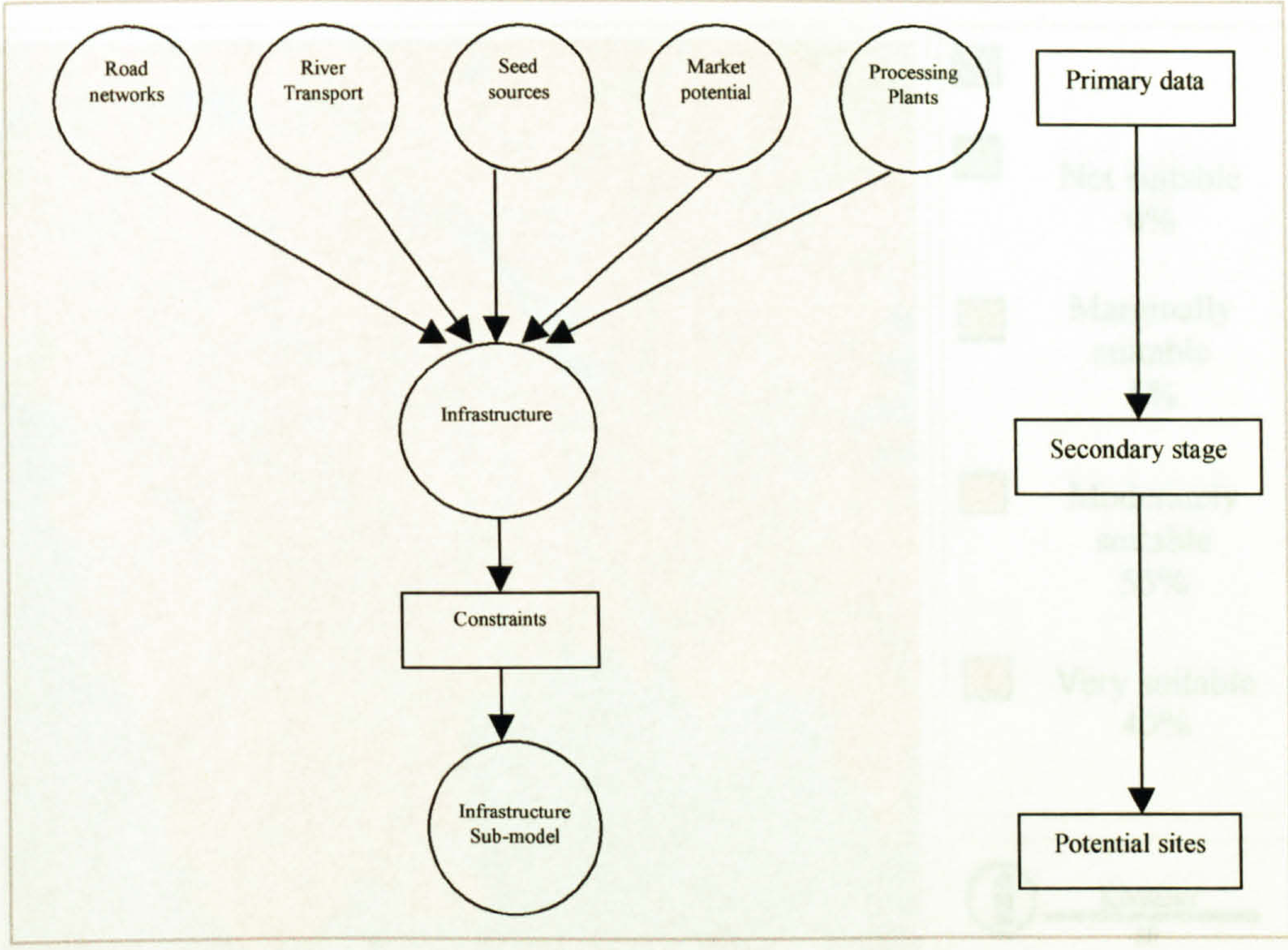

Figure 5.48. Schematic diagram of infrastructure sub-model for brackish water shrimp culture development in the Khulna region, Bangladesh.

Mathematical expression:

InfraS = (PoPlnt x 0.1590) + (SFry x 0.3598) + (MarS x 0.1799) + (Rdist x 0.2113) + (Rivdist x 0.0900), Where, InfraS = infrastructure for shrimp culture, PoPlnt = processing plants, SFry = available shrimp seed, MarS = market for shrimp, Rdist = distance from roads and Rivdist = distance from rivers respectively.

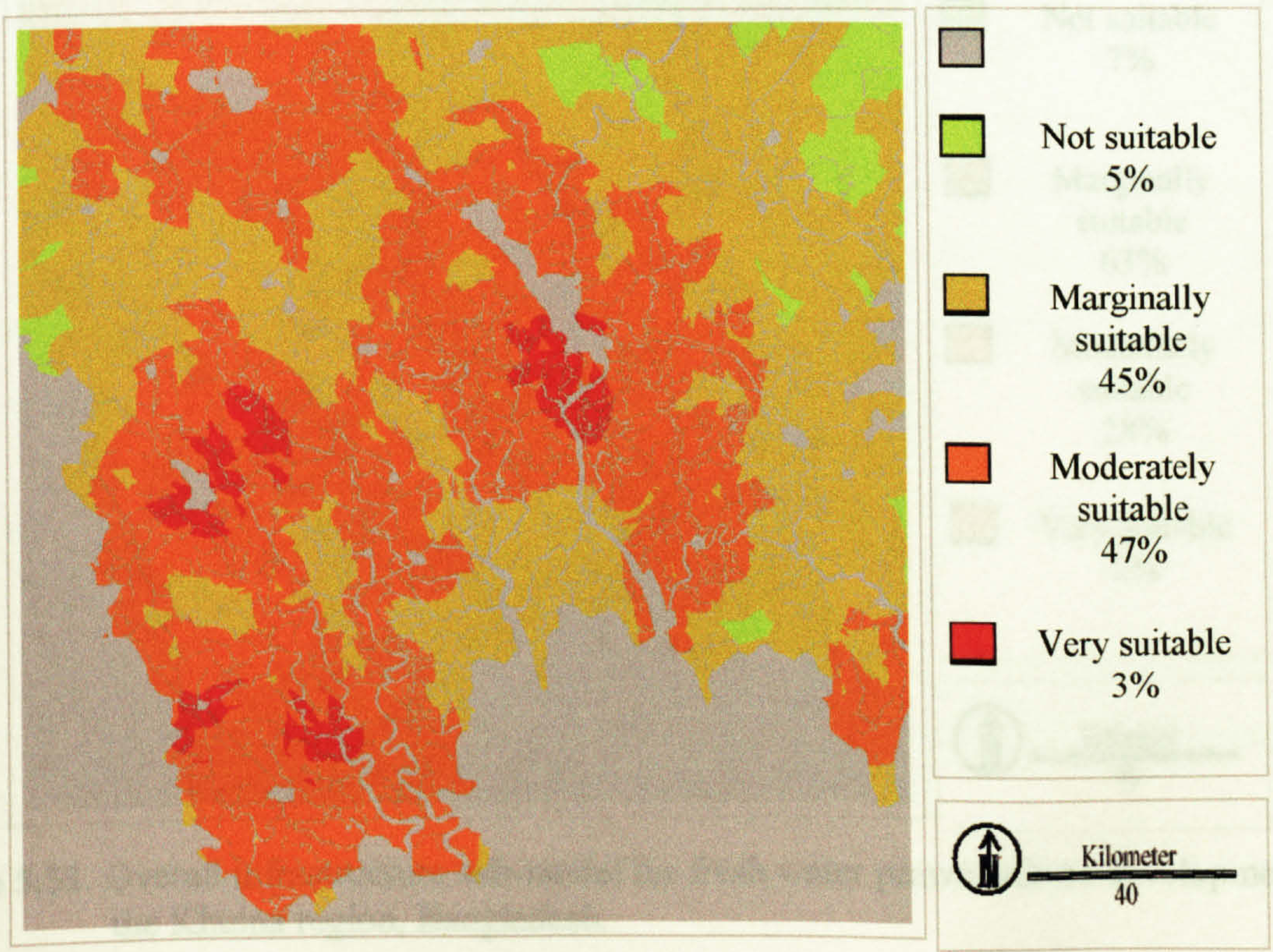

Figure 5.49. Overall infrastructure sub-model for brackish water shrimp culture development in the Khulna region, Bangladesh.

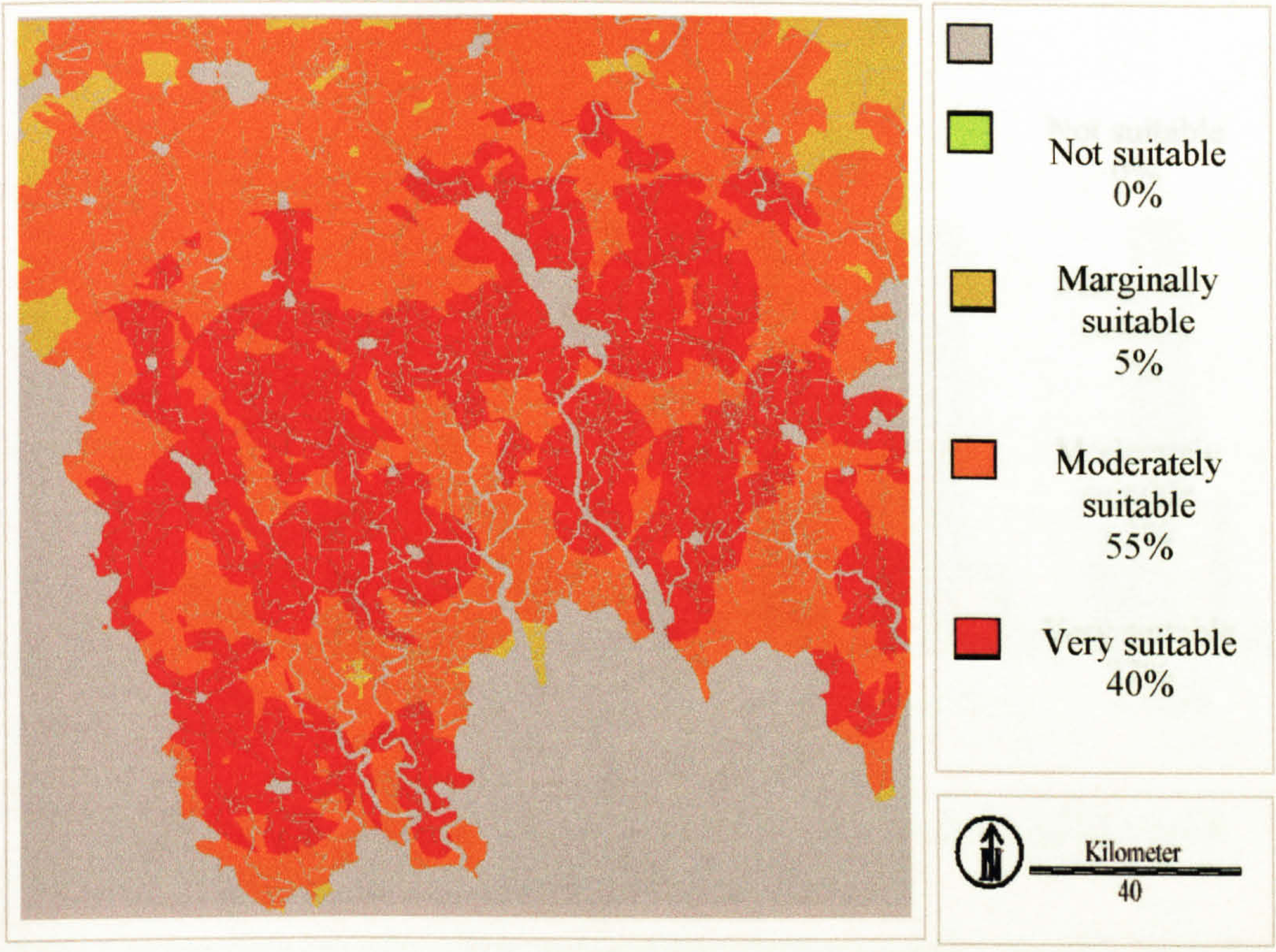

Figure 5.50. Infrastructure sub-model for brackish water crab culture development in the Khulna region, Bangladesh.

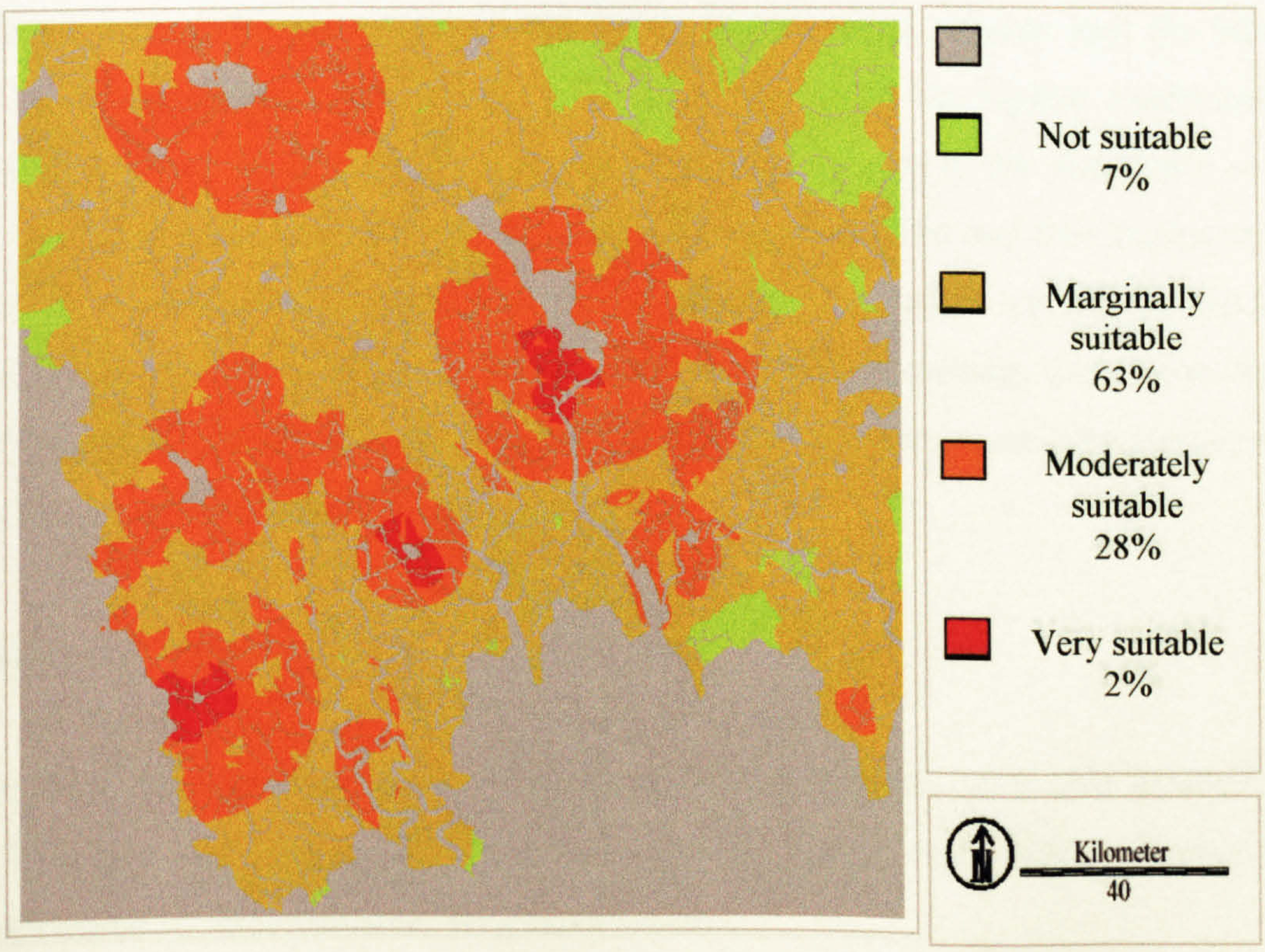

Figure 5.51. Overall infrastructure sub-model for fresh water prawn culture development in the Khulna region, Bangladesh.

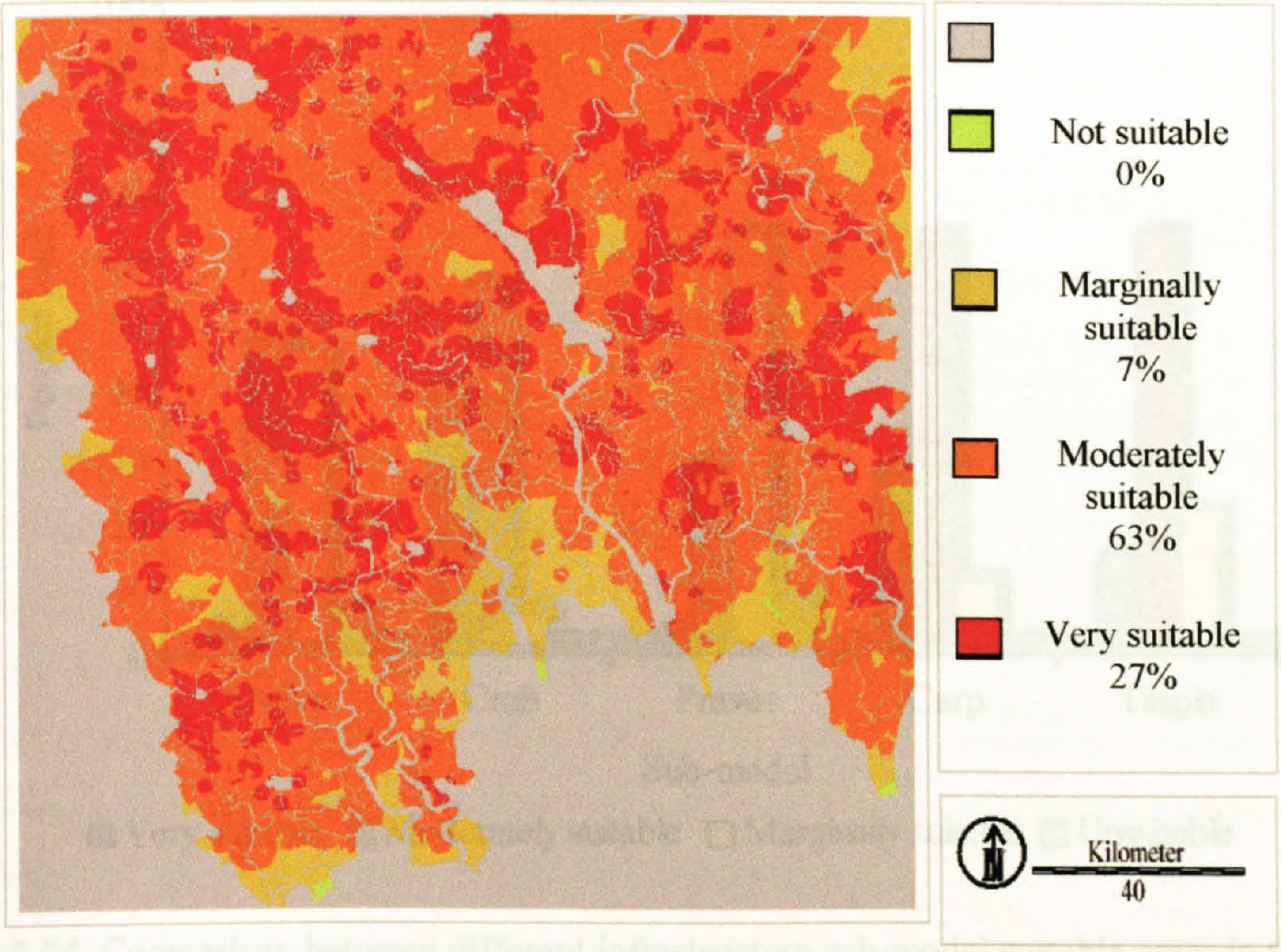

Figure 5.52. Overall infrastructure sub-model for fresh water carp culture development in the Khulna region, Bangladesh.

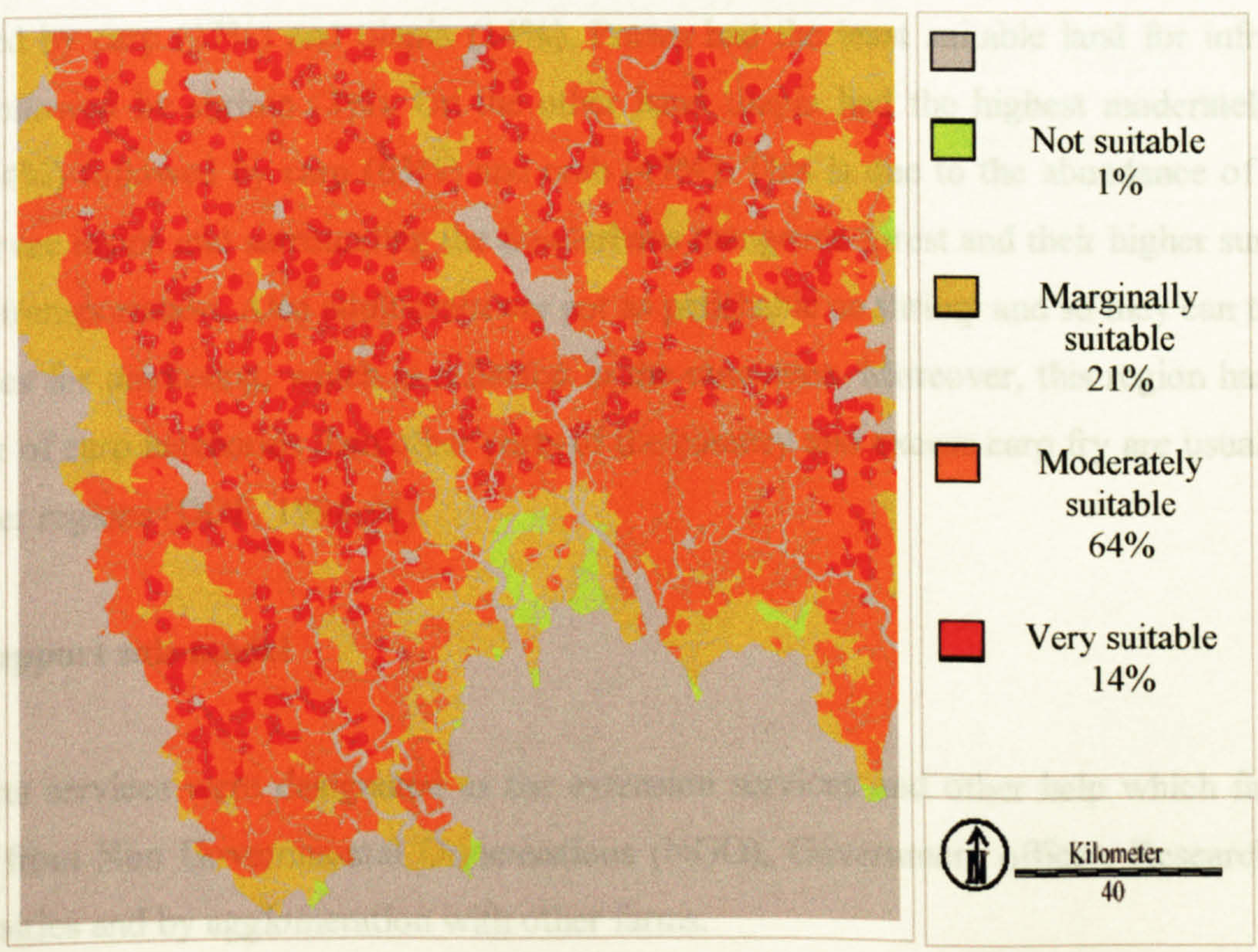

Figure 5.53. Overall infrastructure sub-model for fresh water tilapia culture development in the Khulna region, Bangladesh.

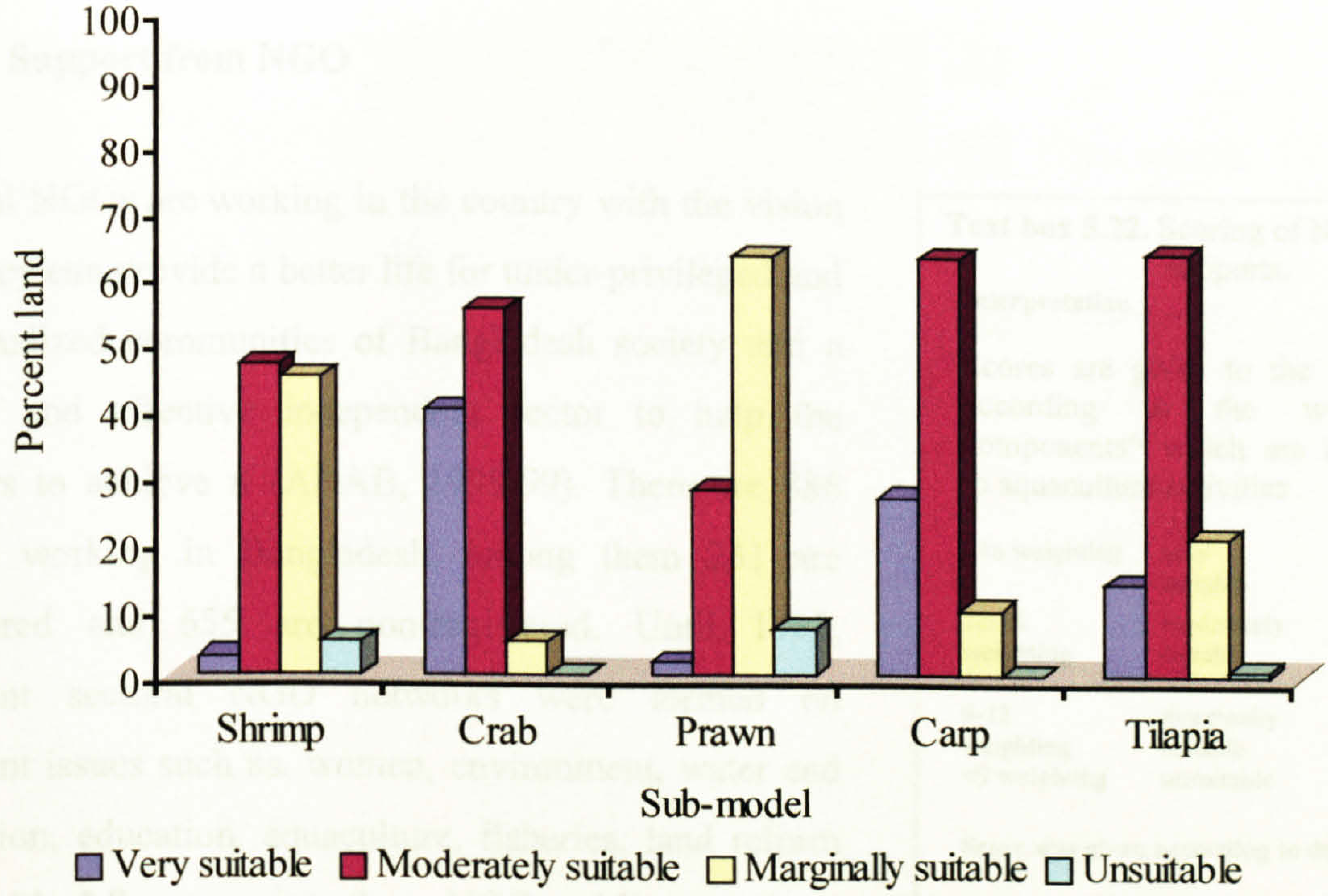

Figure 5.54. Comparison between different infrastructure sub-model suitable areas in the Khulna region for aquaculture development.

Image interpretation showed that crab had the highest suitable land for infrastructure (40%) followed by carp (27%) and tilapia (14%). Prawn had the least suitable land for infrastructure (2%) followed by shrimp (3%). On the other hand tilapia had the highest moderately suitable land (64%) followed by carp (63%) and crab (47%). This is due to the abundance of crab post post-larvae inside and surrounding the Sundarbans mangrove forest and their higher survival rate during transportation. Also adult crabs are not as perishable as shrimp and so they can travel long distances for marketing, which is reflected in the outcomes. Moreover, this region has a higher number of carp hatcheries than other parts of the country and excess carp fry are usually sold to the other regions (DOF, 1994-95).

5.13 Support sub-model

Supports services were designated as the extension services and other help which farmers can obtain from Non Governmental Organisations (NGO), Government offices, Research stations, Universities and by agglomeration with other farms.

5.13.1 Support from NGO

Several NGOs are working in the country with the vision that they can provide a better life for under-privileged and marginalized communities of Bangladesh society and a strong and effective independent sector to help the farmers to achieve it (ADAB, 1998-99). There are 886 NGOs working in Bangladesh, among them 231 are registered and 655 are non-registered. Until 1997, different sectoral NGO networks were formed on different issues such as, women, environment, water and sanitation, education, aquaculture, fisheries, land reform etc. **Table 5.7** summarises those NGOs with aquaculture development objective are working in the region. Data interpretation and scoring is shown in **Text box 5.22** and **Figure 5.55** shows range of NGO support which was created using the distance module and **Figure 5.56** was created according their activities and manpower weightings. **Figure 5.57,** shows the schematic diagram of support from NGO's. **Figure 5.58,** illustrates the range of NGO support in the region.

Text box 5.22. Scoring of NGO supports.

Interpretation		Score
Scores are given to the NGOs according to the working components* which are related to aquaculture activities		
>16 weighting	very suitable	4
12-16 weighting	moderately suitable	3
9-12 weighting	marginally suitable	2
<9 weighting	unsuitable	1
Score was given according to distance		
>5 km	very suitable	4
5-10 km	moderately suitable	3
10-15 km	marginally suitable	2
<15 km	unsuitable	1

*credit=3, fisheries=3, livestock = 1, poultry = 1, training = 3 technical manpower = 5, etc.)

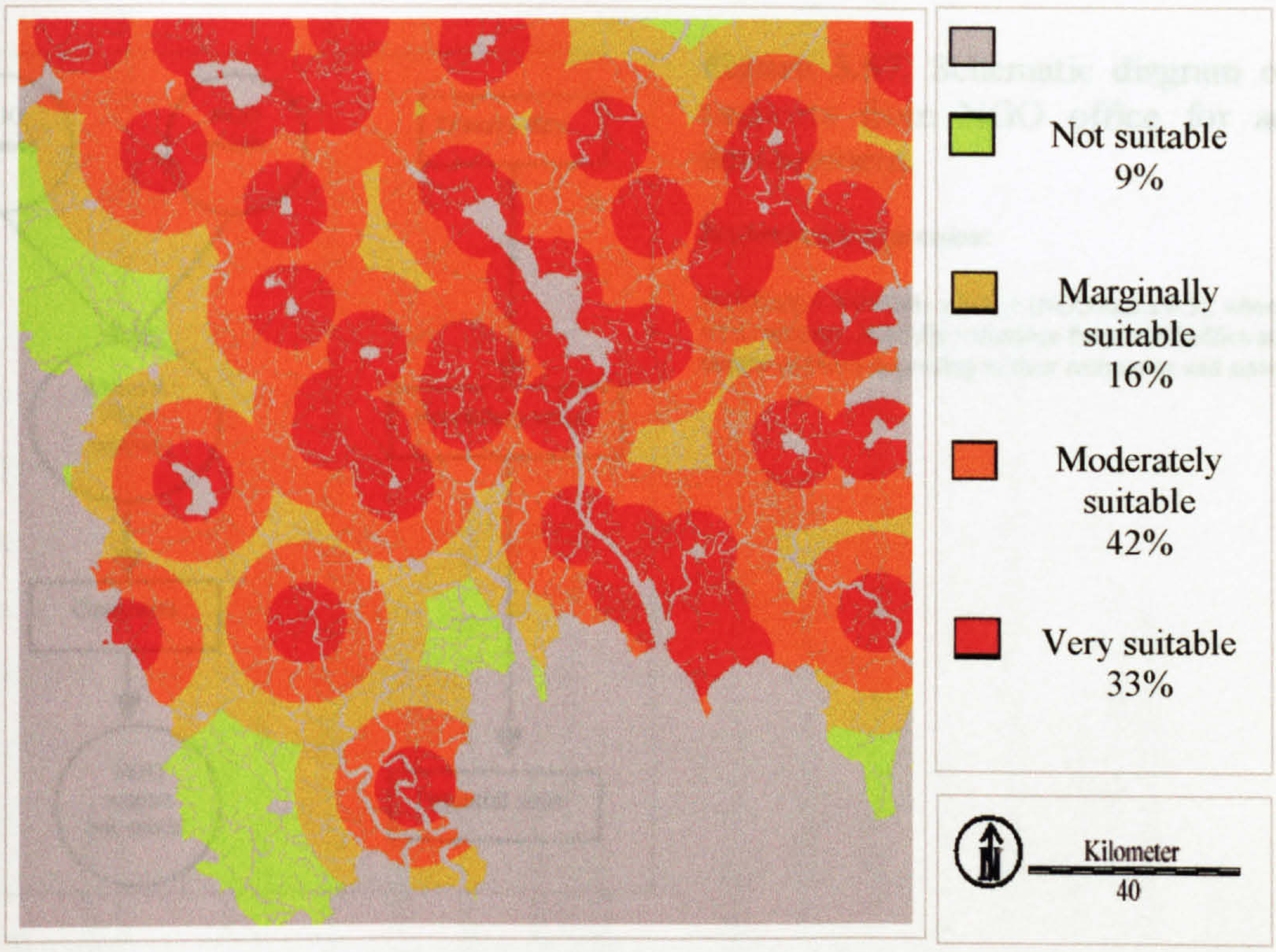

Figure 5.55. The coverage of NGO support in the South-western region of Bangladesh for aquaculture development.

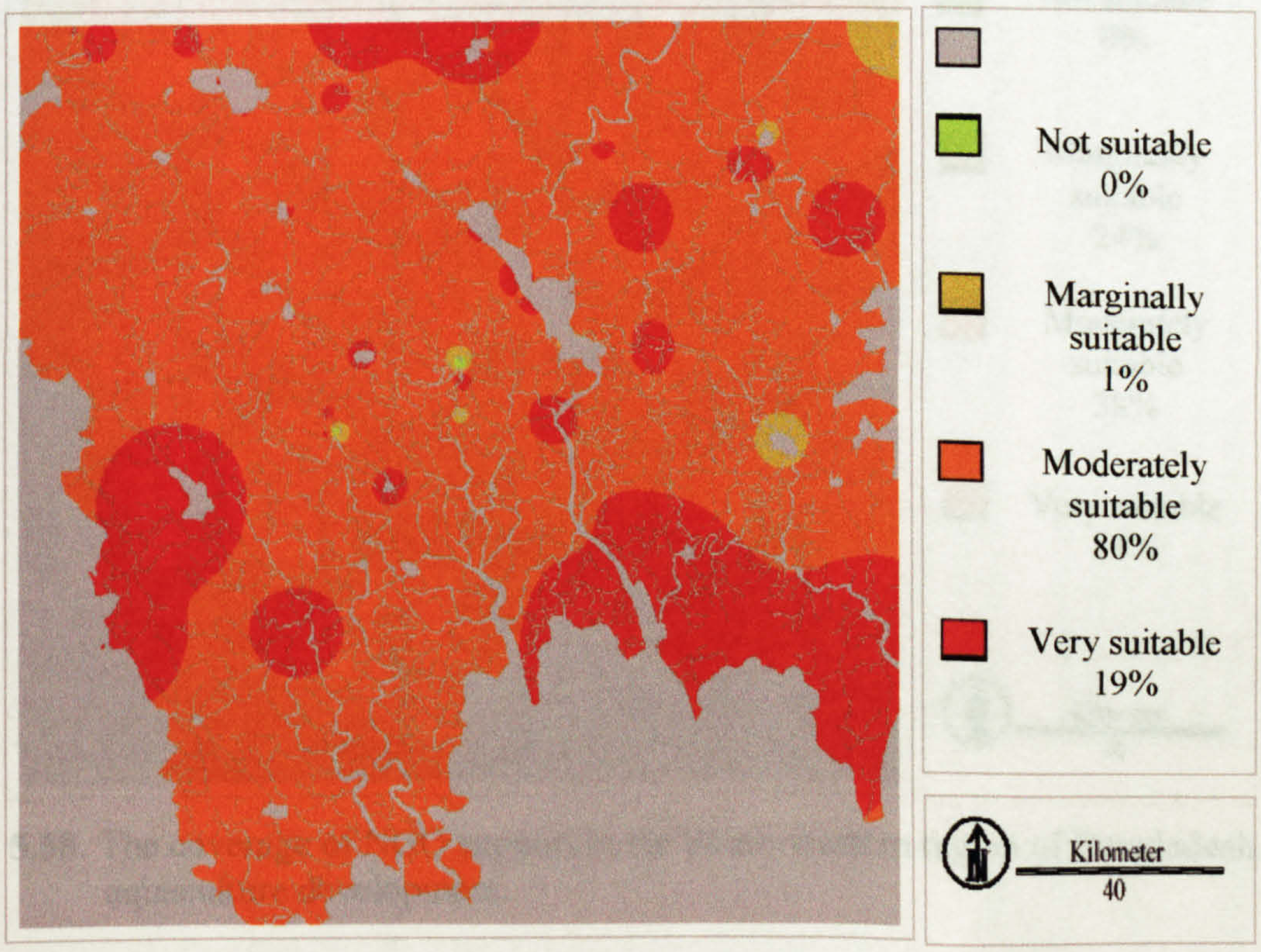

Figure 5.56. NGO support according to manpower and range of activities in the South-western region of Bangladesh for aquaculture development.

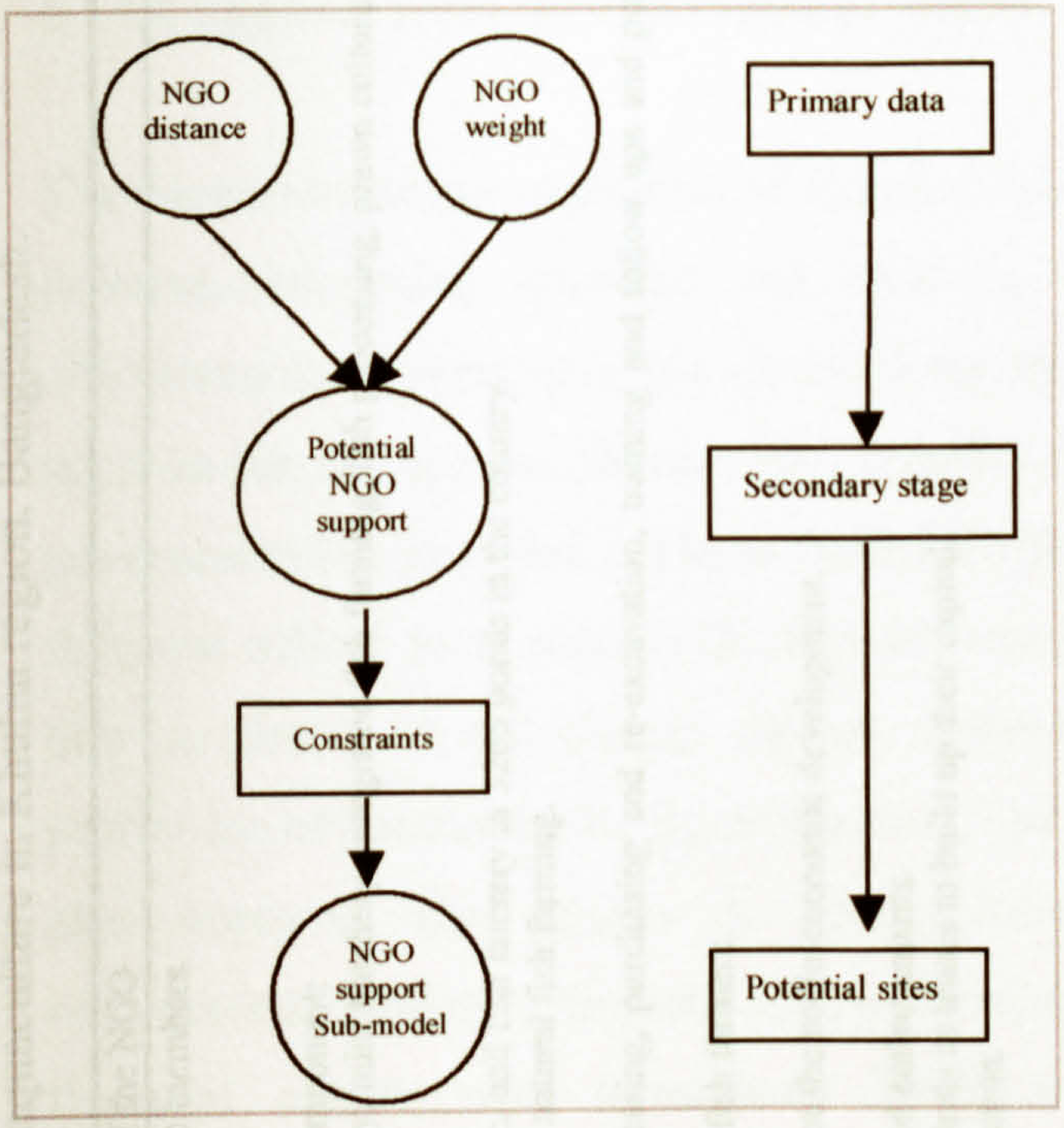

Figure 5.57. Schematic diagram of creating supports from NGO office for aquaculture development.

Mathematical expression:

NGOSutp = (NGOdis x 0.5) + (NGOActi x 0.5), where, NGOSutp = NGO support, NGOdis = distance from NGO office and NGOActi = weight of NGO according to their manpower and activities.

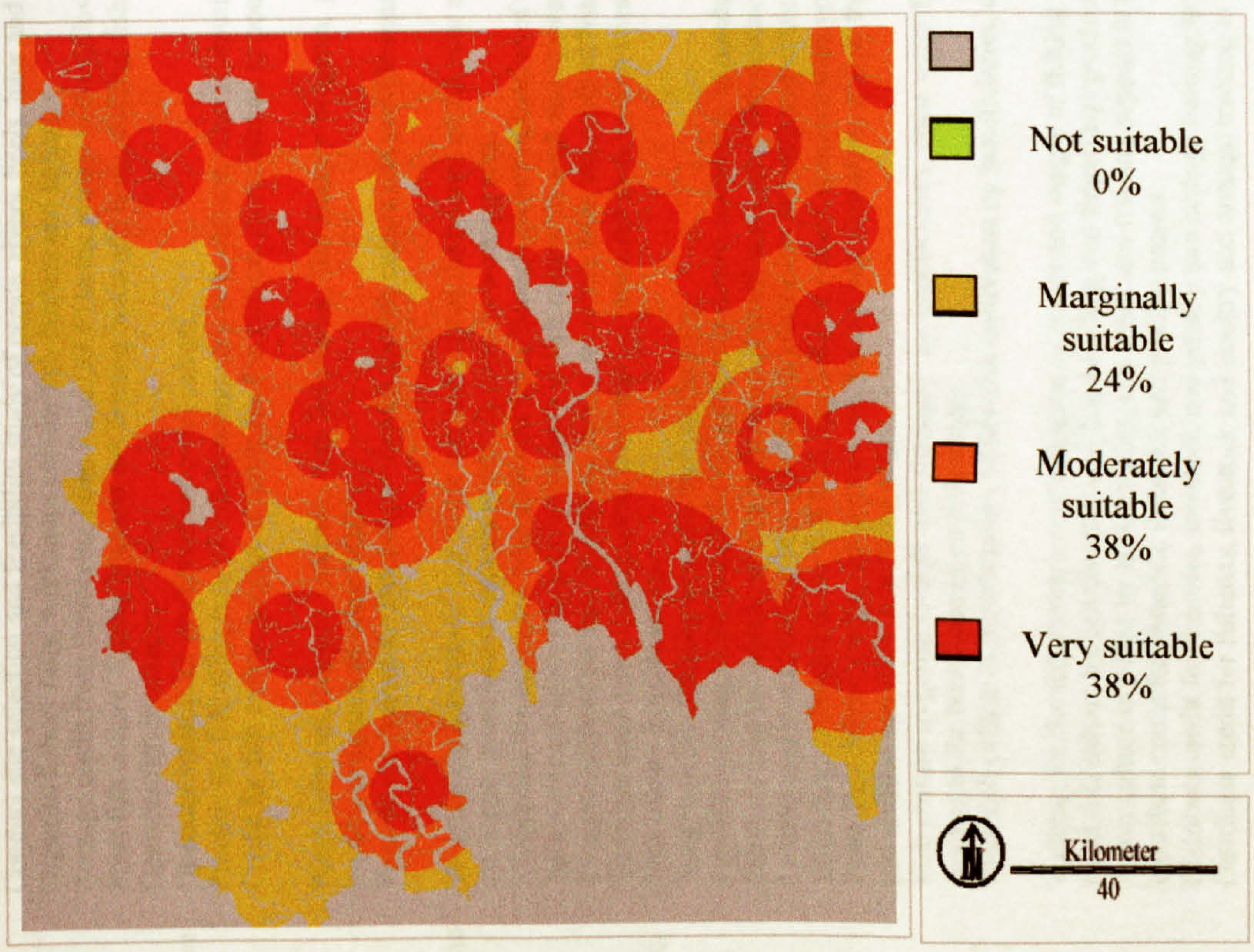

Figure 5.58. The coverage of NGO support in the South-western region of Bangladesh for aquaculture development.

Table 5.7. List of NGOs working in the region and their objectives to development aquaculture in Khulna region, Bangladesh.

Name of the NGO	The Objective of the NGO
Proshika	Provides various aspect of fisheries related training to extension workers and group members. Conduct site selection and feasibility study of ponds, rivers, beels, haor and gher. Organise fishery rally, workshops etc. for fish farmers and fishers. Arrange credit from Revolving Loan Fund (RLF) to the groups in the following component: Pond fish culture, fishing boat and net, leasing boars and beels, fishing, fish nursery, mini hatchery, integrated fish farming, fish processing, prawn culture etc.
Bangladesh Rural Advancement Committee (BRAC)	Operates fish hatcheries. Operates small pilot hatcheries and pearl culture Practice the following type of fish farming: carp poly-culture, Thai sharputi culture, and fish nursery in 3265 ponds in the country.
Barisal Development Society (BDS)	Credit for fish culture project, training for fish culture, re-excavation of ponds and natural fish farming.
Karitus Bangladesh	Pond fisheries, capture fisheries, carp hatcheries, fish nursery program, pond leasing, purchasing and re-excavation, training and follow ups and provide training programs to other NGO's.
Development Partner (DP)	Pond re-excavation for fish culture, credits for fish culture and provide training to fish farmers.
Gono Unnayan Prochesta (GUP)	To establish fish culture as a major bio-industry of the poorest of the poor aiming at the socio-economic development. To supply more animal protein to beneficiaries in working area. To increase the supply of vegetable and fruits through proper utilisation of the pond embankments. To involve co-operative society (Samity) in fish culture through taking over the ponds as leases to build up their capital. To grow habit of savings among the samity members from the profit of fish production. To create employment and protect the fisheries resources from natural hazards.
Gono Shahajjo Sangstha (GSS)	Fish culture in ox-bow lakes. Integrated fish farming in ponds by beneficiaries.
Heed Bangladesh (HB)	Provides training to the beneficiaries, undertake prawn cultivation in ponds, distribute fingerlings to beneficiaries and provide credit to beneficiaries.
ITDG Bangladesh	Provide technical advice mainly in the area of small-scale pond fish culture.
Jagorani Chakra (JC)	Leasing and re-excavation of ponds for fish production, training and credit support to beneficiaries for pond fish culture, production and supply of healthy fish fingerlings to beneficiaries, fish breeding and rice culture demonstration projects.
Nabalok Parishad (NP)	Pond fish culture (carps and prawn), motivation and formation of fish farmers, credit and training services to fish farmers and advocacy and promotion of pisciculture activities in working area.
Prodipan	Fish culture in ponds (carps and shrimps) by beneficiaries, open water fisheries fish stocking in collaboration with the government and credit and training support to the beneficiaries on fish culture.
Rural Reconstruction Centre (RRC)	Pond fish culture of beneficiaries, paddy-fish cultivation by beneficiaries, credit, and training support to the beneficiaries on fish culture.
Bachte Shekha (BS)	Training for the fish farmers, re-excavation of ponds and supply of fishing and credit to beneficiaries
Uttaran	Pond fish culture by beneficiaries and fish breeding and fingerlings production for distribution to beneficiaries.
CARE Bangladesh	Prawn culture in ponds by beneficiaries, and credit and training support to the beneficiaries on prawn culture.
Bridge	Distribute credit for fisheries, livestock and poultry project.
Nijera Kori	Distribute credit for fisheries, livestock and poultry and arrange training to the farmers.
Progati Samaj Kalyan Sangstha	Distribute credit for fisheries, livestock and poultry and arrange training to the farmers.
Punjia Jubo Samaj Kallyan Samity	Distribute credit for fisheries, livestock and poultry and arrange training to the farmers.
Unnayan	Distribute credit for fisheries, livestock and poultry and arrange training to the farmers.
Uttaran	Distribute credit for fisheries, livestock and poultry and arrange training to the farmers.
Bhumija	Distribute credit for fisheries, livestock and poultry project.

5.13.2 Support from the Government offices

The Government has objectives to increase fish production in a sustainable manner, alleviating poverty, improving nutrition and ensuring environmental sustainability. To fulfill these objectives the government has declared shrimp culture as an industry with some concessions such as no tax for the farmers and benefits to the processors and exporters. Moreover, the government has provided a Thana fisheries office to help the farmers. The mode of work of the fisheries officer is to support the fish farmers with the culture technology, extension services, how to deal with the shrimp disease outbreaks, conservation of wild seed and larvae and promotion of hatcheries for fry production. The fisheries officer also approves the shrimp or fish culture projects and recommends which farmers should have credit from the financial organisations throughout. There are 42 fisheries offices scattered. In addition to that there are five district fisheries offices with a district fisheries officer and other staff to support the Thana fisheries officers. **Text box 5.23** shows the data interpretation and scoring and **Figure 5.59** illustrates the distribution of support from government offices.

Text box 5.23. Scoring of Government supports.

Interpretation		Score
<3 km	very suitable	4
3-5 km	moderately suitable	3
5-10 km	marginally suitable	2
>10 km	unsuitable	1

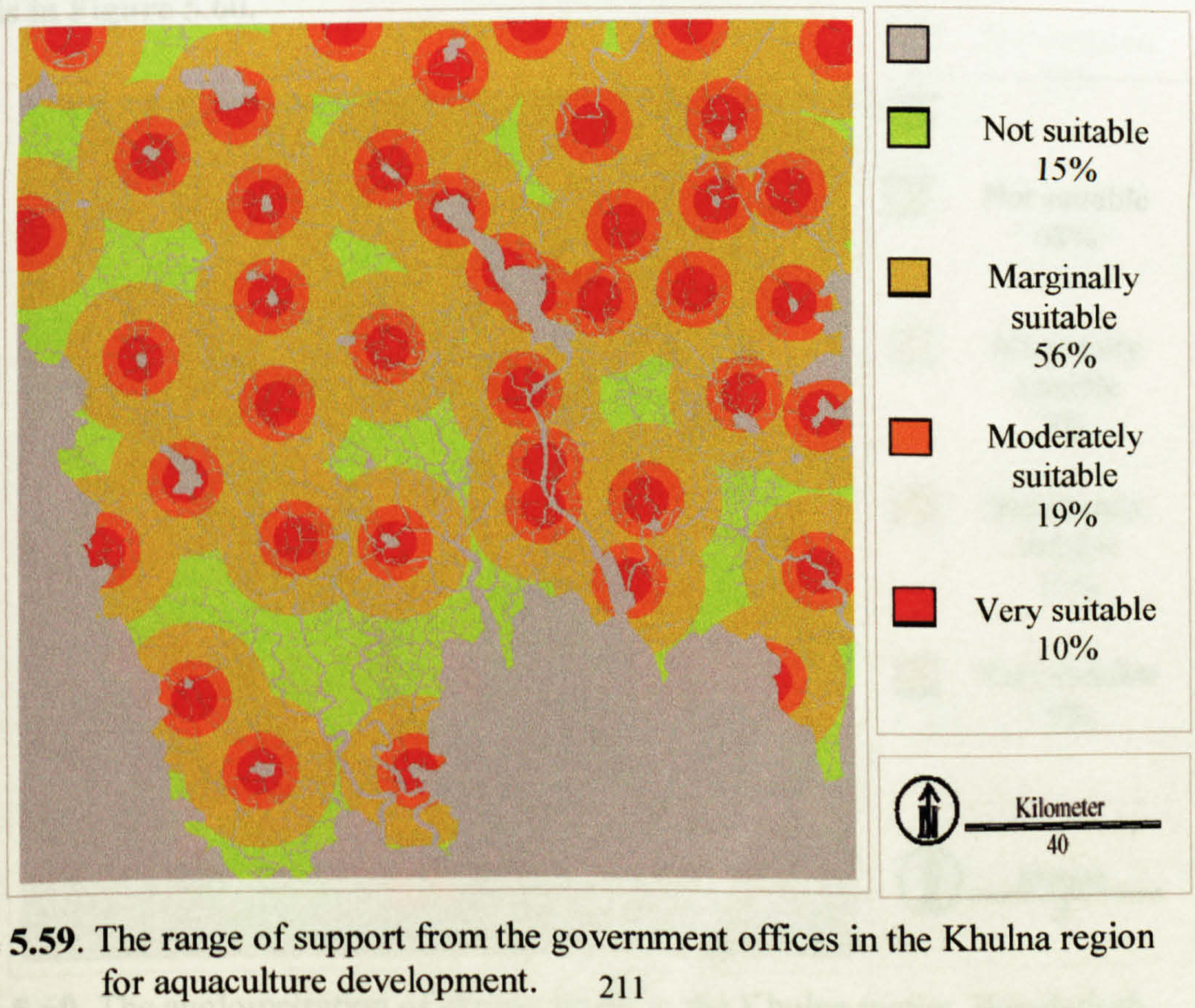

Figure 5.59. The range of support from the government offices in the Khulna region for aquaculture development.

5.13.3 Agglomeration

Meaden and Kapetsky (1991) defined agglomeration as a means of measuring the synergistic influence of existing aquatic farms on the development of new farms. Moreover, recent theories of economic geography suggest that farms in the same industry may be drawn to the same locations because proximity generates positive agglomeration effects (Head *et al.* 1995). The existence of agglomeration is an excellent indicator of the suitability for aquaculture production, since it is only likely to occur in areas which show outstanding production function mixes. Agglomeration implicitly takes into account such factors as established farming skills, availability of broodstock, fingerlings, transportation, equipment facilities, processing plants and markets. By contrast, Meaden and Kapetsky (1991) also note that it is necessary to investigate whether agglomeration advantages will function positively because in some cases it is better to site at a distance from another farm in order to have less competition for land, water and markets and minimum pollution impact. However, for the present study, agglomeration was considered to have a positive influence on aquaculture activities. The data was reclassified according to four suitable classes, that is shown in **Text box 5.24**, and resulted image is in **Figure 5.60.**

Text box 5.24. Scoring of agglomeration.

Interpretation		Score
<1 km	very suitable	4
1-2 km	moderately suitable	3
2-3 km	marginally suitable	2
>3km	unsuitable	1

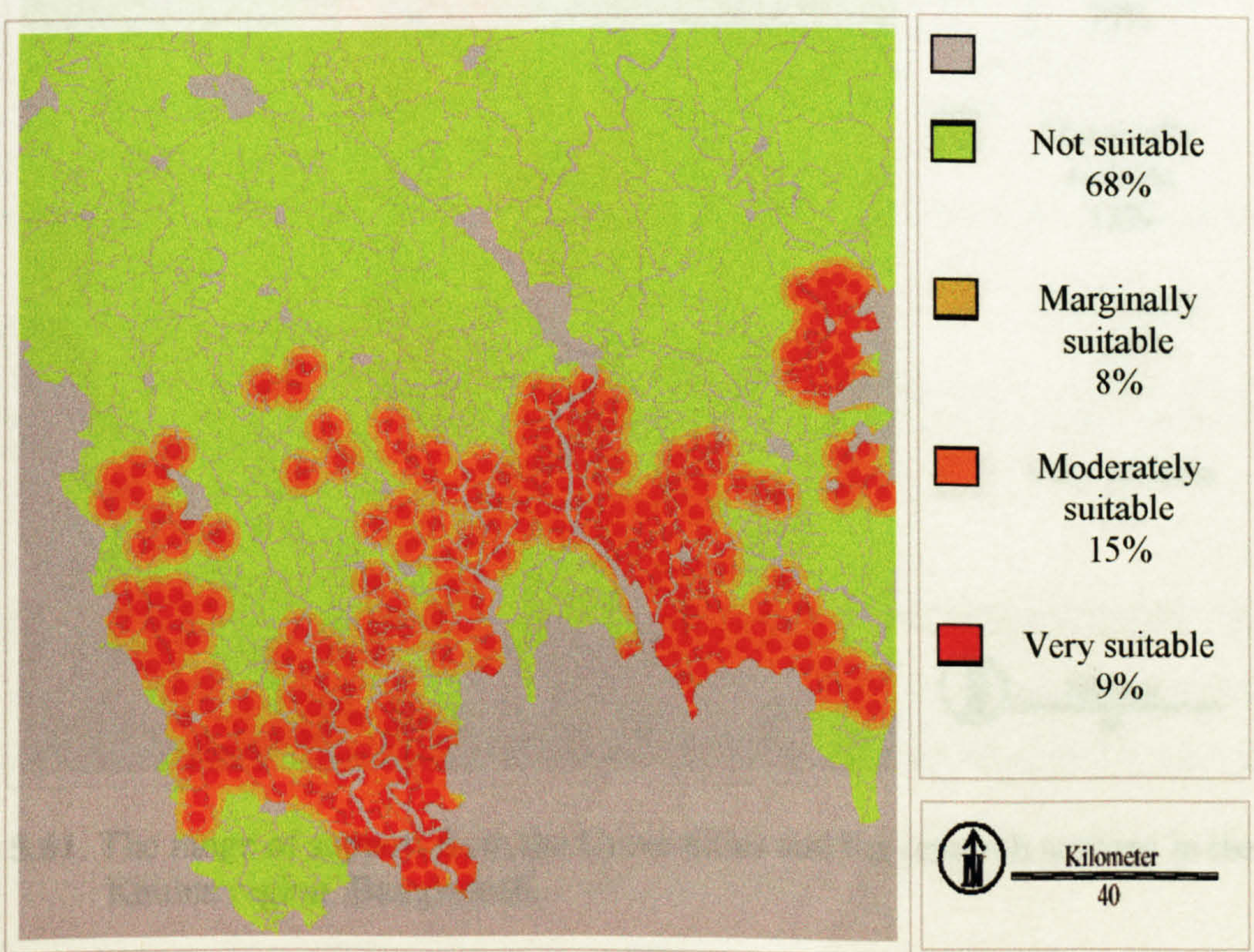

Figure 5.60. The agglometration of shrimp farms in the Khulna region, Bangladesh.

5.13.4 Universities and Research stations

In the past, the sole function of the universities was simply to teach students but today universities perform many tasks other than teaching and research. Universities increasingly play an explicit role in contributing to economic and social development in the country to bring economic and social changes in our society. On the other hand, the research stations are implementing many of programs to transfer new technology to farmers' in collaboration with the department of fisheries (DOF) and Bangladesh agricultural research council (BARC). This transfer occurs through training extension workers, organisation rallies, workshops on fish culture, fish nurseries, mini hatcheries, integrated fish farming, fish processing, shrimp and prawn culture. The mapped data of Universities and Research stations were digitised, rasterised and reclassified according to the suitability ranges shown in **Text box 5.25.** The result is shown in **Figure 5.61**.

Text box 5.25. Scoring of Universities and research stations.

Interpretation		Score
<5 km	very suitable	4
5-10 km	moderately suitable	3
10-15 km	marginally suitable	2
>15 km	unsuitable	1

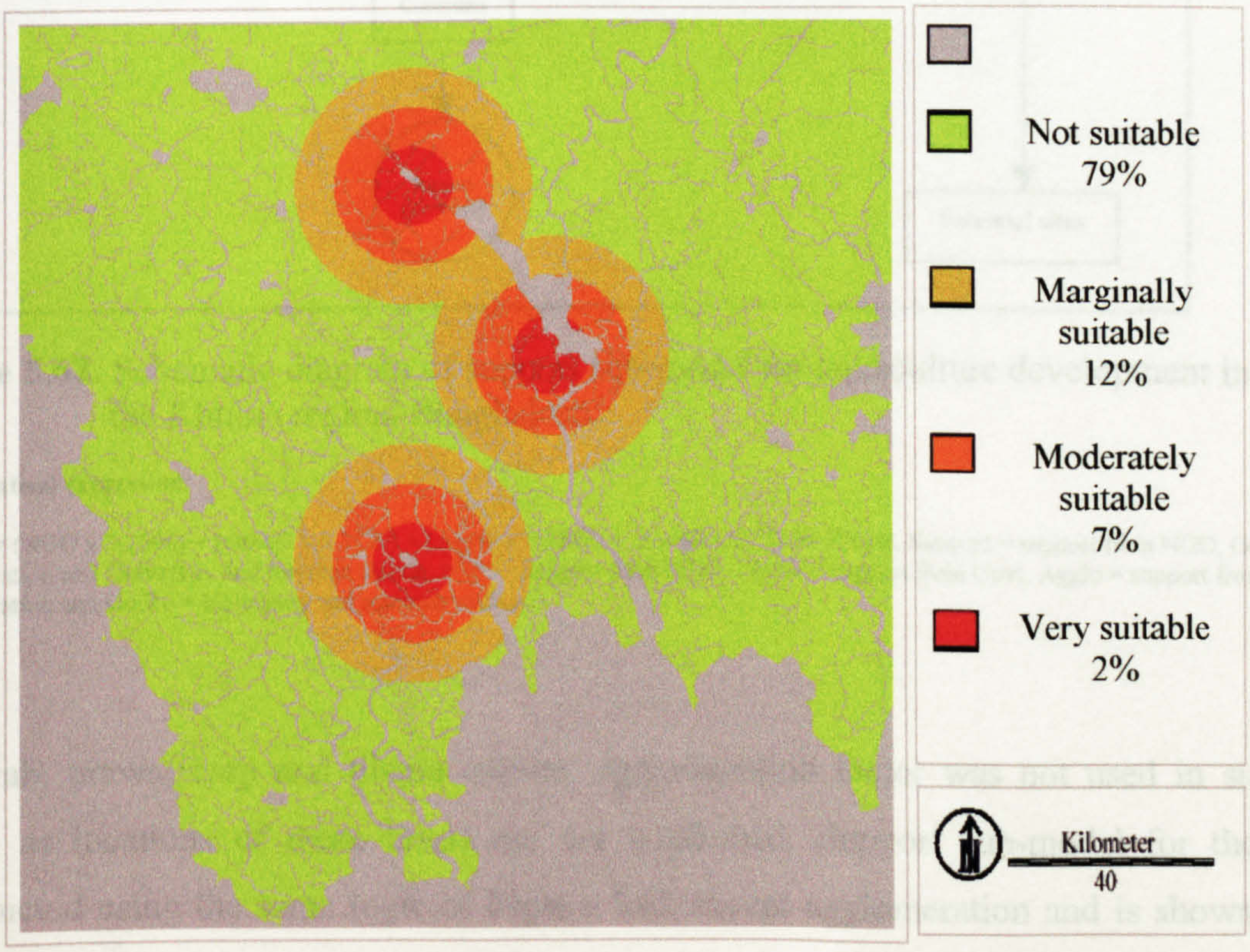

Figure 5.61. The range of support from the Universities and the research stations in the Khulna region, Bangladesh.

5.13.5 Integration of support sub-model

The support sub-model consists of support from NGO's, from the Government offices, agglomeration and support from the Universities and research stations, all of which have a crucial role to aquaculture development in the region. **Figure 5.62** shows the sequence of sub-model development and **Figure 5.63** demonstrates the range of support sub-model in the Khulna region, Bangladesh for aquaculture development.

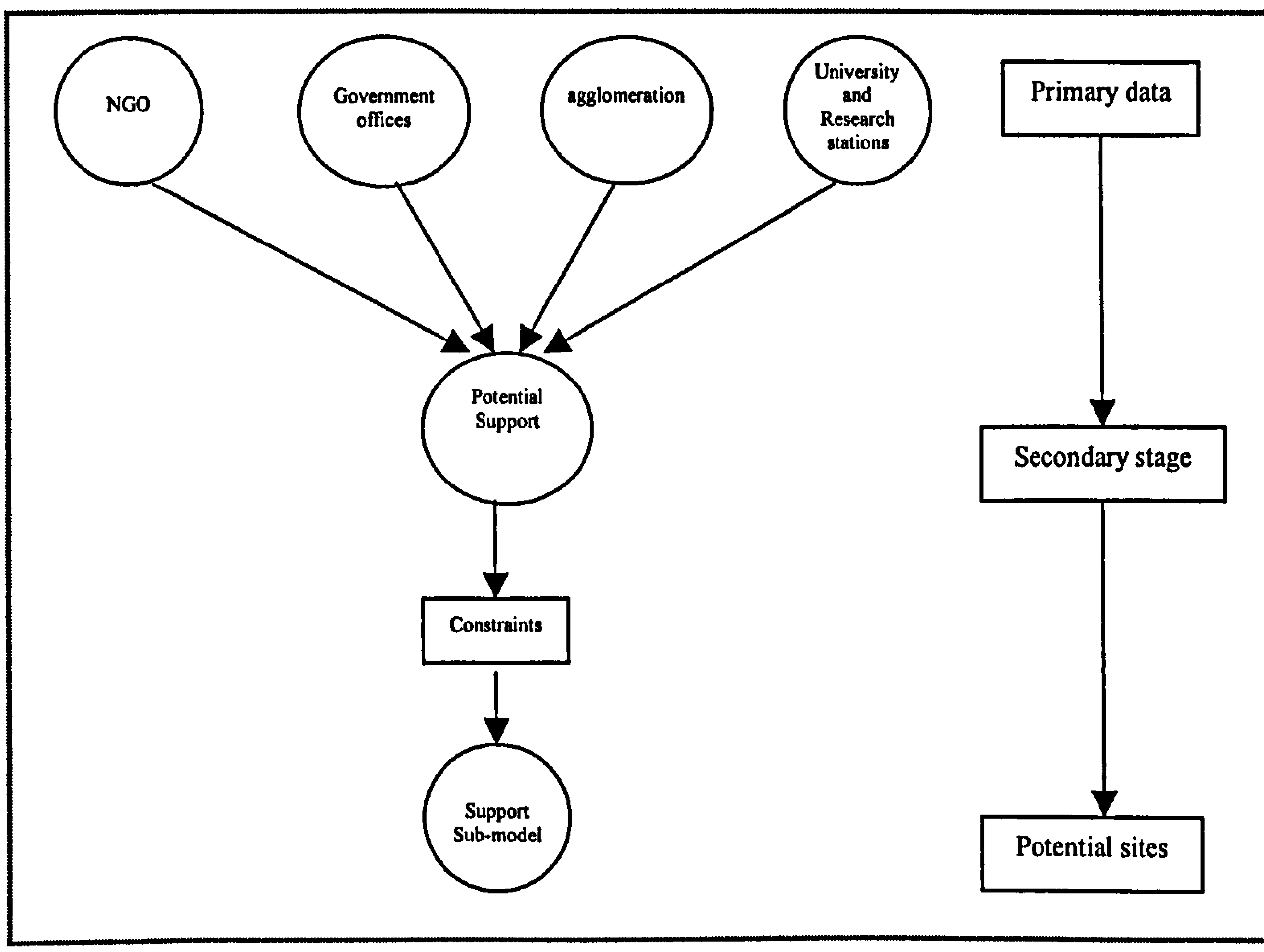

Figure 5.62. Schematic diagram of support sub-model for aquaculture development in the Khulna region, Bangladesh.

Mathematical expression:

Support = (NGO x 0.2595) + (GovtO x 0.3320) + (Agglo x 0.2865) + (UniRe x 0.1220). Where, Support = support from NGO, Govt, agglomeration and University and research station, NGO = support from NGO, GovtO = support from Govt, Agglo = support from agglomeration and UniRe = University and research station.

For crab, prawn, carp and tilapia culture, agglomeration factor was not used in support sub-model as locations of these farms are not confirmed. Support sub-model for these species constructed using the same logic of **Figure 5.61** except agglomeration and is shown in **Figure 5.64.**

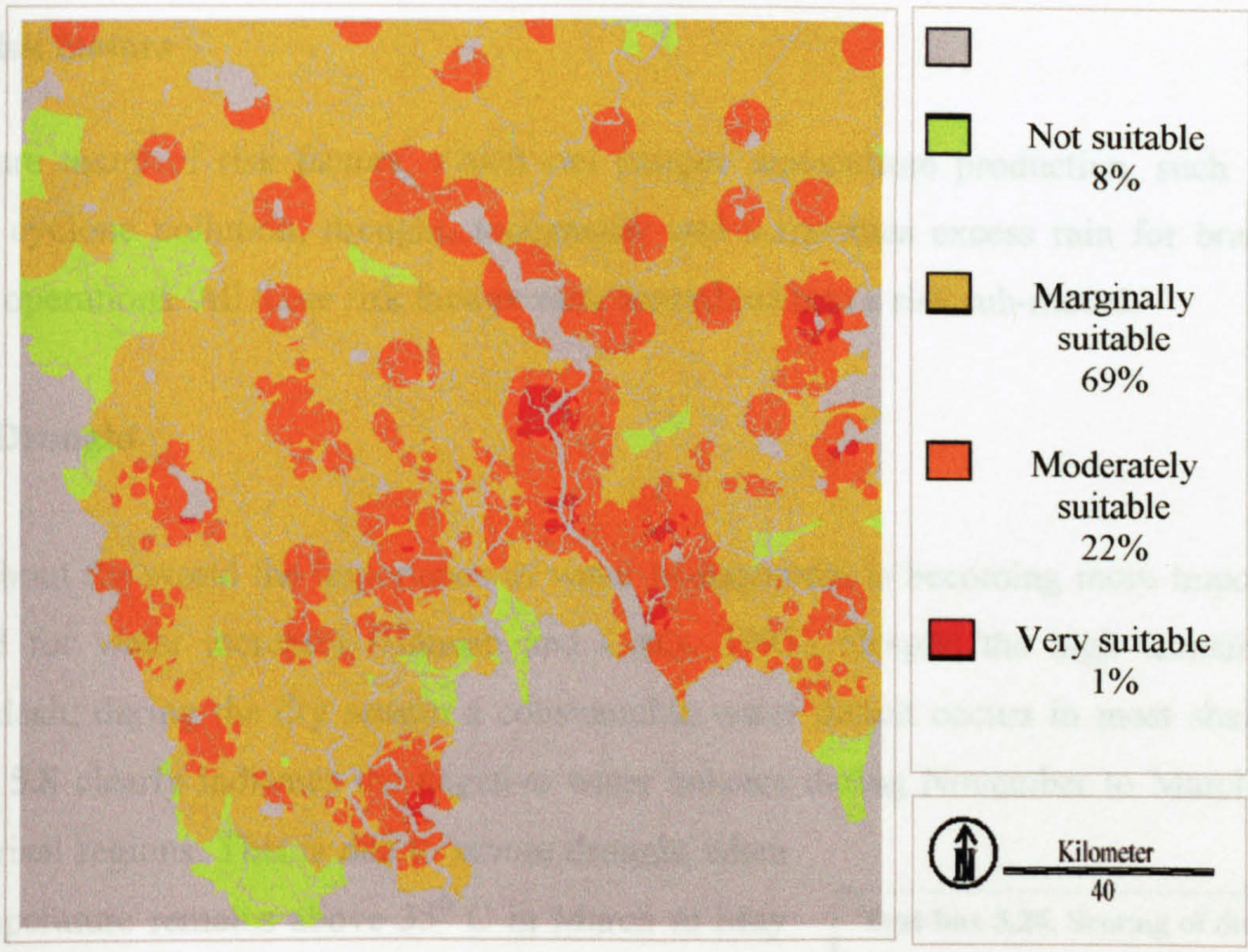

Figure 5.63. The suitable range of support from different organisation for shrimp culture in the Khulna region, Bangladesh.

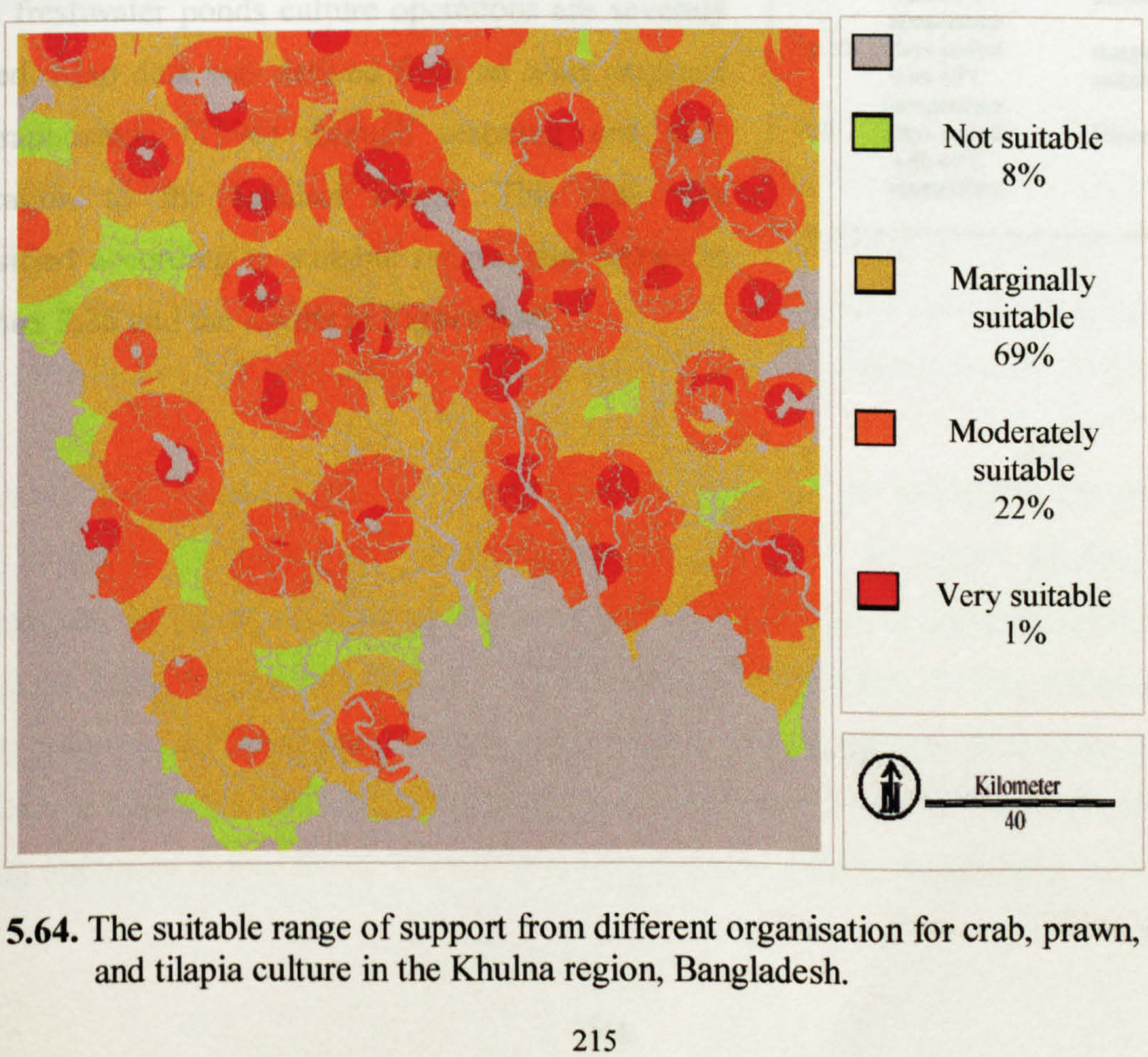

Figure 5.64. The suitable range of support from different organisation for crab, prawn, carp and tilapia culture in the Khulna region, Bangladesh.

5.14 Risk factors

There are many of risk factors, which can hamper aquaculture production, such as diseases, floods, cyclone pollution, drought, topography and sometimes excess rain for brackish water culture operations. All these risk factors were assembled into a risk sub-model.

5.14.1 Drought

Throughout the world the importance of water management is becoming more important as the demand for water increases (Hannan and Coals, 1995). Despite the high annual rainfall in Bangladesh, during the dry season a considerable water deficit occurs in most shallow ponds. **Figure 5.8** clearly indicates the negative water balance during November to March in Khulna and Barisal regions. This is due to severe drought when the temperature remains above 35^0 C in March to May and less rain occurs, which accelerates the evaporation rate. For brackish water aquaculture, drought is not a serious problem because water is exchanged at high tide but in freshwater ponds culture operations are severely affected. Map data was derived from an atlas prepared by Graphosman (1996) through scanning and geo-registration to the Landsat image. This data was reclassified according to suitable ranges, that shows in **Text box 5.26** and the results in **Figure 5.65.**

Text box 5.26. Scoring of drought risk.

Interpretation			Score
<5	days period with 40^0C temperature	very suitable	4
5-10	days period with 40^0C temperature	moderately suitable	3
10-15	days period with 40^0C temperature	marginally suitable	2
>15	days period with 40^0C temperature	Unsuitable	1

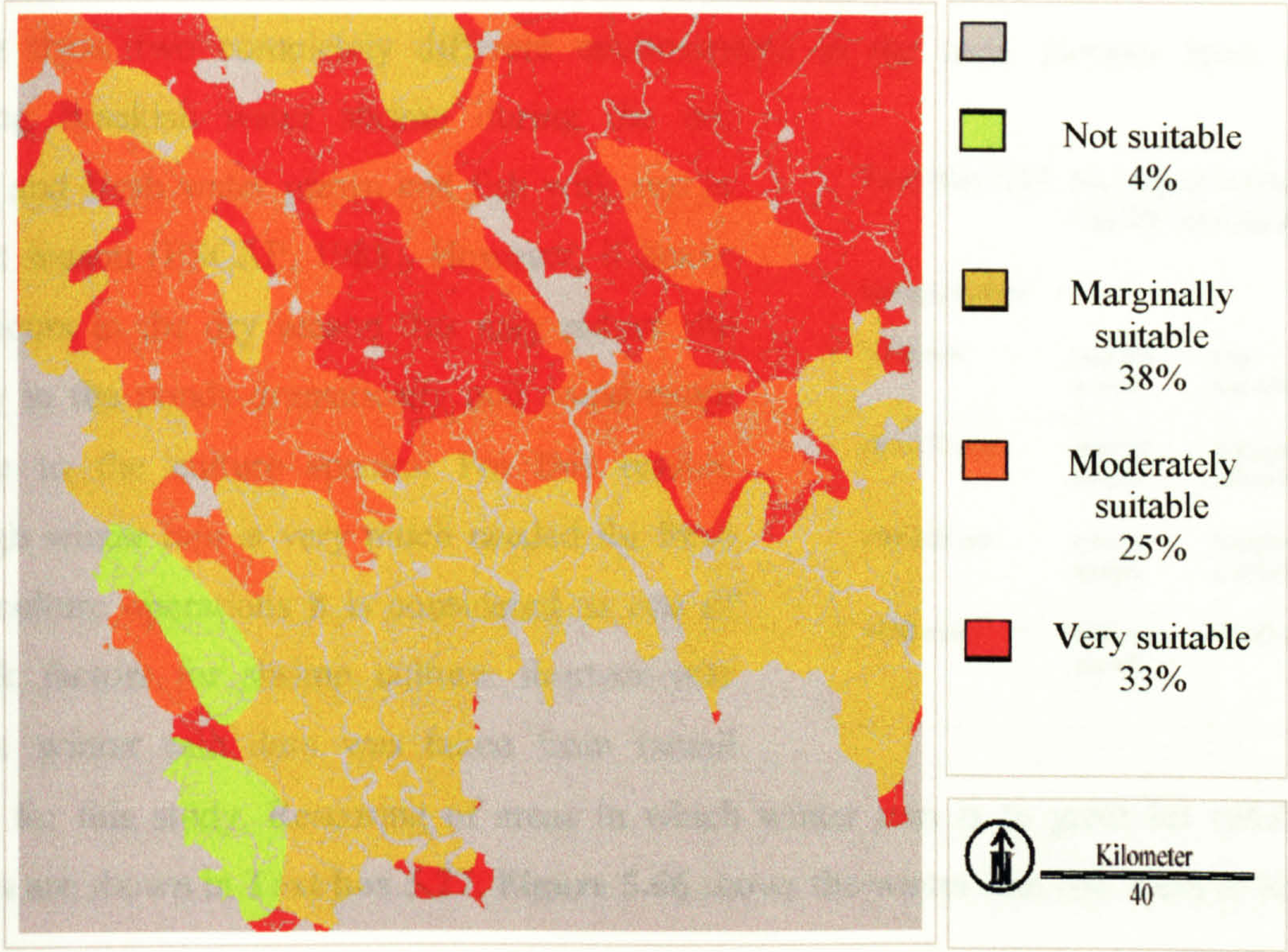

Figure 5.65. The risk of drought for aquaculture development in the Khulna region, Bangladesh.

5.14.2 Winter rain

Salinity is one of the required water quality parameters for brackish water shrimp and crab culture and different species have their optimum ranges of salinity (Allan and Maguire, 1992). However, heavy rain fed floods in the winter can cause stratification, in which the upper water column is diluted by as much as 70% (Oren *et al.* 1995). Sharp declines of shrimp populations are associated with abrupt decreases in salinity due to heavy rain (Huang and Qi, 1997).

In the study area, there are two distinct seasons which change the salinity in the water of the rivers; the wet season and the dry season. In the dry season, less rain occurs and the flow of the rivers reduces. This reduction has been compounded due to a dam constructed over the Ganges river on the India /Bangladesh border near Rajshahi district (Mirza, 1998), which allows sea water to penetrate further inland. However, the situation is just opposite during the wet season, when there is very high rainfall and rivers receive more water from the Ganges as all the gates are being opened to reduce the flood risk. This attenuates the salinity dramatically in the area.

Having these two completely different environments in the area, farmers have adapted to culturing brackish water shrimp during the dry season and fresh water prawn and fish with rice in the wet season (ESCAP, 1988). However, if heavy rain occurs in the dry season this may reduce the salinity in the ponds dramatically and could cause damage to the culture species. For this reason, although winter rain is very much needed for fresh water culture operations it is considered as one of the risk factors for shrimp culture, fourteen-year average winter rain date was taken from Ismail (1990) for this study. Rescoring of areas in which winter rain is to great for reliable shrimp cultures are shown in **Text box 5.27. Figure 5.66** shows the winter rain risk areas in the region.

Text box 5.27. Scoring of winter rain risk for shrimp and crab.

Interpretation			Score
<200 mm	rain per month	very suitable	4
200-250 mm	rain per month	moderately suitable	3
250-300 mm	rain per month	marginally suitable	2
>300 mm	rain per month	Unsuitable	1

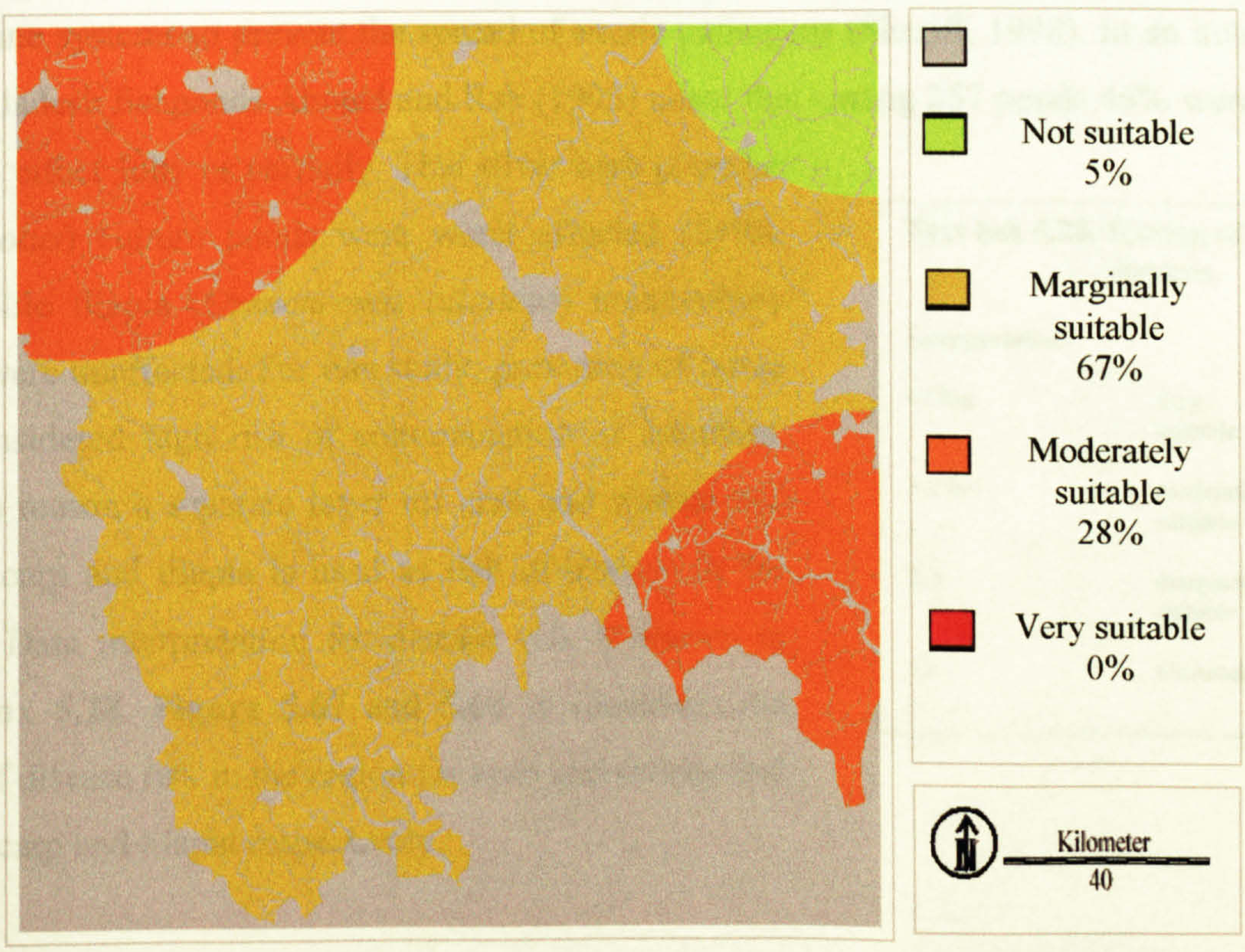

Figure 5.66. Risk of winter rain for shrimp and crab culture development in the Khulna region, Bangladesh.

5.14.3 Risk of diseases

Hundreds of fish and prawn farms have been constructed in the past decades in Southeast Asia (Chin and Ong, 1997). However, many of these farms have ceased operation mainly due to the outbreak of diseases. With population increase, rapid urbanisation and industrialisation, water quality in the estuarine and coastal regions where most of the fish, shrimp and prawn farms are located is deteriorating.

Most Asian countries have increased their aquaculture production markedly, which has caused environmental and socio-economic impacts. Diseases are the major risk factor in commercial aquaculture, with millions of dollars lost annually. There is a tendency for epizootic outbreaks to spread to other areas; lack of knowledge on the aetiology and spread of these fish diseases requires much research. Epizootic ulcerative syndrome (EUS) a fish disease, which is common in Asian countries as well in Bangladesh, was basically introduced from Australia due to lack of quarantine systems to prevent the spread of exotic pathogens (Shariff, 1998). In an investigation in Bangladesh fishponds Ahmed and Rab (1995) noted that among 257 ponds 46% were affected by EUS either fully or partially. Thai silver barb (*Puntius gonioniotus*) culture ponds were worst affected (64%), while Nile tilapia (*Oreochromis niloticus*) monoculture ponds were unaffected. For this study, proximity of farms was considered high risk of contamination of infection. For this reason a separate layer for crab and shrimp and prawn, carp and tilapia is used as risk of disease in the region. Data interpretation for disease risk is shown in **Text box 5.28. Figure 5.67** and **5.68** is illustrates the range of disease risk in the region for crab and shrimp and prawn, carp and tilapia respectively.

Text box 5.28. Scoring of risk of diseases.

Interpretation		Score
<1 km	very suitable	4
1-2 km	moderately suitable	3
2-3	marginally suitable	2
>3	Unsuitable	1

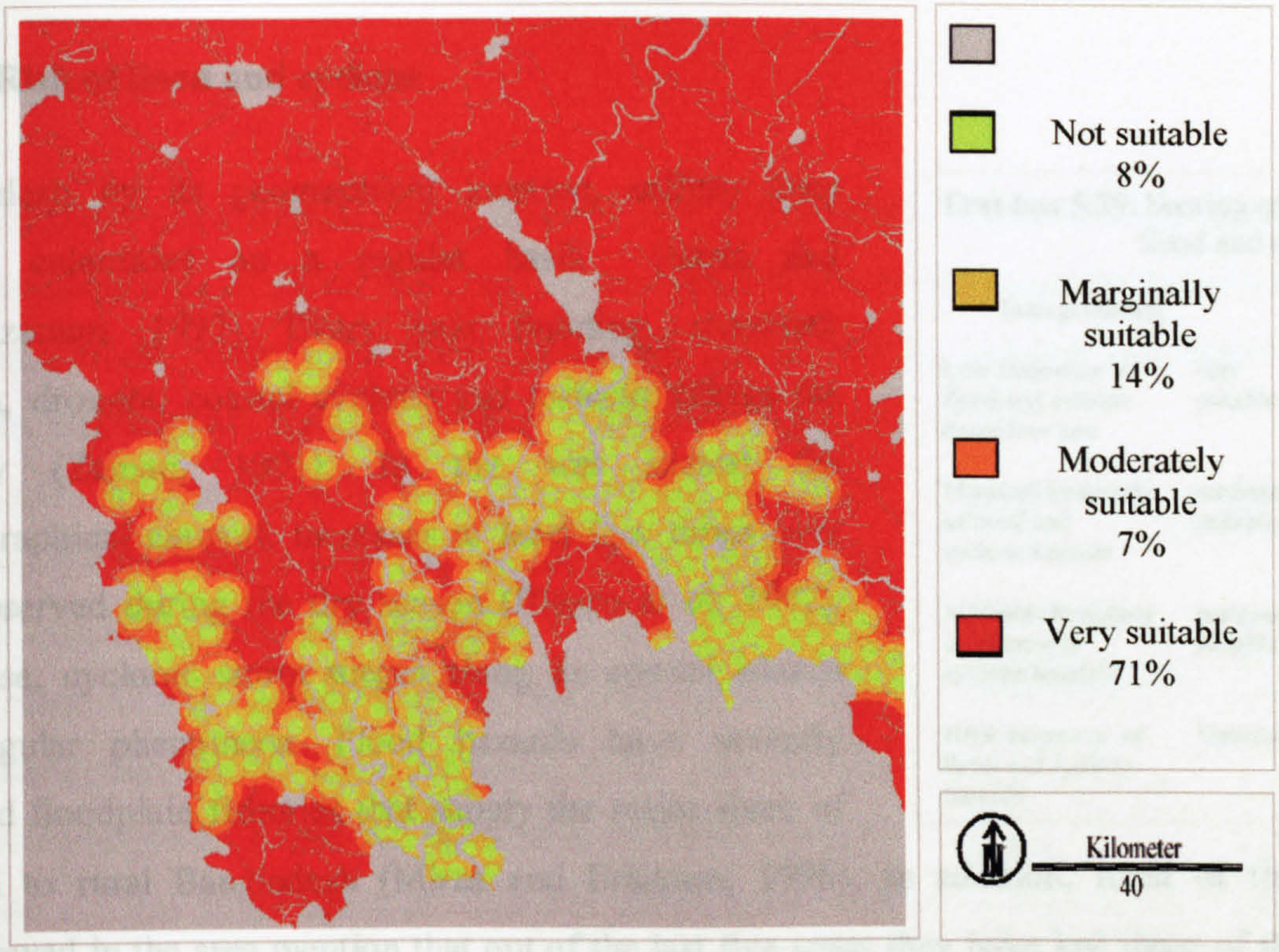

Figure 5.67. The proximity to diseases for shrimp and crab culture in the Khulna region, Bangladesh for aquaculture development.

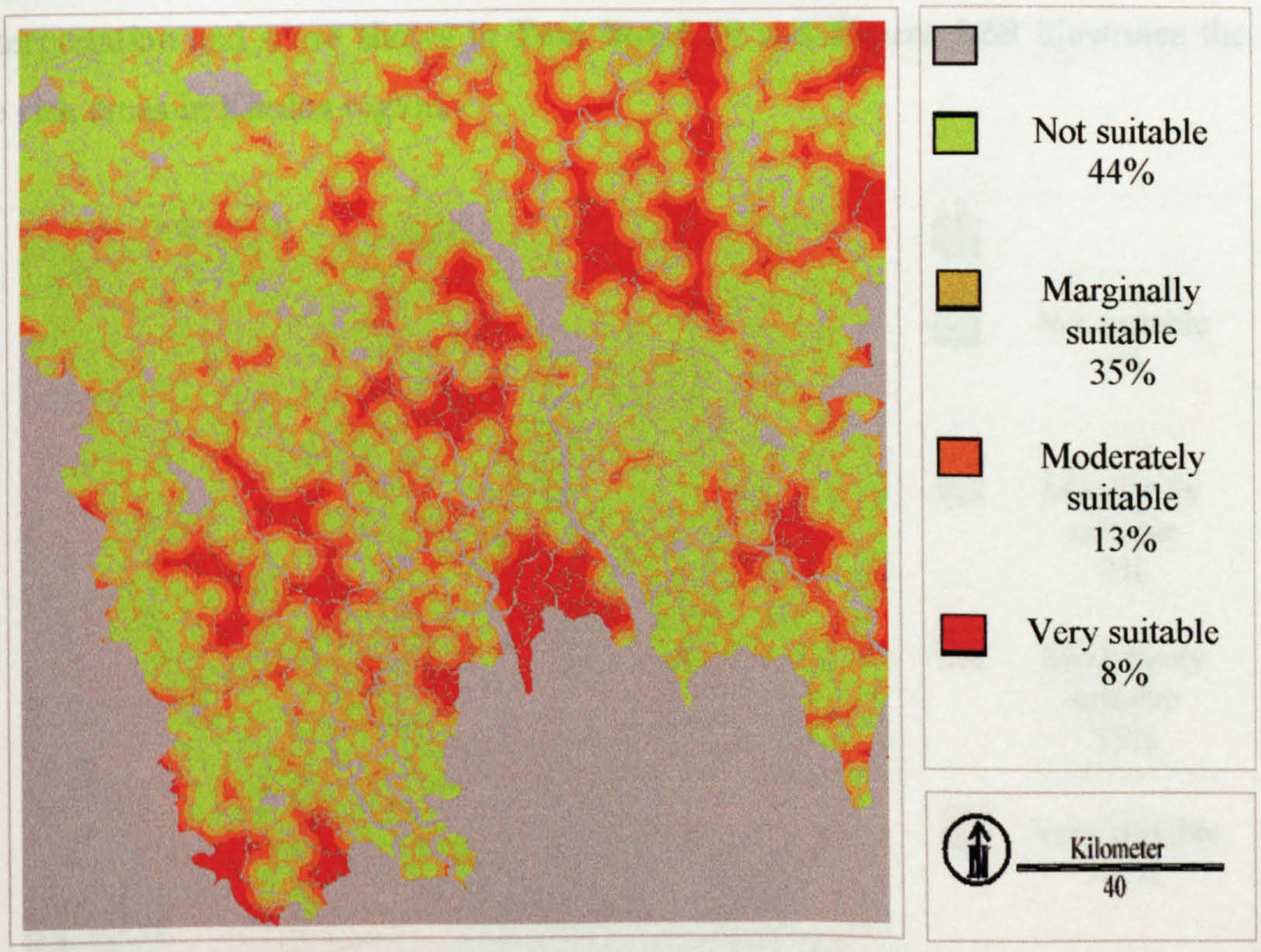

Figure 5.68. The proximity to diseases for prawn, carp and tilapia culture in the Khulna region, Bangladesh for aquaculture development.

5.14.4 Risk of flood and cyclone

Bangladesh by its geographical location, suffers from natural calamities on a regular basis (Seraj and Badruzzaman, 1997). Every year flooding, riverbank erosion, drought, coastal cyclone and tornado affects the country (Zaman, 1991). In the wet season the hydrographical network increases at least four times over that observed during the dry season (Blasco *et al.* 1992). Likewise, cyclonic storm surges along its coastal islands are regular phenomena. Flood hazards have severely affected floodplain fisheries that supply the major share of protein to rural Bangladesh (Mirza and Ericksen, 1996). In addition, most of the farmers interviewed in the area mention that out of the last five years they have lost three of their crops. So, ideally the fishponds should be located where risk of flood is the lowest. Flood and cyclone data for this study was taken from the flood and cyclone maps prepared by SRDI (1998). The data interpretation and score shows in **Text box 5.29** and **Figure 5.69** illustrates the flood and cyclone risk areas in Khulna region.

Text box 5.29. Scoring of risk of flood and cyclone.

Interpretation		Score
Low frequency of flood and cyclone hazards or non	very suitable	4
Marginal frequency of flood and cyclone hazards	moderately suitable	3
Moderate frequency of flood and cyclone hazards	marginally suitable	2
High frequency of flood and cyclone hazards	Unsuitable	1

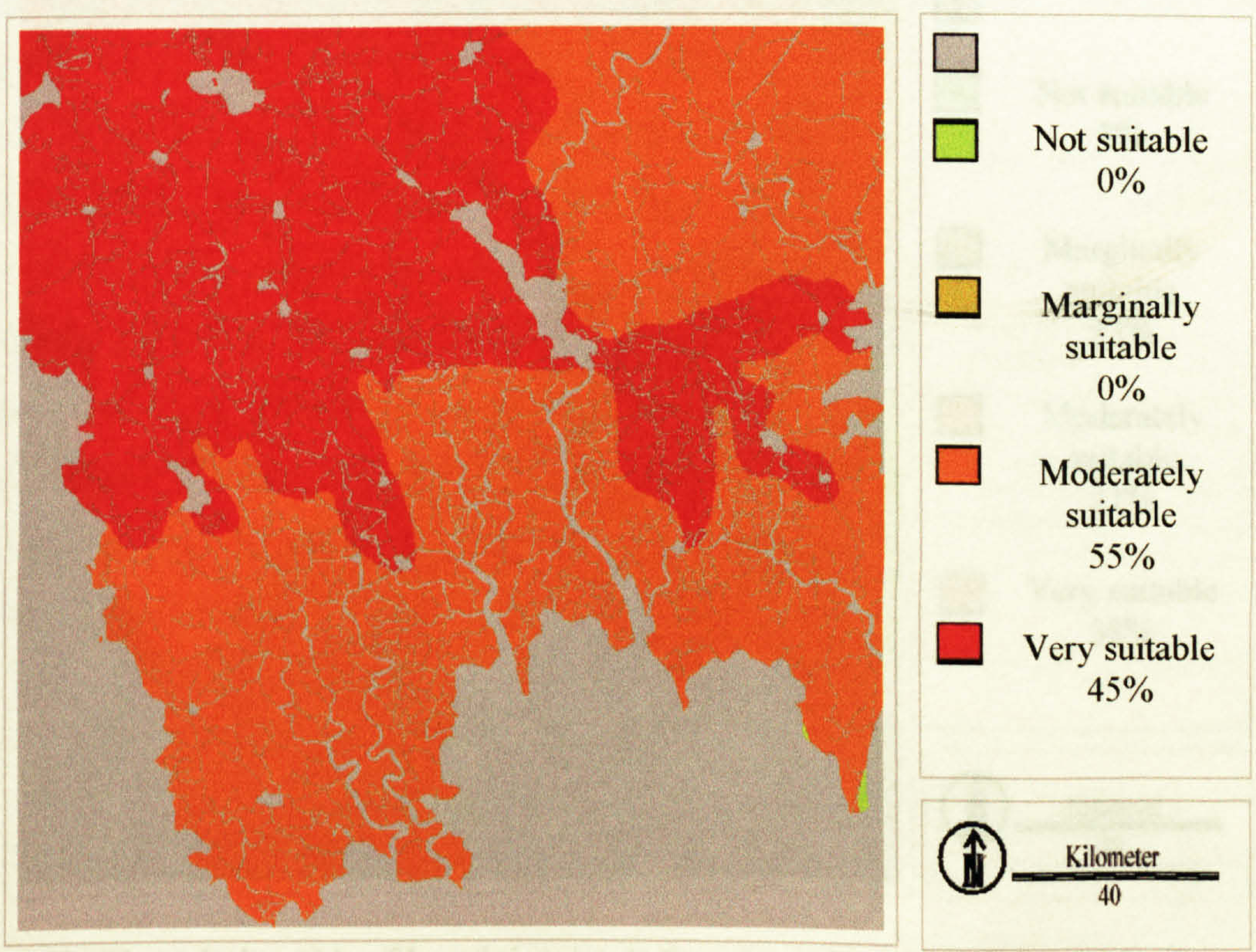

Figure 5.69. The range of flood and cyclone risk for aquaculture development in the Khulna region.

5.14.5 Elevation

Bangladesh is a low lying and deltaic country. Much of its land is within MSL or bit higher. One of the consequences of global warming will be a general rise in sea levels throughout the world. Low lying lands, deltas, river plains and many islands will be flooded, and islands like the Maldives and Kiribati possibly disappear (Roy and Connell, 1992) and Bangladesh will lose most of its low lands (Broadus, 1993). Groundwater degradation due to greenhouse induced coastal erosion and inundation of low-lying ground will further reduce agricultural productivity, fresh water aquaculture and other land resources. For this reason, aquaculture activities should not be sited in such places where flood and cyclone could affect the culture operation. For this study elevation was used as one of the risk factors. This was taken from an elevation map of Bangladesh (Graphosman, 1996). Data interpretation and scoring is shown in **Text box 5.30** and **Figure 5.70** illustrates the relative risk due to elevation in the Khulna region.

Text box 5.30. Scoring of elevation risk.

Interpretation		Score
>3 m meter no risk of flooding by sea level rise	very suitable	4
2-3 m marginal risk of flooding by sea level rise	moderately suitable	3
1-2 m moderate risk of flooding by sea level rise	marginally suitable	2
<1 m high risk of flooding by sea level rise and normal tide	Unsuitable	1

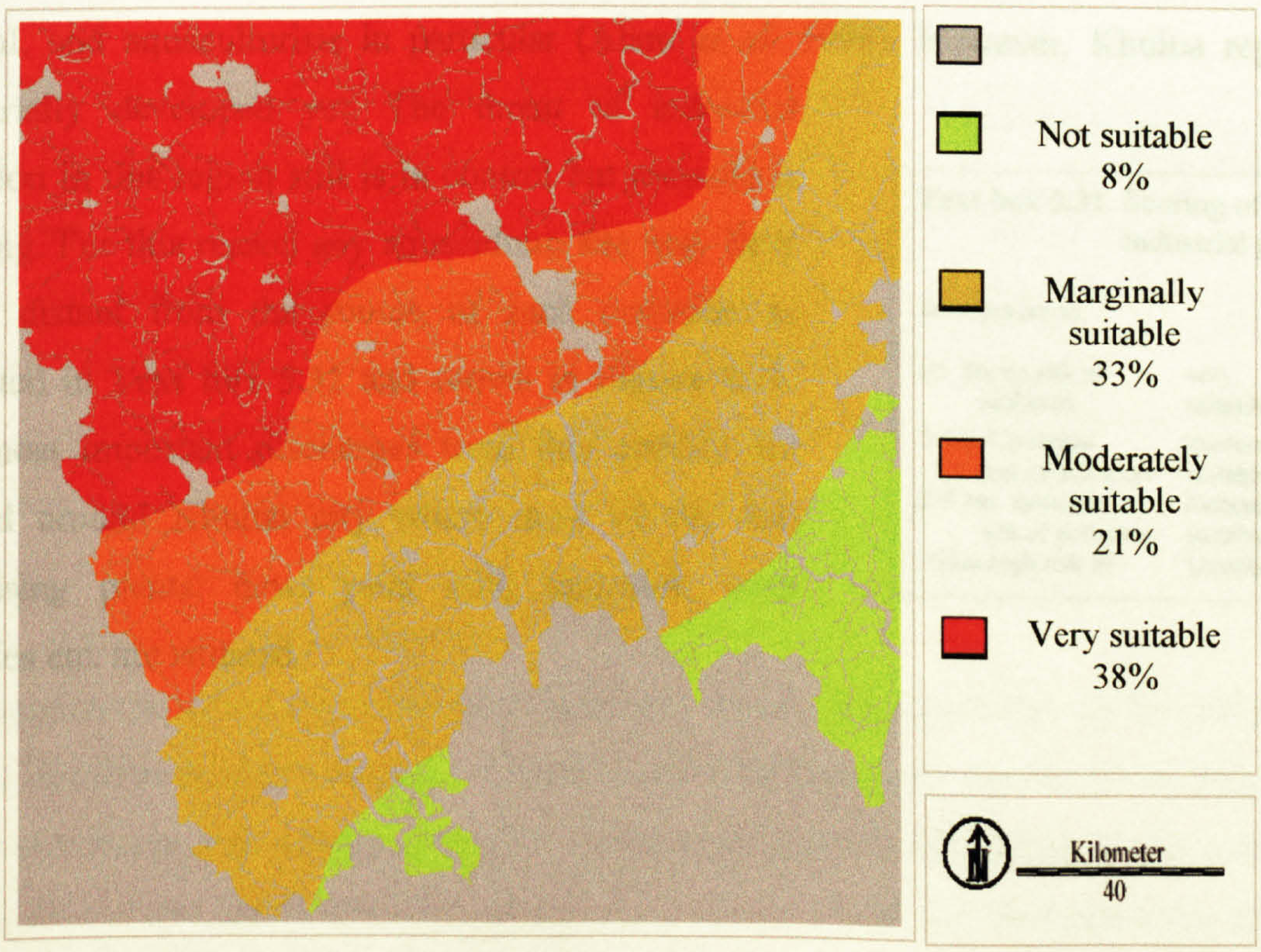

Figure 5.70. The relative risk of low-lying lands for aquaculture development in the Khulna region.

5.14.6 Pollution

The disposal of wastes in the rapidly expanding cities and towns has already become a great concern in the face of increasing potential for pollution. The magnitude and characteristics of the existing pollution from industries and city development in soils are not a great concern but they are very significant in air and the water (Hasan and Mulamoottil, 1994).

5.14.6.1 Industries

Alam *et al.* (1998) carried out a pollution study and considered that the heavy metal from the industrial effluents is causing a decline of natural fish production. They also note that due to rapid industrial development of the country, industrial pollution may, in time, become a threat to the aquatic environment. Industrial effluents especially the discharge from fertiliser factories, petrochemical industries, tanneries, pulp and paper mills, distilleries and thermal power plants might have adverse effects on aquatic life. It is also clear that indiscriminate use of pesticides for crop production may be partially responsible for hydrological degradation of rivers leading to the decline of fish production in open water of Bangladesh. In recent years, the impact of aquatic pollution on human and animal life has become a matter of special concern of ecologists in general, and aquaculturists in particular (Alam *et al.* 1998). However, Khulna region is not industrially developed yet. The threat of industrial pollution in this region still is in control but pressure is growing. For this reason any aquaculture site may have to be distant from the source of such pollution as indicated in **Text box 5.31** and shown in **Figure 5.71.** The most important discharges from this activity are located around Khulna city where most of the fish processing plants, news print mill, tanneries, soap factories etc. are situated.

Text box 5.31. Scoring of industrial pollution.

Interpretation		Score
>5 km no risk of pollution	very suitable	4
3-5 km marginal risk of pollution	moderately suitable	3
2-3 km moderate risk of pollution	marginally suitable	2
<2km high risk of	Unsuitable	1

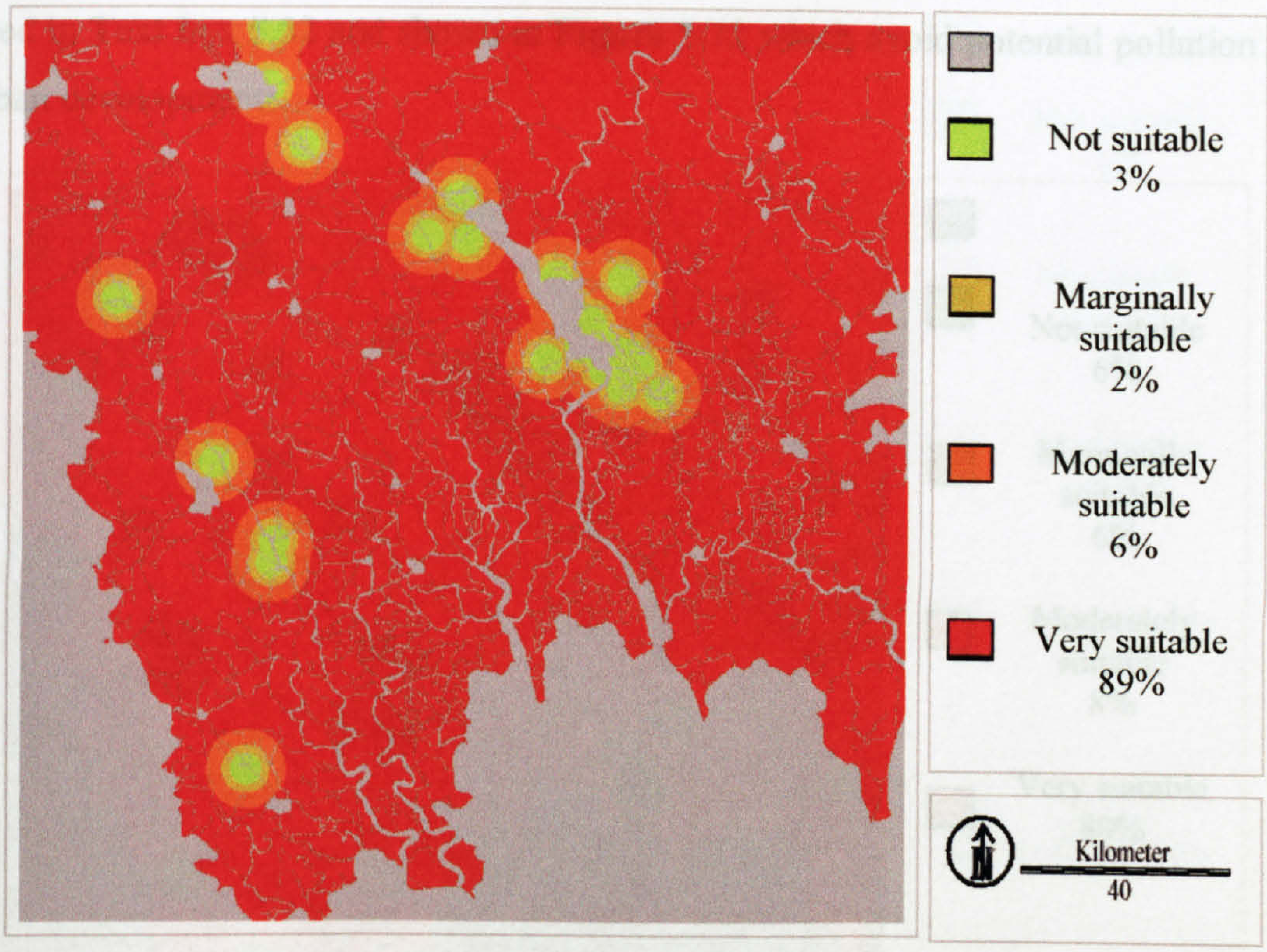

Figure 5.71. The range of risk of industrial pollution for aquaculture development in the Khulna region.

5.14.6.2 Urban development

Dhaka City, the capital of the country, as well as other local cities are facing rapid urbanisation caused by a very high rate of increased migration of rural people, many of whom are affected by natural calamities (e.g. river erosion and flooding). The problem is further aggravated by limited land supply in urban areas, lower land utilisation and lack of proper policy and planning of land use. The rapid influx of population to the cities has extended the cities, using up valuable agricultural land. Moreover, a high land price encourages construction of multi-storied buildings which, has invariably, added pressure to the various, ill-planned, utility services. During occasional floods and regular water-logging due to rains, water mixes with sewage and waste water from septic tanks and pit latrines, decomposes garbage dumps and deteriorates the natural environment (Seraj and Badruzzaman, 1997). Thus any culture activities should be appropriately distant from the urban development. Buffer areas

Text box 5.32. Scoring of urban development.

Interpretation		Score
>5 km no risk of pollution	very suitable	4
3-.5 km marginal risk of pollution	moderately suitable	3
2-3 km moderate risk of pollution	marginally suitable	2
<2 km high risk of pollution	Unsuitable	1

are scored in **Text box 5.32** and shown in **Figure 5.72** which avoid potential pollution problems from urban developments.

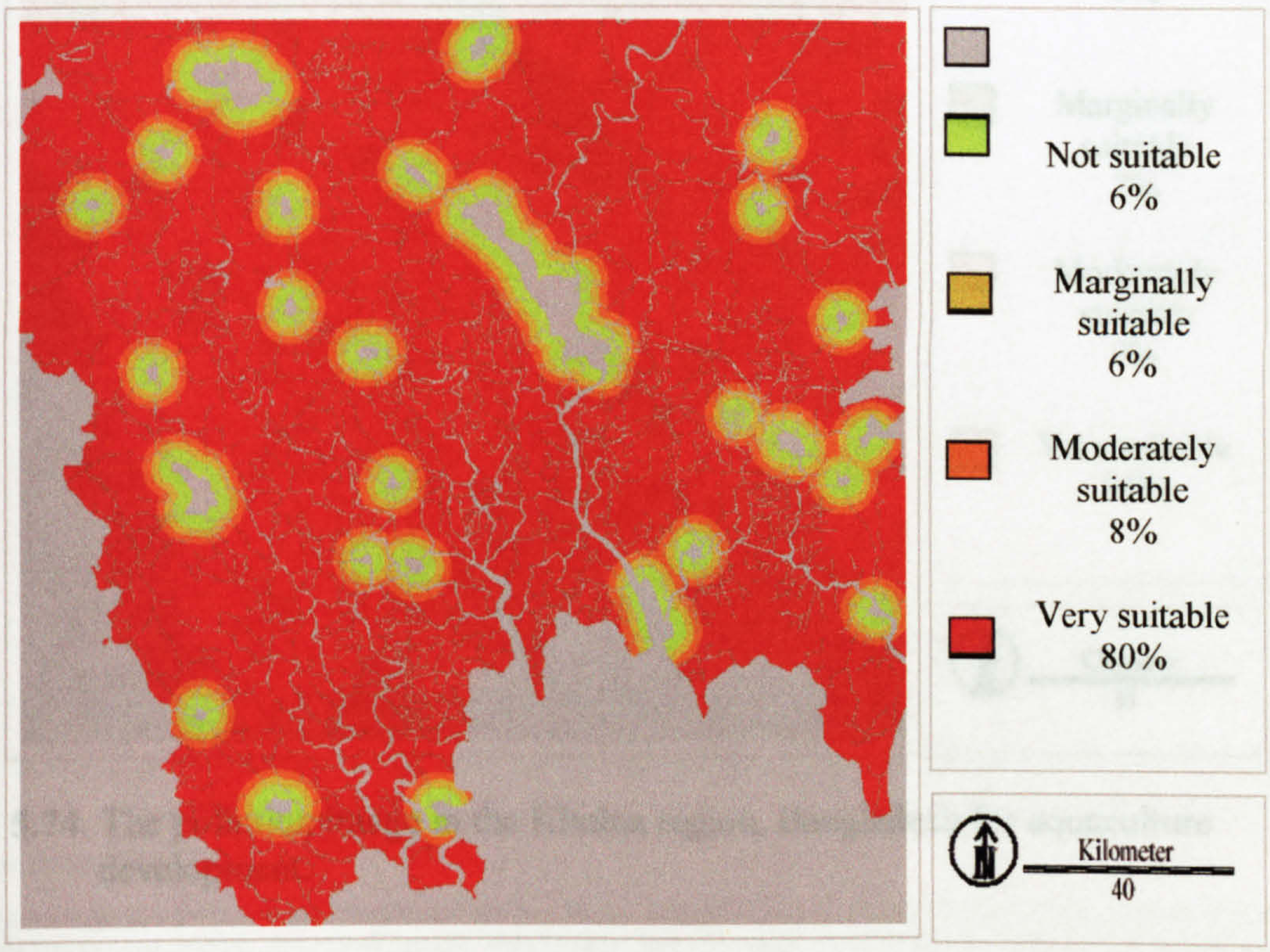

Figure 5.72. The risk of pollution due to urban development for aquaculture development in the Khulna region.

The pollution sub-model development is shown in **Figure 5.73**. The pollution image created using MCE is shown in **Figure 5.74**.

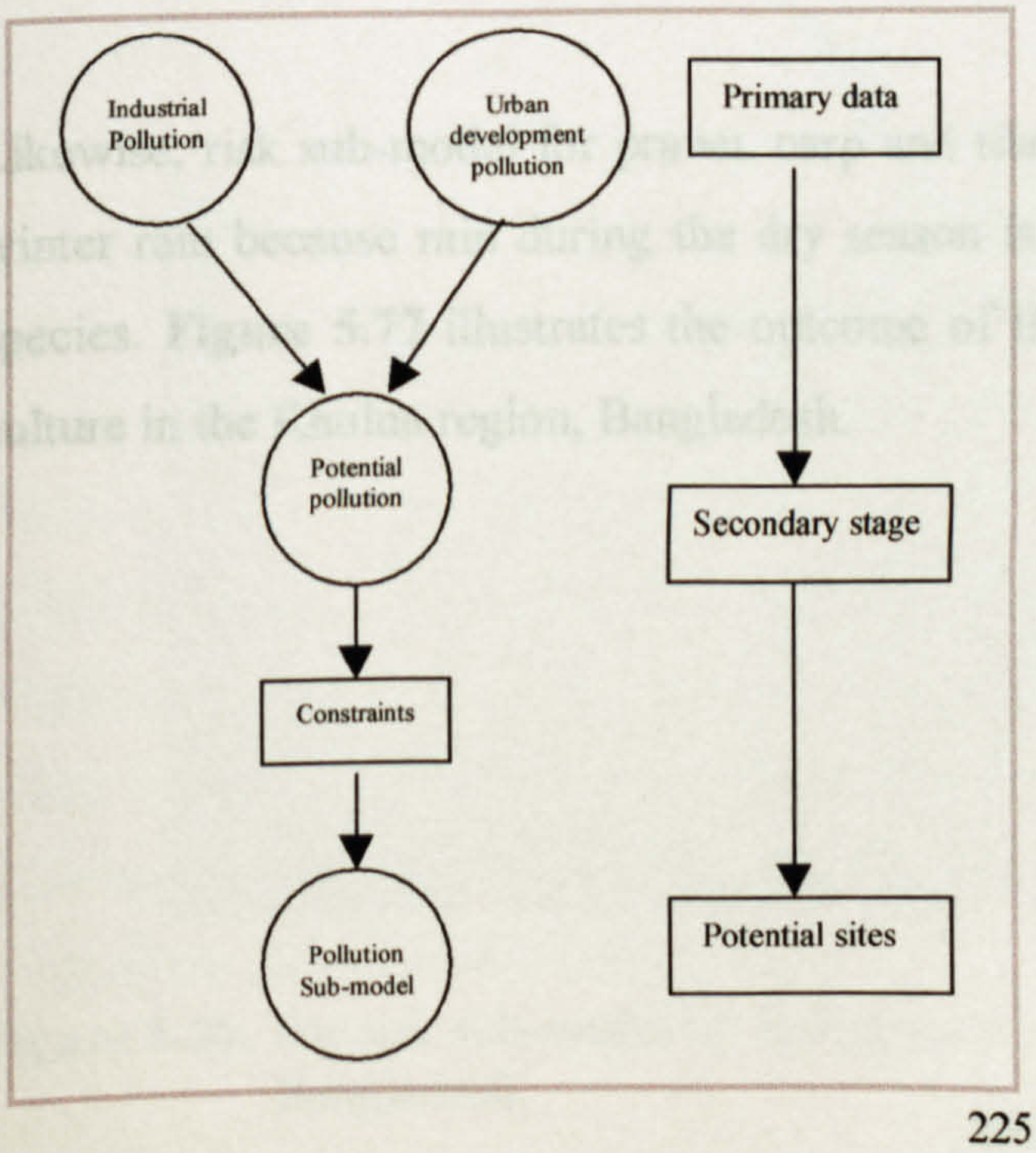

Figure 5.73. Schematic diagram of pollution sub-model for aquaculture development in Khulna, Bangladesh.

Mathematical expression:

Pollut = (Urbadev x 0.5) + (Indus x 0.5). Where, Pollut = pollution sub-model for aquaculture development, Urbadev = pollution from urban development and Indus = pollution from industries respectively.

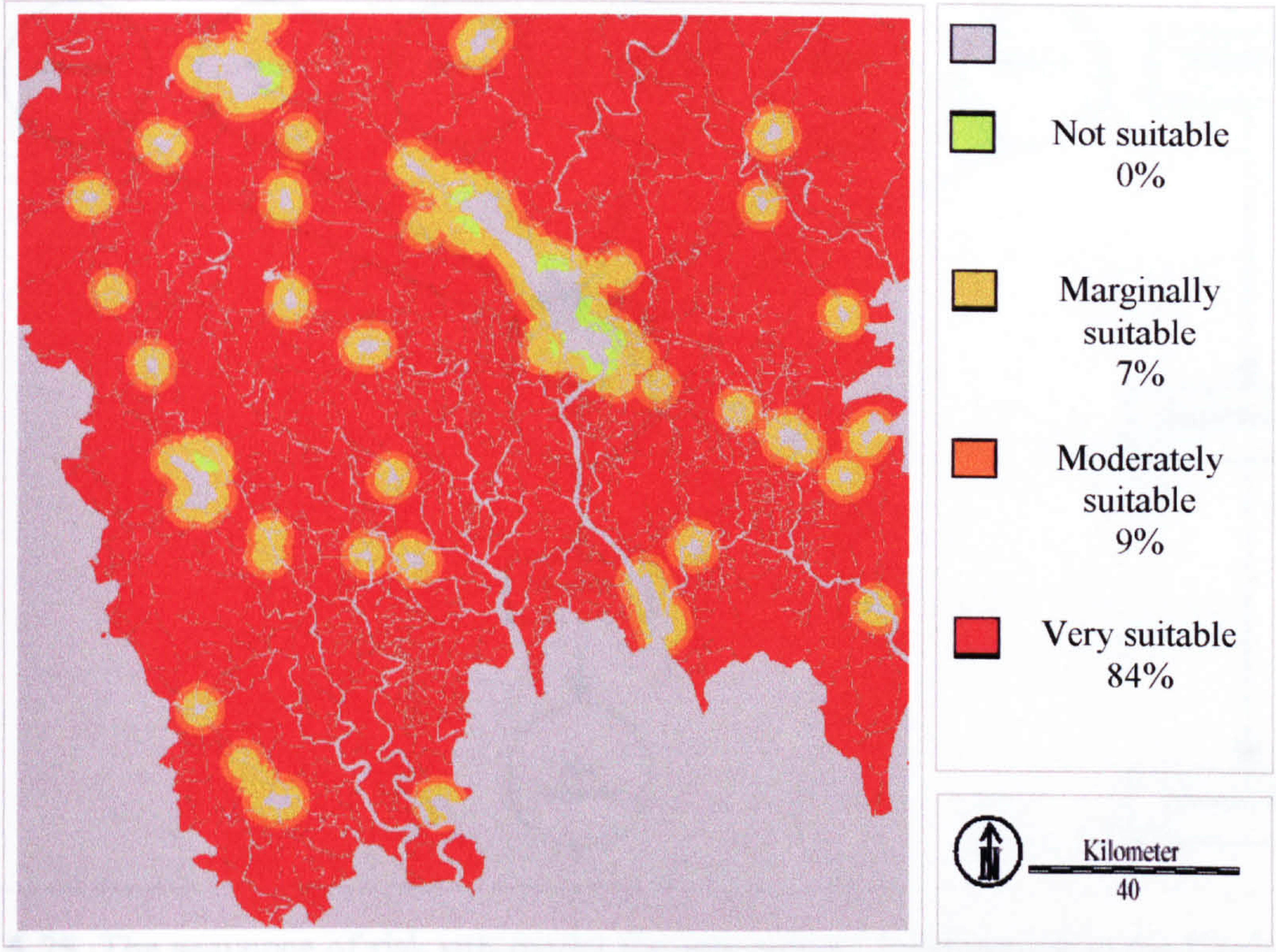

Figure 5.74. The pollution image in the Khulna region, Bangladesh for aquaculture development.

5.15.7 Integration of risk sub-model

All the risk factors were integrated into a potential risk sub-model for aquaculture development. **Figure 5.75** illustrates the sequence of risk sub-model development and **Figure 5.76** shows the outcome of the risk sub-model in the Khulna region, Bangladesh.

Likewise, risk sub-model for prawn, carp and tilapia were created with five risk factors except winter rain because rain during the dry season is very much expected for cultivation of above species. **Figure 5.77** illustrates the outcome of the risk sub-model for prawn, carp and tilapia culture in the Khulna region, Bangladesh.

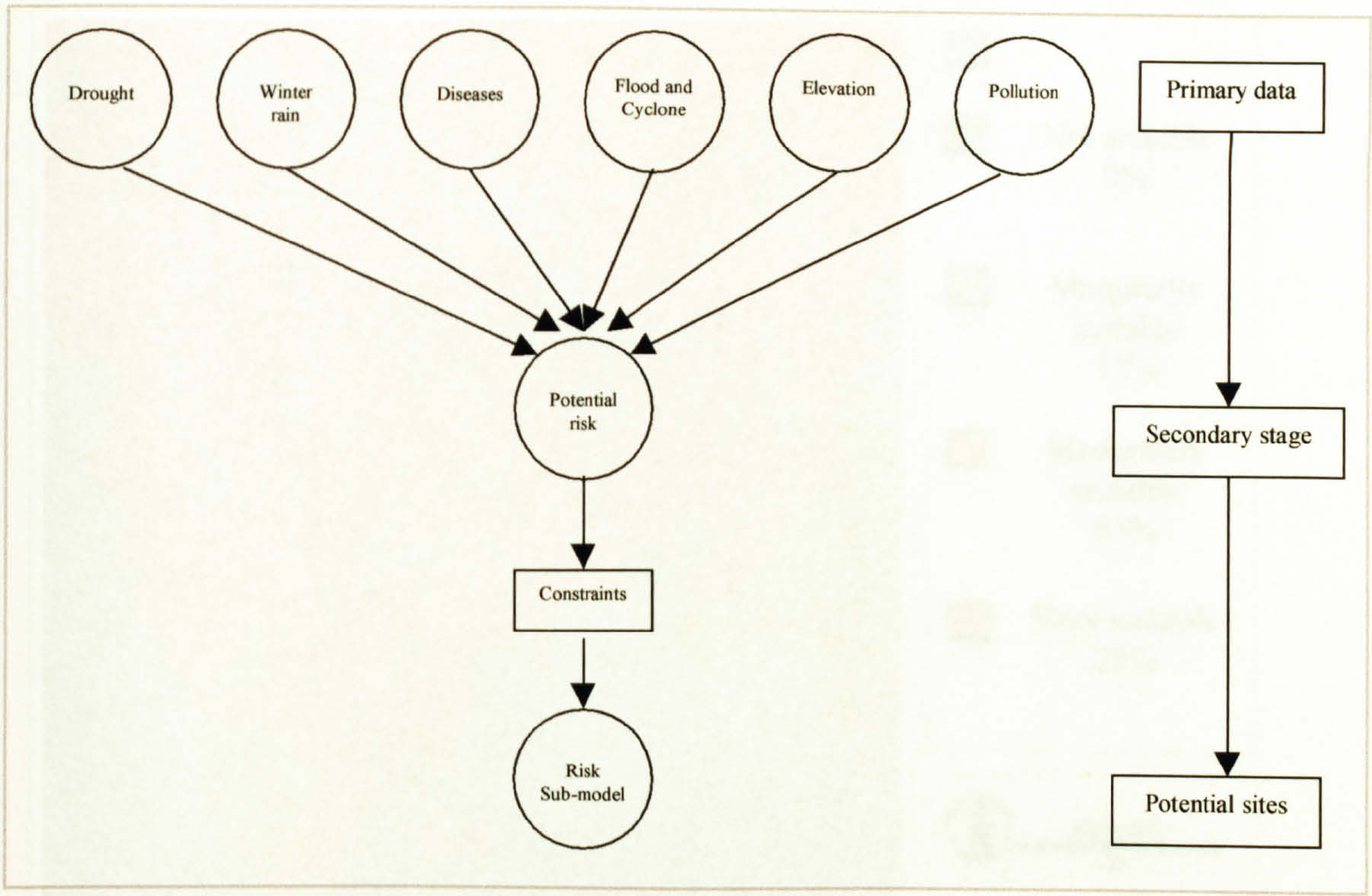

Figure 5.75. The sequence of risk sub-model for aquaculture development in the Khulna region, Bangladesh.

Mathematical expression:

RiskSC = (Dr x 0.2450) + (WiR x 0.3415) + (Dis x 0.0523) + (FlCy x 0.0828) + (Ele x 0.2185) + (Poll x 0.0600). Where, RiskSC = risk sub-model for shrimp and crab culture, Dr= risk of drought, WiR = winter rain, Dis = diseases for shrimp and crab, FlCy = flood and cyclone, Ele = elevation, Poll= pollution from urban development and industries respectively.

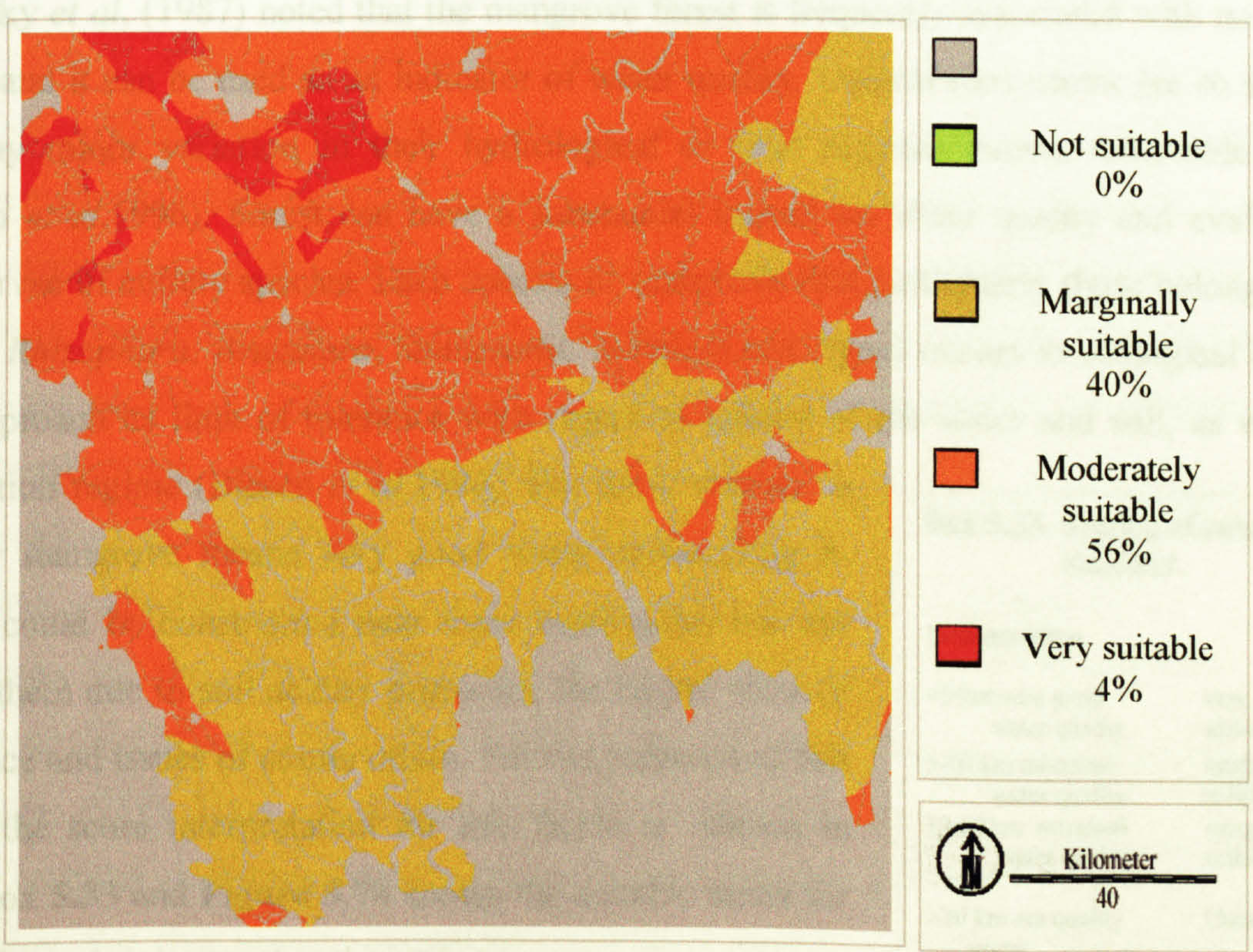

Figure 5.76. The risk sub-model for shrimp and crab culture in the Khulna region, Bangladesh.

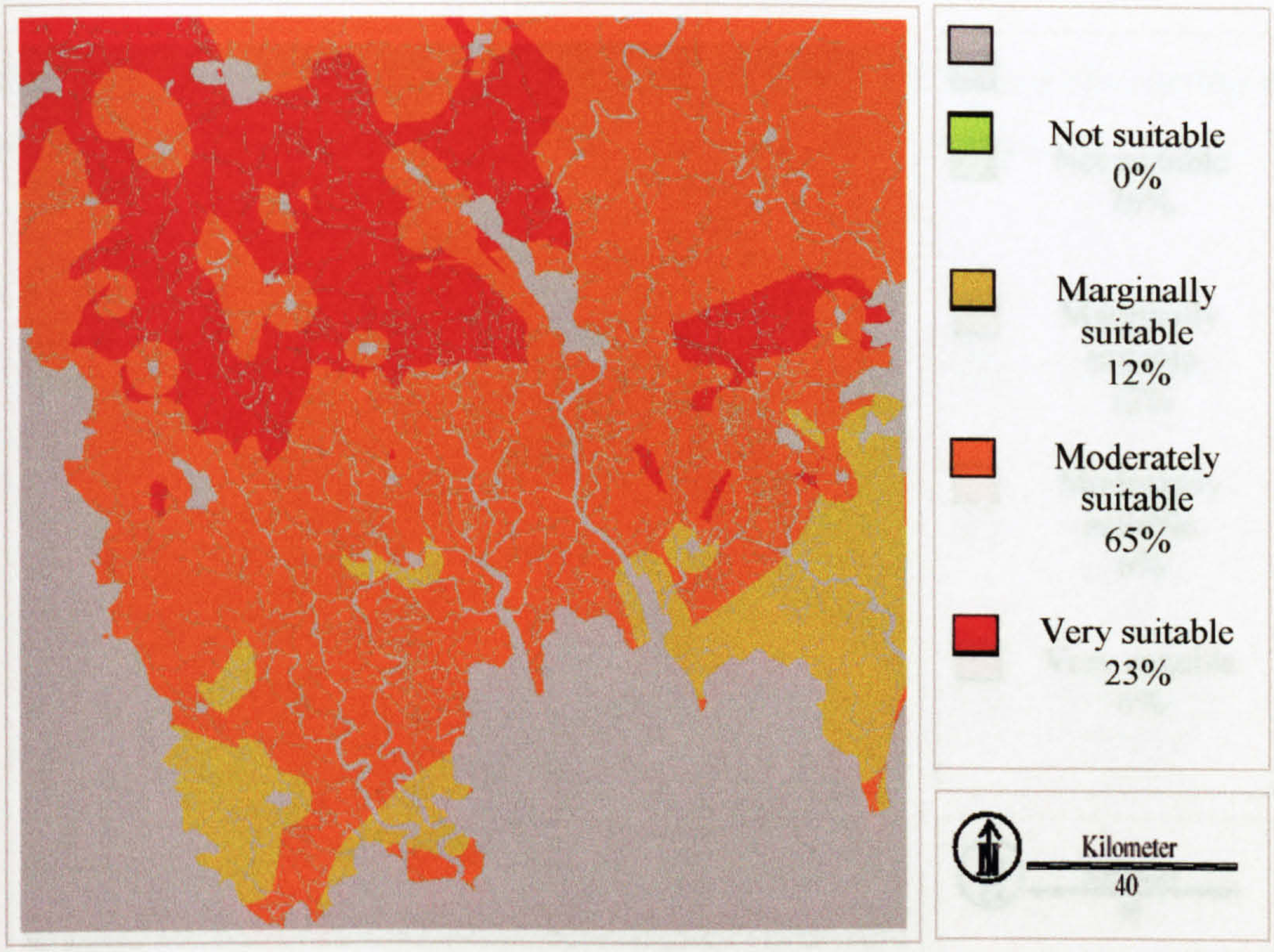

Figure 5.77. The risk sub-model image for prawn, carp and tilapia culture in the Khulna region, Bangladesh.

5.15 Natural indicators

Kapetsky *et al.* (1987) noted that the mangrove forest is frequently associated with non-polluted water, and it can be used as an indicator of water quality. Coastal ecosystems are so specialised that any minor variation in their hydrological or tidal regimes causes noticeable mortality (Blasco *et al.*1996). Forest can have a substantial impact on water quality and availability of post-larvae of culture species. Each species of mangrove (but particularly those belonging to the genera *Rhizophora, Bruguiera, Sonneratia, Heritiera* and *Nypa*) occurs in ecological conditions that approach its limit of tolerance with regard to salinity of the water and soil, as well as the inundation regime (Blasco *et al.*1996). For these reasons, a healthy mangrove means very good water surrounding it. Ponds could be constructed near these ecosystems but not inside them due to soil acidity problems, the higher costs of clearance and issues of conservation. For the purposes of this study, the score interpretation for this factor is shown in **Text box 5.33** and **Figure 5.78** shows the suitable lands for aquaculture development in the region.

Box 5.33. Scoring of natural indicator.

Interpretation		Score
<5 km very good water quality	very suitable	4
5-10 km moderate water quality	moderately suitable	3
10-20km marginal water quality	marginally suitable	2
>20 km not quality water	Unsuitable	1

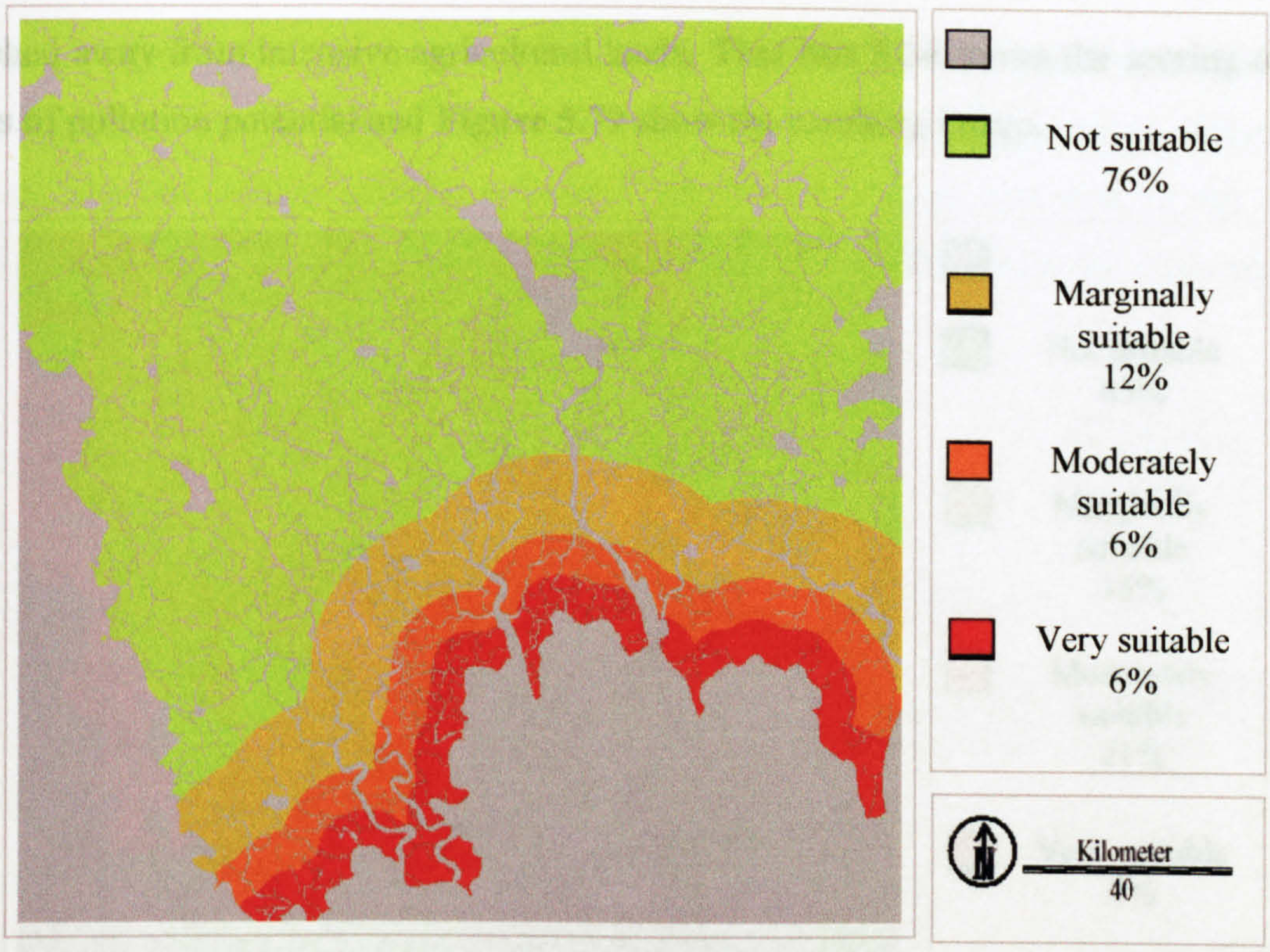

Figure 5.78. The mangrove as an indicator of water quality for aquaculture development in Khulna region.

5.16 Agriculture

In Bangladesh, as in most developing countries, agriculture plays a key role in the overall economic performance of the country, not only in terms of its contribution to GDP, but also as a major source of foreign exchange earnings, and in providing employment to a large segment of the population, particularly the poor. Agriculture is also a key sector to provide export earnings as well as generating jobs not only in farming but also in the highly important agricultural manufacturing sector. The productivity of agriculture in Bangladesh is generally low and agricultural growth, excepting good performance (due to good weather) during 1992-94, has generally stagnated in the 1990s (Rashid, 1995). However, aquaculture is vulnerable to the effects of pollution by intensive agricultural operations such as herbicides, pesticides etc. (Kapetsky, 1989). These can cause reduced production and sudden outbreak of diseases, which ultimately can close the operations. For this reason, aquaculture activities should

Text box 5.34. Scoring of agriculture pollution.

Interpretation	Score
Not suitable for agriculture less pollution	4
Marginal intensity of agricultural activities moderate risk of pollution	3
Seasonal cultivation possible risk of pollution	2
Intensive cultivation all around the year, high risk of pollution	1

established away from intensive agricultural lands. **Text box 5.34** shows the scoring of land use in terms of pollution potential and **Figure 5.79** show the resulting image.

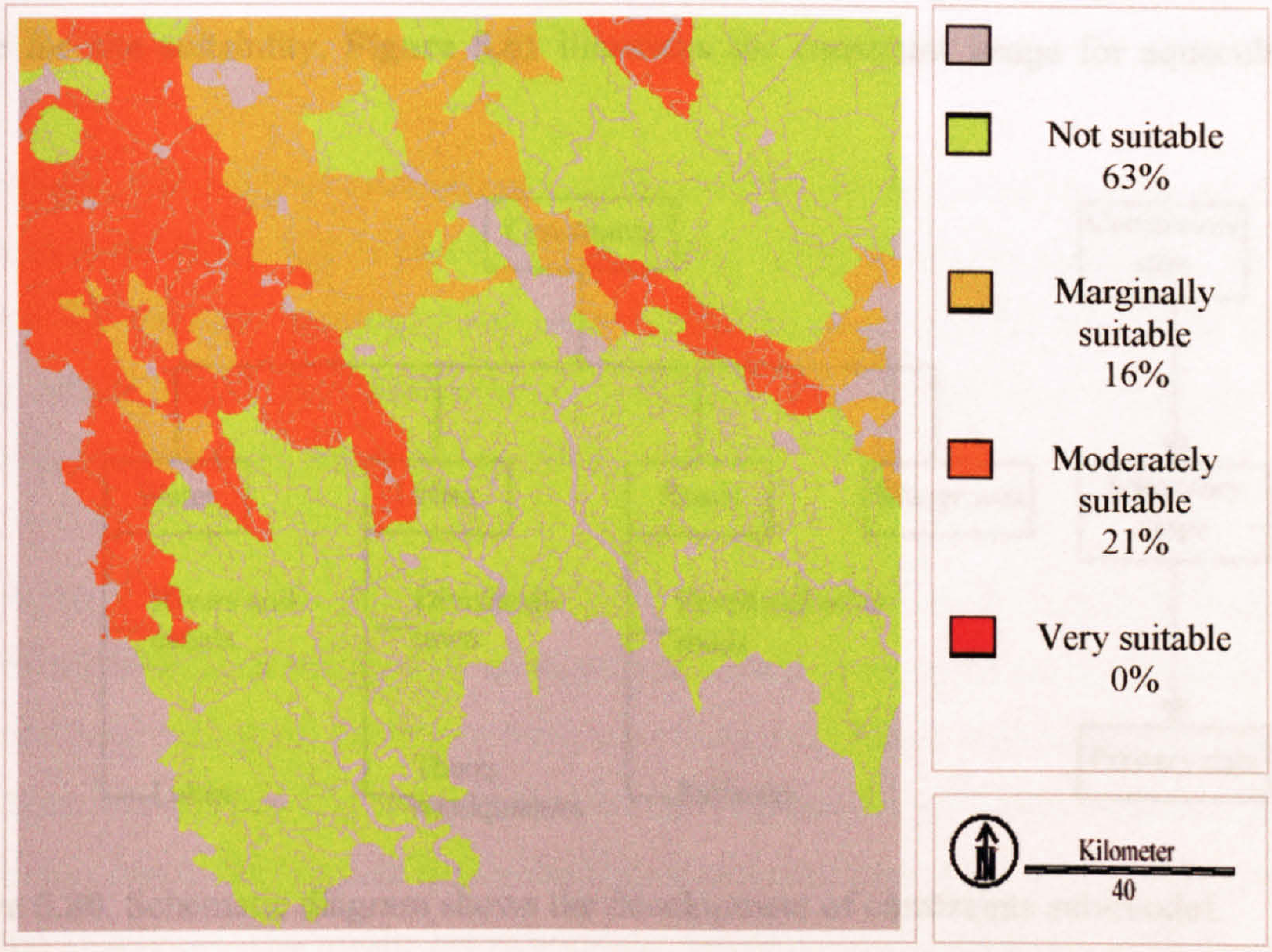

Figure 5.79. Agricultural land reclassified in terms of pollution potential for aquaculture development in the Khulna region, Bangladesh.

5.17 Constraints on aquaculture

As the Sundarbans is a World heritage site and a national treasure, it requires special care to protect it and its flora and fauna. Moreover, for sustainable coastal aquaculture, ponds should be at least a minimum distance from all such environmental sensitive areas. For this study, a value of 1000 m was established as a buffer zone outside these areas to minimise any negative impacts such as pollution. Similar buffer zones were established for a range of other constraints and these are summarised in **Text box 5.35.**

Text box 5.35. Proposed buffer zones around conservation areas.

Interpretation	Score
0-60 m was used as a distance constraint for roads, rivers and railways	0
0-500 m buffer zone was used as a distance constraint for town development	0
0-1000 m buffer zone was used as a distance constraint to protect mangrove ecosystems	0

Boolean images were created with all of the constraints involved in the study and a schematic diagram of their integration is shown in **Figure 5.80**. Data were reclassified either as 0, (areas which are not available) or 1 (areas which are available). All these images were then combined using OVERLAY module into a single constraint sub-model for rivers, roads, railways, lakes, towns and the Sundarbans mangrove forest. This Boolean image was used in the final MCE module for site suitability. **Figure 5.81** illustrates the constraint image for aquaculture in the region.

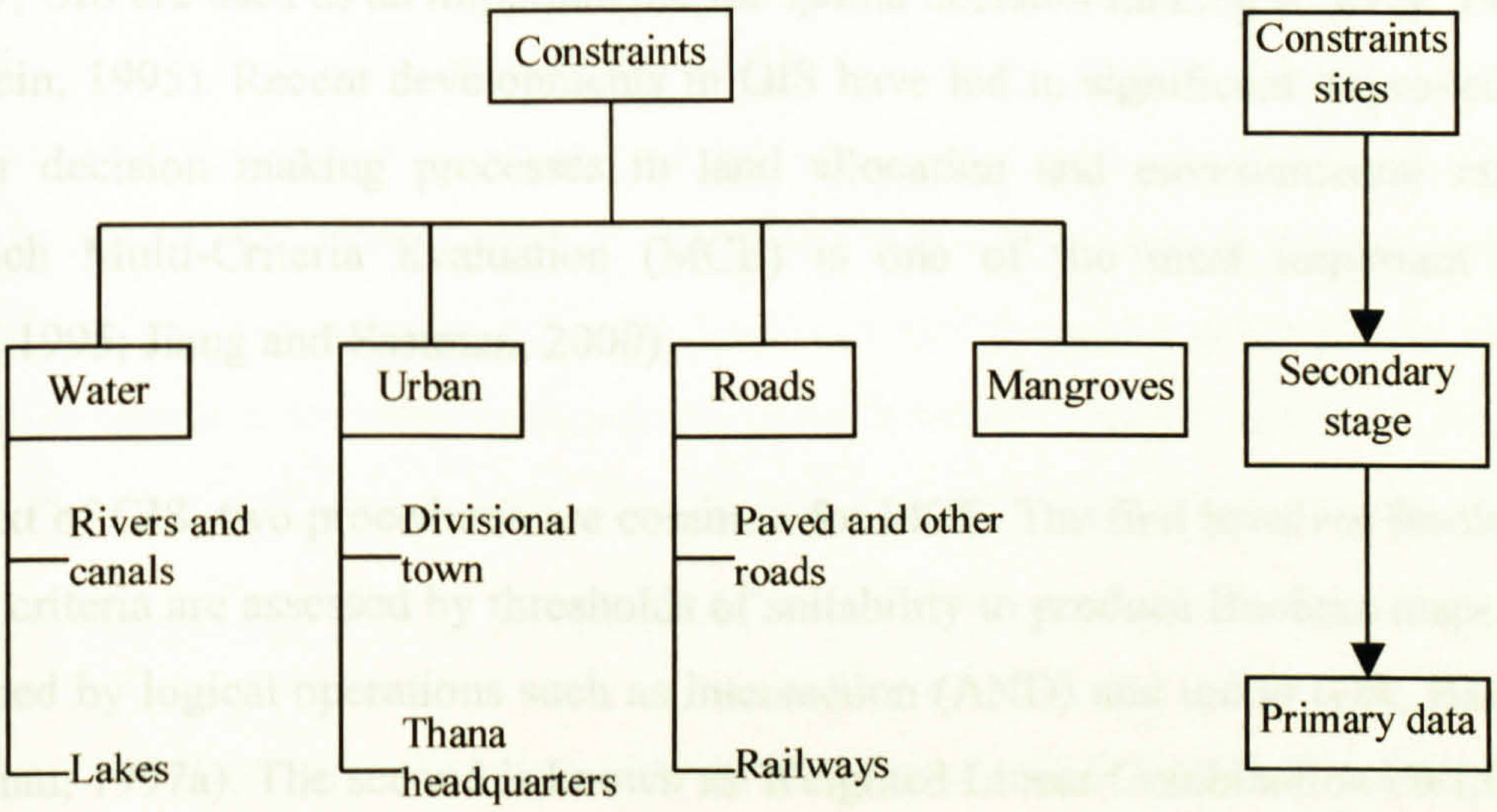

Figure 5.80. Schematic diagram shows the development of constraints sub-model.

Mathematical expression:
ConsA = RivC(c) + Lak (c) + Tw (c) + Than (c) + Rd (c) + Rw (c) + Mgrov (c), where, ConsA = constraints for aquaculture, RivC = rivers and canals, Lak = lake, Tw = town, Than = thana, Rd = road, Rw = railway, Mgrov = mangrove and (c) = for constraint.

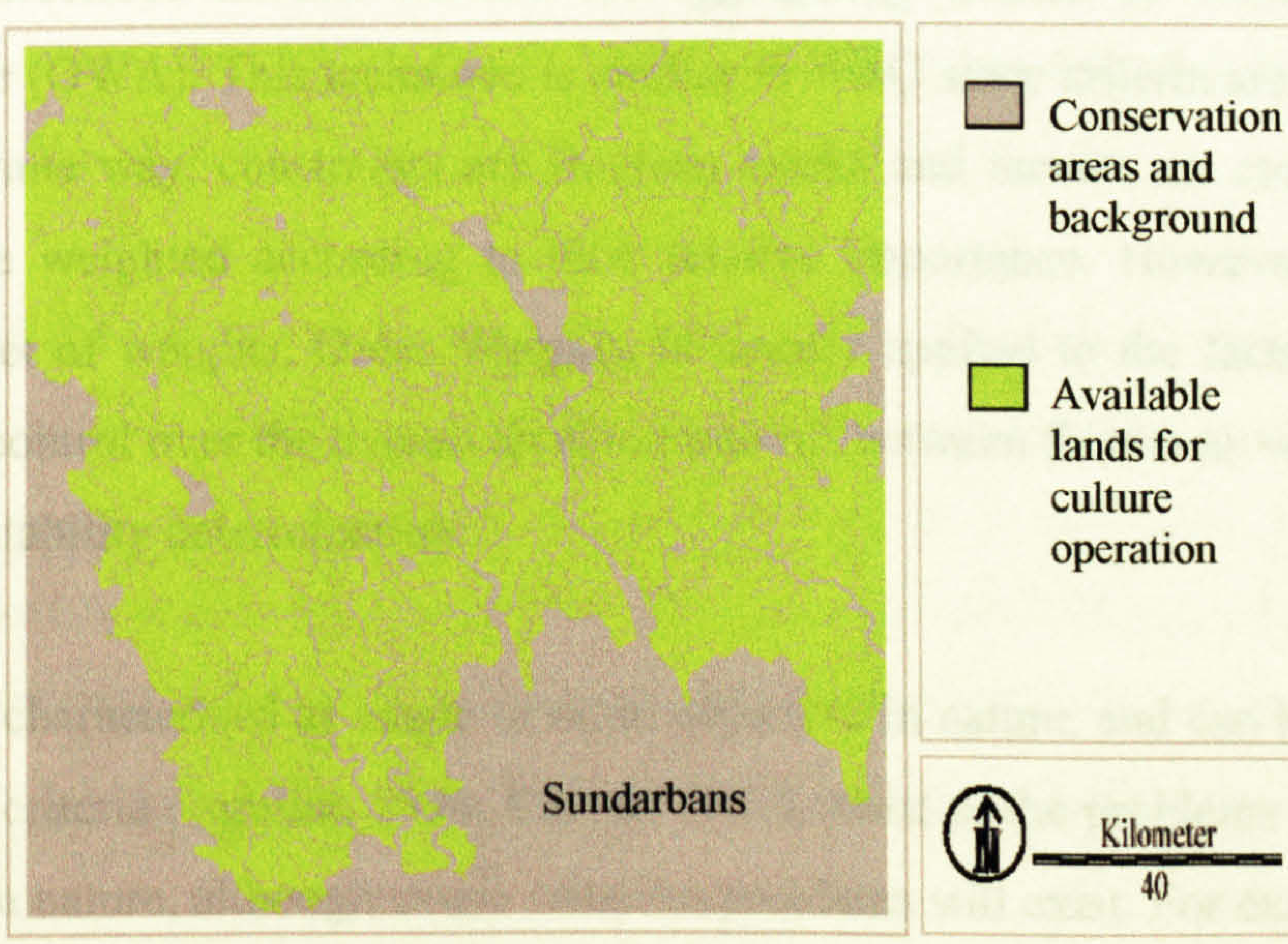

Figure 5.81. The constraint image for aquaculture in the region.

Chapter 6

GIS-based Modelling for aquaculture development in Khulna region, Bangladesh

6.1 Introduction

Increasingly, GIS are used as an important aid for spatial decision-making (Carver, 1991; Pereira and Duckstein, 1995). Recent developments in GIS have led to significant improvements in its capacity for decision making processes in land allocation and environmental management, among which Multi-Criteria Evaluation (MCE) is one of the most important procedures (Jankowski, 1995; Jiang and Eastman, 2000).

In the context of GIS, two procedures are common for MCE. The first involves Boolean overlay whereby all criteria are assessed by thresholds of suitability to produce Boolean maps, which are then combined by logical operations such as intersection (AND) and union (OR, Eastman *et al.* 1995; Eastman, 1997a). The second is known as Weighted Linear Combination (WLC), wherein continuous criteria (factors) are standardised to a common numeric range, and then combined by weighted averaging. The results are continuous mapping of suitability that may then be masked by one or more Boolean constraints to accommodate qualitative criteria and finally thresholded to yield a final decisions (Hall *et al.* 1992). More recently, Eastman (1997b) and Jiang and Eastman (2000) described another method for aggregating criteria by MCE called Ordered Weighted Average (OWA). This technique is similar to WLC since criteria are standardised and weighted in the same way, constraints are Boolean masks and factors are continuous maps of suitability that are weighted according to their relative importance. However, in the case of OWA, a second set of weights, Order Weights, is usually applied to the factors, which give a greater degree of control over the overall level to trade-off between factors as well as the level of risk in the land suitability determination.

Decisions may be characterised as single or multi objective in nature, and can be based on either single or multiple criteria (Aguilar, 1996; Carver, 1991). Most of the problems dealt with in GIS are multi criteria in nature, although single criterion problems still exist. For example, to identify areas for pond construction on the basis of topography, soil texture and land uses; the problem is how to combine these criteria to arrive at a composite decision. Although the problems are multi-objective in nature, they are dealt with from a single perspective (Diamond and Wright, 1988). With the advent of GIS, there is now the opportunity for a more explicitly reasoned environmental decision making process. However, GIS has been slow to develop decision support tools, more typically relying on procedures outside the GIS software (Eastman *et al.* 1995).

Land use planning is a complex process, especially in densely populated areas. For instance, in areas which can be found in the Netherlands (Carsjens, 1995) and in developing countries, a planner has to deal with different types of land use, often with conflicting objectives. Different types of land use can compete for the same locations and decisions on land use, its intensity, location and connection to surrounding areas, must be clear and reproducible. Methods and models, which can clarify and support the planning process in these situations, are therefore necessary.

Until now, little attention has been given to group decision-making problems despite the fact that spatial decision making problems are invariably associated with several individuals who may express 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. Only Eastman (1993), Aguilar (1996), Kapetsky and Nath (1997) have carried out real decision making applications in GIS based on group decisions. At present, IDRISI is one of the leading commercially available GIS software that provides a module specifically designed to support multi criteria evaluation decision making.

The initial stages of the GIS based models were described and developed in **Chapter 5,** in which the primary criteria were integrated together to create a series of sub-models. The overall objective of the study was to use these sub-models further to construct general models to evaluate aquaculture development from which more specific models could be developed (e.g. models based on shrimp, crab, prawn, carp and tilapia culture systems). A schematic diagram of the procedures involved in creating the GIS based models is shown in **Figure 6.1.**

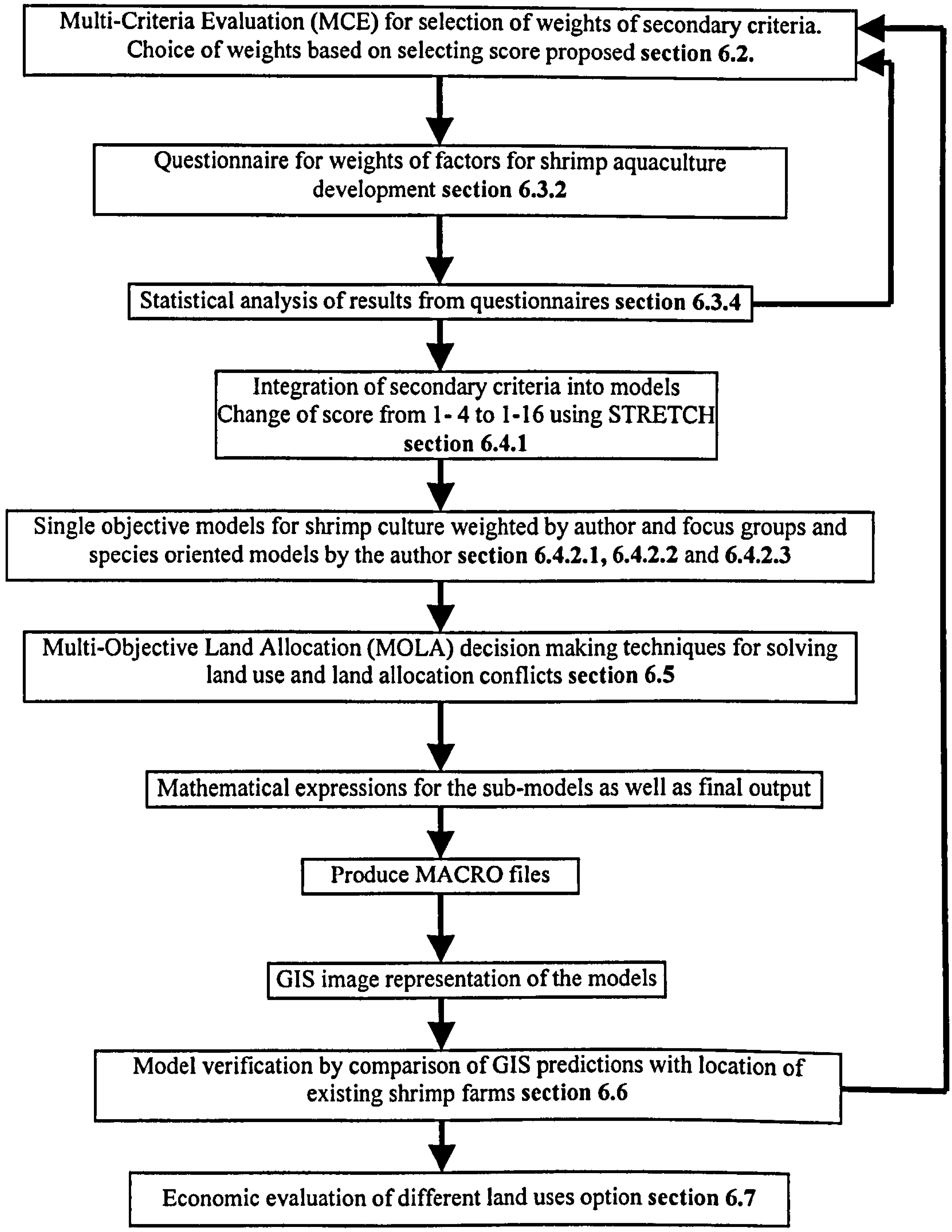

Figure 6.1. Flow diagram showing the multi criteria and multi objective decision making process for integrating secondary criteria in the study. The arrows indicate dynamic nature and feedback parts of the process.

6.2 Choice of weights based on selecting score

The method of pairwise comparisons in MCE was explicitly designed to satisfy the fairness criterion and this process was found to be very efficient in establishing weights of factors. Good results were obtained using the methods when a small number of factors were used. However, Ross (1998) and Aguilar (1996) consider that if the number of layers exceeds about 10, it is difficult to obtain good results through MCE, even in the hands of an experienced modeller. Although logical results can be obtained when dealing with a large number of factors in a single matrix, it becomes difficult to complete the matrix, the accuracy and consistency ratio (CR) may not be within the limits suggested by Saaty (1977) and much time can be lost. Ross (1998) and Aguilar (1996) suggested development of sub-models instead of simultaneous use of a large number of factors in MCE. For instance **Table 6.1** shows a pairwise comparison matrix for obtaining the weights to be used in a nine sub-model for shrimp culture. In this case CR is 0.07, which is acceptable according to Saaty's theory. However, even though the CR suggested that the weights were appropriate, the wrong weight could still be chosen. To overcome this problem, it was found that optimum results were achieved when a relative ranking of the factors was made before completing the pairwise comparison matrix. **Table 6.2** shows the scores that were assigned to the sub-models involved in the study. The ranking was essential not only to achieve a good CR but also to match the ranking to the questionnaires completed by groups of the decision-makers.

6.3. Focus groups and questionnaire development

6.3.1. Focus groups

Scoring of primary criteria and development of sub-models was individually based upon weightings developed by the author, related to species requirements, farming systems and knowledge of the natural environment and infrastructure. For development of the later stage of the models it was decided to base scores and weights on the collected opinions of three focus groups, all of whom had relevant, but differing, experience of the field. The three focus groups chosen were a) 3 Bangladeshi Ph.D. students and a Postdoctoral fellow studying aquaculture at Stirling (group I), b) 5 aquaculture support officers working with government and NGO's on shrimp culture in the Khulna region, (group F), and c) 7 field staff working with a DANIDA project on fresh water fish culture in Mymensingh (group D) region. The objective was to compare the responses and weightings suggested by 3 groups, although the final judgement in model development would be based on the author's decision.

Table 6.1. The pairwise comparison matrix for assessing the comparison importance to the 9 factors for aquaculture developments in Khulna region, Bangladesh (numbers show the rating of the row factor relative to the column).

	Water chemistry	Available Water	Land use	Soil chemistry	Infrastructure	Support	Inputs	Risk factors	Mangrove as indicator	Weights
Water Chemistry	1									0.2286
Available Water	1	1								0.2028
Land use	1/2	1/2	1							0.1818
Soil chemistry	1/2	1/2	1/2	1						0.1373
Infrastructure	1/3	1/2	1/3	1/3	1					0.0978
Support	1/6	1/6	1/4	1/5	1	1				0.0466
Inputs	1/6	1/3	1/6	1/3	1/6	1	1			0.0420
Risk factors	1/7	1/7	1/7	1/4	1/3	1/2	1/2	1		0.0328
Mangrove as indicator	1/4	1/3	1/5	1/4	1/6	1/2	1/2	1/3	1	0.0303

CR = 0.07

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**

Table 6.2. Factors interpretation and score for aquaculture developments in the Khulna region (source: Aguilar and Nath, 1998).

Factors	Criteria for score	Score (1-9)
Water chemistry	Water parameters are very crucial for all aquaculture activities and play a vital role in determining where should be the ponds for aquaculture.	9
Available Water	Water is essential for all forms of aquaculture and is a key factor in determining the aquaculture activities.	8
Land use	Non-acid sulphate, impermeable and compatible. Silty clay loam, clay loam or clay soils are preferable. Play an important role to siting ponds.	7
Soil chemistry	As water parameters, soil properties also has great influence to the culture species and thus important in aquaculture activities.	6
Infrastructure	Infrastructure consists of availability of seeds, distance to processing plants, distance to roads, rivers, and markets, which are very important to transport, marketing the products and site suitability factors.	5
Support	Support sub-model includes Government offices, NGO offices, Research station and University, which play a great role during site selection, financial as well as necessary training for carry out culture activities.	4
Inputs	Important as a source of low cost feed and fertiliser for aquaculture practices.	3
Risk factors	Risk sub-model consists of drought, topography, cyclones, floods, and rains (which reduce the salinity in the ponds) are playing great roles in production activities.	2
Mangrove as indicator	A healthy mangrove ecosystem means good water quality in the region and available source of seed and food for culture species.	1

6.3.2. The questionnaire

A standard questionnaire was developed for use with all these groups. The questionnaire has three sections. In the first section participants were asked to identify the most important factors involved in coastal aquaculture. In the second section, they were asked to name some constraints or limiting factors that are very important from a conservation point of view for coastal aquaculture and coastal protection. In the final part they were asked to rank the factors listed. The full questionnaire is shown in **Appendix 6.1**.

The aim of the questionnaire was to use the experience of the focus groups consensus the factors and constraints and also their ability to distinguish the most important factors which are involved in coastal aquaculture.

Prior to handing over the questionnaire to the focus group participants, a short introduction of the aim of the project was given. When they had filled in the first two sections of the questionnaire, then they were asked to rank the sub-models according to a score of 1-9, shown in **Table 6.2.** The questionnaire was completed in the presence of the author and enough time was given to think about the situation.

6.3.3. Questionnaire results

The weights and ranking given by the three focus groups of decision-makers are shown in **Tables 6.3** to **6.5.**

Table 6.3. The relative scoring of factors by focus groups in the in the fields for aquaculture development in the Khulna region, Bangladesh.

Factors	A	F-1	F-2	F-3	F-4	F-5	Σ Ri	Mean	A	F-1	F-2	F-3	F-4	F-5	Mean
Water chemistry	9	7	5	8	4	6	30	6	0.23	0.16	0.07	0.23	0.06	0.1	0.14
Available Water	8	6	9	9	2	9	35	7	0.2	0.11	0.3	0.3	0.03	0.3	0.21
Land use	7	5	3	7	3	1	19	3.8	0.18	0.07	0.04	0.15	0.04	0.02	0.09
Soil chemistry	6	9	8	6	9	8	40	8	0.14	0.3	0.22	0.12	0.31	0.22	0.22
Infrastructure	5	8	6	3	8	5	30	6	0.1	0.21	0.11	0.04	0.22	0.08	0.13
Support	4	4	7	5	7	7	30	6	0.05	0.05	0.15	0.07	0.15	0.16	0.11
Inputs	3	1	2	1	6	4	14	2.8	0.04	0.02	0.03	0.02	0.1	0.05	0.04
Risk factors	2	2	4	2	4	2	14	2.8	0.03	0.03	0.06	0.03	0.07	0.03	0.04
Mangrove as indicator	1	3	1	4	1	3	12	2.4	0.03	0.04	0.02	0.05	0.02	0.03	0.03
		-	-	-	-	-	-	-	1	1	1	1	1	1	1
CR									0.07	0.05	0.05	0.04	0.04	0.04	0.05

W=0.56; Xr^2= 22.58 and critical values of chi-square distribution [V=(n-1)= 8]= 15.51
Terminology: A = Author, F-1-F-5 = Field decision-makers.

Table 6.4. The relative scoring of factors by focus groups from the Institute of aquaculture, University of Stirling, for aquaculture development in the Khulna region, Bangladesh.

Factors	I-1	I-2	I-3	I-4	ΣRi	Mean	I-1	I-2	I-3	I-4	Mean
Water chemistry	6	6	3	5	20	5	0.11	0.12	0.03	0.07	0.08
Available Water	8	9	9	1	27	6.75	0.21	0.31	0.32	0.02	0.22
Land use	9	8	7	8	32	8	0.31	0.22	0.15	0.23	0.23
Soil chemistry	7	7	8	9	31	7.75	0.16	0.15	0.19	0.31	0.2
Infrastructure	5	5	5	4	19	4.75	0.07	0.07	0.09	0.05	0.07
Support	4	3	6	6	19	4.75	0.05	0.03	0.12	0.12	0.08
Inputs	3	4	4	2	13	3.25	0.04	0.05	0.05	0.03	0.04
Risk factors	2	2	2	7	13	3.25	0.02	0.02	0.03	0.14	0.05
Mangrove as indicator	1	1	1	3	6	1.5	0.02	0.02	0.02	0.03	0.02
	-	-	-	-	-	-	1	1	1	1	1
CR							0.04	0.04	0.05	0.06	0.05

W= 0.64, Xr^2= 20.09 and critical values of chi-square distribution [V=(n-1)= 8]= 15.51
Terminology: I-1-I-4 = decision makers from the Institute of Aquaculture.

Table 6.5. The relative scoring of factors by focus groups working with DANIDA in Mymensingh in the fields for aquaculture development.

	D-1	D-2	D-3	D-4	D-5	D-6	D-7	ΣRi	Mean	D-1	D-2	D-3	D-4	D-5	D-6	D-7	Mean
Water chemistry	6	7	6	9	5	3	3	26	5.57	0.12	0.1	0.1	0.3	0.1	0	0	0.12
Available Water	8	9	2	8	9	7	2	28	6.43	0.21	0.3	0	0.2	0.3	0.2	0	0.18
Land use	9	4	4	6	7	8	9	34	6.71	0.29	0.1	0.1	0.1	0.2	0.2	0.3	0.17
Soil chemistry	7	5	3	7	8	9	4	31	6.14	0.15	0.1	0	0.2	0.2	0.3	0.1	0.14
Infrastructure	4	2	8	3	2	4	5	22	4	0.06	0	0.2	0	0	0.1	0.1	0.07
Support	5	8	1	5	6	6	1	19	4.57	0.09	0.2	0	0.1	0.1	0.1	0	0.09
Inputs	2	3	7	1	3	5	8	24	4.14	0.03	0	0.2	0	0	0.1	0.2	0.08
Risk factors	3	1	5	4	1	2	7	19	3.29	0.04	0	0.1	0	0	0	0.1	0.06
Mangrove as indicator	1	6	9	2	4	1	6	22	4.14	0.02	0.1	0.3	0	0.1	0	0.1	0.09
Total	-	-	-	-	-	-	-	-	-	1	1	1	1	1	1	1	1
CR										0.04	0.1	0.1	0	0	0	0	0.04

W= 0.074, Xr^2= 4.15 and and critical values of chi-square distribution [V=(n-1)= 8]= 15.51.
Terminology: D-1-D-7 = DANIDA decision-makers.

In general it was found that most of the focus groups were in agreement with the most important factors, except the focus groups from DANIDA, from Mymensingh. For the first part of the questionnaire all of the decision-makers were able to identify some factors which are relevant to coastal aquaculture, although some of the factors chosen were not appropriate for this purpose (i.e., shape and size of ponds, food conversion ratio, harvesting method and role of water development board). However, they did identify some important factors, which could be included in the model (i.e., hardness, alkalinity and electricity supply). By contrast, only one of the participants in all 3 groups was able to cite one of the constraints properly. Most of them cited the risk factors as constraints (i.e., disease, flood, cyclone and pollution) and it seems that they have failed to distinguish between risk factors and constraints.

Table 6.6. The relative mean scoring of factors by focus groups working with DANIDA, students of the Institute and decision-makers working with farmers for aquaculture development in the Khulna region, Bangladesh.

	F	I	D	Mean		F	I	D	Mean
Water chemistry	7	6	6	6.3	6	0.12	0.08	0.12	0.11
Available Water	8	7	8	7.7	8	0.18	0.22	0.18	0.19
Land use	4	9	9	7.3	7	0.17	0.23	0.17	0.19
Soil chemistry	9	8	7	8	9	0.14	0.2	0.14	0.16
Infrastructure	6	5	3	4.5	4	0.07	0.07	0.07	0.07
Support	5	4	5	4.7	5	0.09	0.08	0.09	0.09
Inputs	3	3	4	3.3	3	0.08	0.04	0.08	0.07
Risk factors	2	2	1	1.7	2	0.06	0.05	0.06	0.06
Mangrove as indicator	1	1	2	1.3	1	0.09	0.02	0.09	0.07
						1	1	1	1
CR						0.04	0.05	0.04	0.05

W= 0.91; Xr^2= 21.79 and critical values of chi-square distribution [V=(n-1)= 8]= 15.51.
Terminology: F = Field decision-makers, I = decision makers from the Institute of Aquaculture and D = DANIDA decision-makers in Mymensingh.

6.3.4 Statistical analysis of questionnaires

Statistical analysis was carried out on the questionnaire outcomes to judge whether the rank scores initially assigned by the author matched the rank scores of the focus groups. For this, the non-parametric Kendall coefficient of concordance was used. Non-parametric statistical analysis was used because: 1) data was not collected at random as the questionnaire had to be assessed by experienced aquaculture personnel; 2) the sample size had to be small to run the MCE module reliably as the module trends to be more problematic with a large sample size. Kendall's coefficient of concordance (W) is commonly used to express the intensity of agreement among several rankings. The test is based on the hypothesis:

H_0: The m sets of rankings are not associated

H_1: The m sets of rankings are associated and is derived using the following formula:

$$W = \frac{\Sigma Ri^2 - \frac{(\Sigma Ri)^2}{n}}{\frac{m^2(n^3 - n)}{12}}$$

Where, W = Kendall's coefficient of concordance; Ri = sum of the ranks assigned by focus groups; m = number of sets of rankings and n = number of individuals.

The value of W may range from 0 (when there is no agreement among the sets of ranks) to 1 (when there is a complete agreement among the sets of ranks). Therefore large valves of W rejected H_0 (Kendall, 1984a, b). Moreover, it was possible to compute Xr^2 = m (n-1) W, and compare it with the value of chi $\chi^2 = (n-1)$. If the Xr^2 was larger than chi-square, rankings were associated and therefore there was an agreement.

Footnotes to **Table 6.3** and **6.4** show that the author's results were very similar to focus group F, the decision-makers from the field working with the shrimp farmers and with group I, the students from the Institute of Aquaculture. However, the author's results differed from those of focus group D, the decision-makers from DANIDA working with the fresh water fish farmers in Mymensingh (**Table 6.5**). The value of the Kendall's coefficient of concordance (W) were 0.56 and 0.64 group F and I, respectively, and therefore the m sets of ranking were associated (i.e., null hypothesis was rejected). Xr^2 values (22.58 and 20.09) were considerably larger than the chi-square at 95% confidence level (15.51). This means that the ranks by the author, group F and group I agreed but were not matched with those of group D. In this case W was 0.074 and Xr2 was 4.15 (i.e., null hypothesis was excepted), which was much smaller than the chi-square at 95% confidence level (15.51). The main reason behind such dissimilar rankings from the DANIDA workers was probably the fact that they are working with fresh water aquaculture.

To resolve this problem, the mean ranking values from the three different groups were used (Malczewski, 1996). From the **Table 6.6** it is clear that the rankings were perfectly matched with the author and with the mean rankings of three groups, where W was 0.91 and Xr2 was 21.79 (i.e., null hypothesis was rejected) considerably larger than the chi-square at 95% confidence level (15.51). As shown in this table, four rank orders (water chemistry, soil chemistry, infrastructure and support) out of nine did not match the exact rank order when compare to those of the author. The author and the focus groups agreed that available water and land use were the most important factors for aquaculture development. However, the focus groups gave highest rank to the soil chemistry while the author gave water chemistry the highest rank

6.4 Integration of secondary criteria into models

6.4.1 Change of score

In the initial stages of classification of the primary criteria where the maximum number of criteria involved in a MCE evaluation at this stage was only six (e.g. risk sub-model, **Chapter 5**) the score range used was 1 to 4. However, the number of criteria was involved in later MCE was 9. If a 1 to 4 score range was used with 9 sub-models in the final MCE evaluation, much valuable information would be lost and the final image would be very simple. Therefore, the STRETCH module was used to change the score range from 1 to 4 to 1 to16 (i.e., a maximum of 16). This range was still relatively small, but was enough to reveal detail in the model output.

6.4.2 Single Objective Model

6.4.2.1 Shrimp culture model weighted by the author

Based on the source data, and sub-models outcome models were developed which focused on different aquaculture themes. The sub-models were developed using different approaches. Some were created using, MCE while others, such as the inputs sub-model, was created using mathematical expression.

Model integration involved five stages, which are illustrated in **Figure 6.2.**

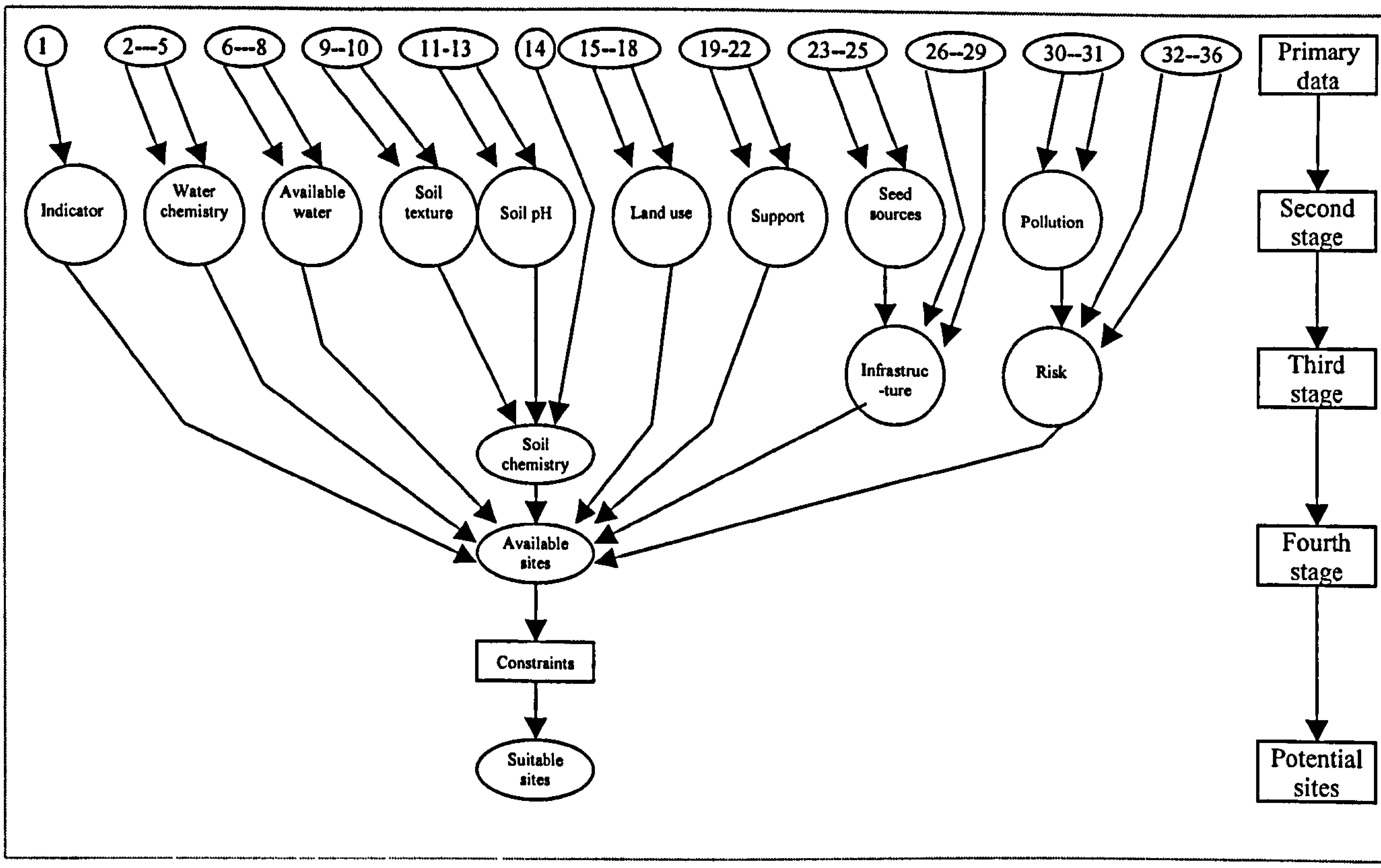

Figure 6.2. Integration of criteria into models for development of shrimp aquaculture in the Khulna region.

Primary data: 1= mangrove forest, 2= Temperature, 3= dissolve oxygen, 4= pH, 5= Salinity, 6= rivers, 7= lakes, 8= under ground water, 9= sub soil texture, 10= surface soil texture, 11= surface soil pH, 12= sub soil pH, 13= field visit soil pH, 14= soil salinity, 15=agriculture land, 16= land under shrimp culture, 17= land under cities, 18= villages, 19= NGO offices, 20= Government offices, 21= Research station, 22= Universities, 23= seed from nature, 24= seed from hatcheries, 25= seed from local marker, 26= roads, 27= rivers, 28= markets, 29= processing plants, 30= pollution from industries, 31= pollution from urban development, 32= risk of drought, 33= risk of winter rain, 34= risk of disease, 35= risk of flood and cyclone and 36= elevation.

Using the weights derived by the author and the above structure, models for culture shrimp, crab, tilapia, prawn and carp were developed. **Figure 6.3** shows the area allocated for shrimp culture in south-western part of Bangladesh. **Text box 6.1** shows the macro file for the shrimp culture model.

Text box 6.1. IML macro files for shrimp culture model.

Primary Criteria
Secondary Criteria
Stretch of 1-16 was applied to all sub-models prior to run MCE module.

stretch x schmbgd schbgd 1 min max 1 16 clases
mce x shrdsf shr-suit

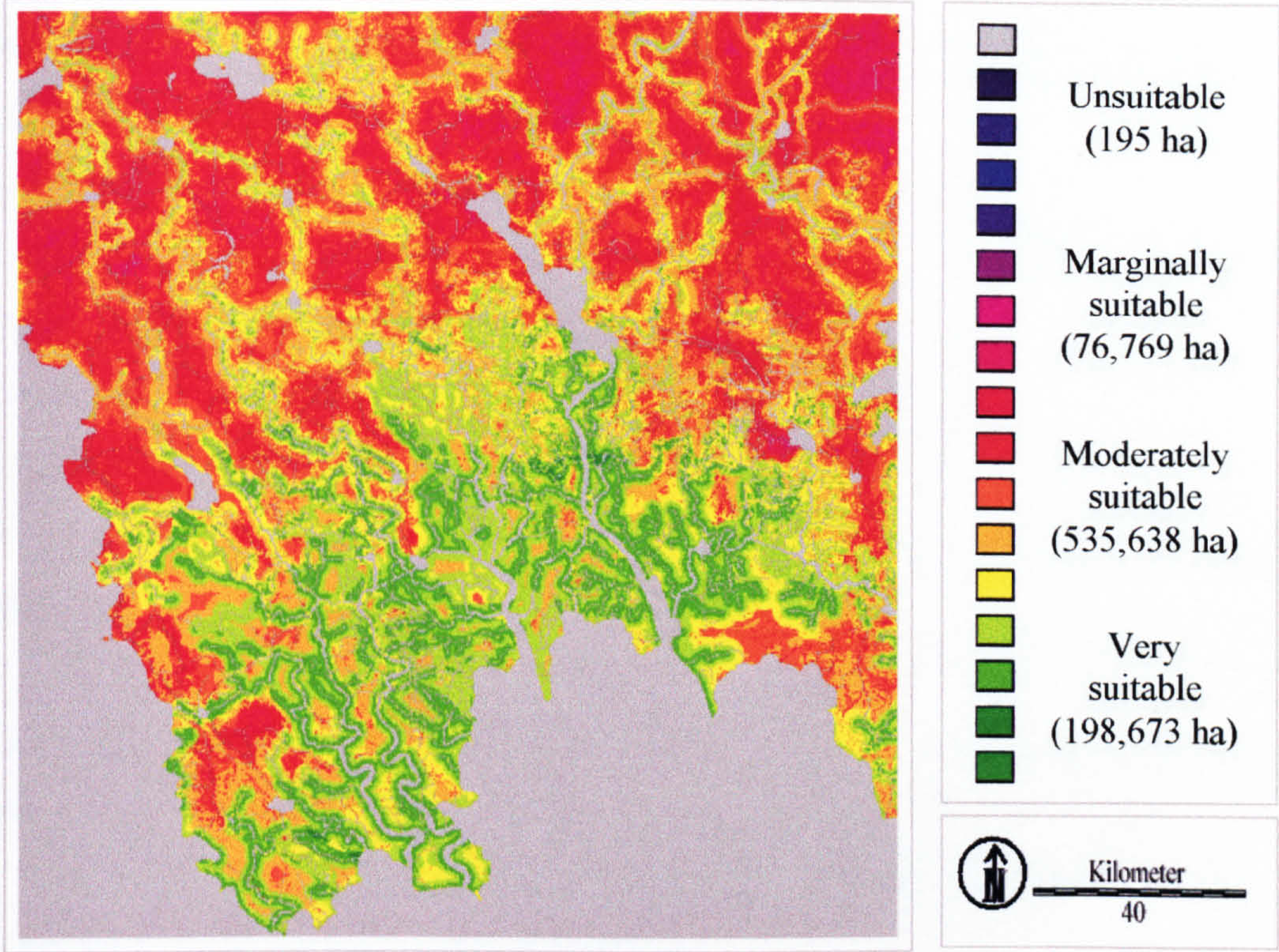

Figure 6.3. Sites suitable for coastal shrimp (*Penaeus monodon*) culture in the Khulna region weighted by the author.

Mathematical expression:

Suitbgd = (Wc-bgd x 0.2286) + (Wa-bgd x 0.2028) + (TM-luse x 0.1818) + (schmbgd x 0.1373) + (Inf-shr x 0.0978) + (support x 0.0466) + (inputs x 0.0420) + (riskbgd x 0.0328) + (m-indica x 0.0303). Where, Suitbgd = GIS predicted suitable site, Wc-bgd= water chemistry sub-model, Wa-bgd= available water sub-model, TM-luse= land sub-model, schmbgd= soil chemistry sub-model, Inf-shr= infrastructure sub-model, support= support sub-model, inputs= inputs sub-model, riskbgd = risk sub-model for shrimp culture and m-indica = mangrove as an indicator of good water quality.

6.4.2.2 Shrimp culture model weighted by the focus groups

For comparison, the GIS model was re-run using the weights of the focus groups (the mean value and rank obtained by statistical analysis). **Figure 6.4** illustrates the area which is suitable for coastal shrimp culture in the Khulna region weighted by the focus groups.

Due to strong agreement between the weights and rankings of the criteria assigned by the author and the focus groups, 87.41% suitable sites were matched for all classes of suitable categories with the author weighted model **(Table 6.7).** Moreover, Kappa value of the cross tabulation was 0.90, which means that the two images are very close match with each other.

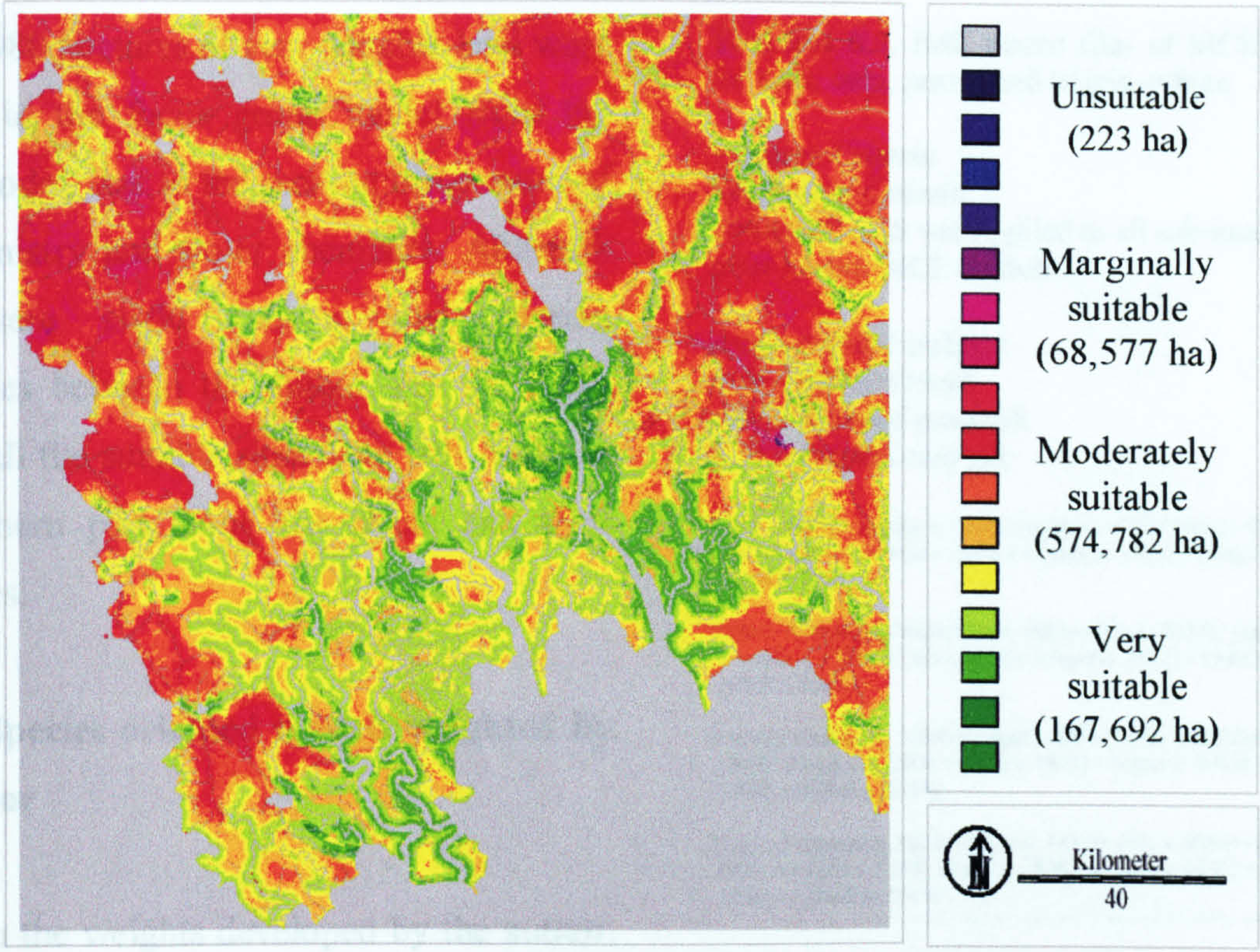

Figure 6.4. Sites suitable for coastal shrimp (*Penaeus monodon*) culture in the Khulna region weighted by the focus groups.

Mathematical expression:

Suitshrd = (Wc-bgd x 0.1098) + (Wa-bgd x 0.2266) + (TM-luse x 0.1587) + (schmbgd x 0.2947) + (Inf-shr x 0.0526) + (support x 0.0769) + (inputs x 0.0362) + (riskbgd x 0.0255) + (m-indica x 0.0189). Where, Suitshrd = GIS predicted suitable site for shrimp culture weighted by decision-makers.

Table 6.7. The cross tabulation matrix for shrimp culture model weighted by the author (as reference) and the focus groups (as mapped).

	Unsuitable	Marginally suitable	Moderately suitable	Very suitable	Total pixels	Error Commission
Unsuitable	**2165**	318	0	0	2483	12.81
Marginally	0	**616,438**	145532	0	761,970	19.1
Moderately	0	236,229	**5601,586**	548646	6386,461	12.29
Very suitable	0	0	204,419	**1658,828**	1863,247	10.97
Total cells	2,165	852,985	5951,537	2207,474		
Error Omission	0	27.73	5.88	24.85		
Sum of the major diagonal (pixels)	7879,017					
Total pixels in column	9014,161					
Overall accuracy	87.41%					
Overall Kappa	0.90					

The, 30,980 hectares of very suitable land were reduced in the focus group model from the author model, due to the ranking differences of soil chemistry and water chemistry. Although there were slight ranking and scoring differences between the author and the focus groups, all the suitable sites were still found in the *southern part along the rivers and their* tributaries.

Text box 6.2. IML macro files of MCE module for crab, carp, prawn and tilapia culture.

Primary Criteria
Secondary Criteria
Stretch of 1-16 was applied to all sub-models prior to rum MCE module.

mce x crabdsf crabsuit
mce x tlpdsf tlpsuit
mce x prwndsf prawsuit
mce x carpdsf carpsuit

Note: crabdsf= (tmluse x .2304)+(infcb x .1325)+ (rbgd x 0.440)+ *(supt x .0634)+ (wcbgd x .2296)* + *(sbgd* x .1600) + (wbgd x 0.917) + (mindi x .0484)

Tlpdsf=(tmluse x .1746)+(inftl x .0924)+ (rfis x .0322)+ (supt x .0593)+ (wcfis x.1658) + (sfis x .1250) +(input x .0577) + (wfis x.2669) + (mindi x .0261)

Prwndsf=(tmluse x .1808)+(infgld x .0886)+ (rfis x .0352)+ (supt x .0464)+ (wcgld x .1869) + (sgld x .1413) + (input x .0413) + (wfis x .2508) + (mindi x .0289)

Carpdsf=(tmluse x .1813)+(infcp x .1416)+ (rfis x .0366)+ (supt x .0613)+ (wcfis x .2168) + (sfis x .1528) + (input x .0732) + (wfis x .1049) + (mindi x .0315)

6.4.2.3 Species oriented models weighted by the author

Based on the weights developed by the author, and using the general structure of the shrimp culture model (**Figure 6.2**), species oriented models were developed for crab, tilapia, prawn and carp culture. **Figures 6.5**, **6.6**, **6.7** and **6.8** show the outcome of these models. **Text box 6.2** represents the macro files for crab, tilapia, prawn and carp culture model in the region.

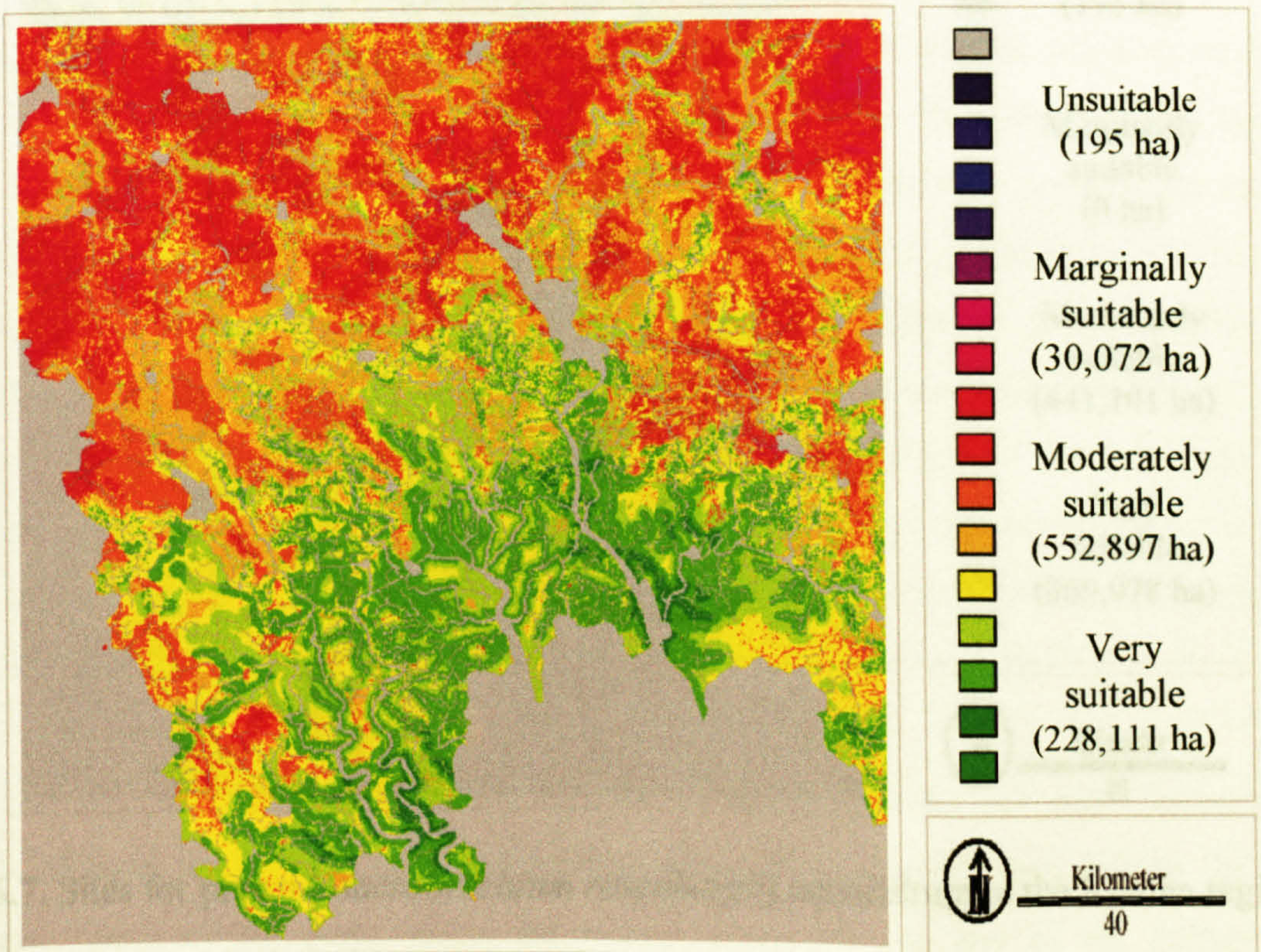

Figure 6.5. Sites for crab aquaculture in Khulna region.

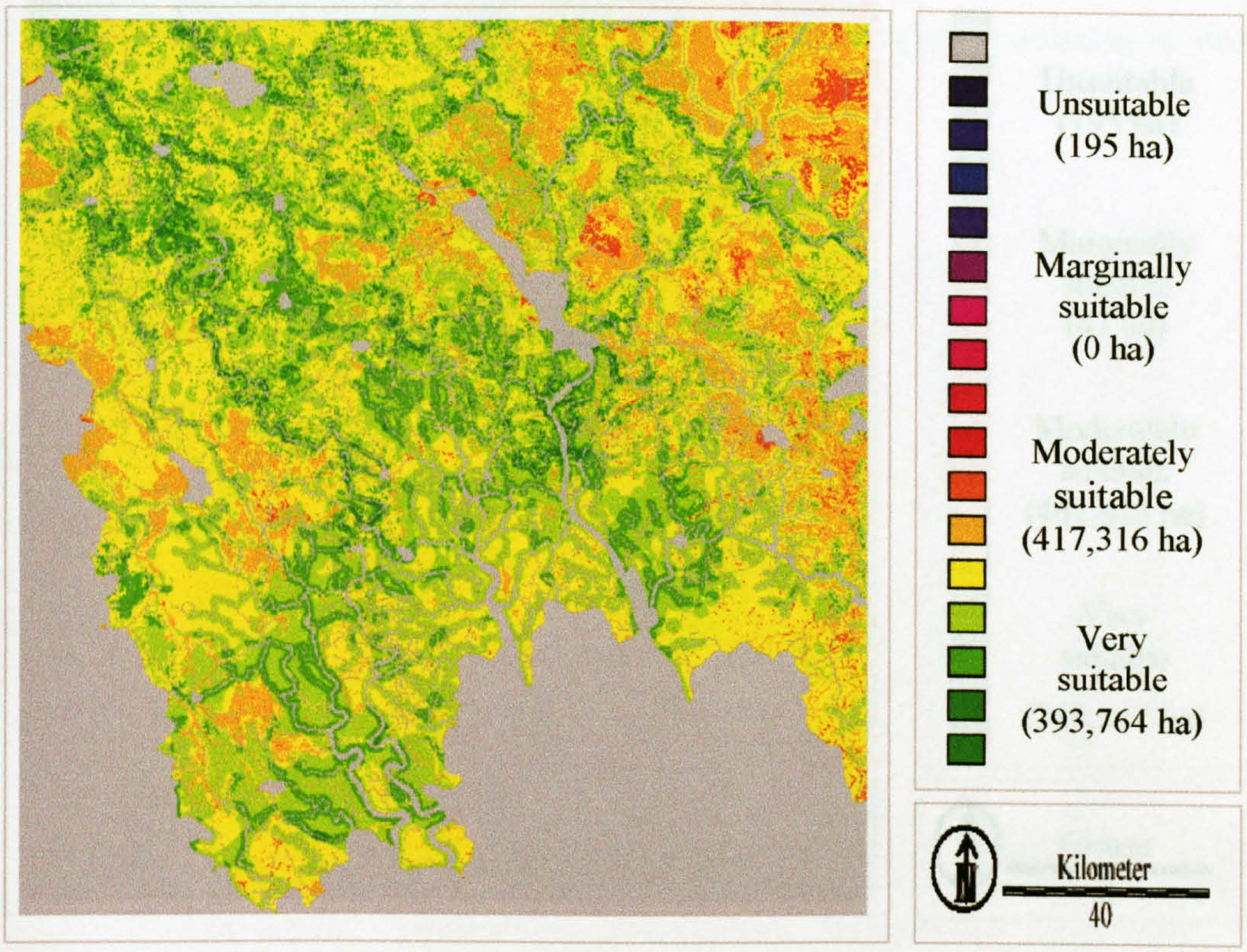

Figure 6.6. Sites for tilapia aquaculture in Khulna region.

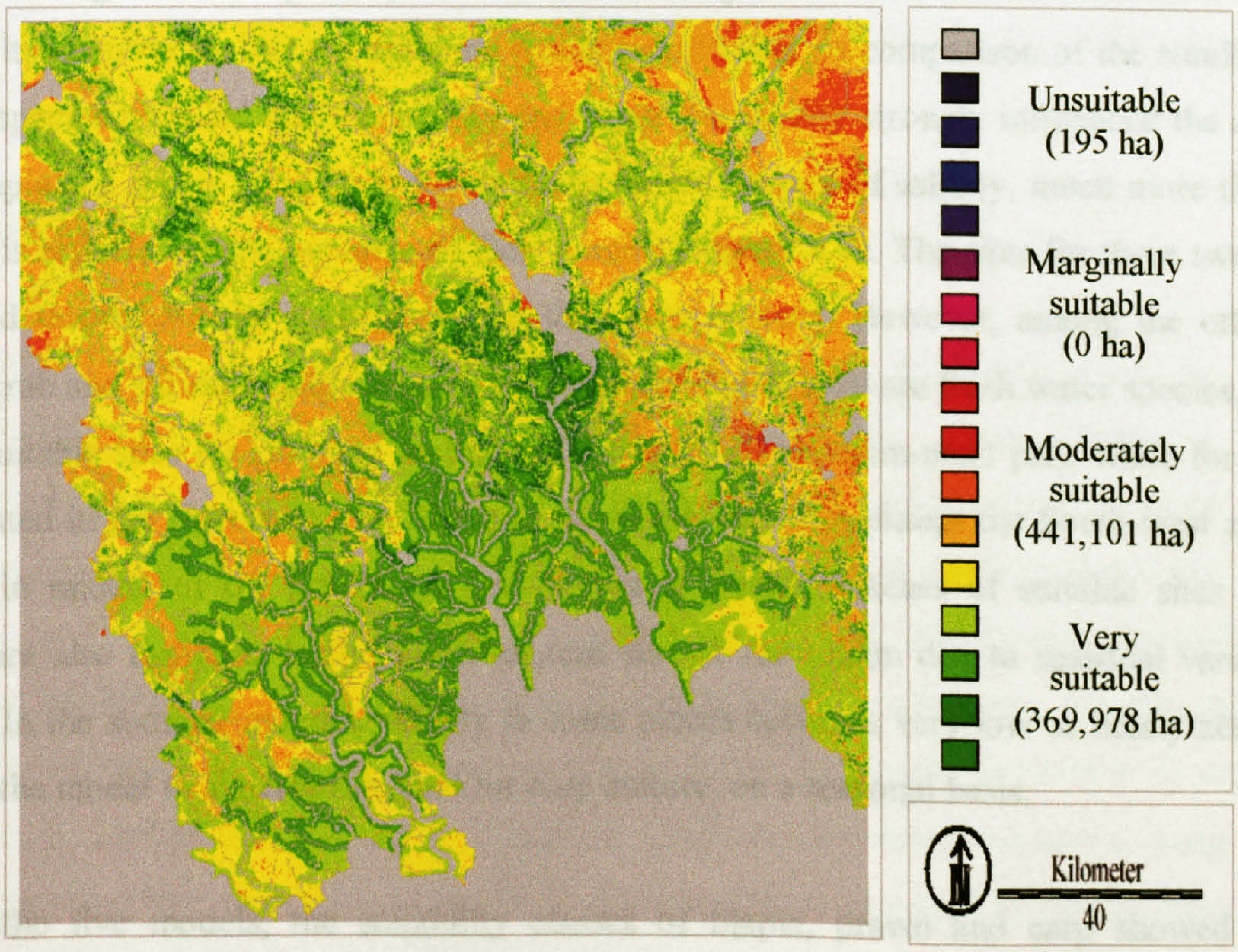

Figure 6.7. Sites for prawn (*Macrobruchium rosenbergii*) aquaculture in the Khulna region.

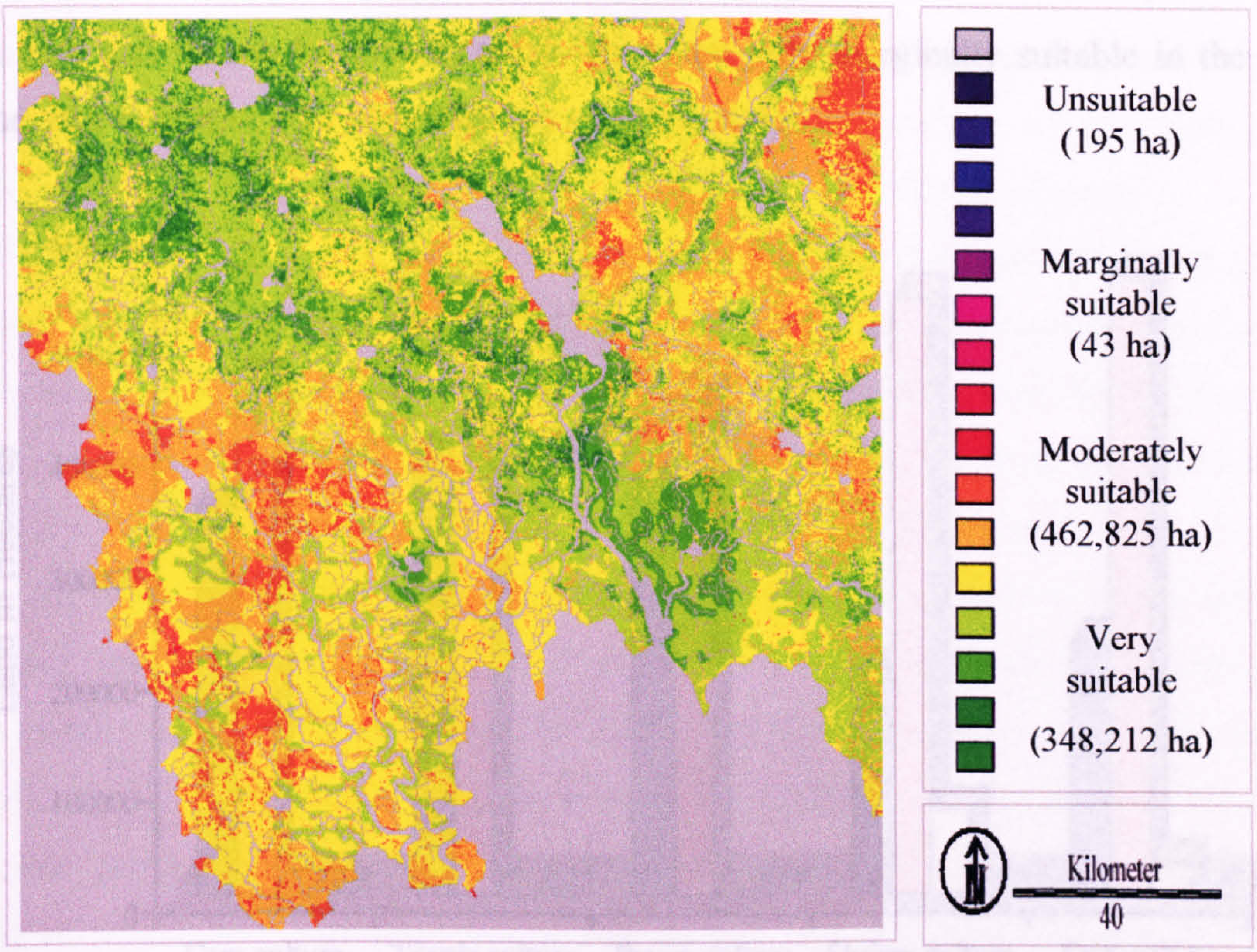

Figure 6.8. Sites for carp (mixed culture) aquaculture in the Khulna region.

Since the weights of the primary criteria and ranking of sub-models were different for each species, it was obvious that the outcome would be different. A comparison of the results among the five species revealed that the salinity and water availability strongly influenced the outcome. Both tilapia and prawn are able to tolerate a moderate amount of salinity, much more than carp, and this is reflected in the outcome of their models (**Figure 6.9**). The sites for these two species are found throughout the study area near the water sources. However, among the other three species crab and shrimp require a saline environment, while carp are fresh water species. For this reason suitable sites for crab and shrimp are found in the southern-most part, while for carp are best located in the North-west, middle and the South-east area except the South-west and some patches in middle of the Southwest and Northeast corner. Patches of suitable sites for carp culture are also available in the south-western part in the region due to seasonal variances of salinity. In the summer months, salinity in some places becomes very low or nearly zero which allowed the model to allocate this land for carp culture, on a seasonal basis.

Among the five models, the suitability classes of tilapia, prawn and carp showed greatest similarity of their results and crab and shrimp followed a similar trend due to their habitat preference. There are no areas which are totally unsuitable for any of the culture species, although crab and shrimp have some areas which are only marginally suitable in the northern part of the area because of the unavailability of saline water.

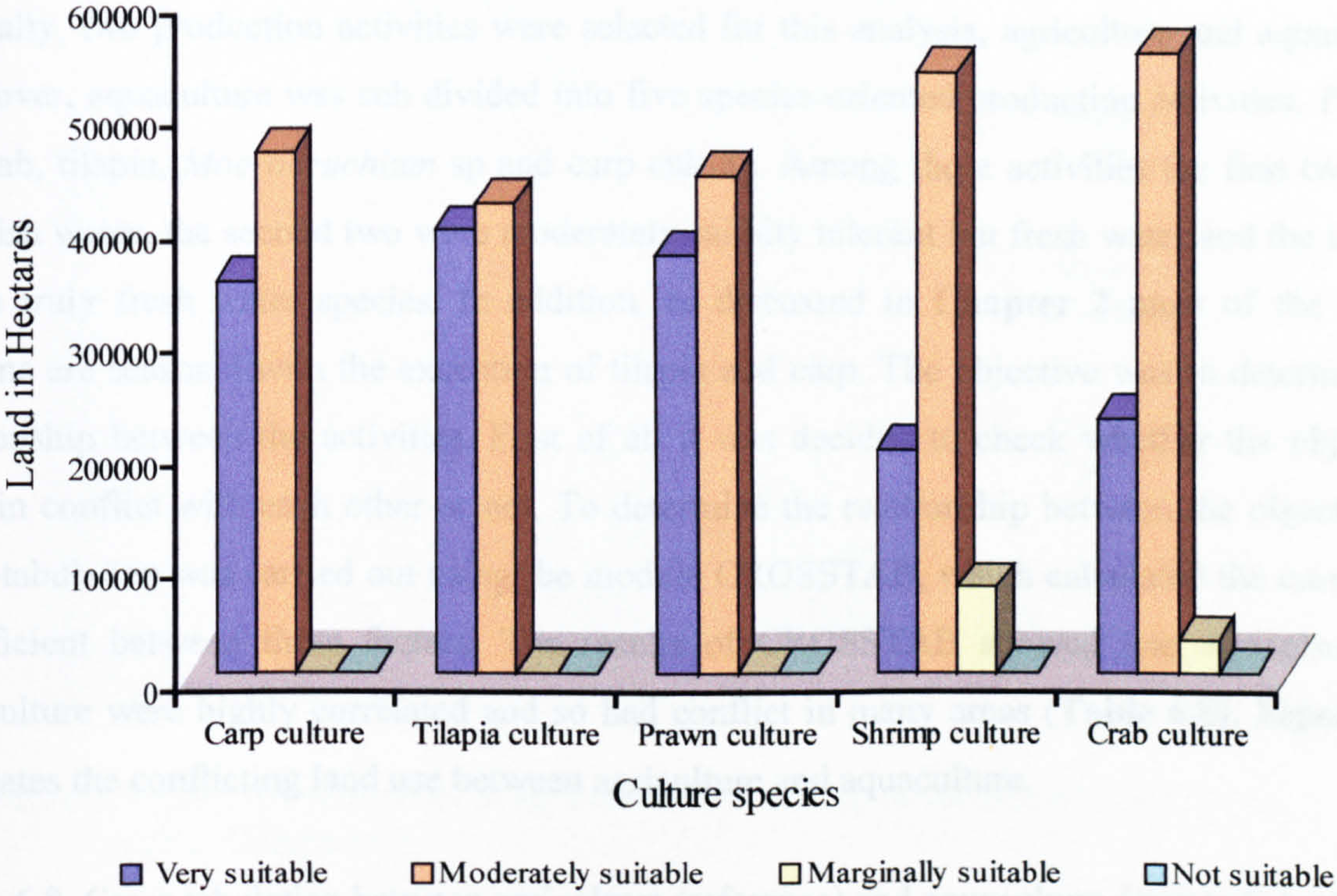

Figure 6.9. Categories of land allocated by GIS modelling for aquaculture of different species in the Khulna region.

6.5 Multi objective models

In Decision theory, a decision process in which several objectives must be satisfied simultaneously is referred to as multi-objective evaluation. These objectives may be complementary, (i.e. two or more objectives are met through this decision in some specified manner at the same time) or conflicting, (i.e. they cannot be met at the same time). For example, land is to be allocated to various types of land use and wildlife preservation (objective 1) and recreation (objective 2) which can be seen as complementary objectives. On the other hand, wildlife preservation (objective 1) and maximum timber harvesting (objective 3) are usually considered as conflicting (competing) objectives. Decision rules determine how to judge between conflicting objectives. One implementation of this approach is provided by Multi Objective Land Allocation (MOLA), which in IDRISI helps to solve multi-objective land allocation problems for cases with conflicting objectives. MOLA is based on the information from a set of suitability maps, one for each objective, and the relative weights to assign to objectives and the amount of area to be assigned to each. MOLA then determines a compromise solution that attempts to maximise the suitability of lands for each objective given the weights assigned.

Basically, two production activities were selected for this analysis, agriculture and aquaculture. Moreover, aquaculture was sub divided into five species-oriented production activities, *Penaeus* sp, crab, tilapia, *Macrobruchium* sp and carp culture. Among these activities the first two were brackish water, the second two were moderately salinity tolerant but fresh water and the last one was a truly fresh water species. In addition, as discussed in **Chapter 2** most of the culture systems are seasonal with the exception of tilapia and carp. The objective was to determine the relationship between the activities. First of all it was decided to check whether the objectives were in conflict with each other or not. To determine the relationship between the objectives, a cross-tabulation was carried out using the module CROSSTAB, which calculated the correlation co-efficient between these factors. The results of CROSSTAB showed that agriculture and aquaculture were highly correlated and so had conflict in many areas **(Table 6.8). Figure 6.10** illustrates the conflicting land use between agriculture and aquaculture.

Table 6.8. Cross tabulation between agriculture (reference) and aquaculture (mapped) land use to measure the conflict between the culture activities in the Khulna region.

	Unsuitable	Marginally suitable	Moderately suitable	Very suitable	Total pixels	Error Commission
Unsuitable	**181,075**	125,596	706,827	266,137	1279,635	85.85
Marginally suitable	579,672	**10,156**	202,414	152,633	944,875	98.93
Moderately suitable	369,484	55,146	**1415,904**	1285,603	3126,137	54.71
Very suitable	639,194	662,087	3626,392	**503,101**	5430,774	90.74
Total pixels	9053,379	852,985	5951,537	2207,474		
Error Omission	0	98.81	76.21	77.21		

Sum of the major diagonal	2110,236
Column total	10781,421
Over all accuracy	19.57%
Overall Kappa	0.30

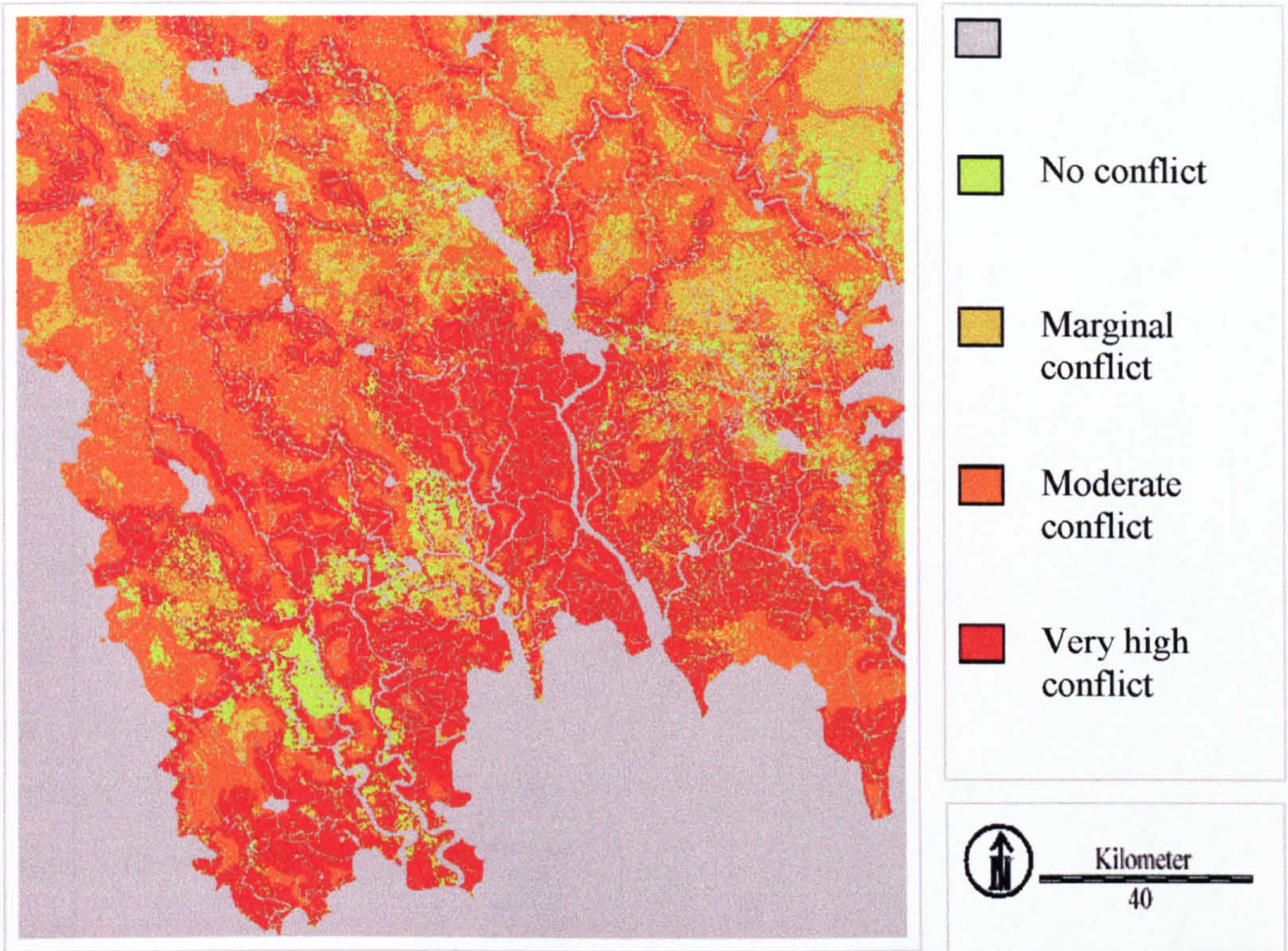

Figure 6.10. Conflict between areas of agriculture and shrimp aquaculture in the Khulna region, Bangladesh.

6.5.1 Crab and shrimp culture model compared with agriculture in winter season

As a source of inputs, agriculture is often considered to be a complementary activity with aquaculture, but in practice agriculture can conflict with aquaculture as a source of pollution. For this reason, and because both activities are competing for the same land they were considered to be in conflict. To resolve this conflict the MOLA module was used. MOLA uses the set of ranked suitability maps for agriculture, crab and shrimp culture activities, which were weighted and to which area tolerances were assigned. From this analysis, a compromise solution was determined, which maximised the availability of suitable land for each activity. **Figure 6.11** shows the schematic diagram for resolving conflict between activities such as agriculture, shrimp and crab culture in the Khulna region.

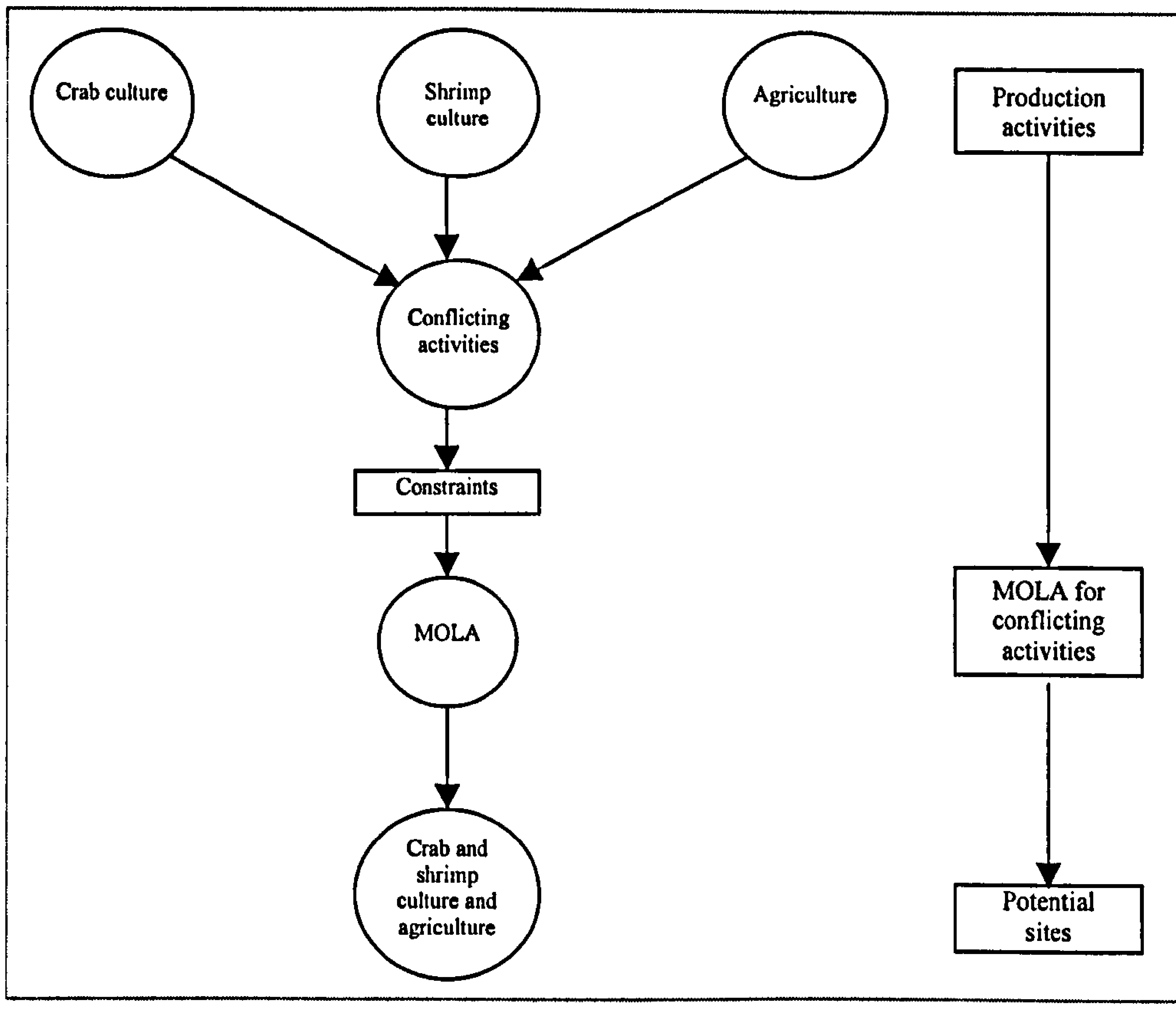

Figure 6.11. Schematic diagram of resolution of conflict between *Penaeus* sp, crab and agriculture in a single model.

Mathematical expression:

MOLA-asc= (Agril X 0.5) + (Shrimp X 0.25) + (Crab X 0.25), where, MOLA-asc = MOLA to resolve the conflicts between agriculture, shrimp and crab culture, Agril= agriculture, Shrimp = shrimp culture and Crab = crab culture, respectively.

The model involved a series of stages:

(1) potential areas of each production activity were treated as primary data; (2) creation of rank images through RANK; (3) constraints layer was incorporated; and (4) the MOLA decision making technique was used to resolve the conflicts based on the weights assigned for each activity.

Weights for each activity were set to agriculture 50, crab 25 and shrimp 25 to give agriculture more and crab and shrimp equal emphasis. A trade off was achieved between the production alternatives on the basis of weights and area goals established (**Text box 6.3**). An area tolerance of 300-m (distance of 10 pixels) was set between the activities to keep the pollution level minimal and create scope for integration with other land use types such as livestock rearing. The ranked maps for crab and shrimp (*Penaeus* sp) culture were derived from MCE suitability maps and agriculture was derived from the classified Landsat TM image. Maps were ranked using the

RANK module in IDRISI and area goals were set as suitable area obtained from MCE evaluation and reclassifying Landsat TM image. The aquaculture model refers to shrimp and crab culture only. However, a different version of this model was created by changing the aquaculture model to deal with the different types of culture systems.

Text box 6.3. Weights assigned to crab, shrimp and agriculture and area goals for each activity to run MOLA.

Interpretation	weight	Area in pixels
Conflicting activities		
Agriculture	.50	4791,580
Crab culture	.25	1855,165
Shrimp culture	.25	1396,964
Area tolerance between the activities	-	10 pixels

Figure 6.12 demonstrates the conflict resolution and land allocation for crab, shrimp and agriculture through MOLA, and **Text box 6.4** shows the macro files for the MOLA technique to resolve the conflicts. From this figure it is clear that shrimp and crab are best placed in the southern part and agriculture in the north, because shrimp and crab are saline water species while most agricultural crops are totally opposite. However, there are patches of land allocated for agricultural crops in the south-western region inside the crab and shrimp culture, particularly because those areas were too distant from the water sources. A few patches of lands were allocated by the model for crab culture which was beyond the saline area in the north-eastern region, probably based on support, infrastructure, soil and water criteria. A trade off was then made between the activities for possible integration of aquaculture culture, agriculture and livestock rearing.

Text box 6.4. IML macro file for MOLA to resolve conflicts between agriculture and crab and shrimp culture.

```
mce x crabdsf 16-crab
rank x 16-crab none inta d a
mce x shrmdsf 16-shrim
rank x 16-shrim none intb d a
rank x 16-agril none intc d a
mola x 3 mola-asc 16 agr-suit .5 intc
4791,580suit-bgd .25 intb 1396964 crb-suit
.25 inta 1855165
```

Note: same constraint file was used which is not shown here.

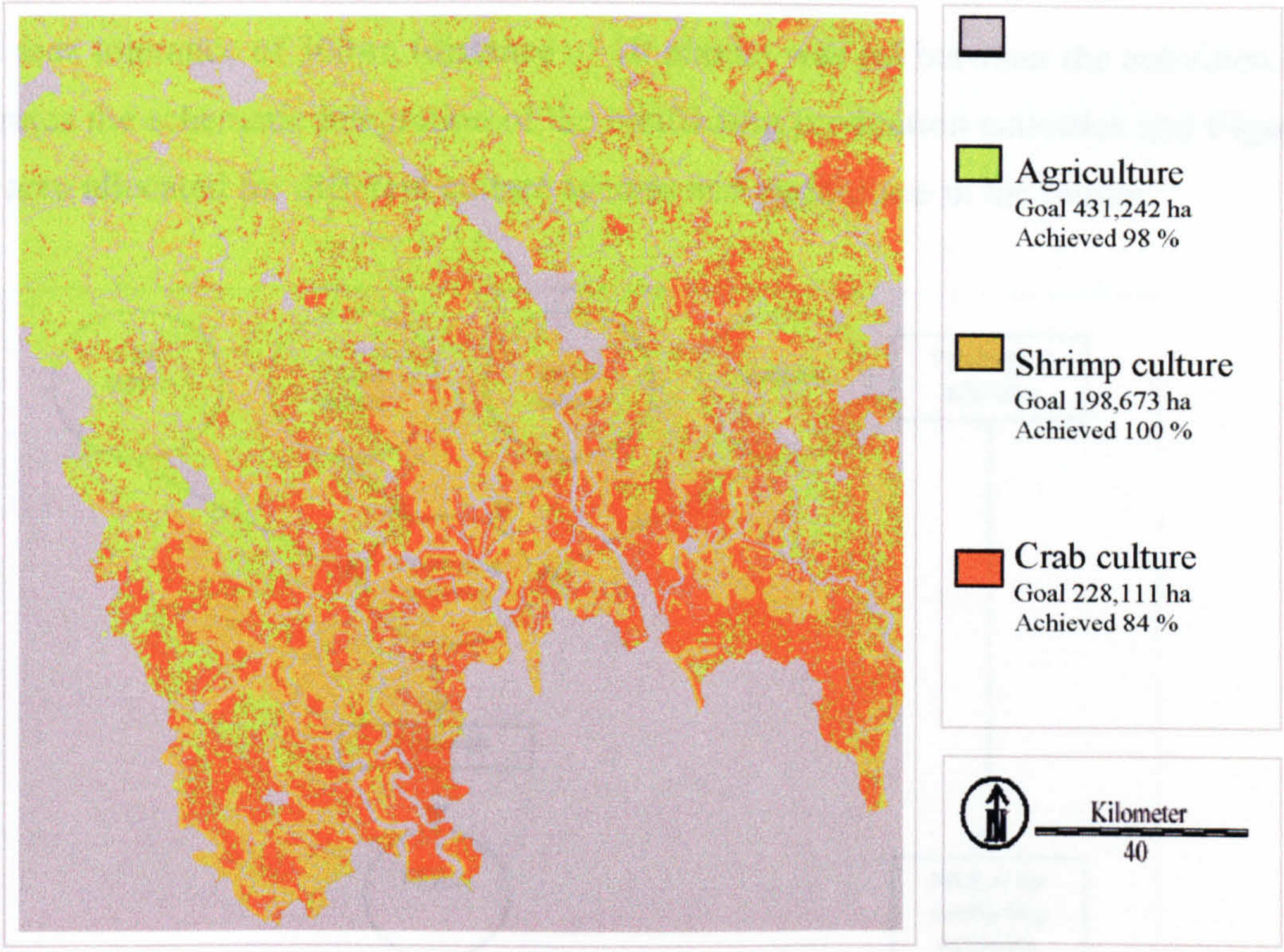

Figure 6.12. Conflict resolution and land allocation for crab, shrimp and agriculture through MOLA technique in the Khulna region, Bangladesh.

6.5.2 Integrating agriculture with tilapia, carp and prawn culture in summer

Agriculture, tilapia, carp and prawn culture was found to be conflicting and they were competing for the same land and water. For this reason it was necessary to resolve the conflicts between these activities. Weights were assigned equal for each activity to give them all equal emphasis and area goals were set on the basis of the amount of land classified as very suitable for each objective (**Text box 6.5**). The images for the activities were obtained from MCE evaluation (aquaculture) and Landsat TM images through reclassification (agriculture). Area targets were set the suitable area for each activity, which were obtained through MCE procedure and reclassification of Landsat

Text box 6.5. Weights assigned to activities and area goals for agriculture, tilapia, carp and prawn culture.

Interpretation	weight	Area in pixels
Conflicting activities in terms of land used and rank order according to preferences of farmers of each activity in the country.		
Agriculture	.40	4791,580
Tilapia culture	.15	1676,230
Carp culture	.20	1460,146
Prawn culture	.25	1875,623
Area tolerance between the activities	-	10 pixels

image. An area tolerance of 300-m (distance of 10 pixels) was set between the activities. **Figure 6.13** illustrates the schematic integration of the conflicting production activities and **Figure 6.14** shows the area allocated for different culture species and agriculture in the region.

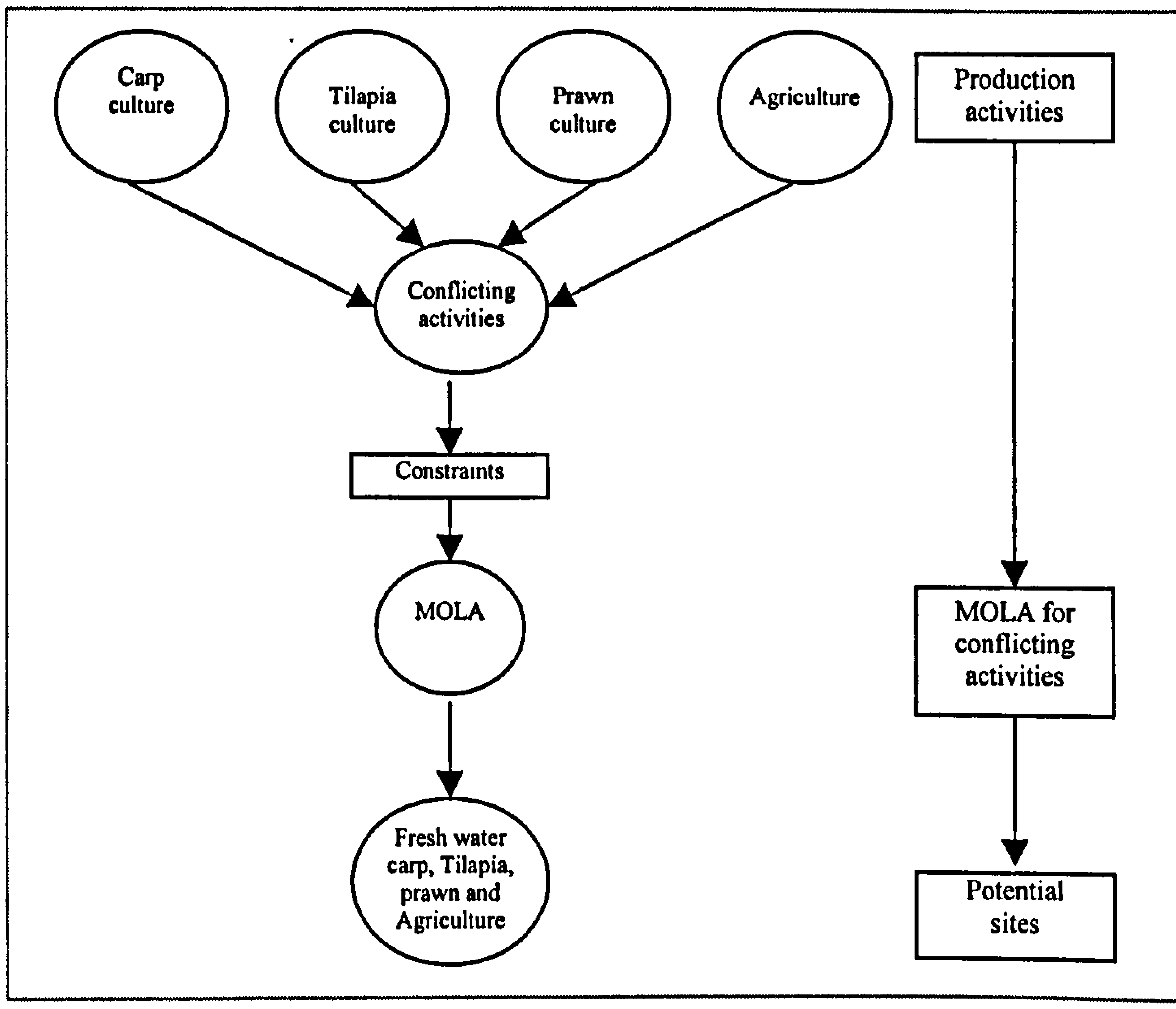

Figure 6.13. Integration of fresh water carp, tilapia and prawn culture and agriculture in a single model through MOLA technique.

Mthematical Expression:

MOLAaptc= (Agril X 0.5) + (Prawn X 0.2) + (Tilapia X 0.15)+ (Carp X 0.15), where, MOLAaptc = MOLA to resolve the conflicts between agriculture, prawn, tilapia and carp culture, Agril= agriculture, Prawn = prawn culture, Tilapia = tilapia culture and Carp = carp culture respectively.

Text box 6.6 shows the macro files for resolving conflicts between fresh water aquaculture and agricultural activities.

Text box 6.6. IML macro files for MOLA to resolve conflicts between agriculture and carp, prawn and tilapia culture.

```
mce x carpsf 10-carp
rank x 10-carp none inta d a
mce x prawndsf 10- prawn
rank x 10-prawn none intc d a
mce x tilapdsf 10-tilap
rank x 10-tilap none intd d a
rank x 10-agril none intf d a
mola x 4 mola-atp 10 agr-st .4 intf 5430774 suit-crp .2
inta 1660146 suit-tlp .15 intd 1676230 suit-prn .25 intc
1875623
```

Note: same constraint file was used which is not shown here.

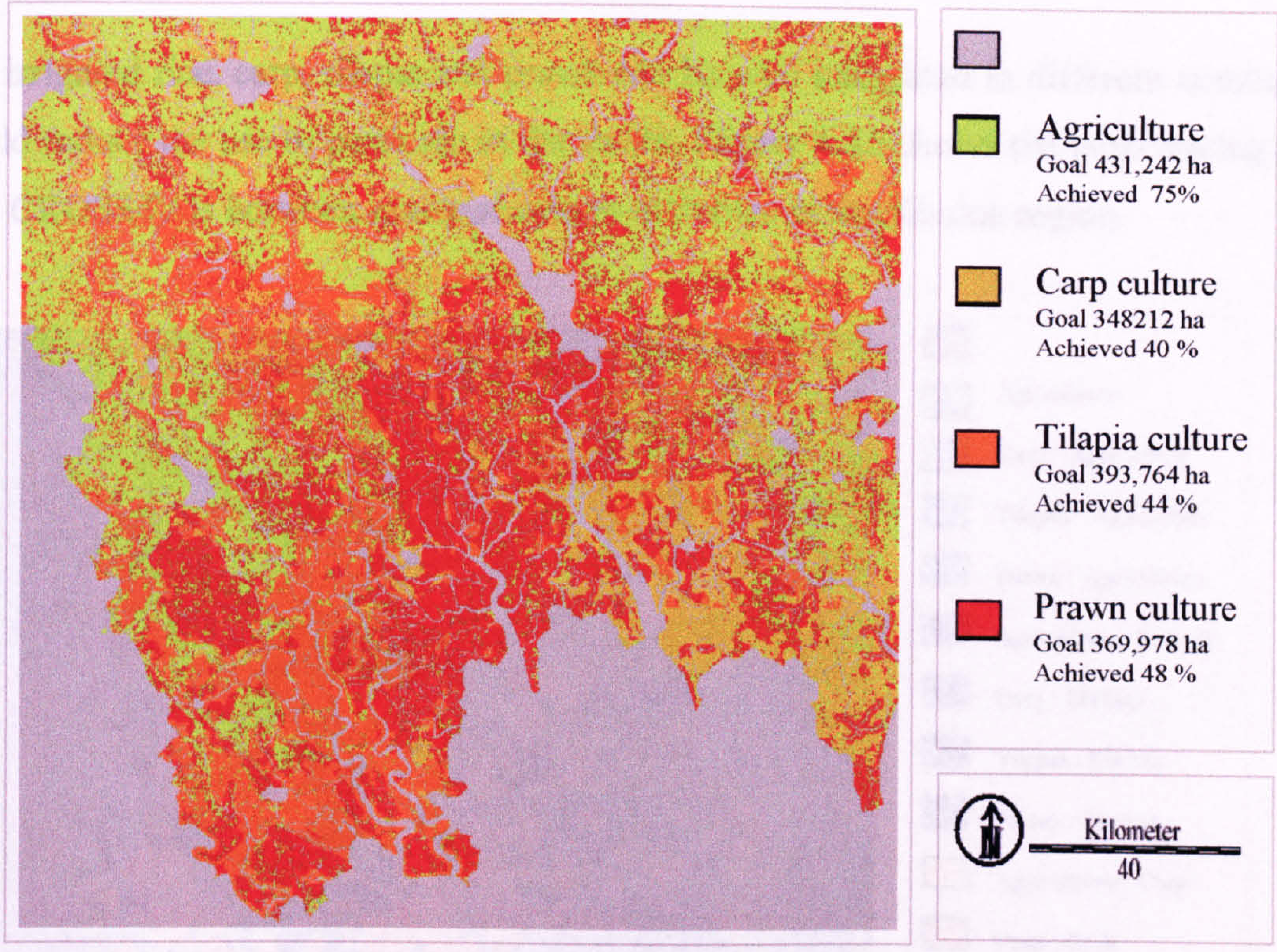

Figure 6.14. Land allocated for agriculture, carp, tilapia and prawn (*Macrobruchium* sp) aquaculture in the Khulna region, Bangladesh.

From **Figure 6.14** it is clear that tilapia and prawn culture suitable sites are widely distributed near to the water sources due to their moderate salinity tolerance. Carp was placed towards the south-west and south-eastern part of the region because the middle is dominated by saline water. In the summer months rain reduces the salinity and water becomes fresh allowing some carp culture to be carried out. In this period the land remains fallow or only under rice. It is not possible to grow other agricultural crops because of water logging in most places during this season. Nonetheless, there is a considerable amount of conflict between these two-culture systems, although, they could be beneficially integrated to reduce the use of pesticide in rice field. If this sort of integration is done, it could increase the fertility of the land for future crops and reduce the pest infection of rice, as fish will graze on them (Cagauan *et al*. 2000; Yee, 1999).

As noted in **Chapter 2,** the culture systems in this region are seasonal. Crab, shrimp and most of the agricultural crops and irrigated rice are grown in February to June and tilapia, prawn, carp and agricultural crops specially irrigated rice are grown in July to January each year (DOF, 1996). Moreover, crab, shrimp, tilapia and prawn could be grown in saline ponds as tilapia and prawn can withstand a considerable level of salinity. These species can be integrated in almost any combination to optimise their production in the region. On the other hand agricultural crops especially irrigated rice, carp, tilapia and prawn can be well integrated in different combinations which could reduce the use of pesticide in the fields. **Figure 6.15** shows the land-sharing pattern created by CROSSTAB between seasonal culture activities in the Khulna region.

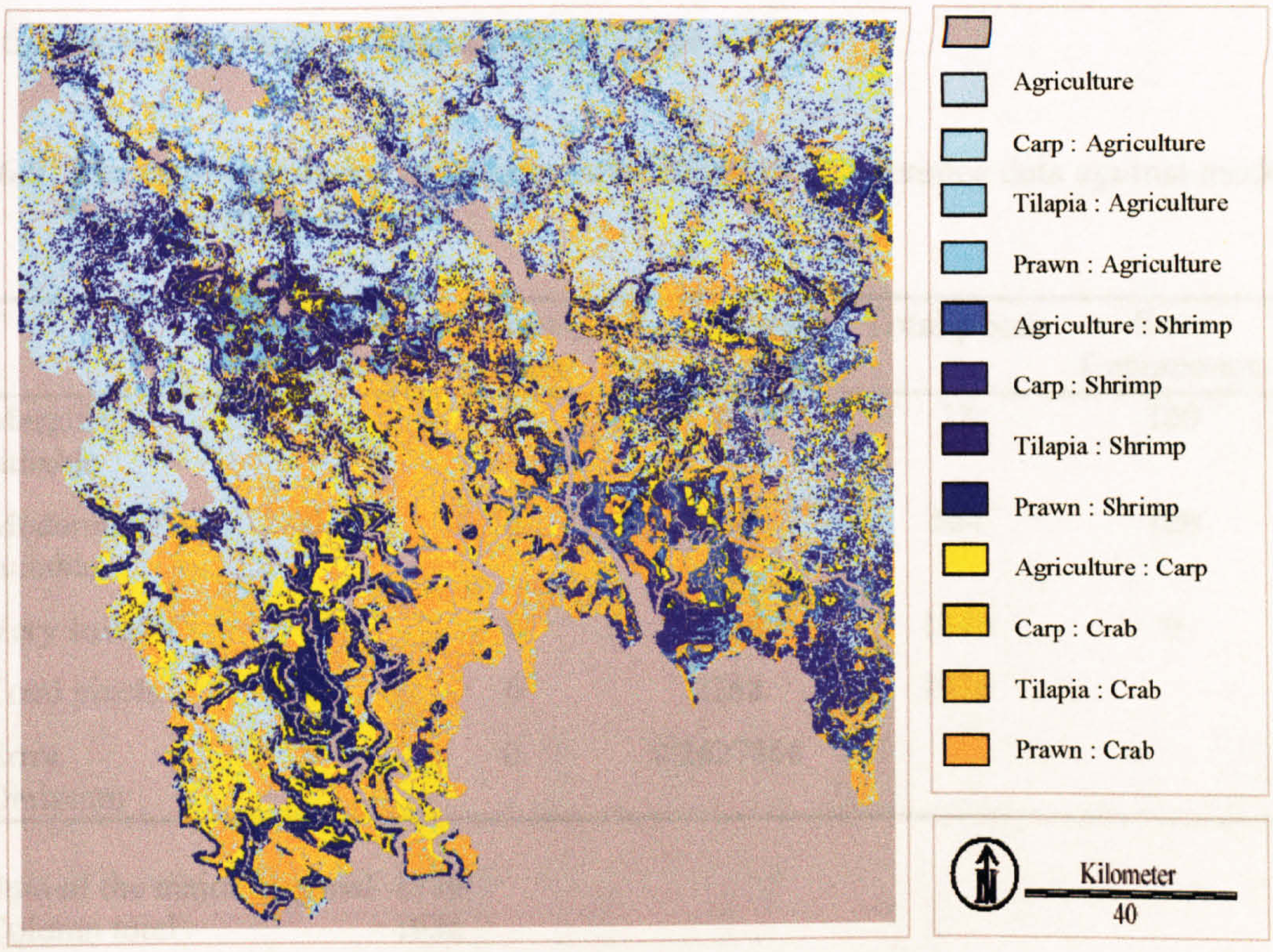

Figure 6.15. Land allocated for different aquaculture species such as carp, tilapia, prawn and agriculture in summer months and shrimp, crab and agriculture in winter season in the region.

6.6 Model verification

The overall goal of verification was to compare the sites predicted to be suitable for aquaculture by the GIS with the existing aquaculture farms. Verification was confined only to suitable sites for shrimp culture, which was carried out by comparing the existing location of shrimp farms with the prediction images. Model verification was also done using a hand held GPS during the field visit in January-February 1999. Cross-tabulation was carried out between the verified data and the GIS generated prediction image. Analysis reveals that 69.2% of the very suitable model output matched with the existing shrimp farm locations. Although the percent of error commission for moderately suitable and marginally is considered as 100%, in reality it is not because in the reference map there was no other category than very suitable. However, 0.26%

error of omission has occurred in the cross-tabulation matrix. From 319 shrimp farm locations, 35 were prawn and 27 fall within the mangrove area may be due to registration error or error in the reference map. This was not considered because no shrimp farm was seen inside the mangrove in the Landsat TM image. Overall kappa for this cross-tabulation was 0.78, which well within the acceptable range of kappa values (**Table 6.9**).

Table 6.9. The cross-tabulation of shrimp farms location as reference data against model output as mapped data.

	Marginally suitable	Moderately suitable	Very suitable Shrimp farm	Total pixels	Error Commission
Marginally suitable	**0**	0	12	12	100
Moderately suitable	0	**0**	584	584	100
Very suitable	0	0	**1340**	1340	0
Total pixels	0	0	2268	1936	
Error Omission	0	0	0.2627866		

Sum of the major diagonal	1340
Column total	1936
Over all accuracy	69.22%
Overall Kappa	0.78

6.7 Economic evaluation of different land uses

In order to compare the economic value of the culture alterations, the outcomes in terms of income from one hectare of land were calculated for the different culture species. One hectare of lease land was taken for all the culture species and the culture period was one year for carp, while a six month period was used for all other species, or the land is used for rice cultivation in the remaining time. The input parameters are summarised in **Table 6.10**.

To calculate total outcomes from the GIS predicted suitable land; it is necessary to identify the probable area required for roads, dikes, and inlet and outlet channels, guardrooms and office. If 15% of land is allowed for that purpose, the rest of the land will be the actual pond area available for culture practise. At present, average shrimp, crab, tilapia, carp and prawn production with comparison to rice culture land use option are shown in **Table 6.11**.

Table 6.10. Economic evaluation of shrimp, crab, tilapia, carp and prawn culture in Khulna region for one crop.

Development, production and management cost	Shrimp[1]		Crab[2]		Tilapia[3]		Carp[4]		Prawn[5]	
	Amount and rate	Amount in Tk/ha	Amount and rate	Amount in Tk/ha	Amount and rate	Amount in Tk/ha	Amount and rate	Amount in Tk/ha	Amount and rate	Amount in Tk/ha
Embankment, sluice gate, office and guard room construction		40,000		40,000		5,000		5,000		40,000
Seeds for culture species	37,500 x 1 (1 Tk each)	37,500	20,000 x 1 (1 Tk each)	20,000	10000 (0.2 Tk each)	2,000	10,000 (0.7 Tk each)	7,000	20,000 (1 Tk each)	20,000
Fertilizer (organic & chemical) and lime		7,500		2,500		2,500		20,000		2,500
Cast net, bamboo and plankton net		6,000		3,000		1,200		1,200		3,000
Day labour	60 day labour/ha	3,600	60 day labour/ha	3,600	25 day labour/ha	1,500	25 day labour/ha	1,500	60 day labour/ha	3,600
Permanent labour for six months	1 for six month	12500	1 for six month	9000	1 for six month	9000	1 for one year	18000	1 for six month	12500
Lease	for six month	5,000	for six month	5,000	for six month	5,000	for one year	10,000		5,000
Feed cost	50 Tk /kg	30,000	15 Tk /kg	22500	10 Tk /kg	11,000	10 Tk /kg	21,500	17 Tk /kg	32,500
Sub-total		**142,100**		**105,600**		**40,200**		**84,200**		**119,100**
Interest for the total capital (10% rate)	for six months	7,000	for six months	5,175		1,860		4,560		5,850
Total		**149,100**		**110,775**		**42,060**		**88,760**		**124,950**
Production /hectare		600	1,500 kg/ha	1,500	2,000 kg/ha	2,000	3,000 kg/ha	4,000	700 kg/ha	700
total sale of produce fish	375 Tk/kg	225,000	120 Tk/kg	180,000	40 Tk/kg	80,000	40 Tk/kg	180,000	325 Tk/kg	227,500
Profit in Taka		**75,900**		**69,225**		**37,940**		**91,240**		**102,550**
Profit in US Dollar*		**1,518**		**1,385**		**759**		**1,825**		**2,051**

* Only carp culture was calculated one crop/year. 50 Taka=1 US Dollar in 2000.
[1] DOF (1996), [2] Chong (1993), Saha *et al.* (1997), Overton and Macintosh (1997) [3] BFRI (1994 a/1997), [4] BFRI (1994b), [5] DOF (1993), Chanda and Khandaker (1994), Jainal (1997).

From the **Table 6.10** and **Table 6.11** it is clear that the return from rice culture option in the coastal area of Bangladesh is the least, which is lower than the Government recommended Minimum Wage (MW) level. On the other hand, the highest return is given by prawn culture followed by shrimp, crab, carp and tilapia culture respectively. In the case of total farming job potential, prawn culture again offers the highest number of jobs for the region. However, crab culture has a higher job potential than shrimp culture in a single crop in a year, although the return from one hectare of land from shrimp culture is higher than the crab culture.

Table 6.11. The total production potential from the GIS predicted land and potential job opportunities from different culture option of land uses in the summer months in the Khulna area.

Economic benefits	Tilapia	Carp	Prawn	Rice in summer
Culture potential area identified (ha)	172,876	137,073	178,442	322,883
Minimum Wage (MW), in US $/month	30	30	30	30
MW/person/year (US $) (*12)	360	360	360	360
Estimated productivity tons ha /crop	2	4*	0.7	2.4
Earnings ha y-1 ($)	759	982	2,051	140
Farmers earning MW ha/ year	2	2.73	6	0.39
Available land after15% excluded for dikes, guard rooms and office construction and 5% for rice culture	146,945	116,512	151,676	306,739
Total production (tonnes/cycle)	293,889	466,048	618,295	736,173
Total potential man days/cycle	4,321,900	3,426,825	10,706,520	19,372,980
Total permanent job potential /cycle	172,876	137,073	178,442	-
43.3, 20 and 15.6 labour require for prawn, tilapia and carp and rice respectively /tone production	5,877,780	9,320,960	26,772,174	11,484,299
No. of permanent job potential /cycle (180days)	32,654	51,783	148,734	63,802
Number of persons supported at MW level	293,889	318,078	910,054	119,628

* Only carp culture was calculated one crop/year.

Table 6.12. The total production potential from the GIS predicted land and potential job opportunities from different culture option of land use in the winter months in the Khulna region.

Economic benefits	Shrimp	Crab	Rice in winter
Culture potential area identified (ha)	198,673	191,141	421461
Minimum Wage (MW), in US $/month	30	30	30
MW/person/year (US $) (*12)	360	360	360
Estimated productivity tons ha /crop	0.6	1.5	2.4
Earnings ha y-1 ($)	1,518	1,385	140
Farmers earning MW ha/ year	4	3.85	0.39
Available land after15% excluded for dikes, guard rooms and office construction and 5% for rice culture (ha)	168,872	162,470	400,388
Total production (tonnes/cycle)	101,323	243,705	960,931
Total potential man days/cycle	11,920,380	11,468,460	24,023,277
Total permanent job potential /cycle	198,673	191,141	-
43.3 and 15.6 labour require for shrimp and crab and rice respectively /tone production	4,387,286	4,874,100	14,990,524
No. of permanent job potential /cycle (180d)	24,374	27,078	83,280
Number of persons supported at MW level	675,488	625,509	156,151

From table 6.11 and 6.12 it can be inferred that rice culture was allocated the highest amount of land in both cases as in the summer and winter months, followed by prawn, tilapia and carp in the summer and shrimp in the winter months respectively. On the other hand, crab was allocated the least, even though the suitable land was higher for crab than shrimp before the MOLA conflict resolution was applied. It is found that agriculture had the highest job potential, but in the economic benefit was rated least.

6.8 Discussion

The areas predicted as suitable for shrimp culture from this GIS evaluation can be partly verified by the location of existing shrimp farms in the area. Comparison has been made with the satellite image and published data. GIS predicted that 125,727 hectares of land are suitable for shrimp farming, whilst DOF (1994-95) has shown that 104,624 hectares are already in operation in the area. However, there was considerable variation among the predicted and actual locations, possibly due to the one kilometre buffer zone created around the mangroves, the weighting method used and the different factors employed in the models.

Much of the area ranked most suitable for brackish water shrimp and crab culture, is situated near the riverbanks and their tributaries in the tidal zone. This ensures easy access to saline water. On the other hand ample areas are found suitable for prawn, tilapia and carp culture throughout the area in the summer months due to the moderate salinity tolerance of prawn and tilapia and available fresh water for carp culture in the region. The highest amount of suitable land is predicted for tilapia culture by the GIS model because tilapia has a wide range of salinity tolerance and availability of seeds as this species is a pond breeder. After tilapia, prawn is allocated more land than carp, as carp is totally fresh water dominant species and can not tolerate a trace amount of salinity. However, for tilapia, prawn and carp culture most of the land is moderately suitable and no unsuitable land exists for these species in the region.

For shrimp and crab culture most of the areas were ranked as moderately suitable because of lack of other facilities, such as obtaining water and drainage difficulties. Large water bodies, which contain fresh water, were not considered of potential use because of problems with the low salinity. Natural forest and wild life refuges, Sundarbans, roads, rivers and urban areas were not considered for culture activities.

There are ample areas ranked as moderately suitable but not yet under culture. Crop agriculture, which is a traditional source of income, has not yet been affected by the development of brackish water shrimp culture. Although shrimp and crab culture in the region have created new sources of income, there has been a drastic reduction of livestock and poultry in the shrimp farming areas. (Rahman *et al.* 1995; Khan and Hossain, 1996).

Crab culture in the region is in its initial stage and there is lots of potential to expand it in future. Crab culturists could earn many times that shown here if they intensify their culture, for example, culture undertaking conventional production methods and ripe female production and crab fattening in cages at the same time (Cholik and Hanafi, 1992; Overton and Macintosh, 1997). Further, crab culture is more environmentally friendly than shrimp culture as it can be integrated with horticulture, conventional forestry, rice culture and polyculture with fish (Chong, 1993; Chandrasekaran and Perumal, 1993). However, mud crab culture is totally dependent on wild seed supply, so there is a scope for establishing hatcheries to continue supply of seed.

It is interested to note that, unlike some other areas of Bangladesh only one crop of shrimp is cultured in the region as the salinity of water falls to nil in the months of July-January. This is a suitable time for rice production and fresh water prawn and fish culture. (Rahman *et al.* 1995).

Chapter 7

General Discussion

The purpose of this project was to investigate the feasibility of integrating GIS and remote sensing for aquaculture development and as an assessment tool for site suitability for different culture species in the south-western region of Bangladesh. The ability to use satellite imagery integrated with traditional information sources such as hard copy maps and tabular data is clearly enhanced by the use of raster/vector GIS. GIS allowed data to be readily accessible, easily combined and flexibly modified. Although the main focus was on shrimp farming, the analytical methodology used to develop the GIS-based models in this study was also used for crab, tilapia, prawn and carp culture models, all of which had potential in other locations.

There were a considerable number of criteria to be considered in the site selection process for crustacean and fish culture, including environmental and socio-economic factors. Most of the data was in maps, tabular forms and from literature. Some of the maps were of very high quality as they were produced through reconnaissance land survey and verified by satellite image and photo interpretation (i.e., topographic maps of Bangladesh and forest inventory map). Others were of acceptable quality for this type of modelling over a large area. Some of the first hand data were also incorporated through interpolation techniques. Most of the data were either digitised or scanned for incorporation into the GIS databases.

In this work, the weighting of the factors used at various stages was decided by the author, based on experience and consultation of the literature. However, in order to reduce the subjectivity of this process and thus improve the reliability of the results, the opinion of various experts was included in the weighting process. Models in this study were then developed on the basis of integrating data into sub-models or natural groupings rather than treating all data together. The general approach of establishing sub-models within an overall model was proved to be a meaningful way to integrate and achieve specific tasks. The overall purpose of the model was divided into stages where each solves a partial problem and the final goals of the study are addressed by a further integration of data from the sub-models.

The use of macro files in the modelling process made it flexible and dynamic in nature. Once the database is established it can be updated and the aquaculture suitability model refined with minimal effort. Moreover, macro files can be incorporated into any modelling process of similar kinds by changing the criteria weights only.

MCE is an excellent decision analysis tool for land use issues because of its simplicity, its treatment of multiple objectives, and its capacity to handle many different types of criteria. It can analyse the complex trade-off between choice alternatives using the different environmental and socio-economic impacts (Carver, 1991). MCE is especially useful in reflecting the preferences of decision-makers and in allowing sensitivity analysis, which enables decision-makers to test validity of the weights used and ranking of the alternatives (Jankowski and Richard, 1994). MCE was successfully used in this study to explore the site suitability for different species related culture operations and the trade-off between the activities.

One of the important tasks was to give weights to the criteria in aquaculture site suitability analysis through the MCE decision making process. This process was enhanced by including the opinion of experts through a personalised questionnaire interview. The experts had to compare a set of n suitability factors in a pairwise comparison matrix and had to answer n(n-1)/2 questions for each group of factors. The pairwise relationship of these factors can be presented in a two-dimensional matrix as suggested by Saaty (1977) and is shown in **Table 6.1**. However, this can be confusing and most of the experts felt much more comfortable and less confused with the questionnaires than the matrices (Xiang and Whitley, 1994). Based on this, experts then provided a simple questionnaire of numerical values from which the pairwise comparison matrices were prepared later.

Various advantages were discovered when using MCE along with the Kendal's coefficient of concordance statistical test because all site factors could be evaluated and it was possible to define the relative importance of each factor. It is apparent that different results can be achieved from the same set of data at the weighting stages since different individuals can consider different factors to be more or less important for their own objectives. Nonetheless, a strong general agreement was obtained, because it included expert opinion from various decision-makers across the field and this combined techniques gave very useful results.

Some of the major constraints in the development of aquaculture are the conflicts that may arise in terms of use of land and water for various activities (Pollnac, 1992). Aquaculture has been involved in land-use conflict issues in several parts of the tropics, particularly in highly urbanised and overcrowed areas (Beveridge and Philips, 1993). The Bangladesh National Conservation Strategy has identified six important areas of conflicting land use in rural areas. They are (a) agriculture vs. shrimp and capture fisheries; (b) forest land vs. shrimp and capture fisheries; (c) agriculture vs. livestock; (d) agriculture vs. settlements; (e) agriculture vs. brick-fields; and (f) agriculture vs. newly accreted char lands (Nishat and Bhuiyan 1995). Moreover, because of the Muslim law every year land is being fragmented, breaking down the available per capita agricultural land into smaller parcels. As a result, more intensified land uses, such as intensified monocropping, and shrimp cultivation and extensive brickfields are degrading long-term soil fertility. Cropping on fragile char lands before it has stabilised causes rapid erosion. Flood control and drainage structures have altered land and water use patterns, and led to the decline of fish stocks and production by more than 25% in recent years (Nishat and Bhuiyan 1995).

Multi Objective Land Allocation (MOLA) allows resolution of multi-objective problems in decision-making strategy in the real world. It can solve problems which are complimentary or conflicting in nature and can analyse up to15 objectives at a time (Merwe and Handrik, 1997). A maximum of four objectives was used here in conflict resolution and this performed well, allocating land between carp, tilapia, prawn aquaculture and agriculture. The relative ranking and weighting of objectives ensured that conflict resolution would give preference to existing uses, followed by new use allocation and this was optimised through trial and error practices.

There was a significant trade-off to be made between the carp, tilapia, prawn aquaculture and agricultural crop goals. Therefore, a comprehensive analysis with reasonable compromise gave an ideal solution. Area goals were set at 348, 212, 393,764, 369,978 and 431,242 hectares for carp, tilapia, prawn aquaculture and agriculture respectively and the achieved target areas were 137,073, 172,876, 178,442 and 322,883 hectares for carp, tilapia, prawn aquaculture and agriculture respectively. Incorporation of agriculture objectives encouraged consideration of more environmentally sound culture practices, in particular, environmentally sustainable cropping practices through integrated farming systems.

To resolve the conflict between shrimp, crab and agriculture, weights for each activity were set to agriculture 50%, crab 25% and shrimp 25% to give agriculture more and crab and shrimp equal emphasis. On the other hand 40%, 20%, 15% and 25% weights were applied for agriculture, tilapia, carp and prawn respectively in the summer months. A trade off was achieved between the production alternatives on the basis of weights and area goals established. Clearly, different weights could be applied to the activities and alternative solutions could be obtained. In this way the optimum production potential can be achieved using the MOLA technique.

Implementation of this integrated modelling system in a multi objective decision-making context is challenging because it requires an enormous amount of data, a wide range of software and computing tools and the co-ordination of many agencies and disciplines. Co-ordination is defined as a team approach with cost sharing across the agencies so that their decisions are in harmony with the goals of society. This co-ordination effort must transcend the boundaries of all participants so that the complimentary of skills, datasets and goals, if they exist, are utilised to the full and contradictions are minimised (Lakshminarayan *et al.* 1995).

Nearly 60% of the data used in this study were incorporated into the GIS database by manual digitisation. A total period of 8 months was spent in digitising and in database establishment and management, and an average 4 to 6 hours per day was spent for this purpose. The digitising technique was tedious and can be prone to error, depending on operator skills and attention to detail during digitising. Some data in the form of choropleth maps was difficult to digitise and incorporated through scanning facilities available in the lab. The forest inventory map was also difficult to digitise, as all the vegetation types polygons had to be included. During editing of the scanned forestry images only the required data, about 10 to 20% of the total, were kept and the rest were discarded. Good results were obtained through this process although there was some ambiguity when the scanned image was geo-referenced to the Landsat image for merging into the GIS database.

It was found that some of the required data were not available in any form. In these cases, surrogate or proxy data were used. For example, ambient air temperature was used to derive water temperature based on a GIS study of Africa by Kapetsky (1994) and dissolved oxygen was obtained from the relationship of dissolved gas concentrations in water as functions of temperature, salinity, and pressure (Colt, 1984).

In some images, gaps existed between the available data, or images were prepared from tabular data sets. Consequently, it was necessary to use the INTERPOLATION technique to create the appropriate layers. Although this technique proved to be very useful there could be a certain level of inaccuracy because INTERPOLATION only creates circular distance bands which in most cases do not give an authentic representation of the factors involved. For example, a city is commonly mapped as a point location but the real area of the city is not always circular. This was taken into consideration and points were replace by polygons wherever possible.

Acidity is a problem in the Southwest part of Bangladesh (Deb, 1998). In ponds, constructed within or adjacent to mangrove forests, highly pyritic soils are formed which lead to high acidity and high aluminium concentrations in and around shrimp farms. Acidity cause severe stress making cultured animals vulnerable to disease or even death. Moreover, during rains, the sudden influx of toxins from the sides of dikes is commonly lethal to a large proportion of fish and shrimps. In the Southwest Bangladesh, several shrimp disease syndromes and production losses are linked to acid sulphate soils. Management cost of the ponds in the pyritic soil is normally much higher and very difficult to overcome. For this reason, it needs to be taken into consideration during evaluation of primary criteria.

GIS modelling is not the only way to evaluate potential aquaculture. The basis of the present study is in many ways similar to the traditional studies for assessing aquaculture development (Muir and Kapetsky, 1988). The primary difference is that the use of GIS in this case greatly enhanced the evaluation and is far more powerful. Most certainly, one of the greatest advantages of GIS over manual techniques is the capability to quantify the predicted potential.

In accordance with the suitability scheme, ranges of data that pertain to a desired level of suitability for each criterion as well as the sub-models must be selected. The selection of such weights involved interpretation of the data selected and such interpretation was guided by literature research and opinions of focus groups working in the fields with the brackish water as well as freshwater aquaculture. The weights given by the focus groups were incorporated with the primary criteria and also with the sub-model and compared with the model outcomes of the authors' models. Out of three groups, one group significantly differed with the authors' model; however, other two were similar with the authors' models.

The existence of agglomeration is considered as an excellent indicator of the suitability for aquaculture production, since it is only likely to occur in areas which show outstanding production function mixes (Meaden and Kapetsky, 1991). Agglomeration implicitly takes into account such factors as established farming skills, availability of broodstock, fingerlings, transportation, equipment facilities, processing plants and markets. However, agglomeration also has its negative affects like vulnerability to diseases outbreak and pollution impact. In polluted regions amounts often exceed recommended levels, and pollution problems become frequent in the great agglomeration areas, especially in peak periods of culture operation. It might also be the case that the area has sufficient producers, i.e. from the considerations of water quality and quantity, markets saturation, potential site availability and pollution impact. More research work is needed to define what level of agglomeration could be an acceptable range in the region.

In the present GIS site evaluation, mangrove based aquaculture development is avoided, not only for cost effectiveness but also for environmental considerations. To avoid mangrove based farming practices in the region, a 1-kilometre buffer zone was proposed, and all the model outcomes fit well using this criterion. In addition, the mangrove in the region is separated from the mainland by rivers, so farmers cannot cross the boundary to dig a pond inside the forest. The shrimp farm location data suggests that 27 shrimp farms were located inside the mangrove, although there were not visible in the Landsat image.

In this study, the GIS modelling covered a very large area; more than 14,000Km^2. The database has a resolution of 30m and so it is possible use the GIS models for much smaller land parcels, for example the Thana level. Clearly the modelling developed here can be can be applied to other areas relatively easily.

Aquaculture projects have many sociological impacts, either in a beneficial way, such as the stimulation of development, improvement in the standard of living, employment generation, or as negative social impacts, such as changing of traditional social values, privatisation of common properties, use of natural resources, activity conflicts and unsuitable technologies. Employment opportunities generated through aquaculture development, including processing, transport and marketing can be expected to affect, to some extent, the flow of rural people to urban areas. Large-scale development of aquaculture can also eventually lead to better communications in rural areas, as they are needed also for proper management of aquaculture production and distribution.

Skilled manpower is essential for successful aquaculture operation and usually can be detected in the regions where aquaculture has been established. People with suitable hands-on experience, with some technical background and an education in science, can be found in most areas, and can be trained accordingly. Requirements for well trained and experienced technical staff are most important in intensive aquaculture projects, whereas those on a small-scale can be supported by extension agencies (Pillay, 1994). In addition, there may be a need for a range of professional and associated services. Obviously the requirement for and availability of each of these will vary from region to region. Technical support is especially difficult to obtain in regions where aquaculture is not established and when problems arise during production.

Texture, pH and salinity of soil were incorporated in the GIS evaluation from a range of data sources mostly in the map forms. In addition, soil pH and soil salinity tests were performed during the field visit in 1998. Soil pH and salinity test was carried out using a field method (Coche and Laughlin, 1985) on a random sampling basis. Although not comprehensive method for testing soil properties, the primary data obtained was given a very low score when used in the soil sub-model.

Several factors affected the various outcomes of this study. These include factors that may have been derived from inaccurate data sources, their spatial and temporal variability and the analytic approaches and assumptions adopted here. Nonetheless, the rapidly expanding access to digital datasets at low cost and in some cases free through the web, the rapid development of more powerful hardware and affordable software continues. These simple but extremely powerful tools are invaluable for solving many real-world problems of planning applications, and providing information for decision-making. Most of the possible problems affecting this study will be minimised or eliminated as more data become available and experience is gained with aquaculture related GIS application.

The areas predicted as suitable for shrimp culture from this GIS evaluation can be partly verified by the location of existing shrimp farms in the area. Comparison has been made with both the satellite image and published data. Multi Criteria Evaluation (MCE) predicted that 198,673 hectares of land are suitable for shrimp farming but 168,872 hectares were allocated through the MOLA technique while resolution between shrimp, and crab aquaculture and agriculture. DOF (1994-95) has shown that 104,624 hectares of land are already in operation in the area. However, there was considerable spatial variation among the predicted and actual locations, possibly due to the weighting method used and the different factors employed in the models.

A comparison of the results among the five species revealed that the salinity and water availability have strongly influenced the outcomes. Both tilapia and prawn are able to tolerate a moderate amount of salinity, compared to carp, and this is reflected in the outcome of their models. Much of the land ranked most suitable for brackish water shrimp and crab culture, is situated near the riverbanks and their tributaries in the tidal zone. This ensures easy access to saline water. However, most suitable land for tilapia and prawn are also found throughout the study area near the water sources, as they are moderately saline tolerant fresh water organisms. Carp culture is best located mostly in the Northwest, middle and the Southeast of the study area. Patches of suitable sites for carp culture are also available in the South-western part of the region due to seasonal variances of salinity and the high rainfall in summer months. Most of the areas in the Northeast were only ranked as moderately suitable for shrimp and crab culture because of the lack of saline water, drainage difficulties and other facilities, such as insufficient fry supply. Natural forest and wild life refuges, the Sundarbans, roads, rivers and urban areas were discounted for culture activities.

There are ample areas ranked as moderately suitable for shrimp culture but which are not yet under culture. Although the introduction of shrimp and crab culture in the region has created new sources of income, there has been drastic reduction of livestock and poultry in the shrimp farming areas. (Khan and Hossain, 1996; Rahman *et al.* 1995). Crop agriculture, which is a traditional source of income, has not yet been affected by the development of brackish water shrimp culture.

Crab culture in the region is in its initial stages and there is lots of potential for expansion in the future. Crab culturists could earn many times that shown here if they could intensify culture, by changing to a system of conventional production methods based on ripe female production and crab fattening in cages (Cholik and Hanafi, 1991; Overton and Macintosh, 1997). Further, crab culture is more environmental friendly than shrimp culture as it can be easily integrated with horticulture, conventional forestry and rice culture, as well as polyculture with fish (Chandrasekaran and Perumal, 1993; Chong, 1993). However, mud crab culture is currently totally dependent on wild seed supply, so there is considerable scope for establishing hatcheries to ensure continuous supplies of seed.

The region has sufficient carp hatcheries at present, which can supply required carp fry and fingerlings in the near future. There are 223 hatcheries in the region, among them 6 that are government managed and 217 that are privately owned. Out of 10 prawn hatcheries, 4 have closed as farmers preferred natural fry than hatchery fry. The region has only one shrimp hatchery and shrimp and prawn post-larvae are in short supply at the moment. When culture operations begin, the middlemen supply shrimp and prawn post-larvae from Barisal, Patuakhali, and Chittagong where they are caught in large numbers. So there is great potential for establishing shrimp and prawn hatcheries to ensure a continuous supply of post-larvae. Before these hatchery developments can be successful, there is a great need to motivate the farmers through extension work to use hatchery post-larvae in their culture operations.

Distances from collection sources of post-larvae and processing plants were classified according to the literature (Aguilar, 1996; Hoque *et al.* 1997). However, it was found that the post-larvae were also transported from distant places. Generally shrimp and prawn post-larvae were carried from Barisal, Patuakhali, Pirojpur and nearby Islands by the middlemen in the study area. Sometimes post-larvae were collected by boats from Chittagong and Cox's Bazar which are 100-300 km away from the region. Nevertheless, losses due to transport are much higher if carried long distances, thereby consequently decreasing survival when released into the ponds (Kapetsky *et al.* 1987).

The GIS models allocated the second highest amount of land to prawn culture in the region. Culture of this species is currently increasing, as it is more environmental friendly than the saline water culture operation. For example, prawn can be integrated with rice culture, as well as polyculture of fishes, which reduces the total cost of the culture operation. In addition, with saline water culture operations there is a potential for salinisation of fresh water sources as well as groundwater which is the source of drinking water and irrigation to agriculture.

It is probably fair to say that classification of the satellite images in this study includes a number of errors, especially in the classification of the vegetation categories. This is because single date satellite imagery rarely permits accurate classifications of a wide range of agricultural and vegetation cover types due to their spectral ambiguity at given phenological stages (Hill and Sturn, 1991). Also, some of the spectral classes derived from the unsupervised classification procedure (as used in this study) do not correspond to real differences in land cover, but to differences in pixel illumination due to terrain slope and orientation (Pons and Sole-Sugranes, 1994). In addition, automatic clustering identification is strongly influenced by shadows and illumination effects. Nevertheless, the results of the mangrove and land use classification and inventory of small water bodies showed that satellite remote sensing can be a valuable tool to classify and update the thematic maps and to locate and inventory small water bodies for fishery and aquaculture development (Yee, 1999). However, the advantages and limitations of the techniques need to be fully understood.

It should be noted that the gap between the Landsat TM image acquisition (1996) and the preparation of the mangrove inventory map (1985) is 11 years. Thus, changes could have occurred in these areas especially due to erosion and accretion because of the dynamic nature of the rivers and regeneration of the mangrove forests.

Tidal height at the time of imaging can affect the mapping accuracy of the mangrove forest as well as inland. Mangroves, which are located in the flat, shallow inter-tidal zone, have a spatial extent and spectral features that are highly vulnerable to fluctuation in tidal height. A high tide causes muddy ground and even some of the shorter mangroves to be totally submerged, whereas a low tide exposes them and the muddy ground. In the former case, the disappearance of bare muddy ground drastically reduces the confusion of mangroves with mud flats, and to a lesser degree, with bare land. Although the area classified as mangrove is reduced, the mapping accuracy is higher due to decreased confusion. Gao (1998) encountered a similar situation.

Land cover is a dynamic feature that can change rapidly across the landscape, and this adds to the difficulty of making generalisations and extensions of sparse data over a large area. Forest regeneration, dry shrimp ponds and newly planted rice fields were difficult to distinguish using automated classification techniques and with limited ground truth input. It was also difficult to separate cities, stubble and shrimp ponds while working with the whole image. Discrimination between stubble and cities and rice with crops were probably the largest source of error in the classification procedure. For these reasons shrimp ponds, cities and the rest of the land was masked out and separately classified and this substantially improved the results from both the unsupervised and supervised procedure.

Registration differences occurred while scanning the 1:50,000-scale forest inventory maps. This was revealed following visual inspection of the colour composite image and the inventory maps. Other problems were that the size class (i.e., diameter of the trees, shape and size of the water bodies) can change between the time of the inventory map and remotely sensed data acquisitions, especially in a fast growing area such as the Sundarbans mangrove forest. Moreover, inconsistencies in human interpretation, especially for heterogeneous areas, can be a very difficult factor to control. Measures of variation in interpretation need to be further developed that can test the validity of class boundaries while at the same time providing for allowable variances in the accuracy assessment (Congalton and Green, 1993; Lunetta *et al.* 1991).

Ideally, for this type of study, the ground truthing should be done in the area of study at about the same time as the satellite images are taken because tidal fluctuations can cause a lot of differences between the actual and classified image. However, this could involve a huge amount of money, manpower and time if planned in advance. Instead, data from forest inventory map and personal communication with individuals who are familiar with the area were relied upon for guidance in verifying the interpretation of a purchased image. However, this method of verification is not fully effective, as information obtained can sometimes be ambiguous. In order to achieve high levels of mapping accuracy, ground truthing and probably photo-interpretation need to be done

Despite these reservations, it is possible to have reasonable confidence in the classification of land cover categories. Any inconsistencies will not pose major problems in achieving the aim of the study because the preliminary aim was to classify the land use to feed into the GIS modelling process.

Agricultural by-products and animal wastes were calculated according to crop intensity and number of animals per km^2 in the region according to Kapetsky (1994). However, it is difficult to predict how much waste and by-product would be available for aquaculture, as there are many other competing uses for the same resources in the region. For example, animal waste is extensively used as an agricultural fertiliser and for household fuel purposes. Rice husk, wheat bran and oil seeds are also used as a cheap sources of animal and poultry feed in the region. Therefore, it is uncertain whether enough animal wastes and agricultural by products would be left for fish feed supplement or not.

In the modelling process, the land use image was reclassified according to the cropping intensity for use in the aquaculture model. The highest suitability score was employed for the fallow lands or existing shrimp ponds to avoid land use conflicts with other entrepreneurs. These lands which were between the two crops, were also designated as fallow. However, these lands could not be available for aquaculture as they have other uses.

The reclassified soil map showed that some land (3%) is unsuitable for pond construction. However, the final output image through MCE showed that a negligible amount of land (0.03%) was within the unsuitable categories and this might have been compensated by other suitable factors in the region (i.e., temperature; DO).

Simple economic assessment of shrimp farming and alternative land uses in the Khulna region was carried out. Five land use options were studied based on economic output. From the study, it is clear that rice farming scored rather poorly in comparison to all other land use activities considered. Hambrey (1996) obtained similar results in a comparative economic study of seven land-use options in the mangrove land in Indonesia. The highest return came from fresh water prawn (*Macrobrachium rosenbergii*) culture followed by brackish water shrimp (*Penaeus* sp) and crab culture. Employment generated was also measured in terms of average annual labour requirements per hectare of land and the highest employment was created by prawn culture followed by crab, shrimp, carp, tilapia and rice cultivation, respectively, in the region.

In considering natural resource use and aquaculture development in coastal areas of Bangladesh, it is important to take account of the certain effects of sea level rise. It now seems certain that global warming will cause a rise in sea water level, as much as 3 m by the year 2100 (Woods Hole Oceanographic Institution, 1986; Castro-Ortiz, 1994), or 4.5 m by the year 2100 (Milliman *et al.* 1989). This will affect Bangladesh seriously, and the coastal areas such as the Sundarbans in particular (Ali, 1996). Latest information shows that sea water level will rise between 20 cm to 150 cm by the year 2030 (Rob, 1999). By the year 2050, if the sea level rises one meter, Bangladesh could lose 12% of its land surface. This represents the living space of 9 million people and the mangrove areas will be reduced by 50% (FAO/UNDP, 1994). The additional loss of shoreline by erosion, loss of mangrove forests by 75 to 95% and decreased agriculture and fisheries would exacerbate environmental and economic impacts (Broadus, 1993).

Global warming and future sea-level rise scenarios were considered and estimates were made of how much suitable land predicted by the GIS model would be lost through sea level rise. For this, medium sea level rise scenarios of 50 cm, 100 cm, 150 cm and 200 cm were considered to estimate the land lost and people displaced from the area by the year 2050 when the projected population of the country would be 360 millions (Brammer, 1996). From the digital elevation model, it is clear that there is virtually no change following a 50cm rise of sea water level in the region. However, 4.0, 7.2 and 26.0 thousand hectares of land and 4.09, 5.67 and 20.17 millions of people would be displaced in 100, 150 and 200 cm rise at sea level in the study area respectively. **Figures 7.1** and **7.3** demonstrate the land lost from the different culture practises that were predicted by the GIS model and the total land lost and people displaced from the study area by the year 2050, respectively, in various sea levels rise scenarios in the region.

The impacts of climate change on coastal areas in the South and Southeast Asia could be severe. Assuming no adaptation and existing population, a one meter rise in sea level could displace nearly 15 million, 7 million and at least 2 million people from their homes in Bangladesh, India and Indonesia, respectively. Millions more people are threatened in Viet Nam (Nicholls *et al.* 1995). **Figure 7.3** describe the land lost and people displaced from the study area following sea level rise scenarios by the year 2050.

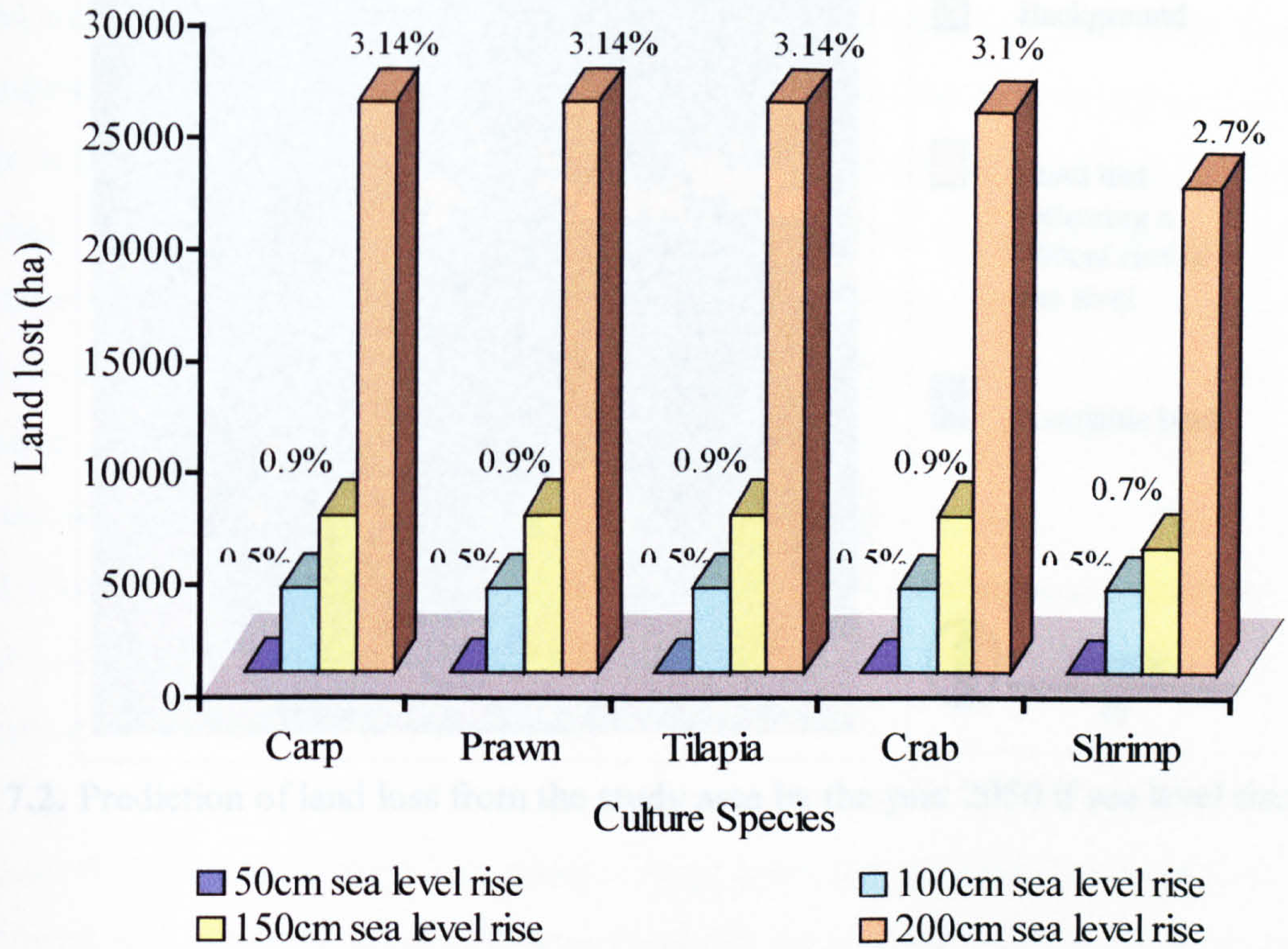

Figure 7.1. GIS model prediction of loss of land from major aquaculture systems following global warming and sea level rise.

From **figure 7.1** it is apparent that all the aquaculture systems would lose a similar amount of land predicted by the GIS model when sea level rises by100 cm. On the other hand, except shrimp culture model, all other systems would lose same amount of land at that time when sea level rises by 150 cm. If sea level rises 200 cm, shrimp culture will lose the least amount of land followed by crab culture and carp, prawn and tilapia culture will lose the same land in the area. It can be infer from this situation that more land will lose in the interior part of the country than in the coastal areas. Most of the low-lying areas in the middle and middle-eastern part of the Khulna, Bagerhat, Mollarhat, Chitalmari and Fakiarhat will be lost, as well a few patches in the Southwest part of Satkhira region (Castro-Ortiz, 1994; **figure 7.2**). The effect on coastal areas would of course, be exacerbated by prevailing weather systems and storm surges.

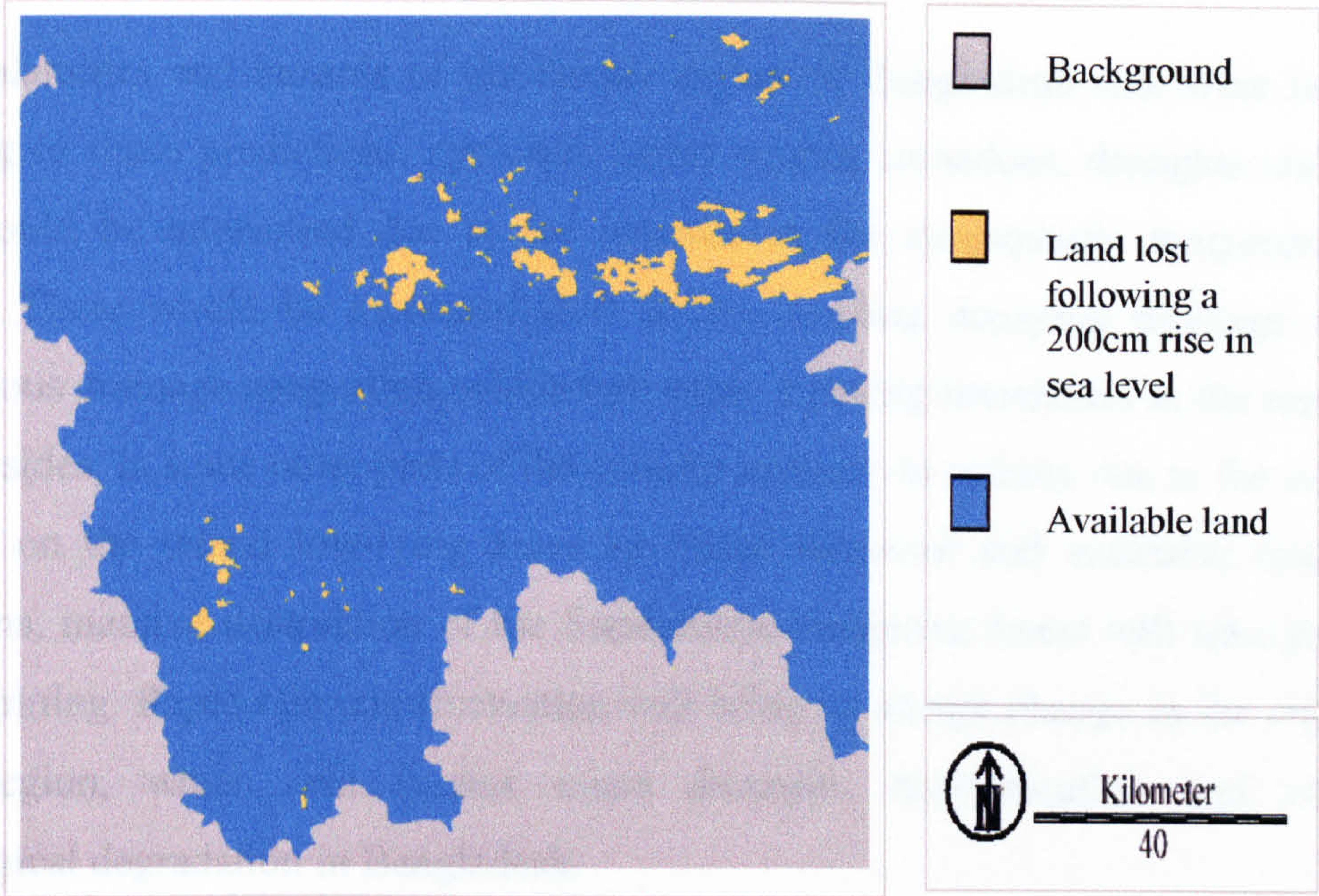

Figure 7.2. Prediction of land loss from the study area by the year 2050 if sea level rises 200cm.

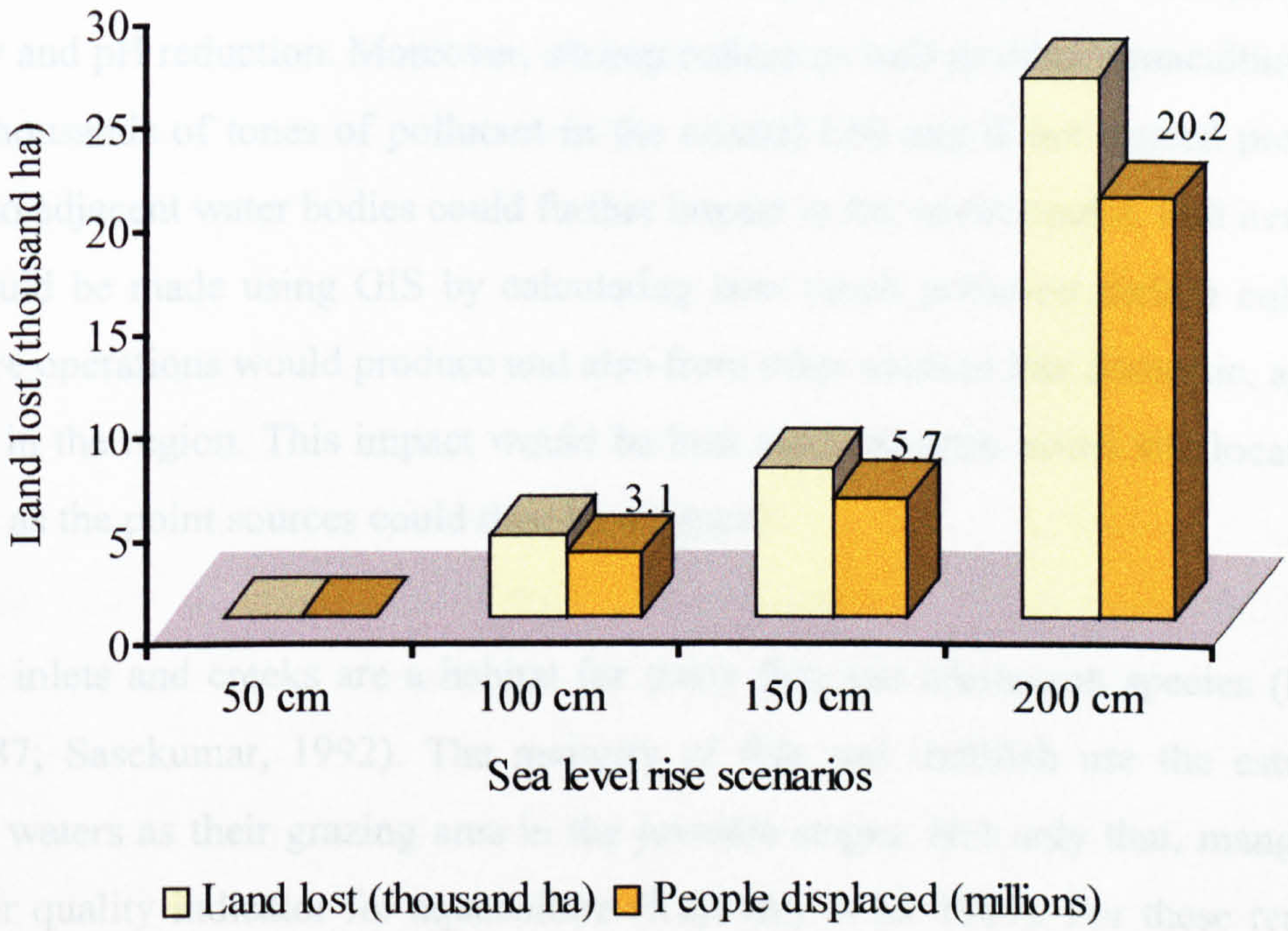

Figure 7.3. The GIS model prediction of land loss and people displaced from the study area following global warming and sea level rise.

It is thought that the consequences of global warming and sea level rise will be more drastic than the land lost and people dispersed from the area. Rob (1999) in a review article notes that the possible impacts of global warming due to the greenhouse effect will greatly add to the normal natural calamities and hazards of the deltaic region of Bangladesh and West Bengal in India. According to these predictions, cyclones, storm surges, tornadoes, droughts and floods of the region would be intensified due to the increase in the atmospheric temperature and global warming. There would be increased flow in the existing decaying drainage systems and a simultaneous drainage congestion, which will cause a lasting inundation in the region (Brammer, 1996). Besides, in some other parts of the country increase in salinity due to the encroachment of sea-water on the inland low-lying areas by raised sea-level and extensive inundation in the depressions, massive destruction of the Sundarbans mangrove forest will take place due to the global warming. Rapid climatic fluctuation will bring an abrupt change in the climatic situation of the region, which will further cause droughts, desertification and other abnormal climatological degradation in Bangladesh.

The coastal waters of Bangladesh receive huge amounts of untreated wastes from domestic, agricultural and industrial sources. These create adverse effects such as eutrophication, oxygen deficiency and pH reduction. Moreover, shrimp culture as well as other aquaculture practices can produce thousands of tones of pollutant in the coastal belt and if not treated properly and this release into adjacent water bodies could further impact in the environment. Full evaluation of this impact could be made using GIS by calculating how much pollution shrimp culture and other aquaculture operations would produce and also from other sources like domestic, agricultural and industries in the region. This impact would be best assessed once actual site locations had been identified, as the point sources could then be mapped.

Mangrove inlets and creeks are a habitat for many fish and crustacean species (Robertson and Duke, 1987; Sasekumar, 1992). The majority of fish and shellfish use the estuaries and the mangrove waters as their grazing area in the juvenile stages. Not only that, mangroves act as a good water quality indicator for aquaculture (Kapetsky *et al.* 1987). For these reasons, most of the shrimp farms around the world have been established either by clearing the mangrove vegetation or vegetation adjacent to the mangrove (Menasveta, 1996 and 1997). The role of mangroves as nursery and feeding grounds for fish and crustacean and interaction with shrimp farms could be assessed through GIS modelling.

Site selection through GIS alone cannot prevent environmental impacts if the whole process does not follow certain rules. Shrimp producers are not the only parties responsible for improving sustainability of shrimp aquaculture. Other members of the shrimp aquaculture community, from researchers to feed producers to sellers of farmed shrimp, must also contribute to this effort. Moreover, the government must institute and enforce strong oversight systems for shrimp farming, including environmental protection laws and protection of human rights.

The weighting of the factors, as well as sub-models, was done logically following earlier work by various authors or the authors' own consideration. Some of the weightings were adjusted after feedback from the field. Different outcomes can be obtained and changing the weighting of criteria as well as the sub-models can identify most important factors. Cost effectiveness can be calculated by changing the criterion weight. For example, in a cost modelling exercise Muir and Kapetsky (1988) found that extending road access from 200 to 2000m and water access from 100m to 500m, a 7% change in capital cost and 3% change in operating cost was occurred. However, in a more extreme example where road access extends to 10 to 20km, the fuel cost increased by 39% and additional accommodation may be needed, which clearly limits the viability of projects. Clearly, the viability of potential projects can be determined by manipulating the weights.

A further consideration in how to involve the shrimp and fish farmers in this modelling. Incorporation of the farmers in this GIS modelling and feed back from them, with a greater degree of co-operation among government, NGO workers and local community is needed. Steps need to be taken to create institutional linkages between the farmers, field workers and government. However, the linkages between these sectors and the academic community in the region are weak.

Hence, GIS can be a potential tool for linking organisations to the rural communities.

The benefits of using GIS for natural resource modelling, management and decision-making are clear. The wide range of application of the approach has recently been developed into aquaculture and fishery management and this trend is sure to continue. The strengths of GIS include the ability to handle a wide range of data sources and resolutions, speeding up work and allowing for easy updating of spatial databases and the ability to handle time series analysis and to generate specialist output. The extensive model-building capabilities and the range of decision support tools allow real decisions to be made and trade-off allocations of land and resource use and their benefit to be evaluated quantitatively. In addition to clear management benefits, the understanding of processes and events, which such approach can elucidate, is very powerful and means that GIS has a role in research as well as in end-user applications (Ross, 1998).

Conclusion

The results of this study are indicative of the modelling power of GIS for this application and could be used to refine the models in future, particularly if supported by further field data. For further developments, it could be important that a detailed study is made of the availability of agriculture by-products, especially oil cake, rice bran, wheat bran and other products which could be used as low cost feed. Their known availability could then be used to greatly enhance aquaculture development opportunities in the area. There is considerable potential for further exploitation of GIS for optimisation of competing aquatic production activities and their interaction with land based farming systems. The GIS planning process has an important role, particularly where land use patterns are intensive, and where developments must be sustainable in terms of sensitive environmental issues, as in most parts of Bangladesh (Salam and Ross, 1999).

Overall, GIS has an excellent future in the aquatic sector. The rapidly expanding access to digital datasets at low cost and in some cases via the Internet, mean that the difficulties of time investment in establishment of spatial databases is also becoming easier. Hardware is also developing rapidly and is more powerful and affordable than was and software is more comprehensive in its capabilities. In general terms, GIS is now becoming more widely adopted, to the point at which many agencies expect to see it used in project planning rather than treating it as an interesting add-on (Ross, 1998). There is, nevertheless, a real requirement for sound expertise in the techniques of GIS and remote sensing, and a proper understanding of the processes involved, in order to ensure good results. GIS should not be considered as a hardware and software-based "point and click" solution to decision-making. It is particularly important to recall that a spatial database creates a virtual environment and it is the manipulation of data and modelling of problems within that environment that is the real heart and philosophy of GIS.

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Appendix 3.1. Degree, minutes and second is converted to decimal degree by dividing minutes by 60.

Serial No.	A Degrees	B Minutes	C B/60	D A+C	A Degrees	B Minutes	C B/60	D A+C
1	89	3.98	0.066333	89.06633	23	12.732	0.2122	23.2122
2	89	3.278	0.054633	89.05463	23	11.958	0.1993	23.1993
3	89	3.089	0.051483	89.05148	23	11.04	0.184	23.184
4	89	2.452	0.040867	89.04087	23	9.814	0.163567	23.16357
5	89	3.572	0.059533	89.05953	23	8.098	0.134967	23.13497
6	89	5.905	0.098417	89.09842	23	6.162	0.1027	23.1027
7	89	5.068	0.084467	89.08447	23	5.821	0.097017	23.09702
8	89	5	0.083333	89.08333	23	5.795	0.096583	23.09658
9	89	11.647	0.194117	89.19412	23	10.241	0.170683	23.17068
10	89	11.53	0.192167	89.19217	23	10.149	0.16915	23.16915
11	89	4.696	0.078267	89.07827	23	5.721	0.09535	23.09535
12	89	0.401	0.006683	89.00668	23	4.582	0.076367	23.07637
13	88	59.969	0.999483	88.99948	23	3.449	0.057483	23.05748
14	88	59.922	0.9987	88.9987	23	2.686	0.044767	23.04477
15	88	59.923	0.998717	88.99872	23	2.686	0.044767	23.04477
16	88	58.789	0.979817	88.97982	22	58.503	0.97505	22.97505
17	88	59.077	0.984617	88.98462	22	57.034	0.950567	22.95057
18	89	0.784	0.013067	89.01307	22	54.81	0.9135	22.9135
19	88	57.629	0.960483	88.96048	22	53.505	0.89175	22.89175
20	88	57.171	0.95285	88.95285	22	53.828	0.897133	22.89713
21	89	2.122	0.035367	89.03537	22	48.174	0.8029	22.8029
22	88	58.938	0.9823	88.9823	22	41.756	0.695933	22.69593
23	89	2.442	0.0407	89.0407	22	41.419	0.690317	22.69032
24	88	59.911	0.998517	88.99852	22	34.668	0.5778	22.5778
25	89	1.556	0.025933	89.02593	22	28.492	0.474867	22.47487
26	89	1.993	0.033217	89.03322	22	27.509	0.458483	22.45848
27	89	2.907	0.04845	89.04845	22	24.653	0.410883	22.41088
28	89	4.701	0.07835	89.07835	22	23.418	0.3903	22.3903
29	89	6.346	0.105767	89.10577	22	18.203	0.303383	22.30338
30	89	5.425	0.090417	89.09042	22	14.9	0.248333	22.24833
31	89	6.315	0.10525	89.10525	22	19.66	0.327667	22.32767
32	89	12.424	0.207067	89.20707	22	46.882	0.781367	22.78137
33	89	16.226	0.270433	89.27043	22	49.369	0.822817	22.82282
34	89	19.085	0.318083	89.31808	22	49.952	0.832533	22.83253
35	89	33.037	0.550617	89.55062	22	49.46	0.824333	22.82433
36	89	33.42	0.557	89.557	22	48.883	0.814717	22.81472
37	89	27.111	0.45185	89.45185	22	47.816	0.796933	22.79693
38	89	18.385	0.306417	89.30642	22	50.2	0.836667	22.83667
39	89	16.01	0.266833	89.26683	22	51.364	0.856067	22.85607
40	89	13.214	0.220233	89.22023	22	55.793	0.929883	22.92988
41	89	13.824	0.2304	89.2304	22	58.909	0.981817	22.98182
42	89	14.138	0.235633	89.23563	23	1.219	0.020317	23.02032
43	89	14.614	0.243567	89.24357	23	6.065	0.101083	23.10108
44	89	12.71	0.211833	89.21183	23	8.693	0.144883	23.14488
45	89	13.583	0.226383	89.22638	23	4.552	0.075867	23.07587
46	89	17.555	0.292583	89.29258	22	43.006	0.716767	22.71677
47	89	18.243	0.30405	89.30405	22	38.827	0.647117	22.64712

Continued Appendix 3.1

Serial No.	A Degrees	B Minutes	C B/60	D A+C	A Degrees	B Minutes	C B/60	D A+C
48	89	18.556	0.309267	89.30927	22	36.152	0.602533	22.60253
49	89	18.464	0.307733	89.30773	22	35.787	0.59645	22.59645
50	89	18.451	0.307517	89.30752	22	41.212	0.686867	22.68687
51	89	21.06	0.351	89.351	22	49.409	0.823483	22.82348
52	89	32.09	0.534833	89.53483	22	48.005	0.800083	22.80008
53	89	34.84	0.580667	89.58067	22	48.107	0.801783	22.80178
54	89	36.242	0.604033	89.60403	22	47.593	0.793217	22.79322
55	89	38.449	0.640817	89.64082	22	43.448	0.724133	22.72413
56	89	38.476	0.641267	89.64127	22	38.961	0.64935	22.64935
57	89	38.82	0.647	89.647	22	36.528	0.6088	22.6088
58	89	35.376	0.5896	89.5896	22	31.105	0.518417	22.51842
59	89	35.635	0.593917	89.59392	22	29.397	0.48995	22.48995
60	89	38.479	0.641317	89.64132	22	39.162	0.6527	22.6527
61	89	39.305	0.655083	89.65508	22	44.47	0.741167	22.74117
62	89	41.987	0.699783	89.69978	22	42.107	0.701783	22.70178
63	89	44.531	0.742183	89.74218	22	40.454	0.674233	22.67423
64	89	45.521	0.758683	89.75868	22	39.63	0.6605	22.6605
65	89	46.71	0.7785	89.7785	22	40.489	0.674817	22.67482
66	89	47.294	0.788233	89.78823	22	38.936	0.648933	22.64893
67	89	48.054	0.8009	89.8009	22	38.691	0.64485	22.64485
68	89	49.453	0.824217	89.82422	22	37.761	0.62935	22.62935
69	89	49.196	0.819933	89.81993	22	38.256	0.6376	22.6376
70	89	50.932	0.848867	89.84887	22	35.487	0.59145	22.59145
71	89	50.724	0.8454	89.8454	22	33.807	0.56345	22.56345
72	89	52.32	0.872	89.872	22	31.724	0.528733	22.52873
73	89	51.669	0.86115	89.86115	22	28.054	0.467567	22.46757
74	89	50.544	0.8424	89.8424	22	26.857	0.447617	22.44762
75	89	49.766	0.829433	89.82943	22	25.548	0.4258	22.4258
76	89	48.82	0.813667	89.81367	22	23.573	0.392883	22.39288
77	89	46.727	0.778783	89.77878	22	20.242	0.337367	22.33737
78	89	45.936	0.7656	89.7656	22	20.181	0.33635	22.33635
79	89	51.106	0.851767	89.85177	22	27.282	0.4547	22.4547
80	89	50.967	0.84945	89.84945	22	36.358	0.605967	22.60597
81	89	46.697	0.778283	89.77828	22	39.436	0.657267	22.65727
82	89	39.656	0.660933	89.66093	22	43.518	0.7253	22.7253
83	89	40.841	0.680683	89.68068	22	44.897	0.748283	22.74828
84	89	42.717	0.71195	89.71195	22	46.459	0.774317	22.77432
85	89	43.527	0.72545	89.72545	22	47.17	0.786167	22.78617
86	89	43.852	0.730867	89.73087	22	47.677	0.794617	22.79462
87	89	44.171	0.736183	89.73618	22	48.068	0.801133	22.80113
88	89	45.185	0.753083	89.75308	22	49.684	0.828067	22.82807
89	89	44.851	0.747517	89.74752	22	52.078	0.867967	22.86797
90	89	46.161	0.76935	89.76935	22	54.022	0.900367	22.90037
91	89	48.181	0.803017	89.80302	22	55.036	0.917267	22.91727
92	89	48.602	0.810033	89.81003	22	55.754	0.929233	22.92923
93	89	48.265	0.804417	89.80442	22	55.96	0.932667	22.93267
94	89	49.31	0.821833	89.82183	22	57.082	0.951367	22.95137

Continued Appendix 3.1

Serial No.	A Degrees	B Minutes	C B/60	D A+C	A Degrees	B Minutes	C B/60	D A+C
95	89	48.896	0.814933	89.81493	22	58.885	0.981417	22.98142
96	89	49.362	0.8227	89.8227	23	0.158	0.002633	23.00263
97	89	50.625	0.84375	89.84375	23	0.798	0.0133	23.0133
98	89	51.973	0.866217	89.86622	23	0.25	0.004167	23.00417
99	89	52.549	0.875817	89.87582	22	59.082	0.9847	22.9847
100	89	52.247	0.870783	89.87078	22	58.335	0.97225	22.97225
101	89	49.712	0.828533	89.82853	23	0.489	0.00815	23.00815
102	89	49.003	0.816717	89.81672	23	3.028	0.050467	23.05047
103	89	50.364	0.8394	89.8394	23	3.882	0.0647	23.0647
104	89	53.012	0.883533	89.88353	23	5.69	0.094833	23.09483
105	89	54.216	0.9036	89.9036	23	7.173	0.11955	23.11955
106	89	31.844	0.530733	89.53073	22	50.145	0.83575	22.83575
107	89	31.406	0.523433	89.52343	22	44.673	0.74455	22.74455
108	89	31.415	0.523583	89.52358	22	44.667	0.74445	22.74445
109	89	30.819	0.51365	89.51365	22	53.105	0.885083	22.88508
110	89	32.575	0.542917	89.54292	22	48.973	0.816217	22.81622
111	89	34.703	0.578383	89.57838	22	48.262	0.804367	22.80437
112	89	34.811	0.580183	89.58018	22	48.44	0.807333	22.80733
113	89	34.777	0.579617	89.57962	22	48.488	0.808133	22.80813
114	89	34.894	0.581567	89.58157	22	47.159	0.785983	22.78598
115	89	34.172	0.569533	89.56953	22	48.832	0.813867	22.81387
116	89	36.182	0.603033	89.60303	22	28.243	0.470717	22.47072
117	89	35.094	0.5849	89.5849	22	27.246	0.4541	22.4541
118	89	35.406	0.5901	89.5901	22	26.166	0.4361	22.4361
119	89	35.391	0.58985	89.58985	22	25.692	0.4282	22.4282
120	89	37.866	0.6311	89.6311	22	35.309	0.588483	22.58848
121	89	23.979	0.39965	89.39965	23	1.77	0.0295	23.0295
122	89	47.471	0.791183	89.79118	23	48.132	0.8022	23.8022
123	89	1.833	0.03055	89.03055	23	15.491	0.258183	23.25818
124	89	1.495	0.024917	89.02492	23	15.603	0.26005	23.26005
125	89	1.215	0.02025	89.02025	23	15.16	0.252667	23.25267

Appendix 3.2 Summary of transformation of resampling operation from plane co-ordinate system to latitude and longitude co-ordinate system

Resample : Summary of Transformation

Computed polynomial surface : Cubic (based on 107 control points)

Overall RMS = 8.716453

Coefficient	X	Y
b0	-41981671.25	26131049.88
b1	1374398.057	-835727.3156
b2	95921.40584	-165403.3865
b3	-14902.95959	8864.14925
b4	-3133.458175	3708.530692
b5	2006.529887	103.7521389
b6	53.42173705	-31.1585195
b7	23.97535245	-21.60217301
b8	-26.10586043	3.763606953
b9	4.434172026	-6.422313113

Control points used in the transformation :

Serial No.	Old X	Old Y	New X	New Y	Residual
1	803.3245	4793.844	23.2083	89.0249	1.108252
2	280.2966	4134.263	89.09027	23.0944	omitted
3	297.0101	4784.997	89.0388	23.2194	omitted
4	1031.365	4159.649	89.2207	23.0318	1.301401
5	450.0935	3976.817	89.0444	23.0069	1.625874
6	1180.415	1449.662	89.1333	22.0305	omitted
7	1015.818	1646.089	89.09718	22.09718	omitted
8	1208.433	2003.641	89.1666	22.4305	7.027213
9	847.0384	2107.238	89.0707	22.4708	13.053548
10	722.3427	3952.562	89.1221	22.9902	6.226044
11	1116.471	4034.534	89.2402	22.9895	16.203481
12	666.8347	3251.424	89.0736	22.7972	4.567994
13	1161.794	3633.134	89.2166	22.8805	omitted
14	1163.927	4373.039	89.2694	23.0861	4.490662
15	1479.954	4715.074	89.3777	23.1625	8.588946
16	1744.987	4641.099	89.45	23.1333	5.365669
17	1901.907	4247.117	89.4777	23.0194	6.750352
18	1343.891	4596.063	89.3319	23.1374	4.551339
19	2473.479	4668.56	89.6625	23.1833	omitted
20	2006.141	4716.633	89.5305	23.1416	1.713104
21	2574.428	4358.549	89.6793	23.0194	7.530625
22	3023.569	3174.554	89.7472	22.6749	4.420869
23	2427.518	2564.169	89.5472	22.5333	4.399861
24	3075.729	2843.697	89.7472	22.5929	omitted
25	2637.286	3258.282	89.6403	22.7138	0.931255
26	1270.918	3623.342	89.2639	22.8749	2.737496
27	1974.518	4145.662	89.4916	22.9861	4.945565
28	2066.386	3518.572	89.4888	22.8111	2.717822
29	1602.615	3748.926	89.3664	22.8958	6.44629
30	3563.664	4239.489	89.9569	22.9416	4.114275
31	3280.523	3829.575	89.8533	22.8416	5.323266
32	3062.449	3637.595	89.7819	22.8	2.677553
33	3520.535	3719.597	89.9166	22.8036	8.147406
34	3214.534	4312.716	89.8583	22.9611	omitted
35	2722.979	3908.65	89.6972	22.8874	4.144526

Continued Appendix 3.2

Serial No.	Old X	Old Y	New X	New Y	Residual
36	2434.119	3516.623	89.5944	22.7958	7.568937
37	2555.046	3824.452	89.6416	22.8749	13.506203
38	3132.022	3150.017	89.7777	22.6625	1.412281
39	3409.577	3368.89	89.8699	22.7077	10.662646
40	3647.333	3040.646	89.9207	22.6097	2.402017
41	3177.386	2084.642	89.7361	22.3666	13.70804
42	3041.034	1659.972	89.6777	22.2561	10.202716
43	2612.885	1903.569	89.5655	22.3411	11.170394
44	2504.461	1686.54	89.5246	22.2866	8.464964
45	2424.608	2417.514	89.539	22.9749	omitted
46	3124.041	2260.498	89.7286	22.4194	14.901266
47	1626.496	2370.576	89.3069	22.5153	5.27194
48	2148.976	2834.563	89.4799	22.6196	4.249452
49	1755.91	3056.684	89.3763	22.6966	2.421554
50	1333.374	3057.514	89.2542	22.7153	1.984653
51	3498.136	1926.199	89.8244	22.3597	omitted
52	3409.04	1726.624	89.7861	22.2583	13.667539
53	3389.451	2595.388	89.8249	22.4986	2.274554
54	3268.549	2282.415	89.7749	22.4194	4.976924
55	3581.997	2332.497	89.8685	22.4194	3.939913
56	1240.356	2721.237	89.2125	22.6334	22.285937
57	934.4727	2978.512	89.1363	22.7125	5.06607
58	640.4783	2889.839	89.0403	22.7033	30.194508
59	824.153	2455.813	89.0799	22.5721	1.884992
60	2379.055	1742.678	89.4916	22.3083	5.584597
61	1949.084	1578.044	89.5597	22.2821	omitted
62	1652.041	1545.483	89.2721	22.2866	8.980078
63	1820.3	2038.628	89.3466	22.4136	3.605839
64	2284.616	2302.462	89.4916	22.4661	3.817253
65	1740.421	2313.575	89.3358	22.4916	7.065306
66	3197.344	4649.647	89.8708	23.0716	5.432747
67	3027.382	4732.496	89.8249	23.103	11.404443
68	3281.995	4835.217	89.9207	22.138	omitted
69	3473.93	4548.128	89.9444	22.0319	omitted
70	461.9354	4139.96	89.0555	23.0519	3.030585
71	1057.905	4329.993	89.2369	23.0777	0.395551
72	744.9177	4465.997	89.153	23.1299	3.908065
73	334.0083	4805.18	89.05	23.2389	6.87443
74	3637.899	840.2171	89.8166	22.0055	4.730626
75	1775.026	934.9688	89.2833	22.1958	omitted
76	2219.431	1713.411	89.1591	22.3083	omitted
77	2397.627	695.6554	89.1591	22.0249	omitted
78	1058.929	682.1139	89.0749	22.0749	omitted
79	2639.443	1260.718	89.5489	22.1666	12.500624
80	3424.281	878.6556	89.74899	22.0291	omitted
81	1149.431	73.60149	89.0666	21.9019	omitted
82	2075.841	208.6714	89.3403	21.8972	17.060971
83	3338.455	383.8522	89.7	21.8916	omitted
84	3660.421	444.2679	89.8055	21.8902	14.571098
85	2611.246	382.6434	89.4916	21.9249	21.92306
86	2454.367	17.20035	89.4319	21.8305	15.439975

Continued Appendix 3.2

Serial No.	Old X	Old Y	New X	New Y	Residual
87	1373.354	146.6128	89.1333	21.9138	omitted
88	3665.333	1347.609	89.85	22.1458	14.563622
89	2045.197	847.3979	89.3583	22.0791	14.03181
90	1431.48	1423.476	89.2055	22.2611	0.907852
91	1278.564	1607.322	89.1685	22.0696	omitted
92	1992.036	2248.364	89.3207	22.45	omitted
93	2207.95	2004.676	89.4533	22.3055	omitted
94	1599.786	2199.037	89.2902	22.4685	1.557877
95	1999.965	1981.108	89.3924	22.3908	9.059335
96	734.0051	2940.99	89.0755	22.0422	omitted
97	1373.106	2517.501	89.2411	22.5658	3.821167
98	910.9726	2234.018	89.09212	22.5036	13.490245
99	3324.927	4495.994	89.9666	23.0227	omitted
100	3027.546	4557.847	89.8177	23.0533	2.837505
101	2940.9	4845.082	89.8133	23.1364	17.410996
102	3032.341	4393.695	89.8092	23.0083	8.002101
103	3646.399	4524.392	89.993	23.0166	7.183335
104	3371.495	2146.635	89.7986	22.3763	1.006352
105	3518.152	1811.514	89.8235	22.0296	omitted
106	3550.531	2601.635	89.8711	22.4936	3.734006
107	3240.215	2435.328	89.7729	22.465	14.178057
108	2186.614	2624.61	89.4791	22.5597	1.514957
109	1885.965	3216.118	89.4202	22.7344	5.356127
110	2827.509	2308.464	89.65	22.4425	8.074237
111	3280.523	2676.032	89.7986	22.5277	7.017816
112	3253.987	3071.958	89.8103	22.6364	3.671198
113	3174.679	3291.479	89.798	22.7	2.941737
114	2187.773	4195.124	89.5555	22.9861	17.384197
115	3455.394	42.87487	89.9269	22.9605	omitted
116	3619.998	4333.235	89.9866	22.9866	omitted
117	3385.841	4139.651	89.8998	22.9221	3.864129
118	1688.189	3365.283	89.3716	22.8689	omitted
119	2019.437	3712.05	89.4836	22.8659	2.769195
120	1574.023	3982.938	89.3664	22.9605	9.377847
121	2934.486	2621.61	89.6944	22.5249	5.349018
122	2723.392	2695.936	89.6361	22.5555	6.613895
123	2353.293	2923.51	89.5416	22.6334	4.293728
124	2408.111	3313.736	89.5769	22.7397	1.921461
125	2111.662	4330.52	89.5416	23.0319	2.913873
126	1980.838	4885.11	89.5904	23.2216	omitted
127	2421.629	4851.776	89.658	23.1611	3.178239
128	1688.866	4416.35	89.42215	23.0749	7.627291
129	1662.43	4865.666	89.4372	23.198	5.691495
130	1248.019	4844.944	89.3165	23.2133	9.738078
131	1183.452	4157.632	89.2633	23.0249	5.017073
132	1063.314	3159.882	89.1816	22.7569	4.730726
133	1195.41	3584.594	89.2416	22.8664	5.073802
134	967.8176	3584.049	89.1747	22.8758	2.352305
135	660.131	3523.857	89.0832	22.8735	1.908914

Note : RMS Error is expressed in input image units.
With low RMS errors, be careful that an adequate sample exists (eg. 2-3 times the mathematical min).

Appendix 3.3 Location of the site used for soil sampling during field visit in 1998.

Date	Site of sampling		very good for pond	Good for pond	Not good for pond	very good for pond	Good for pond	Not good for pond	Soil texture classification	Soil pH
	Latitude	Longitude	very plastic	plastic	non plastic	very sticky	sticky	non sticky		
3/1/98	89.2686	23.2168	very plastic	-	-	very sticky	-	-	Clay soil	6.41
”	89.3172	23.2334	-	plastic	-	-	sticky	-	Clay soil	8.23
”	89.0689	23.2002	-	-	non plastic	-	-	non sticky	Silty soil	8.5
”	89.1603	23.1725	-	-	non plastic	-	-	non sticky	Sandy soil	8.23
”	89.1017	23.3117	-	-	non plastic	-	-	non sticky	Sandy soil	8.9
”	89.0878	23.3078	-	plastic	-	-	-	non sticky	Silty sand	8.2
”	89.2600	23.2875	-	plastic	-	-	-	non sticky	Silty sand	8.65
4/1/98	89.2186	22.9002	-	-	non plastic	-	-	non sticky	Silty soil	7.7
”	88.9500	22.8836	-	plastic	-	-	-	non sticky	Silty soil	7.7
”	89.0658	22.8001	very plastic	-	-	very sticky	-	-	Silty clay	8.0
”	88.9669	22.6835	-	plastic	-	very sticky	-	-	Silty clay	8.6
”	89.2856	22.4002	-	plastic	-	very sticky	-	-	Silty clay	7.9
”	89.2014	22.2336	very plastic	-	-	very sticky	-	-	Clay soil	6.13
5/1/98	89.2169	22.9669	-	-	non plastic	-	-	non sticky	Silty soil	8.3
”	89.2334	23.0781	-	-	non plastic	-	-	non sticky	Silty soil	8.01
”	89.2168	23.2197	-	plastic	-	-	sticky	-	Silty clay	7.8
”	89.2835	22.7167	-	plastic	-	-	sticky	-	Silty clay	8.15
”	89.6335	22.6501	very plastic	-	-	-	-	-	Clay soil	8.13
6/1/98	89.6501	22.7335	very plastic	-	-	-	-	-	Clay soil	8.27
”	89.1961	22.3001	-	plastic	-	-	sticky	-	Silty clay	8.5
”	89.1961	22.3001	very plastic	-	-	-	sticky	-	Clay soil	8.3
7/1/98	89.8002	22.9669	very plastic	-	-	very sticky	-	-	Hard clay	8.0

Appendix 5.1. Calculation of animal wastes from a GIS work in Africa by Kapetsky, (1994).

	Numbers of animals in thousand				Animal waste in thousand tones/sq.km			Total waste
Name of District	Area in km^2	Cattle and Buffalo	Sheep and Goat	Poultry	Cattle and Buffalo wastes NT * LW * W/1000kg LW/A	Sheep & Goat wastes NT * LW * W/1000kg LW/A	Poultry wastes NT * LW * W/1000kg LW/A	
Gopalgang	808	97	41	230	1.512623762	0.106559406	0.011955446	1.631138614
Jessore	518	382	398	1272	9.291891892	1.613513514	0.053396341	10.95880175
Narail	291	108	50	255	4.67628866	0.360824742	0.010706884	5.047820286
Bagerhat	1978	320	135	930	2.038422649	0.143326593	0.019747219	2.201496461
Khulna	2070	434	161	934	2.64173913	0.163333333	0.018950725	2.824023188
Satkhira	2233	445	349	816	2.510971787	0.328213166	0.015347962	2.854532915

Note: NT= Number of animal in thousand, LW= Live weight of animal, W= Total solid waste and A= Area in km^2

Appendix 6.1.

◆ Questionnaire of weighting procedure of Coastal Aquaculture in Bangladesh.

(Name: Md. Abdus Salam, Lecturer, Dept. of Aquaculture, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh)

It is your input which will enable me to produce a detailed model for the Aquaculture activities in South-western part of Bangladesh which it is hoped will be of benefit to people throughout the region.

◆ Name and address:

◆ Field of expertise and mode of work:

◆ **Variables or Factors:** a factor is one of the two types of criteria upon which decisions can be based (the other being constraints). A factor enhances, or detracts from, the suitability of a specific alternative under consideration. It is therefore measured on a continuous scale. Factors are also known as decision variables or structural variables.

◆ **Constraints:** a constraint is one of the two types of criteria on which a decision is based (the other type being factors). A constraint serves to limit the alternatives under consideration.

- What are the factors or variables you consider most important for coastal aquaculture?

Table 1.

1		11	
2		12	
3		13	
4		14	
5		15	
6		16	
7		17	
8		18	
9		19	
10		20	

- What are the constraints or limiting factors you consider most important for coastal aquaculture?

Table 2.

1		11	
2		12	
3		13	
4		14	
5		15	
6		16	
7		17	
8		18	
9		19	
10		20	

- Give score of 1-9 to the following factors according to the most important (9) or least important (1)

Factor	Score
1. water chemistry	
Temperature	
pH	
Dissolved oxygen	
salinity	
2. Risk factors	
Topography (slope)	
pollution	
Potential for flooding & cyclone	
draught	
win-rain	
disease	
3. Inputs	
Agriculture bi-products	
Livestock wastes	
4. Soils chemistry	
Soil pH (surface and sub-surface)	
Texture (surface and sub-surface)	
Soil salinity	
5. Infrastructure	
Transportation network (roads, rails and river)	
Availability of hatchery produced post-larvae	
Availability of natural post-larvae	
Distance from processing plants	
Market (Distance from and size of markets)	
6. Technical support	
Agglomeration (closeness of existing fish farm)	
Govt. offices	
NGO offices	
University and research station	
7. Available land for aquaculture	
8 Availability of water for aquaculture	
Rivers, lakes and Canals	
Coastal Lagoons	
Ground water	
Rain water	
9. Forests (Mangrove)	