9. Current issues, status and applications of GIS to inland fisheries

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9.1 INTRODUCTION

Applications of GIS and remote sensing technologies have increased dramatically since the mid-1980s (Meaden, 2001; Fisher, 2007). Although GIS and remote sensing have been widely applied to marine fisheries, there have been fewer applications of these technologies in inland fisheries management and planning. Like many marine fisheries GIS applications, inland fisheries applications of GIS have largely dealt with mapping the distribution and abundance of fish species, and mapping and modelling habitat in rivers, reservoirs and lakes, and relating the two (Meaden and Kapetsky, 1991; Nishida, Kailola and Hollingworth, 2001; Fisher, 2007; Nishida, Kailola and Hollingworth, 2004; Nishida, Kailola and Caton, 2007). Unlike marine fisheries, which occur widely in oceans and where data on catch and the environment may be dense from landings and remote sensors, freshwater data are sparse and are much more limited in space and time. Geostatistical and distributional modelling of fishes, spatially explicit fish population modelling, predicted species distributions, and the use of remote sensing and sensor networks are some of the challenges and opportunities for freshwater fisheries managers and researchers using GIS.

Meaden and Kapetsky (1991) reviewed GIS and remote sensing applications in inland fisheries and aquaculture, particularly as they relate to spatial decision-making. They describe an approach to decision-making using spatial data that begins with aims and objectives, identifies spatially variable production functions (i.e. factors that control economic activities) and the necessary data to describe them, converts these data into thematic and derived maps in a GIS, and concludes with decisions about locations for fishery production. This approach emphasizes the importance of spatial data, whether it is physical, biological, social or economic, in guiding decisions about fisheries management and planning. Recent summaries of the use of GIS and remote sensing in inland fisheries management and planning provide much of the information used in this technical paper (Nishida, Kailola and Hollingworth, 2001; Fisher and Rahel, 2004a; Nishida, Kailola and Hollingworth, 2004; Nishida, Kailola and Caton, 2007).

The aim of this chapter is to describe the present use of GIS and remote sensing in inland fisheries management and planning. Some detail is given on five main thematic areas in which GIS is applied with respect to inland fisheries. The current status of this GIS work is also examined as it pertains to the main geographic areas where inland fisheries related GIS work is being applied, and the main inland fisheries themes are discussed, i.e. as derived from FAO's Aquatic Sciences and Fisheries Abstracts (ASFA) database on fisheries and aquaculture. The chapter concludes with three case studies on the use of GIS and remote sensing in management and planning for inland fisheries.

9.2 INLAND FISHERIES THEMES AND GIS APPLICATIONS

In Table 1.1 (Section 1.4), the major GIS and fishery themes were identified for marine fisheries, inland fisheries and aquaculture. In Box 9.1, the focus is on themes that are specific to GIS applications in inland fisheries. These themes are an update of those identified by Fisher (2007) for freshwater environments and they focus on GIS processes (operations and analyses).

BOX 9.1
Main themes relating to GIS applications in inland fisheries

Among the variety of GIS applications in inland fisheries, the following themes and operations identify those that are commonly used in freshwater.

- **Visualization and species distribution modelling** – Mapping and visualizing fish distribution and abundance and aquatic habitat remains the most common use of GIS in inland fisheries.
- **Fish movements** – Mapping fish locations and measuring rates of fish movements provide information for managing populations and their habitat.
- **Habitat modelling** – Combining data on fish locations with instream habitat features, such as spawning, feeding and refuge areas, informs stream habitat management and restoration efforts.
- **Watershed management** – Identifying land use and land cover types, topography and elevation, and hydrography and waterbody types and relating these features to fish populations and communities allows for integrated fisheries management.
- **Spatial design and conservation planning** – Developing designs for survey site selection in streams, rivers, reservoirs and lakes enables researchers and managers to efficiently allocate resources for fisheries surveys.

Source: Modified from Fisher (2007).

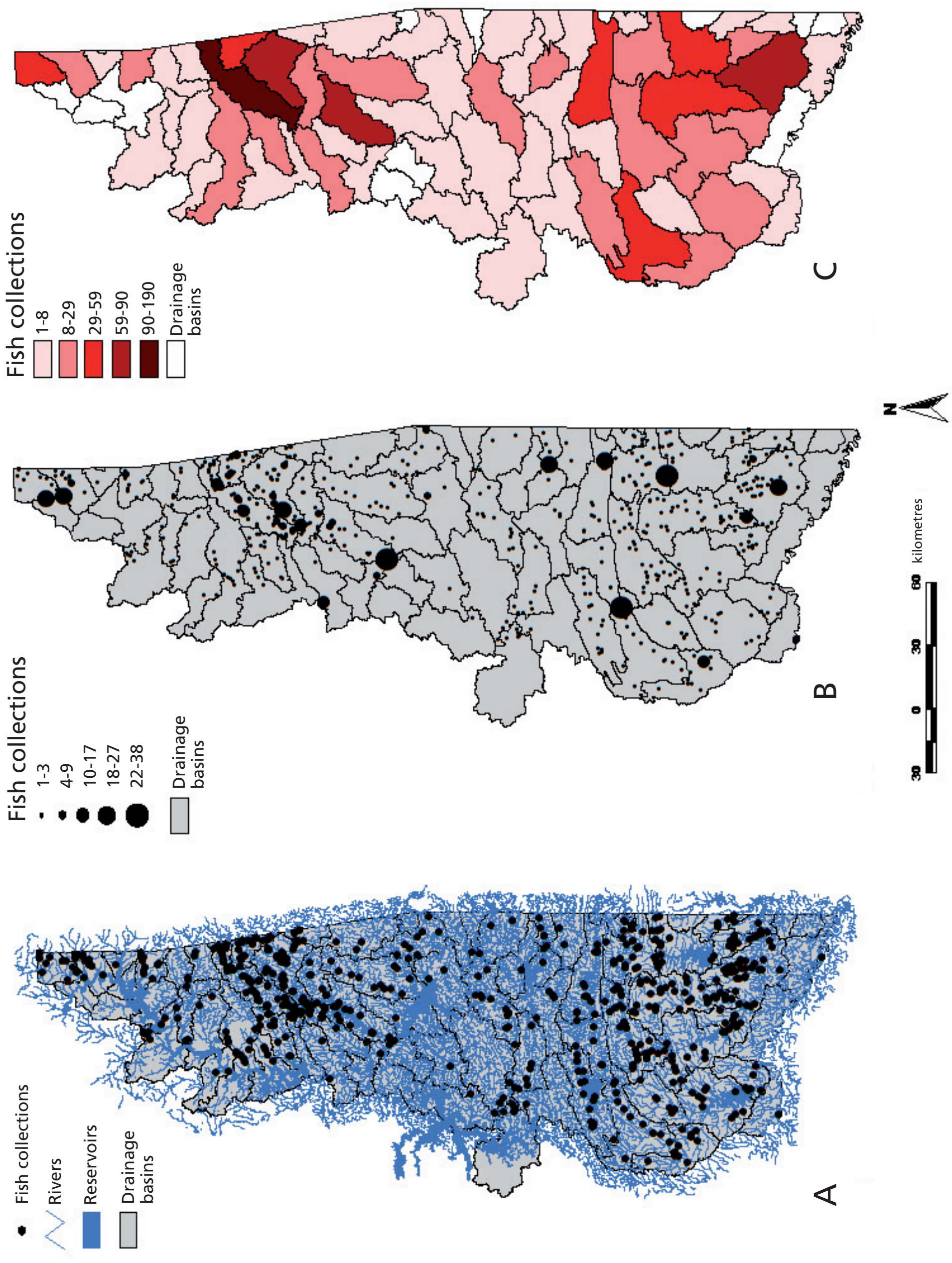
9.2.1 Visualization and species distribution modelling

Nearly all GIS applications in inland fisheries (and all other fisheries for that matter) involve the visualization of fish locations in their environment. This visualization is most often in the form of maps of fish occurrence and/or the habitats they occupy. This fundamental use of GIS provides a geographic frame of reference that can be used to effectively communicate information about the fish population or community. Because of the scalability of GIS, maps can be created at nearly any geographic or spatial scale from a single stream reach to a drainage basin or to an entire continent. These maps can be depicted as point locations in streams or lakes or as drainage basins in a region. For example, Fisher and Rahel (2004b) illustrated the distribution and density of collections of a minnow, the central stoneroller (*Campostoma anomalum*), in streams and drainage basins in eastern Oklahoma, the United States of America (Figure 9.1).

Data on fish species locations is one of the primary components used to model species distributions. This locational data is combined with habitat data about the inland environments, including physical features such as bottom type, vegetation type or woody debris, land use types, and physico-chemical conditions such as water temperature, dissolved oxygen, water depth and water flow. Species-habitat models in GIS are used to model occurrences and suitable areas for fish populations in streams and rivers (Fausch *et al.*, 2002; Fisher and Rahel 2004b) and reservoirs (Amarasinghe, De Silva and Nissanka, 2002; Paukert and Long, 2004) and lakes (Bakelaar *et al.*, 2004; Vander Zanden *et al.*, 2004). Species distribution modelling is a valuable tool for managing and conserving inland fisheries resources.

FIGURE 9.1

Maps of the central stoneroller collections in eastern Oklahoma, United States of America, depicted as occurrence (A) and density by symbol size (B) and drainage basin (C)

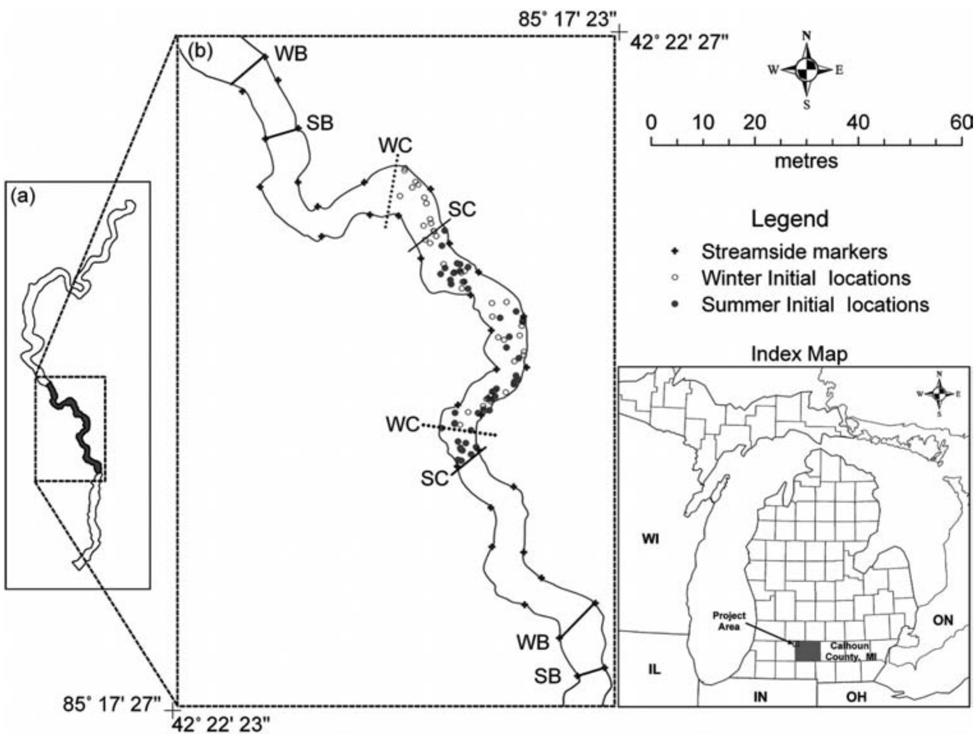


Source: Fisher and Rahel (2004b).

9.2.2 Fish movements

Understanding when and where fish move provides important information for managing fish populations and for location decisions made by anglers. Tracking fish movements in freshwater environments involves using some type of tags (passive integrated transponder, PIT) or tracking (radio or ultrasonic telemetry) device. These devices are inserted (tags) or implanted (transmitters) in fish and tracked either by collecting the fish or detecting the fish with an external sensor or receiver. Fish movements in inland streams, rivers, reservoirs and lakes have been studied extensively, particularly with underwater telemetry (Winter, 1996). Figure 9.2 illustrates summer and winter locations of mottled sculpins (*Cottus bairdii*) that were tagged with PIT tags in a stream in Michigan, the United States of America (Breen *et al.*, 2009)[214]. Fish locations were recorded with a GPS and these data files were exported to a GIS for visualization, error correction and distance measurements. This approach of recording locations of fish tagged with transmitters using GPS and exporting those data to GIS for analysis of movements and home range is increasingly being used in freshwater environments to understand individual and population-level movement patterns.

FIGURE 9.2
Map of PIT-tagged mottled sculpin locations during summer and winter in a 700-m reach of Seven Mile Creek, Michigan, United States of America



Source: Breen *et al*. (2009).

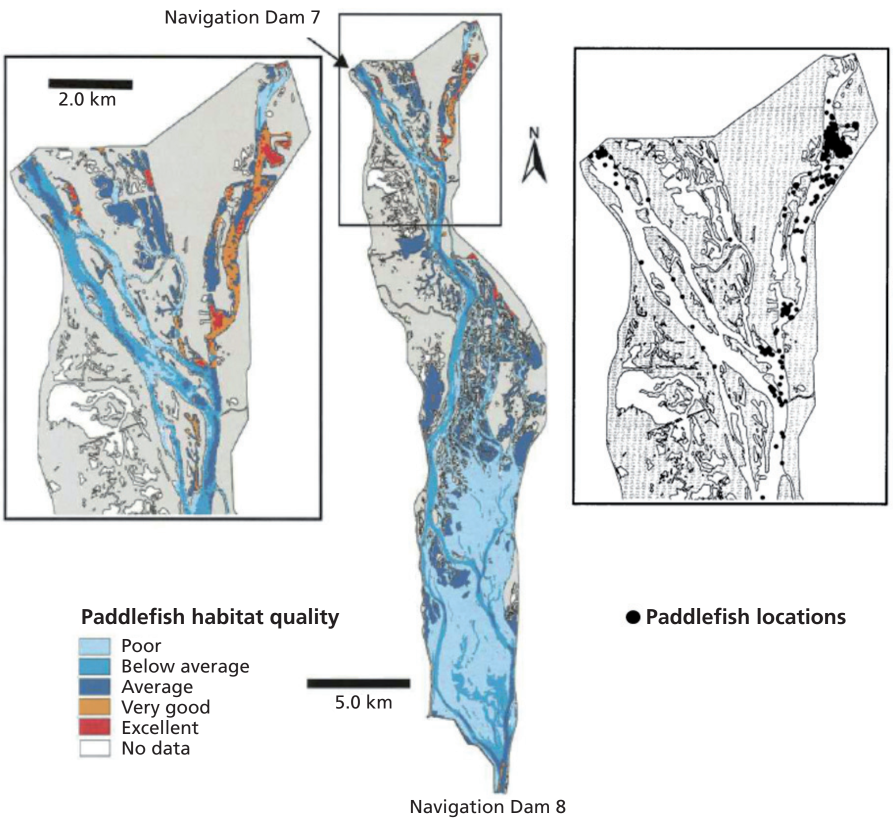
9.2.3 Habitat modelling

GIS has been widely used to model fish habitat in inland rivers and lakes, particularly to assess habitat suitability in relation to physical (e.g. flow, depth, substrate) and chemical (e.g. temperature, dissolved oxygen) conditions. Models can be constructed from independent data or from data collected in the field. These data are incorporated into mathematical models that combine the habitat factors and in some cases weight

[214] Figure 9.2 (a) represents the complete 700-m stretch and (b) represents a central 170-m stretch of the Seven Mile Creek.

them according to their importance based on statistical analyses or expert opinion. The results from the modelling are usually depicted in a GIS map of the freshwater environment. These suitability models can be validated with independent data of fish locations. In Figure 9.3, suitable habitat for paddlefish (*Polyodon spathula*) was modelled for an area (Navigation Pool 8) of the upper Mississippi River, the United States of America (Zigler *et al.*, 2003). A cartographic model was created using GIS layers for bathymetry and current velocity. Areas of the river with deep water (≥ 6 m) and slow flow (< 5 cm/s) were classified as excellent habitat. Areas with "excellent" and "very good" habitat collectively encompassed 74 percent of all paddlefish observations in Navigation Pool 8; however, these areas accounted for only 2.6 percent of the total area of the watercourse between Navigation Dams 7 and 8 (Figure 9.3 – the whole of the middle map). The authors concluded that suitable habitat is relatively limited in the upper Mississippi River system and connections between suitable areas are impeded by the navigation dams.

FIGURE 9.3
Map of suitable habitat for paddlefish in the upper Mississippi River, the United States of America and locations of paddlefish obtained from radio telemetry tracking

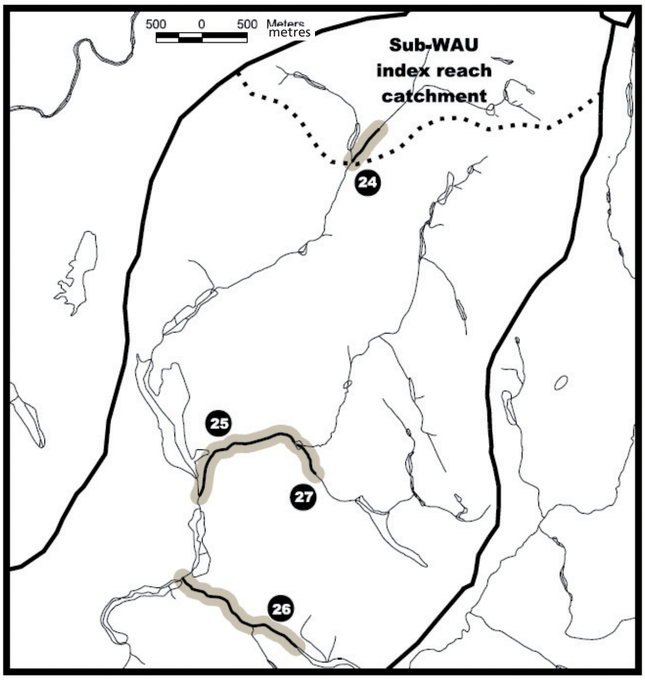


Source: Zigler *et al*. (2003).

9.2.4 Watershed management

Streams and lakes drain watersheds where land use activities, topography, local geology, soil types, hydrology and many other factors can affect the runoff of sediment and nutrients into the stream or lake and thereby affecting fish populations and communities (Wang *et al.*, 1997). Pess *et al.* (2002) explored relationships between adult coho salmon (*Oncorhynchus kisutch*) abundance and landscape characteristics (wetlands, surficial geology, stream gradient, potential for landslides), and land use-land cover types (forest, rural residential, agriculture, urban, roads). Figure 9.4 shows the study area, the four sampling reaches (numbers 24–27) and the 100-m buffers (grey areas) around them from which watershed landform and land use data layers were obtained. Data for these landscape and land use characteristics were obtained using GIS, which is common among studies of this type. The authors found that wetland occurrence, local geology, stream gradient and land use type were significantly correlated with adult coho salmon abundance, and that fish densities were 1.5 to 3.5 times greater in forested areas than in rural, urban and agricultural areas. Understanding the relationship between these watershed factors and fish population and communities enables resource managers to prioritize areas for restoration and protection.

FIGURE 9.4
Stream reach and watershed areas in the Snohomish River, Washington, United States of America

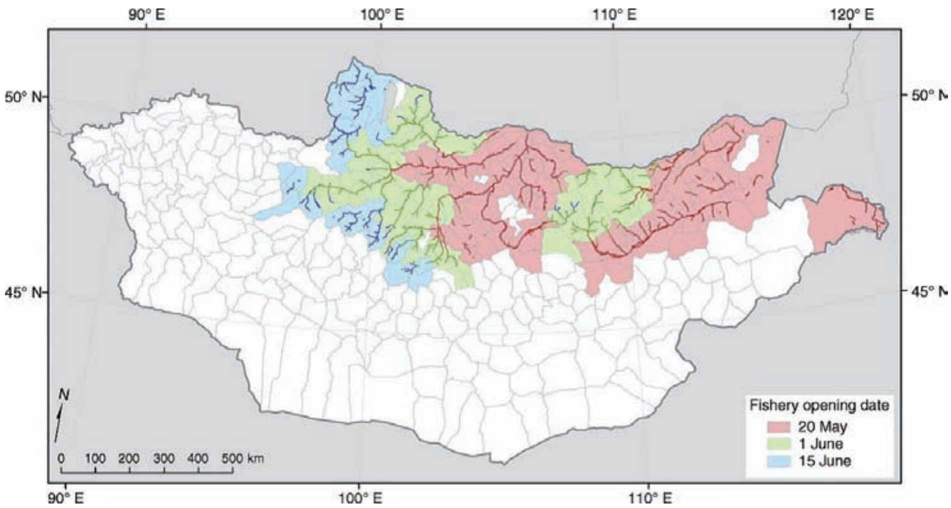


Source: Pess *et al*. (2002).

9.2.5 Spatial design and conservation planning

Designing fisheries surveys and sampling plans in inland freshwater environments can be greatly facilitated by using GIS. For example, Toepfer, Fisher and Warde (2000) developed a multistage approach for estimating the abundance of stream fishes using GIS. The authors mapped stream channel units (riffles, runs, pools) and used information on fish habitat preferences to assign each channel unit to a habitat suitability class. They then determined the abundance of fish in each suitability class and estimated the total abundance of fish throughout the stream using GIS. Designating regional fisheries management areas using GIS and watershed and environmental data provides information that is valuable to fisheries managers (Fisher, Tejan and Balkenbush, 2004). Figure 9.5 shows a map of recommended management zones that were developed for the giant Eurasian trout (*Hucho taimen*) in Mongolia based on spawning dates and potential habitat. Using statistical models, climate data, knowledge of the biology of the Eurasian trout and GIS, Vander Zanden *et al.* (2007) recommended three fisheries management zones that corresponded with opening recreational fish dates that improve on existing fishing regulations and still provide benefits for local economies and conservation efforts.

FIGURE 9.5
Map showing the three recommended management zones based on opening dates for fishing for giant Eurasian trout in Mongolia



Source: Vander Zanden *et al*. (2007).

9.3 THE CURRENT STATUS OF GIS APPLICATIONS TO INLAND FISHERIES

Any attempt to evaluate the current status of GIS applications to inland fisheries is a serious challenge given the rapid changes in technology and the expanding availability and use of GIS across many disciplines. The previous section (9.2) provided several examples of how GIS has been applied across various inland fisheries themes.

Beginning in 2007, FAO compiled a database showing the main uses of GIS for inland fisheries as part of the GISFish Web portal. A search of the 224 records in this GISFish database (Table 9.1) reveals overlaps of many of the themes presented in Section 9.2, plus some additional themes that were not covered. The three most common fishery resource issues and themes were habitat based (linking habitat quality/quantity to plant and animal abundance and distribution; classifying and inventorying habitats; rehabilitating and restoring habitats) and accounted for over half (51 percent) of the records in GISFish. In fact, 8 of the 12 themes under fishery resources refer to habitat, whereas the other themes relate to management, assessing fish diversity, abundance or movements. This is not surprising given the availability of existing GIS data for rivers and lakes, the relative ease of using GIS to classify and inventory habitat, particularly in streams and rivers, and the use of these data to aid in restoring or rehabilitating fish habitat that has been modified by human activities such as agriculture, silviculture and urban development. The environment issues and themes most closely relate to the use of GIS to evaluate the effects of land use practices in watersheds on stream water quality and quantity and the habitats and health of aquatic organisms. Clearly, GIS has played an important role in helping fisheries managers understand how activities on the land (farming, timber harvest, industry) facilitate sediment and pollutant movements over land and into streams, thereby affecting stream and lake habitat and fish populations. GIS training and promotion was not covered in Section 9.2. During the advent of GIS applications in fisheries in the 1990s, there was a greater emphasis on promoting the uses of GIS and in providing training (Nishida, Kailola and Hollingworth, 2001). Although there are now more opportunities for GIS training through university programmes and private companies, fewer articles are being written about it. In fact, GIS is becoming so widespread and ubiquitous that the term is essentially disappearing from titles (Fisher, 2010) and blending into the methods sections of many scientific articles.

TABLE 9.1
Main issues in inland fisheries GIS as derived from the GISFish database (1985–2009)

Main inland fisheries issues from the GISFish database	Number of literature records
GIS training and promotion of GIS	
Promotion	10
Training	7
Fishery resources	
Habitat quality/quantity linked to plant and animal abundance and distribution	67
Classification and inventory of habitats	29
Rehabilitation and restoration of habitats	18
Planning and potential	18
Fisheries management	11
Direct assessments and inventories	10
Habitat approaches to aquatic biodiversity	7
Movements and migrations of aquatic animals	5
Essential fish habitat	3
Artificial habitats	2
Natural habitats	1
Modification of habitats	1
Environment	
Effects of terrestrial activities on habitats and aquatic organisms	18
Water quality and quantity	15
Environmental health	2
Total	**224**

Source: FAO (2012d).

Another way to track the current status of GIS applications in inland fisheries is to assess the countries where the studies were conducted. A sample of 145 literature records from 1996–2010 retrieved from the ASFA database revealed that, of those records that included a country of origin (n = 137), 56 percent were from north America, with most of these being from the United States of America (Table 9.2). Perhaps somewhat surprising, of the remaining 44 percent of records (n=60), south and east Asia accounted for 17 of the studies, and Africa accounted for a further 14 studies. This means that the rest of the developed world (mainly Europe and Australasia) only produced about 16 percent of all GIS related studies of inland fisheries during the 14 year recent period. These percentages parallel those reported by Fisher (2007) in his review of recent trends in fisheries GIS. He reviewed 100 studies of GIS applications to freshwater and marine fisheries GIS and found that 47 percent were conducted in the United States of America. The dominance of this country is most likely due to the widespread availability of GIS data and software to government agencies and to relatively many university researchers who publish their findings in scientific journals.

TABLE 9.2
Country of application for 145 literature records on papers covering inland fisheries + GIS in FAO's ASFA database (1996–2010)

Region	Country of application	Number of applications
North America	United States of America	42
	Great Lakes area	28
	Canada	7
Latin America	Latin America (general)	3
	Argentina	1
	Brazil	1
	Chile	1
	Mexico	1
Asia	Bangladesh	5
	Thailand	3
	Asia (general)	2
	Laos	2
	Cambodia	1
	China (People's Republic)	1
	India	1
	Indonesia	1
	Japan	1
Africa	Nigeria	4
	Africa (general)	3
	Cameroon	1
	Ethiopia	1
	Kenya	1
	Morocco	1
	South Africa	1
	Uganda	1
	West Africa (general)	1
Europe	Greece	3
	France	2
	Portugal	2
	Sweden	2
	Europe (general)	1
	Lithuania	1
	Norway	1
	Spain	1
Australasia	New Zealand	7
	Australia	1
	Fiji	1
Not area specific		8
Total		**145**

Source: FAO (2012b).

A final way of analyzing the work being carried out with respect to GIS applications to inland fisheries is through recognizing the main institutions where this type of work is proceeding. Box 9.2 provides an overview of this situation. The highly technical nature of much of this work means that most of it is pursued in research institutes in the developed world. At the world scale there are relatively few institutions that specialize in GIS applications to inland fisheries, and this is mostly related to the comparative lack of commercial fisheries in these waters, plus the complexities of using GIS in the context of mapping linear freshwater systems.

BOX 9.2
Overview of major organizations carrying out inland fisheries-related GIS research and projects

This box can only be illustrative because it is impractical to list the exact range or number of institutions carrying out inland fisheries-based GIS work:

- **Australia.** The Australian Rivers Institute at Griffith University focuses on understanding catchment and river ecosystem processes, aquatic biodiversity and conservation, and rehabilitation science and environmental flows.
- **Canada.** The GIS Unit, Fisheries and Oceans Canada, provides support for the protection and conservation of fish and fish habitats in the Pacific Region.
- **The French Republic.** The Hydro-ecology of Rivers team – at the National Research Institute of Science and Technology for Environment and Agriculture, Hydrosystems and Bioprocesses Research Unit – investigates the contemporary evolution of fish populations and the impact of fish habitats on their distribution.
- **The Republic of Italy.** The Asia-Pacific Fishery Commission (APFIC), working through the Food and Agriculture Organization, recognizes the contribution of often overlooked and ignored inland fisheries to the livelihoods and well-being of significant populations. Documents are available through GISFish and describe inland fisheries by country.
- **New Zealand.** The National Centre for Water Resources at the National Institute of Water and Atmospheric Research provides public information and monitors and researches freshwater rivers, lakes and groundwater conditions across New Zealand.
- **New Zealand.** The Centre for Freshwater Ecosystem Management and Modelling at Massey University applies developments in theoretical ecology and ecological modelling to new and novel ways of addressing current issues in freshwater ecosystem management, conservation and bioassessment.
- **The Republic of South Africa.** The South African Institute for Aquatic Biodiversity generates, disseminates and applies knowledge to understanding and solving problems on the conservation and wise use of African aquatic biodiversity, including developing a GIS atlas of southern African freshwater fish.
- **The United States of America.** The Great Lakes Basin Ecosystem Team at the U. S. Fish and Wildlife Service provides information on threatened endangered and invasive species, and interjurisdictional fisheries in the Great Lakes by addressing landscape-scale resource objectives using an ecosystem approach and GIS.
- **The United States of America.** The Aquatic Gap Analysis Program of the U. S. Geological Survey evaluates aquatic biological diversity and aquatic habitats using GIS-based spatial analysis and habitat suitability models to identify gaps in species distribution and works toward more effective conservation prioritization. .
- **The United States of America and Canada.** The Great Lakes Fishery Commission and Great Lakes Information Network partnership provides online facilities to find information relating to the binational Great Lakes-St. Lawrence region of North America.

9.4 SPATIAL ANALYSIS

Freshwater inland systems, including rivers, streams, lakes and reservoirs, present different challenges compared with marine systems for mapping and modelling fish distributions and habitats with GIS. Lakes, reservoirs and ponds are areal features on the landscape and, as such, they are amenable to many of the GIS techniques used for terrestrial ecosystems[215]. In contrast, rivers and streams are linear features on the landscape. Although at small scales they are considered areal features, as networks they present a greater challenge for acquiring, analysing and displaying spatial data. This challenge, however, presents an opportunity because streams and rivers are much like transportation or other linear systems (roads, highways, pipelines, etc.) for which there have been considerable advances in the application of GIS (Goodchild, 2000),

[215] Scale is important to representation because, at a small scale, lakes, ponds, etc., can be mapped as point features.

often under the heading of "network analysis" (see Section 7.6). The following sources provide detailed information on data acquisition and processing for inland fisheries in rivers and streams (Fisher and Rahel, 2004b), reservoirs (Paukert and Long, 2004), lakes (Bakelaar *et al.*, 2004) and in aquaculture (Meaden and Kapetsky, 1991).

Spatial tools (i.e. GIS, remote sensing, spatial models) provide a variety of procedures for analysing inland fisheries and freshwater ecosystems. These procedures can be used to define drainage systems, describe watershed characteristics, and characterize fish populations and communities. Streams and rivers are linear 1D features on the landscape, and depending on the scale of mapping, they are relatively stable over time. Operations on linear systems are used to classify and analyse linear features (e.g. stream segments) that possess various attributes (e.g. stream habitat types or fish abundances). Such features may be fixed (e.g. roads) or ephemeral (e.g. fish movements) and real (e.g. stream channels) or contrived (e.g. political boundaries) (Johnston, 1998). Measurements of linear features, such as stream channels, tend to be less complicated and are more accurate with vector than raster data structures in GIS. Linear operations are particularly useful in characterizing hydrological aspects of stream ecosystems, and ArcGIS by the Environmental Systems Research Institute (ESRI) contains a tool "ArcHydro" (www.crwr.utexas.edu/gis/archydrobook/ArcHydro.htm) that processes digital elevation models (DEMs), delineates watersheds and conducts flow path analysis (Jensen and Dominque, 1998). Flow path analysis can be used to construct a stream network and trace pollutants through the stream. Inland freshwater ecosystems consist of many 2D areal features, such as stream and lake habitats, riparian zones and land use types.

Common GIS procedures used in inland freshwater ecosystems include overlaying fish distributions on habitat features and generating buffer zones around objects. Narumalani, Yingchun and Jensen (1997) identified critical areas for establishing riparian vegetation by using buffers to delineate existing riparian zones around stream channels. Operations on 3D topographic features are used to analyse the change in an attribute, such as surface elevation, bathymetry or other continuous data surfaces, over space. Elevation data are usually derived from DEMs using raster GIS (see Section 7.7). Spatial interpolation has many applications in inland freshwater ecosystems. Whole area interpolation methods, such as trend surface analysis and Fourier series, use all the points in a study area to interpolate a surface, whereas local interpolation methods use only neighbouring points to estimate values (see Section 7.5.3). For example, Gardner, Sullivan and Lembo (2003) used interpolation (kriging)[216] with three different metrics (i.e. Euclidean distance, instream distance along the stream network, and instream distance along the network weighted by stream order) to model stream temperature at target locations based on data from temperature loggers placed throughout a watershed in New York, the United States of America. Isaak *et al.* (2010) provide another example of predicting stream temperature using GIS and multiple regression, spatial statistical models that included air temperature, radiation and stream flow to compare climate change scenarios for two species of salmonids in a mountain river network.

9.5 CASE STUDIES

Applications of GIS in inland fisheries have occurred throughout all types of freshwater habitats, including streams and rivers, lakes and ponds, and impoundments (reservoirs). The following three case studies illustrate how GIS has been used in river and reservoir environments in relation to fish conservation and management. All represent different

[216] Kriging is an interpolation technique in which the surrounding measured values are weighted to derive a predicted value for an unmeasured location. Kriging is unique among the interpolation methods in that it provides an easy method for characterizing the variance, or the precision, of predictions. Kriging is based on regionalized variable theory, which assumes that the spatial variation in the data being modeled is homogeneous across the surface. That is, the same pattern of variation can be observed at all locations on the surface.

approaches to applying GIS analytical tools in freshwater habitats. The three studies chosen provide examples of:

- The application of landscape concepts and the development of customized GIS tools to manage stream fishes in riverine environments (Section 9.5.1).
- The use of GIS-based land use data in the development of fisheries yield models for reservoir environments in a developing country (Section 9.5.2).
- A large-scale application of GIS in a developed country for the identification of streams with high fish diversity in need of conservation efforts (Section 9.5.3).

9.5.1 Managing stream fishes in riverscapes

Original publication reference: Le Pichon, C., Gorges, G., Boët, P., Baudry, J., Goreaud, F. & Faure, T. 2006. A spatially explicit resource-based approach for managing stream fishes in riverscapes. *Environmental Management*, 37(3): 322–335.
Spatial tool: GIS.
Main issues addressed: Habitat quality/quantity linked to plant and animal abundance and distribution; classification and inventory of habitats; rehabilitation and restoration of habitats; direct assessments and inventories; habitat approaches to aquatic biodiversity; movements and migrations of aquatic animals; natural habitats.
Duration of study: Multiple years.
Personnel involved: Six research scientists and managers based at two institutions in the French Republic.
Target audience: River ecologists, fisheries researchers, fisheries and resource managers, government management agencies.

Introduction and objectives: Managing fish in human-impacted streams and rivers requires an understanding of the spatial arrangement of habitats and the fish that occupy them. Many rivers have been impacted by human activities resulting in fragmented and homogenized habitat conditions that adversely affect the aquatic organisms living in these environments. The aim of this paper is to provide a riverscape approach in combination with spatial analysis methods to assess multiscale relationships between patterns of fish habitat and fish movements. The riverscape is defined as a continuous view of the river environment that includes the mosaic of heterogeneous and dynamic habitats, which to most observers is often hidden beneath the opaque layer of water (Fausch *et al.*, 2002; Le Pichon *et al.*, 2006). GIS tools provide a means for measuring relationships between aquatic organisms and their habitats. Fish species occupy a variety of habitats throughout their life cycle. Thus, different life stages, such as eggs, larvae, juveniles and adults, occupy spatial habitats corresponding to activities that include spawning, feeding and seeking refuge. Landscape ecology concepts such as habitat patch dynamics (i.e. accounting for the diversity of habitats within an area), habitat complementation,[217] and source and/or sink habitats (i.e. sources are high-quality habitats that allow a population to increase and sinks are low-quality habitats that provide limited support for a population) are being increasingly used to assess the spatial patterns of fish habitats in river systems. Understanding the spatial and temporal dynamics of fish habitats relative to fish movements and to management and restoration of these habitats can be improved by utilizing GIS tools, models and landscape ecology concepts.

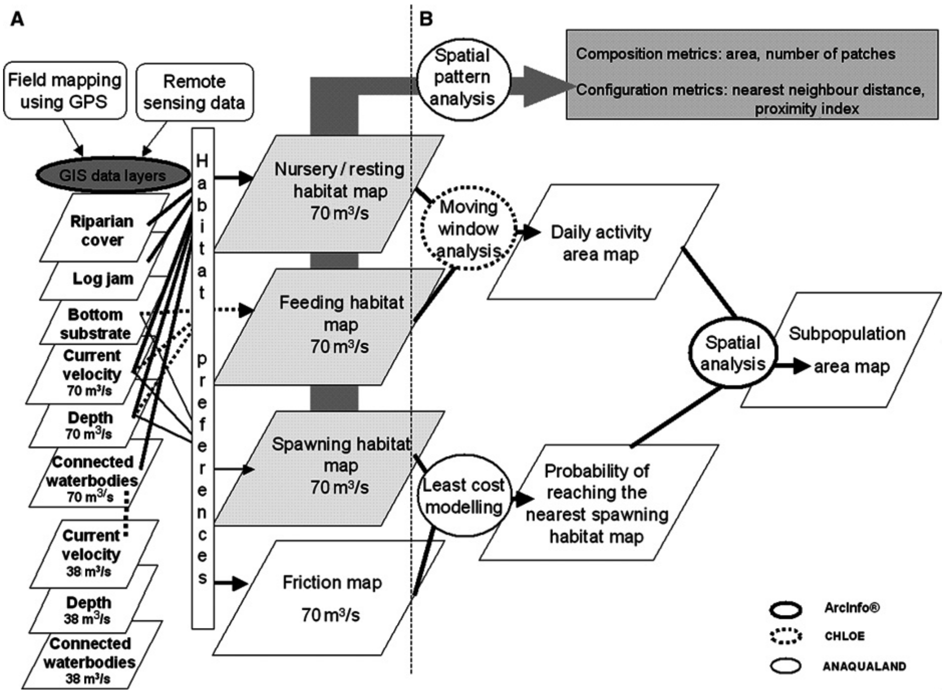
In the riverscape environment, habitats have been traditionally classified as discrete areas based on relatively homogeneous characteristics of substratum, depth and flow. This classification of channel units, each of which are more specifically referred to as pools, riffles, runs, etc., can be reclassified using GIS tools according to their suitability for a fish species. However, rather than following this more commonly used habitat classification approach, the authors classified habitat by defining resource-based (i.e. spawning, feeding and resting) habitat patches preferred by individual fish species. The

[217] Complementation is the use of different habitats by a species to complete their life cycle.

extent of these patches, their arrangement and the resolution of habitat measurements should be scaled to the activity patterns and movements of fishes among patch types.

Methods and equipment: Resource-based habitats of a minnow species, *Barbus barbus*, were evaluated in the Seine River, the French Republic. The authors mapped, at a 1-m resolution in two dimensions, a 22-km reach of the river with channel widths reaching to 50 m including lateral waterbodies such as side channels and backwaters. Channel water boundaries were delineated on digital orthophotographs and habitat variables (i.e. depth, current velocity, substrate, log jams) and riparian cover were located during field mapping at 1 m accuracy using differential global positioning system (DGPS) equipment. Raster data from the aerial imagery and vector data from the DGPS were exported into GIS (ArcInfo) and combined according to species habitat preferences to create resource habitat maps (Figure 9.6).

FIGURE 9.6
Flowchart of the processing steps, spatial analysis methods and products for creating resource habitat maps for river fish species



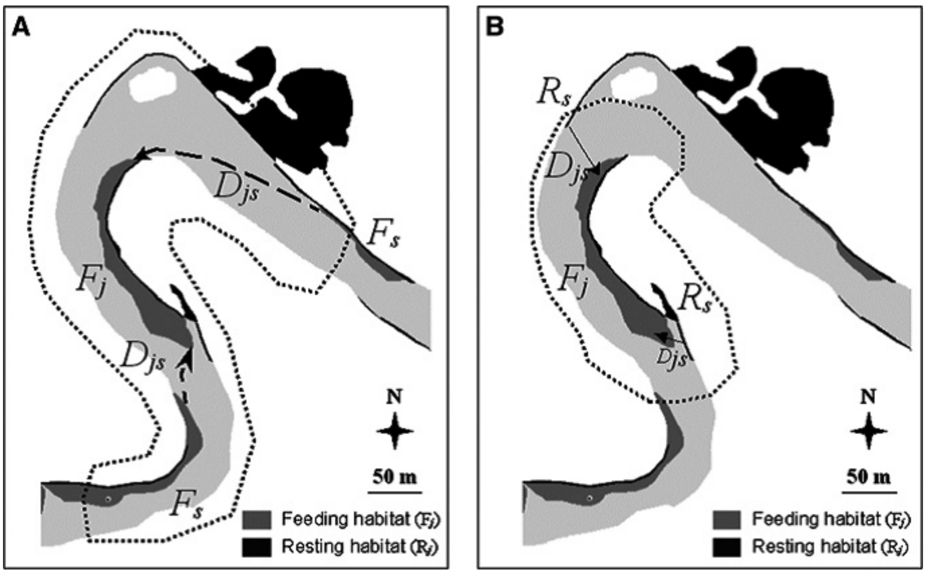
Source: Le Pichon *et al*. (2006).

In Figure 9.6, the operations illustrated in (A) to the left of the dashed line produce GIS-generated maps of resource habitat patches for *Barbus barbus* in the upper Seine River, the French Republic, where the average stream flow rate is 70 m³/s. The friction map consists of a resistance matrix developed using least cost modelling. Least cost modelling is a modelling approach in GIS that identifies areas with the lowest relative resistance (cost) for a species moving through its environment. In the friction map, resistance for the barbel is based on its swimming capabilities and its risk of predation while swimming through different habitats. The operations in (B) to the right of the dashed line are the spatial analyses of habitat and friction maps to determine composition and configuration of habitat maps and their spatial relationships for the fish subpopulation in the mapped area.

Stream habitats and fish populations are often studied at multiple spatial scales (Fausch *et al.*, 2002), and, as such, are well suited for hierarchical-based models. Hierarchical models nest levels of habitat or populations at different spatial scales. For example, the authors describe the smallest spatial scale (ranging from 1 to 100 m) as the resource habitat patch scale where spawning, feeding and resting and nursery habitat patches are represented. The next larger spatial scale (ranging from 10 to 1 000 m) is described as the daily activities areas scale. At this scale, movements of fish for daily activities such as feeding and resting are complemented by the proximity of these habitat types. The largest spatial scale is the subpopulation area scale (ranging from 100 to 10 000 m) where subpopulations of a fish species migrate between complementary spawning habitats. These migrations could occur over tens of metres or tens of kilometres depending on the life cycle and home range of a species.

Quantifying the proximity of habitat patches requires information on the spatial arrangement, area and orientation of different patch types. To compute oriented distances between habitat types upstream and downstream, the authors developed a GIS program Anaqualand.[218] This freeware program integrates the geometry of the river channel and measures distance between two points or patches. To quantify the spatial relationship of a habitat patch with its neighbouring patch, the authors used a proximity index. Using moving window analysis in Anaqualand software, this index calculates the edge-to-edge distance between a patch and the neighbouring patch relative to their areas. Illustrations of the proximity of feeding and resting habitats are shown in Figure 9.7. Shown in these illustrations are the proximity index variables and the arrangement of feeding habitat (Fj) and resting habitat (Rs) within a delimited (dashed line) focal patch (Fj) along a river reach. The edge-to-edge distance (Djs) between habitat patches is indicated with arrows. In Figure 9.7A, the proximity of feeding patches is within a 200-m search radius, which is indicated by the dotted line. In Figure 9.7B, the complementarity of feeding and resting habitat patches (i.e. their proximity) is evaluated within a 60-m search radius, which is also indicated by the dotted line.

FIGURE 9.7
Illustration of the arrangement of feeding habitat along a river reach



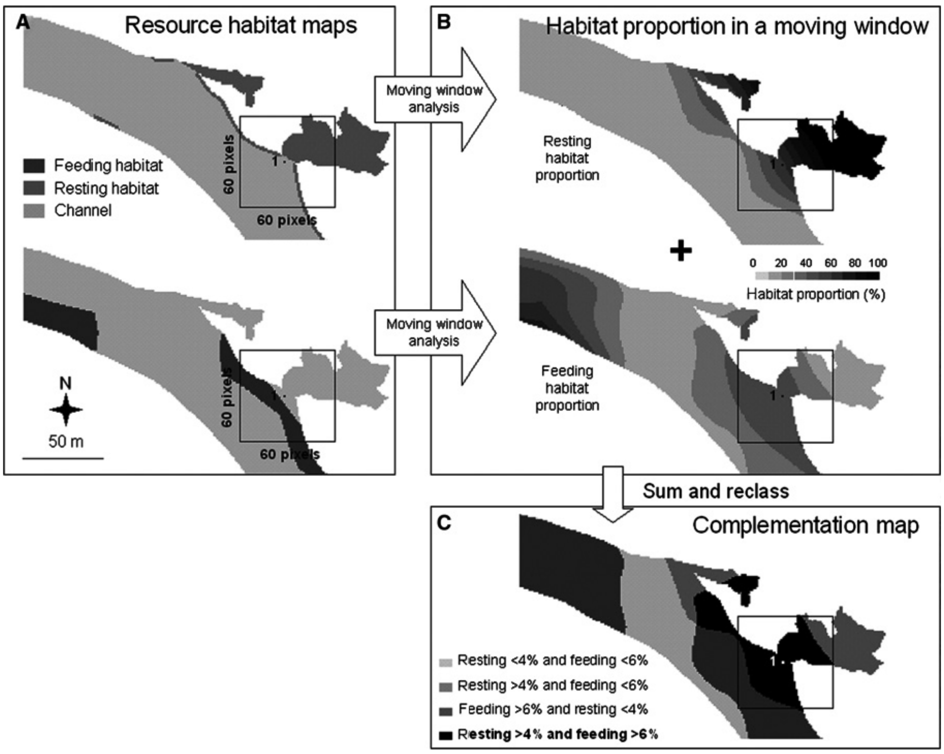
Note: Resting habitat is where fish reside when they are not feeding. Variables are described in the text.

Source: Le Pichon *et al*. (2006).

[218] See INRA: www.rennes.inra.fr/sad/outils_produits/outils_informatiques/anaqualand_2.

In addition to the proximity of different habitat patches with unique resources, the authors developed another freeware software program, Chloe (INRA SAD-Paysage, 2012), that computes multiscale spatial analysis metrics from raster data files, such as relative abundance, richness, diversity and heterogeneity. The software uses a moving window to systematically search the raster image, computes the spatial index for the squared search window and assigns the index value to the central pixel. Moving window analysis is an automated spatial (pixel by pixel) operation with raster data sets where the value of the raster cell is examined and operations are performed on it before moving on to the adjacent cell. An example of this process is illustrated in Figure 9.8. Note that GIS operations are used to summarize and reclassify the habitat proportions computed with the moving window analysis using Chloe to produce the complementation map. Figure 9.8A shows how raster maps of resource (feeding and resting) habitat patches are reclassified using moving window analysis in a 60 (m) × 60 (m) pixel window to create new maps of the proportion of each habitat that are shown in Figure 9.8B. Habitat proportions range from 1 to 100 percent. The resting and feeding maps are overlaid in GIS and reclassified to identify complementation of the two habitats within a radius of 30 pixels of potential daily activity areas, which is shown in Figure 9.8C. Complementation is defined by thresholds of 4 percent for resting and 6 percent for feeding. The number 1 is a reference point for the moving window analysis and resulting maps.

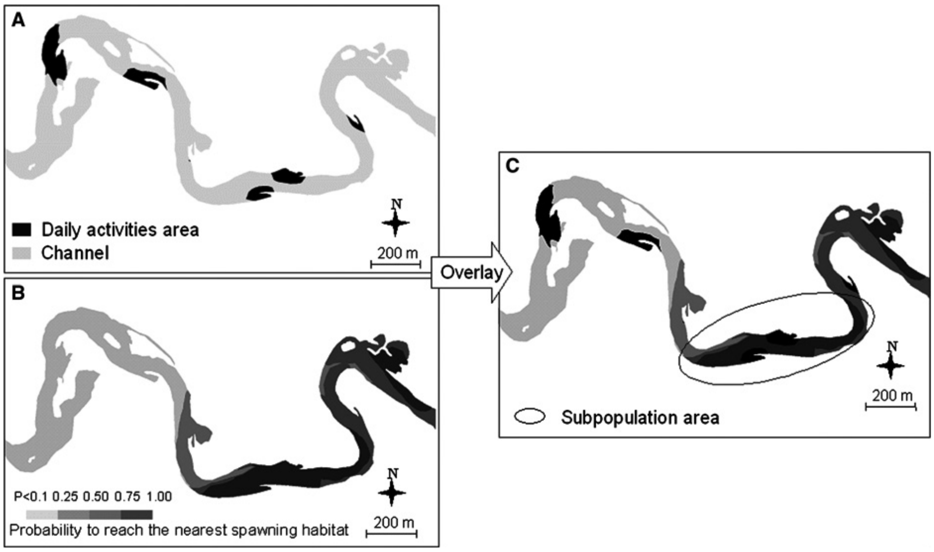
FIGURE 9.8
Illustration of the process of creating a complementation map of stream fish habitats using the moving window analysis



Source: Le Pichon *et al*. (2006).

In the fish subpopulation area (i.e. the study area of interest), the authors evaluated habitat complementation between the daily activity areas for feeding and resting and their connectivity to spawning habitats. Connectivity between areas was modelled using the minimal cumulative resistance, which is a least cost model that determines the path from a source point (e.g. feeding habitat) to a destination point (e.g. resting habitat). The model assigns a resistance or permeability value for fish movement to each habitat based on factors such as the risk of mortality, energy expenditure or movement costs, which provides a more realistic path for fish movements compared with simple straight line estimates. A resistance matrix for *Barbus barbus* was created based on swimming capacity and predation risk, which produced a friction map (shown in Figure 9.6). Using Anaqualand, the least cost model was applied to the map of spawning habitat and the friction map to produce a map of the probability of a fish reaching the nearest spawning habitat. An overlay of the probability map with a threshold probability on a daily activities area map delineated areas that could support a subpopulation (Figure 9.9). Figure 9.9A is a map of fish activity areas and Figure 9.9B is a probability map of a fish reaching the nearest spawning area. This map was also created with Anaqualand. The resulting subpopulation area map, shown in Figure 9.9C, shows low probability areas ($P < 0.25$) with potential gaps in connectivity and high probability areas ($P > 0.75$) that fish within a daily activity area will reach the nearest spawning habitat.

FIGURE 9.9
Process for delineating potential subpopuation areas using an overlay of the daily activity areas map created with Chole software



Source: Le Pichon *et al*. (2006).

Discussion, conclusions and recommendations: The approach presented in this paper provides a flexible framework for mapping habitat resources for stream fishes to help evaluate any future impacts of habitat alteration and to inform prioritization of stream restoration and species management based on the spatial proximity of habitats and at different spatial scales. The important contributions of the approach are that it includes aquatic habitats that support the entire life cycle of a species at multiple spatial scales and in the spatially continuous river environment. This differs from the more traditional reach-scale, site-based approach to representing stream habitat. The identification of high-quality, complementary habitat patches needed to sustain fish populations versus low-quality habitat areas in need of restoration provides the information needed by river managers. An important next step in the evaluation of this approach is validation of the indexes and maps using spatially continuous surveys of fish populations, which was not included in this study.

Le Pichon *et al.* (2009) validated this approach by applying their results from this natural reach of the the upper Seine River, the French Republic, to an artificial, channelized reach of the river downstream.

Challenges and lessons from case study: This case study demonstrates complex spatial analyses using specialized GIS software programs to analyse fish habitat affinities for critical life cycle activities in river environments. Replication of this study in another river system with other fish species would be challenging without a team of river ecologists and spatial data analysts. Nevertheless, this approach has great potential for applying GIS to manage and conserve fish in river environments. The authors identified two main challenges of their approach: (i) mapping habitat patches using relatively simple GIS-based methods; and (ii) calculating distance in two dimensions along a river. Additional challenges relate to the methodological difficulties of applying the approach to the shifting and dynamic nature of fish habitat in river environments. Much of habitat variability is the result of water-level fluctuations related to temporal (daily, monthly, seasonal, annual) trends in river discharge. These discharge events and those over longer time scales (decades, centuries) shape river channels and affect resource habitats of fishes. Mapping habitat under these dynamic conditions that requires measurements at different river stages (dry, average, flood) is a complex task, which is one reason why inland freshwater GIS applications are lagging behind marine GIS applications. The task of river habitat mapping can be facilitated by using remotely sensed data, including panchromatic digital aerial photography, laser telemetry (LIDAR), side-scan sonar (Kaeser and Litts, 2010), and interferometric synthetic aperture radar (i.e. the use of two or more radar images to generate elevation maps) to map channel bathymetry as well as other spectral devices, particularly in turbid rivers (Wright, Marcus and Aspinall, 2000; Vierling *et al.*, 2008). Clearly, standard GIS operations and new programs (Anaqualand, Chloe) coupled with landscape ecology indices are redefining the way conservation agencies are managing streams and rivers.

9.5.2 Predicting fish yields in tropical reservoirs

Original publication reference: Amarasinghe, U.S., De Silva, S.S. & Nissanka, C. 2004. Fish yield predictions based on catchment features, quantified using Geographical Information Systems, in lowland reservoirs of Sri Lanka. In T. Nishida, P.J. Kailola & C.E. Hollingworth, eds. *GIS/Spatial Analyses in Fishery and Aquatic Sciences, (Vol. 2)*, pp. 499–514. Saitama, Japan, Fishery-Aquatic GIS Research Group.
Spatial tools: GIS.
Main issues addressed: Habitat quality/quantity linked to plant and animal abundance and distribution; classification and inventory of habitats; planning and potential fish yields; direct assessments and inventories; effects of terrestrial activities on habitats and aquatic organisms.
Duration of study: 1997–2002.
Personnel involved: Three research scientists based at three institutions in the Democratic Socialist Republic of Sri Lanka and Australia, and two managers based at a Sri Lankan government agency.
Target audience: Reservoir and lake ecologists, fisheries researchers, fisheries and resource managers, government management agencies.

Introduction and objectives: The continental island of the Democratic Socialist Republic of Sri Lanka has one of the highest densities of reservoirs in the world. The primary purpose of these reservoirs is to provide irrigation for water-supplied agriculture; secondarily, they are the location of the island's inland fisheries, which consists mostly of exotic cichlids *Oreochromis mossambicus* and *O. niloticus*. In these artisanal fisheries, fishers use gillnets from canoes to capture fish (Amarasinghe, De Silva and Nissanka, 2002). These fisheries have received little management, in part because the reservoirs are scattered throughout the country in areas that are difficult to conduct individual assessments. The authors have been studying various aspects of selected reservoirs for over two decades, most recently focusing on developing models of fish yield. De Silva *et al.* (2001) used GIS to quantify catchment land use in nine reservoirs and related fish yield to land use patterns, to selected limnological characteristics (conductivity, chlorophyll-*a*) and to reservoir morphometry (area and capacity). The resulting single and multiple regression models produced highly significant relationships (r = 0.70–0.91) between fish yield and forest cover, shrubland and ratios of these, reservoir area and capacity, and a morphoedaphic index. In a follow-up study, Amarasinghe, De Silva and Nissanka (2002) evaluated the robustness of the predictive yield models developed by De Silva *et al.* (2001), by validating model predictions with independent data from five Sri Lankan reservoirs. The authors validated the predictive fish yield models and suggested that, with the aid of GIS-derived information, they could provide an accurate yield assessment of reservoir fisheries. The objective of the current paper was to synthesize findings from the previous studies on Sri Lankan reservoir fisheries and further support the use of GIS as a tool for developing fish yield-prediction models.

Methods and equipment: The methods provided in this paper are described in greater detail in De Silva *et al.* (2001) and Amarasinghe, De Silva and Nissanka (2002) and therefore only a brief description of the methods will be included here.

For the nine study reservoirs (Figure 9.10),[219] GIS was used to digitize land use types, rivers, roads and point features in catchment areas of each reservoir using ARC/INFO software and 1:50 000 scale topographic maps obtained from the Department of Irrigation of the Democratic Socialist Republic of Sri Lanka. The resulting GIS included the following layers: land use layer, drainage (rivers), roads, catchment boundaries and important point features (Figure 9.11). GIS was then used to determine the area of 16 land use types. The major land use types included forest cover, shrubland, chena (shifting cultivation land) and homesteads, with smaller areas of home gardens, paddy land, plantations, grasslands, waterbodies and rocks.

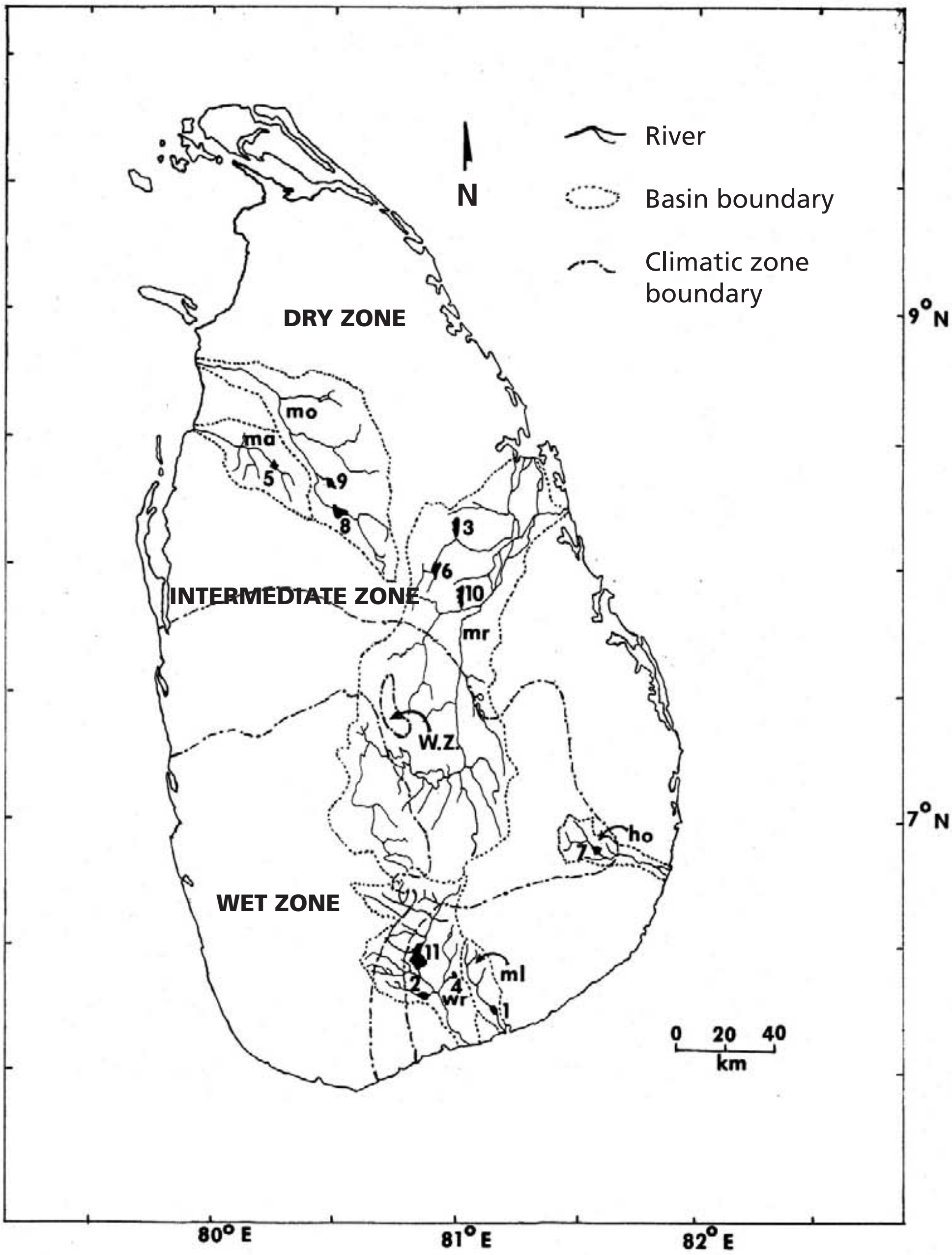
Morphological data for the study reservoirs, that is, reservoir area and capacity, and catchment area, were obtained from the Department of Irrigation of the Democratic Socialist Republic of Sri Lanka. Limnological data were collected once every two months at three stations in each reservoir. Parameters measured included conductivity, alkalinity, total nitrate, total phosphate and chlorophyll-*a* (Nissanka, Amarasinghe and De Silva, 2000). These data were used to calculate morphoedaphic indices defined as the ratio of conductivity to mean depth (MEI_C) and the ratio of alkalinity to mean depth (MEI_A), which were shown by Nissanka, Amarasinghe and De Silva (2000) to be significantly related to fish yield.

Fisheries data for the nine reservoirs were collected from 1997–1999. Fish were sampled with gillnets from canoes manned by two people. The catch from all reservoirs was dominated by two exotic cichlids: *Oreochromis niloticus* and *O. mossambicus*. These data were expressed as fisheries yield (kg/ha/yr) and fishing intensity (boat days/ha/yr). Analysis of relationships between catchment land use, reservoir physico-chemical characteristics and fisheries yield data were investigated by the authors. Statistical analyses included multiple regression of fish yield relative to reservoir morphometric and limnological characteristics (Nissanka, Amarasinghe and De Silva, 2000) and land use patterns (De Silva *et al.*, 2001), principal components analysis of limnological characteristics, catchment land use patterns and fish yield (Amarasinghe, De Silva

[219] Data from reservoirs 5 (Mahawilachchiya) and 7 (Muthukandiya) were not included in the analyses for this study.

and Nissanka, 2002) and validation of the yield models using independent data (Amarasinghe, De Silva and Nissanka, 2004).

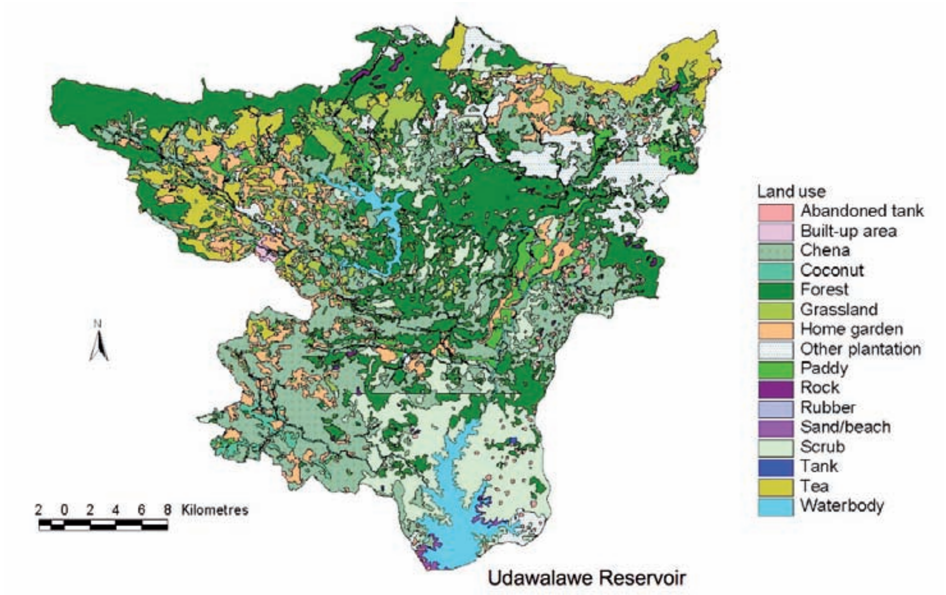
FIGURE 9.10
Map of Sri Lanka with climatic zones and the location of 11 reservoirs in six river basins: Modargum Aru (ma); Malwathu Oya (mo); Mahaweli River (mr); Walawe River (wr); Heda Oya (ho); and Malala River (ml)



Source: De Silva *et al*. (2001).

FIGURE 9.11

Map of catchment land use patterns for Udawalawe reservoir in southern Sri Lanka



Source: Upali Amarasinghe.

Discussion, conclusions and recommendations: Based on the findings of Nissanka, Amarasinghe and De Silva (2000), De Silva *et al.* (2001) and Amarasinghe, De Silva and Nissanka (2002), Amarasinghe, De Silva and Nissanka (2004) developed four models relating fish yield and catchment land use and physical and chemical characteristics of Sri Lankan reservoirs and validated them using fish yield estimates from five reservoirs sampled in an independent study. The four predictive yield models are shown in Table 9.3.

TABLE 9.3

Multiple regression models relating ratios of watershed and reservoir characteristics and fishing intensity to fish yield

Model	R^2
FY = -154.42 + 41.283 ln(FC/RC)	0.900
FY = -158.0 + 29.8 ln(FC/RC) + 10.5 FI	0.875
FY = -16.53 + 32.5 ln(FC/RA) + 12.5 FI	0.868
FY = 64.931 + 43.32 ln(FC/RA)	0.830
FY = -170.7 + 38.265 ln((FC+SC)/RC)	0.796
FY = 16.558 + 47.124 ln((FC+SC)/RA)	0.775
FY = -176 + 30.9 ln((FC+SC)/RC) + 7.86 FI	0.740
FY = 8.6 + 30.0 ln((FC+SC)/RA) + 6.85 FI	0.625

Note: R^2 is the coefficient of determination.
Source: Amarasinghe, De Silva and Nissanka (2004).

In an attempt to validate these models, Amarasinghe, De Silva and Nissanka (2004) estimated fish yield using the average of the eight models shown in Table 9.3 for five reservoirs in the Democratic Socialist Republic of Sri Lanka. These models relate ratios of forest cover (FC, in km^2), shrubland cover (SC, in km^2), reservoir surface area (RA, in km^2), reservoir capacity (RC, in km^3) and fishing intensity (FI, in boat days ha^{-1} yr^{-1}) to fish yield (FY, in kg ha^{-1} yr^{-1}) for nine reservoirs in Sri Lanka. Those estimates were compared with actual fish yield from the reservoirs. Differences between estimated and actual fish yield ranged between 1.3 kg ha^{-1} yr^{-1} to –42.8 kg ha^{-1} yr^{-1} with an absolute average value of 19.02 kg ha^{-1} yr^{-1}. The models with the greatest predictive power ($R^2 \geq 0.830$) included the ratio of forest cover (FC) to either reservoir capacity (RC) or reservoir surface area (RA) and two of those models included fishing intensity (FI).

Challenges and lessons from case study: For this series of studies, GIS allowed the researchers to determine catchment land use with a high degree of accuracy that was not attainable with traditional mapping methods over such a large area. Land cover type, particularly forest cover and to a lesser extent shrubland cover, was strongly linked to reservoir morphometry and directly related to fish yield in these reservoirs. Land cover influences nutrient supply, which can result in increased production from the aquatic ecosystem.

The authors noted that in the Democratic Socialist Republic of Sri Lanka reservoir water regimes are controlled by irrigation authorities depending on agricultural and domestic needs, and fisheries are rarely taken into consideration in irrigation management and development plans. They called for an integrated approach to watershed management that would optimize resource use in the reservoirs of the Democratic Socialist Republic of Sri Lanka. Clearly, this is a good opportunity for implementation of an ecosystem approach to fisheries.

9.5.3 Conservation of freshwater biodiversity

Original publication reference: Sowa, S.P., Annis, G., Morey, M.E. & Diamond, D.D. 2007. A gap analysis and comprehensive conservation strategy for riverine ecosystems of Missouri. *Ecological Monographs*, 77: 301–334.
Spatial tools: GIS
Main issues addressed: Habitat quality/quantity linked to plant and animal abundance and distribution; classification and inventory of habitats; rehabilitation and restoration of river habitats; habitat approaches to aquatic biodiversity.
Duration of study: 1997–2006.
Personnel involved: Four research scientists based at a university in the United States of America and affiliated with state and federal agencies.
Target audience: Aquatic ecologists, river conservationists, natural resource managers, government management agencies.

Introduction and objectives: Freshwater ecosystems in the United States of America are very diverse. They contain 10 percent of the world's freshwater fish species, 30 percent of freshwater mussel species and 61 percent of all freshwater crayfish species (Sowa *et al.*, 2007). Although the diversity of these freshwater ecosystems is impressive, many of these ecosystems are in peril. For example, over the past 100 years, 123 freshwater animals in North America have become extinct (Ricciardi and Rasmussen, 1999), and in the United States of America, 71percent of freshwater mussels, 51 percent of freshwater crayfish and 37 percent of freshwater fish are considered vulnerable to extinction (Sowa *et al.*, 2007). Although considerable attention has been focused on tropical ecosystems, given these stark statistics on the decline of freshwater biodiversity, more attention is needed on causes of decline and in identifying gaps in existing efforts to conserve freshwater biodiversity and prioritizing efforts to fill these gaps.

The national Gap Analysis Program (GAP) of the United States Geological Survey (USGS) was started in 1988 to provide a coarse-filter approach for identifying biodiversity conservation needs. The approach identifies species, habitats and ecosystems that are not sufficiently represented in land management areas (i.e. gaps) that may be filled by establishing new management or protected areas or by implementing changes in land management practices. This spatially oriented approach uses remote sensing and GIS technologies, and it has been applied to terrestrial ecosystems across the United States of America. This article by Sowa *et al.* (2007) is the first published application of GAP in an aquatic ecosystem, in particular to riverine ecosystems in the State of Missouri.

Biodiversity conservation using GAP proceeds through several steps, including identifying gaps and developing criteria for what constitutes effective conservation (Sowa *et al.*, 2007). The steps are as follows:

- The first step is establishing the goal of the planning effort, which in biodiversity conservation is conserving native species, habitats and ecological processes in an area of interest.
- The next step is to select an appropriate geographic framework. This framework consists of the planning region, which is the area where the conservation plan will be developed, and the assessment units, which are the geographic sub-units of the planning region.
- Next, the biodiversity conservation targets need to be identified and mapped, and this information coupled with the planning regions and assessment units is used to select priority areas within the regions. Selecting priority areas or locations, a logistical process, is facilitated by the use of GIS and expert opinion.
- The final step is to establish a monitoring programme to ensure successful conservation efforts or modification of management actions.

The objectives of this study were to provide details on complementary conservation planning efforts: the Aquatic GAP Project for Missouri and the State Wildlife Action Plan for Missouri. Much of the focus of this case study is on the methods used in the Aquatic GAP Project. Results from the State Wildlife Action Plan are presented as an application of GAP in Missouri.

Methods and equipment: Four primary GIS data sets were used in this study: (i) hierarchical classification of river ecosystem; (ii) species distribution modellling; (iii) public land ownership and stewardship;[220] and (iv) human threats. The methodological stages are detailed as follows.

(i) Hierarchical classification of river ecosystems. This classification system consists of eight levels that were used to identify, classify and map distinct ecological units and habitats of rivers at multiple spatial levels. This system considers structural features, functional properties, and biological (ecological and taxonomic) composition of riverine ecosystems (Figure 9.12). Levels 1–3 are zoogeographic strata and include the zones, subzones and regions and follow the ecological units delineated by Maxwell *et al.* (1995). Level 4 is aquatic subregions (n = 3 for Missouri) and they are the physiographic or ecological subdivisions of regions that account for differences in the ecological composition of riverine assemblages resulting from variation in ecosystem structure and function. Level 5 is the ecological drainage units (n = 17 for Missouri) that account for differences in taxonomic composition. These units are empirically defined by the USGS eight-digit hydrologic units. Level 6 is the aquatic ecological system's types (n = 542 for Missouri). These types were derived from 22 landscape variables (geology, soils, landform, and spring/groundwater inputs) that establish the hydrologic and physico-chemical conditions of stream ecosystems. Level 7 is valley-segment types (n = 74 types for Missouri), which represent hydro-geomorphic units defined by local physical and fluvial factors and position in the stream network. These segments were mapped at the 1:100 000 scale based on the United States National Hydrography Data set. Finally, level 8 is habitat types, that is, fast-flowing (e.g. riffles) and slow-flowing (e.g. pools) habitats. These types were not mapped in this case study because the spatial area covered was too large for an appropriate resolution.

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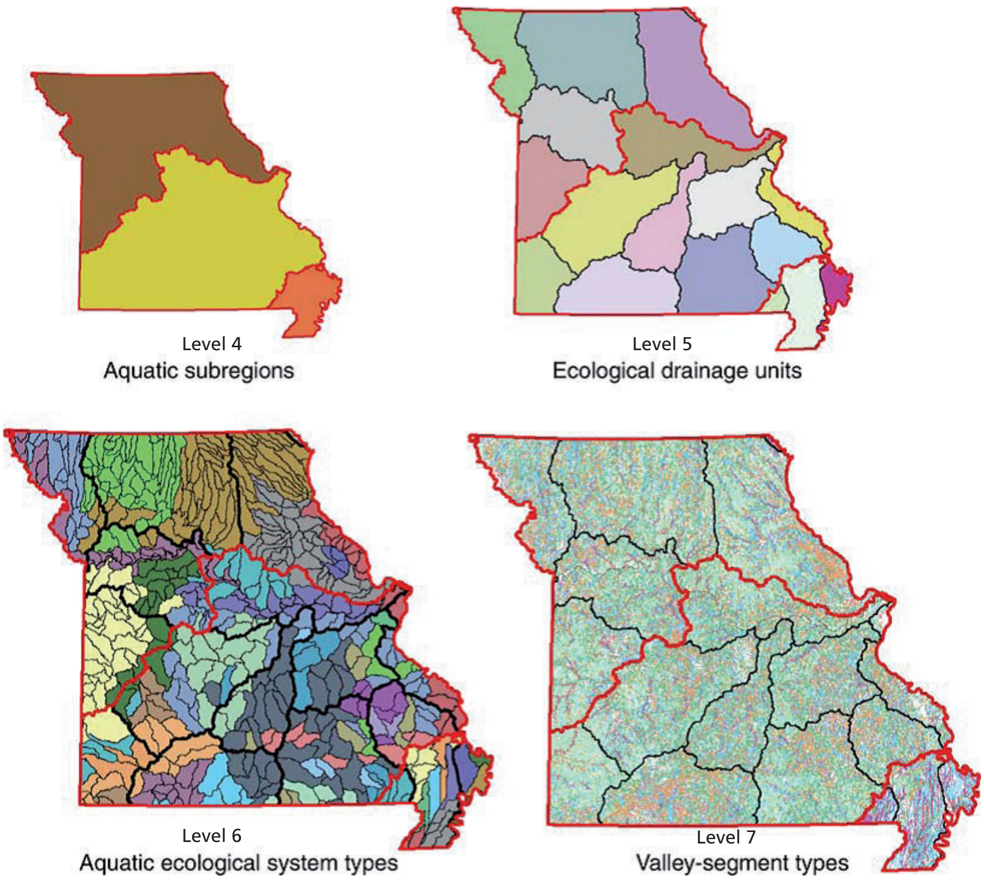
[220] Conservation practices are more easily implemented in the United States of America on public than on private lands.

FIGURE 9.12

Maps of the aquatic ecological classification hierarchy for four levels (4–7) in Missouri, United States of America



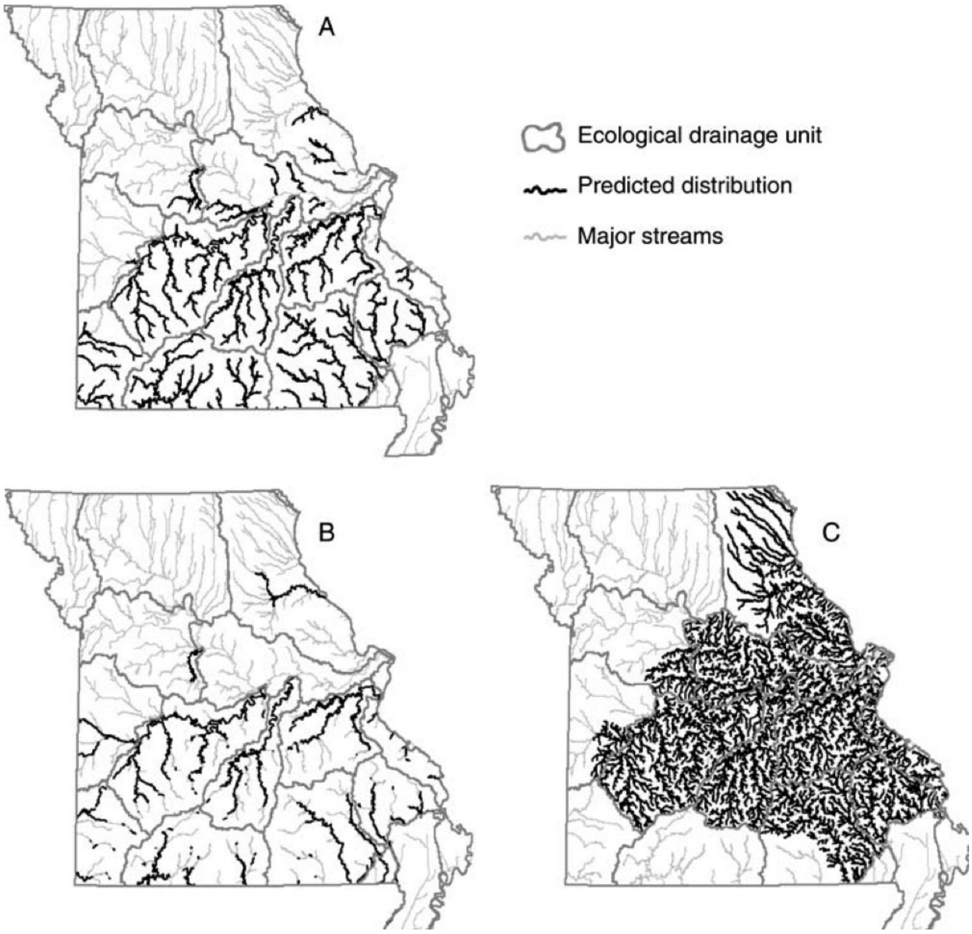
Source: Sowa *et al*. (2007).

(ii) Species distribution modelling. Predicted distributions of 315 aquatic species, including 32 crayfishes, 67 mussels and 216 fish species, were made from nearly 6 000 collection records and a suite of seven environmental predictor variables of stream size, stream gradient, stream temperature and stream flow (Figure 9.13). Range maps were created for each species at the 14-digit hydrologic unit (hierarchical classification of drainage basins used by USGS that is numerically coded) using GIS. Ranges were predicted using classification and regression tree analysis[221] using the AnswerTree 3.0 software. Because of regional variation in species distribution and habitat, regionally specific models were constructed for some species, and the number of regional models ranged from 1 - 4 for any given species, although most species required two models.[222]

[221] Regression tree analysis is a form of decision tree learning often used to mine data in which the leaves of the tree represent classifications and the branches represent the conjunction of features (variables) that lead to those classifications. The goal of a regression tree analysis is to create a model that predicts the value of a variable based on several input variables.

[224] Two models are required because any species can evolve to become regionally specific according to variations in physical conditions.

FIGURE 9.13
Predicted distribution maps for (A) a fish species, black redhorse (*Moxostoma duquesnei*), (B) a mussel species, round pigtoe (*Pleurobema sintoxia*), and (C) a crayfish species, golden crayfish (*Orconectes luteus*)



Source: Sowa *et al*. (2007).

(iii) Public land ownership and stewardship. To assess gaps in biodiversity conservation areas, an assessment is needed of mapped species that occur within existing public land holdings and the management status of these holdings. GAP uses a stewardship scale to denote the relative degree of biodiversity maintenance for a land area that ranges from 1 (the highest level of maintenance) to 4 (the lowest level of biodiversity management). Each stream segment flowing through public lands was attributed with a stewardship status in the valley segment layer.

(iv) Human threats. A human threat index was developed to provide a measurement of the degree of human disturbance affecting freshwater ecosystems. A suite of 65 threat metrics was compiled from state and federal environmental databases and attributed to the aquatic ecological systems. Using correlation analysis, the final set was reduced to 11 relatively uncorrelated metrics of human disturbance (Table 9.4).

TABLE 9.4
Eleven metrics for the human threat index and the criteria used to define their relative ranks for Missouri, the United States of America

Metric	Relative rank			
	1	2	3	4
1. Number of introduced species	1	2	3	4–5
2. Percentage urban	0–5	5–10	11–20	> 20
3. Percentage agriculture	0–25	26–50	51–75	> 75
4. Density of road/stream crossings (no./km^2)	0–0.09	0.10–0.19	0.2–0.4	> 0.4
5. Population change 1990–2000 (no./km^2)	16–0	0.04–5	6–17	> 17
6. Degree of hydrologic modification and/or fragmentation by major impoundments	1	2 or 3	4 or 5	6
7. Number of federally licensed dams	0	1–9	10–20	> 20
8. Density of coal mines (no./km^2)	0	0.1–2	2.1–8	> 8
9. Density of lead mines (no./km^2)	0	0.1–2	2.1–8	> 8
10. Density of permitted discharges (no./km^2)	0	0.1–2	2.1–8	> 8
11. Density of confined animal feeding operations (no./km^2)	0	0.1–2	2.1–4	> 4

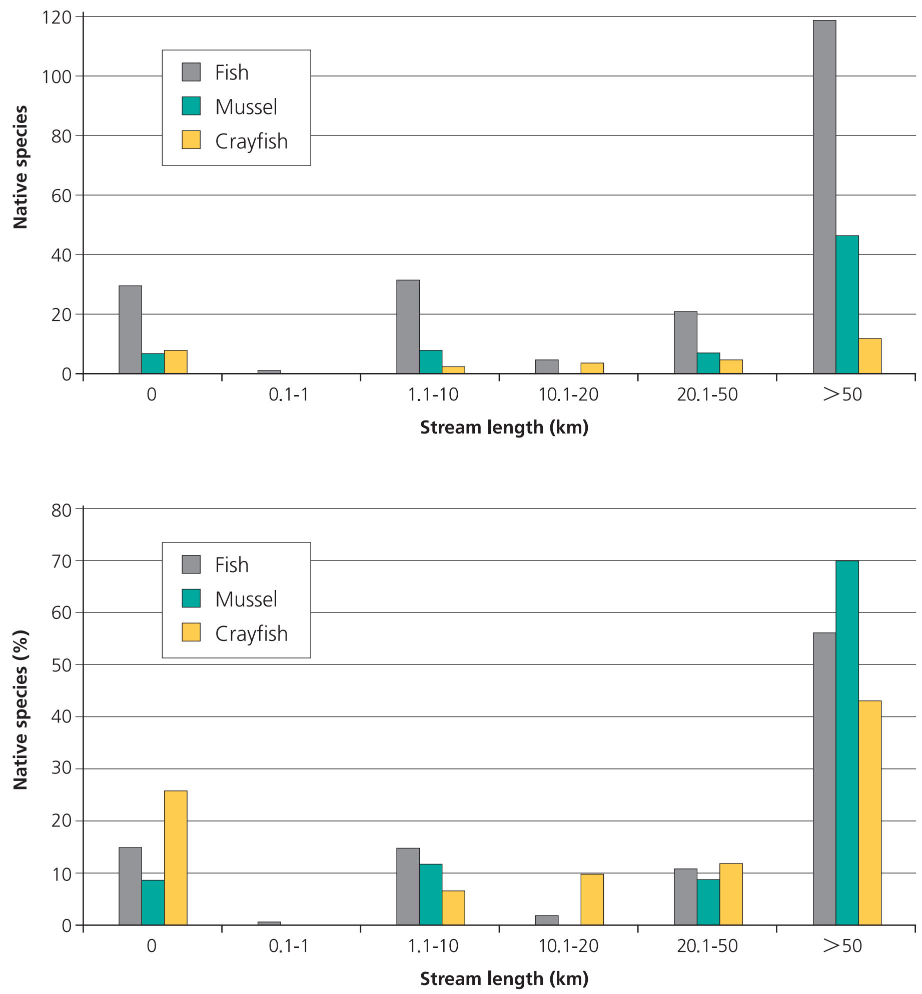
Source: Sowa *et al.* (2007).

The metrics in Table 9.4 were not weighted. The relative ranks provide an increasing measure of human threats from low (rank = 1) to high (rank = 4). For example, threats related to human habitation are measured by the percentage of an area that is urban (compared with rural) and how the population has increased in an area over the past decade. Both metrics quantify the potential threat of urbanization to streams and their aquatic organisms.

Results: Sowa *et al.* (2007) analysed both abiotic (habitat) and biotic (fish, mussels and crayfish) elements of biodiversity focusing on lands classified as management-status categories 1 and 2, which are considered to have reasonably secure conservation plans and management actions that benefit biodiversity conservation, compared with management-status categories 3 and 4, which provide limited or little protection to conserving biodiversity. At the valley-segment type (Level 7), 55 of the 74 types (74 percent) in Missouri contained status 1 and 2 lands. Habitat features associated with these 55 types included coldwater streams, streams flowing through igneous geology and large rivers. With regard to analysis of the target species, 19 of the 315 species were either non-native or cryptic (cave-dwelling) and therefore the authors limited their final analyses to the 296 native species of fish, mussels and crayfish and their association with management status 1 or 2 lands. When broken down by stream length, most of the 296 species of fish, mussels and crayfish have more than 50 km of their predicted distribution within management status 1 or 2 lands (Figure 9.14). For example, nearly 120 native fish species, or about 56 percent of all native fish species that occur in stream lengths greater than 50 km, are in management status 1 or 2 lands.

FIGURE 9.14

Graphs of (A) the number of native species and (B) percentage of native species within each taxon in management status 1 or 2 lands and their distribution by six categories of stream length



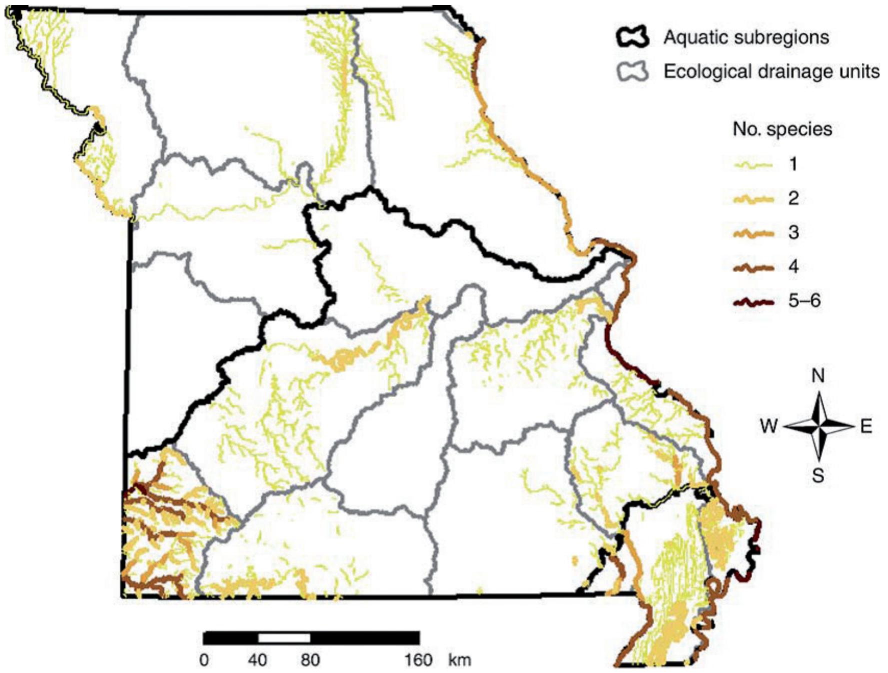
Source: redrawn from Sowa *et al.* (2007).

When broken down by aquatic subregion, the Ozark region in southern Missouri had the greatest number of native species (278) with only 52 species not represented in status 1 or 2 lands, which was followed in order by the Mississippi Alluvial Basin in southeastern Missouri (163 native species; 69 not in status 1 or 2 lands) and the Central Plains (178 native species; 90 species not in status 1 or 2 lands). These results were used to illustrate gaps for streams with species not currently represented in management status 1 or 2 conservation lands in Missouri (Figure 9.15)[223].

To help ensure the long-term persistence of native biota, Sowa *et al.* (2007) compiled a team of aquatic resource professionals from Missouri to identify and map a set of aquatic conservation-opportunity areas (COAs) that would represent the breadth of distinct riverine ecosystems and habitat in Missouri and multiple populations of species. These areas were selected as targets for the State Wildlife Action Plan. The team developed a portfolio of COAs based on quantitative and qualitative assessment criteria

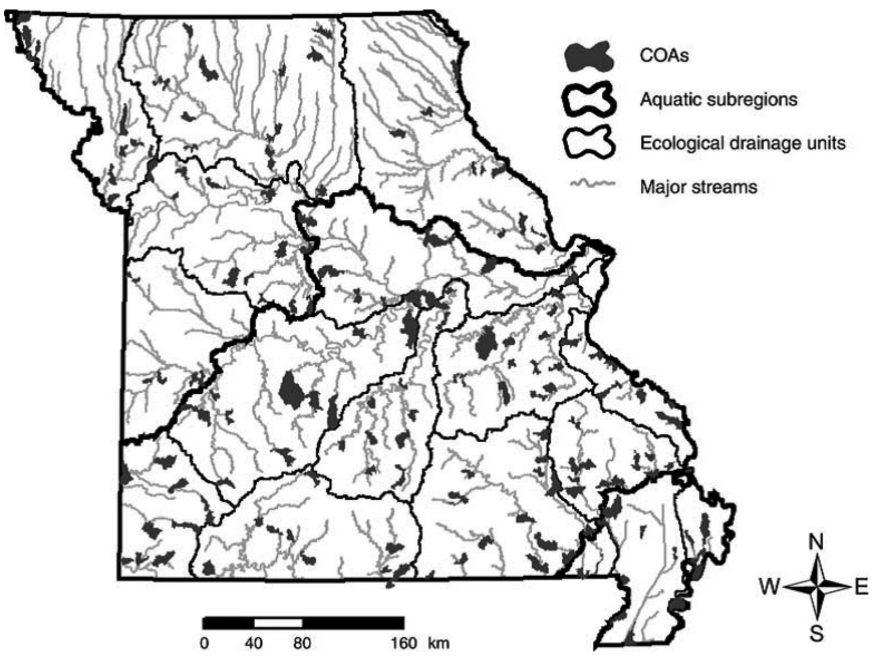
[223] Category 1 species lines are thinner than category 2 species. There is only one small segment of category 5–6 species in southwestern Missouri.

FIGURE 9.15
Map of species richness for 45 native fish, mussel and crayfish species not currently represented in GAP management status 1 or 2 conservation lands in Missouri, United States of America



Source: Redrawn from Sowa *et al*. (2007).

FIGURE 9.16
Map of 158 conservation-opportunity areas (COAs) selected by the aquatic resource professional team for Missouri, United States of America



Source: Redrawn from Sowa *et al*. (2007).

for aquatic ecological system polygons and valley-segment type complexes. The resulting assessment identified 158 COAs that include a broad diversity of stream ecosystems, riverine assemblages and populations of all 296 fish, mussel and crayfish species. These COAs contain only 6.3 percent of the total 174 059 km of streams (Figure 9.16). The small percentage of streams with COAs shown in Figure 9.16 compared with the larger number of streams with high species richness shown in Figure 9.15 is due in part to the fact that only 5 percent of the total length of streams in Missouri is in public ownership.

Discussion, conclusions and recommendations: The Aquatic GAP approach, with the aid of GIS, identified priority riverine ecosystems and was an important first step toward implementing effective biodiversity conservation planning. The analysis process was complex and involved large databases and multiple levels of analysis, including statistical techniques, database management and the judgement of technical experts. The authors concluded that establishing geographic priorities for biodiversity conservation is one of the many steps needed to achieve actual conservation on the ground. Implementation of biodiversity conservation in Missouri will entail vigilance and cooperation by government agencies and private land owners, and coordination of the logistical tasks needed to implement the conservation plan. The Aquatic GAP Program is ongoing in many regions of the United States of America and is being managed by USGS (http://gapanalysis.usgs.gov/gap-analysis/aquatic-gap/). This program provides an approach to freshwater river conservation that could, with sufficient access to requisite data, be applied to rivers systems throughout the world.

Challenges and lessons from case study: Projects covering a large geographic area with large and diverse data needs, and the complex analyses used in this study, present a challenge for countries or regions that are lacking financial resources. In the United States of America where these data are available across the country, Gap Analysis projects are currently being conducted regionally (e.g. streams in watersheds of the Great Lakes) rather than in individual states. Where data are available, Gap Analysis provides a powerful planning tool for managing and conserving fish species and other aquatic resources. Geographic information system technology, relational databases and multivariate analyses are the tools and resources needed for both large-scale and small-scale fish and aquatic biodiversity management and conservation.