

Contents

Preparation of this document	iii
Abstract	iv
List of tables	xi
List of figures	xiii
List of boxes	xix
Acknowledgements	xxi
Abbreviations and acronyms	xxii
Foreword	xxiv
1. Introduction	1
<i>G.J. Meaden and J. Aguilar-Manjarrez</i>	
1.1 Spatial challenges confronting fisheries and aquaculture	1
1.2 What are geographic information systems?	8
1.3 The emergence of GIS as a spatial tool	11
1.3.1 A brief history of GIS	11
1.3.2 Reasons for the growth in GIS	13
1.4 Early developments in the use of GIS for fisheries and aquaculture purposes	18
1.5 The aims and the structure of this technical paper	22
2. GIS hardware and software for fisheries and aquaculture	25
<i>G.J. Meaden</i>	
2.1 Introduction	25
2.2 Hardware for data collection, inputs and outputs	26
2.2.1 Hardware for inputting data	26
2.2.2 Processing and storage hardware	30
2.2.3 GIS output devices	33
2.2.4 GIS architecture	35
2.3 GIS software for fisheries and aquaculture	38
2.3.1 General proprietary GIS packages	39
2.3.2 Specialist marine fisheries software	40
2.3.3 Free and open source GIS software	43
3. Spatial data for fisheries and aquaculture: characteristics, quality and data sources	49
<i>G.J. Meaden</i>	
3.1 Introduction	49
3.2 Evaluating data needs for fisheries or for aquaculture GIS projects	49
3.3 Some characteristics of data for GIS use	55
3.3.1 The temporal facet	56
3.3.2 The thematic facet	56
3.3.3 The quantitative facet	56
3.3.4 The spatial facet	57
3.3.5 Scale and resolution facets	64
3.4 Data quality and data standards	64
3.5 Data collection and data sources	66

3.5.1	Primary data collection	67
3.5.2	Secondary data acquisition and sources	74
3.5.3	Proxy data	78
4.	Implementation of GIS	81
	<i>G.J. Meaden</i>	
4.1	Introduction	81
4.2	Initiation of a GIS	84
4.3	Establishing user requirements (a feasibility or scoping study)	84
4.4	Cost-benefit analysis	86
4.5	System requirements and system design	88
4.6	Procuring and initiating the GIS	90
4.7	Testing, refining, managing and operating the system	94
4.7.1	Testing and refining the system	94
4.7.2	Championing and managing the system	94
4.7.3	Working patterns and task allocation	96
4.7.4	System safekeeping and security	96
4.7.5	System maintenance	97
4.7.6	Coping with organizational change	98
4.8	Continuing support and training	100
4.8.1	Instruction manuals and exercises	101
4.8.2	Practical training courses	104
4.8.3	Other published information	106
4.8.4	Conferences, workshops and exhibitions	109
4.8.5	Other GIS users and professionals	111
5.	Preparing data for GIS use	113
	<i>G.J. Meaden, J. Jenness and S. Walker</i>	
5.1	Introduction	113
5.2	Methods of data input	114
5.2.1	Scanning and digitizing	114
5.2.2	Keyboard data entry	115
5.2.3	Digital data transfer	116
5.3	Data validation and editing	117
5.3.1	Graphical editing	118
5.3.2	Non-graphical editing	118
5.4	Geographic data modelling	120
5.5	The storage and management of digital data for GIS purposes	121
5.5.1	Data files	122
5.5.2	Databases	123
5.5.3	Database management systems	124
5.6	Metadata	126
5.7	From real world features to a mapped world	127
5.8	The structure of spatial data	130
5.8.1	Vector data structures	130
5.8.2	Raster Data Structures	134
5.8.3	Terrain (surface) data models	140
5.8.4	Network data models	144
6.	Remote sensing and GIS integration	147
	<i>A.M. Dean and J. Populus</i>	
6.1	Introduction	147
6.2	The background to remote sensing	147

6.2.1	Electromagnetic energy	148
6.2.2	Types of remote sensing systems	149
6.2.3	Platforms and satellite orbits	150
6.2.4	Characteristics of remote sensing systems	152
6.3	Remote sensing output of use to fisheries or aquaculture GIS	153
6.3.1	Optical remote sensing systems and products	154
6.3.2	Radar remote sensing systems and products	156
6.4	Remote sensing applications in fisheries and aquaculture	158
6.4.1	Aquaculture development	158
6.4.2	Aquaculture practice and management	161
6.4.3	Fisheries monitoring and management	162
6.5	The implementation of remote sensing	164
6.5.1	Scoping study	164
6.5.2	Selecting and acquiring remotely sensed data	164
6.5.3	Costs of data	170
6.6	Preparing remotely sensed imagery for GIS use	171
6.6.1	Reference map data	171
6.6.2	Training and validation data	172
6.6.3	Image analysis, processing or classification	173
6.6.4	Accuracy assessment	173
6.7	Change detection	174
6.8	Technical support and training for remote sensing	174
6.8.1	Web resources and organizations	174
6.8.2	Book resources	176
6.8.3	Technical training materials	176
6.8.4	Software and tools	177
6.8.5	Data formats	178
6.9	Case studies	179
6.9.1	Mapping coastal aquaculture and fisheries structures by satellite imaging radar. Case study of the Lingayen Gulf, the Philippines.	179
6.9.2	Ocean monitoring in Chile for harmful algal bloom mitigation	182
6.9.3	Use of SPOT 5 for mapping seagrasses (<i>Posidonia oceanica</i>)	184
6.9.4	Fishing ground forecasts in Japan	187
6.10	Conclusions	189
7.	GIS Functionality	191
	<i>G.J. Meaden, J. Jenness and S. Walker</i>	
7.1	Introduction	191
7.2	Data pre-processing and transformations	192
7.2.1	Data or map pre-processing	192
7.2.2	Generalization	195
7.2.3	Classification and reclassification	197
7.2.4	Buffering	198
7.3	Overlaying	200
7.4	Measurement	202
7.4.1	Raster-based measurement	203
7.4.2	Vector-based measurement	204
7.5	Spatial relationships	205
7.5.1	Measures of centrality	205
7.5.2	Measures of proximity	207
7.5.3	Measures of statistical surfaces	211
7.6	Network and spatial interaction analyses	215
7.6.1	Gravity models	215

7.6.2	Optimum routes and pathways	216
7.6.3	River and stream networks	218
7.7	Topographic surface analyses	220
7.7.1	Gradient (slope) and aspect analyses	220
7.7.2	Visibility (viewshed) analysis	222
7.7.3	Watershed and river flow analysis	223
7.8	Customization and scripting	225
8.	Current issues, status and applications of GIS to aquaculture	227
	<i>J. Aguilar-Manjarrez and J. M. Kapetsky</i>	
8.1	Introduction	227
8.2	Recent reviews dealing with spatial issues in aquaculture	228
8.2.1	The development of aquaculture	229
8.2.2	Aquaculture practice and management	233
8.2.3	Training and the promotion of GIS	237
8.2.4	GIS for multisectoral development and management that includes aquaculture	238
8.2.5	Trends in addressing aquaculture issues using GIS	239
8.3	Geographic distribution of GIS applications to aquaculture	239
8.4	Case studies	243
8.4.1	Sustainable options for People, catchment and Aquatic Resources (SPEAR)	243
8.4.2	AkvaVis decision support system	247
8.4.3	Environmentally sustainable offshore aquaculture: an eco-physical perspective	251
8.4.4	Development of potential and financial viability of fish farming in the Republic of Ghana	259
9.	Current issues, status and applications of GIS to inland fisheries	269
	<i>W.L. Fisher</i>	
9.1	Introduction	269
9.2	Inland fisheries themes and GIS applications	270
9.2.1	Visualization and species distribution modelling	270
9.2.2	Fish movements	272
9.2.3	Habitat modelling	272
9.2.4	Watershed management	273
9.2.5	Spatial design and conservation planning	274
9.3	The current status of GIS applications to inland fisheries	275
9.4	Spatial analysis	278
9.5	Case studies	279
9.5.1	Managing stream fishes in riverscapes	280
9.5.2	Predicting fish yields in tropical reservoirs	285
9.5.3	Conservation of freshwater biodiversity	289
10.	Current issues, status and applications of GIS to marine fisheries	297
	<i>G.J. Meaden and F. Carocci</i>	
10.1	Introduction	297
10.2	Marine fishery thematic areas currently being addressed via the use of GIS	297
10.2.1	Distribution displays	298
10.2.2	Marine habitat mapping and analysis and/or ecosystems relationships	299
10.2.3	Resource analyses	301

10.2.4	Modelling	302
10.2.5	Monitoring management policies	303
10.2.6	Marine protected areas	305
10.2.7	Marine spatial planning	306
10.2.8	The creation of economic surfaces	306
10.2.9	Ecosystem approach to fisheries	308
10.3	The current status of GIS applications to marine fisheries work	309
10.4	Case studies of applications of GIS to marine fisheries	313
10.4.1	Towards the use of GIS for an ecosystem approach to fisheries management (EAFM): CHARM 2 – A case study from the English Channel	314
10.4.2	Estimating reef habitat coverage suitable for the humphead wrasse, <i>Cheilinus undulates</i> , using remote sensing	318
10.4.3	Spatial assessment and impact of artisanal fisheries activity in Cap de Creus	324
11.	Emerging themes or issues in fisheries and aquaculture GIS	331
	<i>G.J. Meaden and J. Aguilar-Manjarrez</i>	
11.1	Introduction	331
11.2	Main drivers affecting future spatially-based work in fisheries or aquaculture	333
11.3	Current issues and developments affecting work in GIS or remote sensing	337
11.4	Emerging themes relating to spatial aspects of fisheries and aquaculture	342
11.4.1	The production of different aquaculture species	342
11.4.2	The potential impacts of aquaculture on the environment	343
11.4.3	Management of freshwater resources for aquaculture	344
11.4.4	Offshore mariculture	345
11.4.5	Growth of inland fisheries and recreational angling	347
11.4.6	The consolidation of the fishing and aquaculture industries	348
11.4.7	Rebuilding depleted marine and freshwater stocks	349
11.4.8	The recording of fishing vessel activities	350
11.4.9	Evaluating fisheries management practices, including sustainability	351
11.4.10	Threats and changes to marine and freshwater ecosystems	352
11.4.11	The standardization of habitat (and other) classifications	355
11.4.12	Working at variable scales and resolutions	356
11.4.13	Studies of temporal change in fishery and aquaculture thematic areas	357
12.	Overcoming the challenges to fisheries or aquaculture GIS work	359
	<i>G.J. Meaden and J. Aguilar-Manjarrez</i>	
12.1	Introduction	359
12.2	Mapping movable variables	359
12.3	Multiple scale and resolution	361
12.4	Handling 2.5-D, 3-D and the 4th dimension	363
12.5	Application of spatial models and statistics	366
12.6	Optimizing visualization and mapping methods	367
12.7	Integration of socio-economic considerations	368
12.8	Data gathering and assembling	369
12.9	Subject breadth and organization	371
12.10	Work management and control	371
12.11	Promotion of GIS output	372

12.12	Expenses associated with fisheries and/or aquaculture GIS	373
12.13	Obtaining funding	374
12.14	Overcoming inertia relating to the cultural ambience	375
12.15	Gaining support and advice	376
12.16	Transcending political or international boundaries	376
12.17	Developing geographic cognition and spatial awareness	377
13.	Conclusions	379
	<i>G.J. Meaden and J. Aguilar-Manjarrez</i>	
14.	Glossary	385
	References	395

Tables

1.1	Examples of fisheries-related GIS work produced during the 1990s	20
2.1	Summary of main hard copy output devices	35
2.2	Overview of five main proprietary GIS software	41
2.3	Functional capabilities of Marine Explorer	44
2.4	Major differences between proprietary and free and open source software	46
2.5	A selection of major free and open source desktop GIS projects	47
3.1	Production functions for fish cage site selection and environmental monitoring in the Mediterranean Sea, Spain	52
3.2	Suitable map projections for highlighting different map attributes	60
3.3	Some sources of GIS databases for inland fisheries in North America	76
3.4	Examples of possible uses and sources of 'proxy' data for aquaculture site selection	78
4.1	Summary of main costs and benefits associated with GIS	88
4.2	GIS manuals and exercise manuals specifically related to marine and inland fisheries or aquaculture	103
4.3	Examples of GIS and fisheries GIS training courses	105
5.1	Hypothetical table (file) showing illustrative fishing vessel registrations in Brazil	119
5.2	Typical numerical coding allocated to vector graphical data	131
6.1	Wavelengths and spectral bands of the electromagnetic spectrum of interest for fisheries and aquaculture applications	148
6.2	Summary of SST-related optical remote sensing systems	154
6.3	Summary of ocean colour related optical remote sensing systems	155
6.4	Summary of optical remote sensing systems relevant for inland and coastal zone mapping	155
6.5	Summary of radar remote sensing systems	157
6.6	Numbers of publications recorded in the FAO ASFA database for 1996–2010 that link 'aquaculture' to 'remote sensing'	159
6.7	Summary of the extent and resolution of GIS and remote sensing data and information needs for different tasks for aquaculture development	160
6.8	Numbers of publications recorded in the FAO ASFA database for 1996–2010 that link 'marine fisheries' to 'remote sensing'	163
6.9	Sources of SST data and information products	166
6.10	Sources of ocean colour data and information products	167
6.11	Sources of optical and imaging radar data products	169
6.12	Sources of radar altimetry products	170
6.13	Indicative costs of satellite image data for two typical fisheries and aquaculture applications	171
6.14	Advantages and disadvantages of thematic classification approaches	173
6.15	Summary of common remote sensing formats for operational oceanography data	178
6.16	Total area covered by the classes of interest (Pangasinan province)	181
6.17	Length of the fish traps detected in the study area	181
7.1	Five methods to define class intervals for numerical data	197

7.2	Example of a reclassification table	198
8.1	Number and percent of main issues and sub-issues addressed among 391 GIS applications to aquaculture in the GISFish database (1985–2012)	228
8.2	Sequential steps for the development of aquaculture	230
8.3	Country or marine area of application for 350 literature records on papers covering GIS + geographic information systems + aquaculture + mariculture in FAOs ASFA database (1996–2010)	241
8.4	Criteria classification	262
8.5	Areas (km ²) and percent suitabilities of lands for the factors, submodels and integrated models for small-scale and commercial farming	264
8.6	Weights derived for the submodels	265
9.1	Main issues in inland fisheries GIS as derived from the GISFish database (1985–2009)	276
9.2	Country of application for 145 literature records on papers covering inland fisheries + GIS in FAO's ASFA database (1996–2010)	277
9.3	Multiple regression models relating ratios of watershed and reservoir characteristics and fishing intensity to fish yield	288
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	293
10.1	Marine fisheries – main issues and themes from the GISFish database (1990–2012)	310
10.2	Country or marine area of application for 207 literature records on papers covering marine fisheries + GIS in the FAO ASFA database (1996–2010)	311
13.1	Suggested main tasks for taking fisheries or aquaculture GIS work forward	383

Figures

1.1	Change in landings and fishing power for the United Kingdom of Great Britain and Northern Ireland, and England and Wales of demersal fish from 1889 to 2007	2
1.2	Overall effectiveness of fisheries management in the world's exclusive economic zones	4
1.3	A simple ratio between a warm-water plankton species (<i>Calanus helgolandicus</i>) and a cold-water species (<i>Calanus finmarchicus</i>) per month from 1958 to 2005 in the North Sea	5
1.4	Changes in computing capacity as noted by the number of transistors in the central processing unit and computer clock speeds	14
1.5	Task components of a fisheries-based GIS	19
1.6	Illustration of typical GIS output from the late 1990s showing suitable areas for shrimp culture in central, west Sri Lanka	21
1.7	Progression of stages in a GIS project and the human influences affecting these process stages	24
2.1	A typical ruggedized tablet computer	28
2.2	Large format scanner	28
2.3	A large, adjustable digitizing table	29
2.4	Screen image of raster to vector conversion software functioning as a split-screen display for digitizing	30
2.5	A typical wireless router	33
2.6	Computer-generated temporary (ephemeral) screen output	34
2.7	Main components and linkages in a personal area network computer architecture	36
2.8	Main components and linkages in a LAN computer architecture	37
2.9	A wide area network (or a distributed computing environment)	38
2.10	Output from Mappamondo GIS showing the development of albacore tuna catches around American Samoa from 2000 to 2003	42
3.1	Illustration of lines of latitude and longitude	58
3.2	The Musquash marine protected area in New Brunswick, Canada	59
3.3	A plane coordinate grid (dotted lines) superimposed onto a projected map	61
3.4	The basis of the Universal Transverse Mercator grid zone designations	62
3.5	Portions of North America at three different scales	64
3.6	Aggregated fishers' perceptions of their fishing locations for the main commercial species in the eastern English Channel	68
3.7	A basic fishing-vessel logsheet (Form A1) recording details of vessel activity. This may be accompanied by many fishing catch logsheets (Form A2)	69
3.8	Simple electronic device for collecting temperature data	70
3.9	A typical waterproofed and ruggedized handheld data logger	71
3.10	An integrated computing and communications-based personal digital assistant	72
3.11	A handheld GPS receiver	72
3.12	Seafloor imaging using multibeam acoustic sonar, a drop camera and a remotely operated vehicle	73

4.1	The main processes and activators involved in GIS implementation	83
4.2	Varying staff roles of groups who might be involved in GIS implementation	93
5.1	Stages in data transformation when used for GIS purposes	113
5.2	Example of a database set up for recording aquaculture production	116
5.3	Typical errors caused through the map digitizing process	118
5.4	Real world spatial features represented as geospatial (mapped) data	128
5.5	Legend to show water-related features on a topographic map	128
5.6	Line, point and polygon representations in vector and raster formats	129
5.7	Raster data set showing land cover on the island of Hawaii, United States of America	130
5.8	Simple vector map with associated topological tables	133
5.9	Examples of raster output for aerial data collected at 30 metre and 1 metre resolutions	134
5.10	Types of raster bands	136
5.11	Demonstration of different pixel resolutions	137
5.12	A simple raster map plus the run-length encoding structure used for data storage	138
5.13	The quadtree raster data compression method	139
5.14	Vector-based approaches to digital terrain modelling	142
5.15	The topology of a TIN	142
5.16	Triangulated irregular network showing bathymetric data for Lake Michigan, United States of America	143
5.17	Digital elevation model of Crater Lake, Oregon, United States of America enhanced by altitude and relief shading	144
5.18	Network data structure showing nodes and impedance plus topological table	146
5.19	The proposed network of high-speed railway lines in Spain (2007)	146
6.1	Spectral signature of water, vegetation and soil surface features	149
6.2	Types of sensor	150
6.3	Geostationary satellite orbits	150
6.4	Polar satellite orbits	151
6.5	Overview of the spatial extent and resolution of selected types of remote sensing imagery	152
6.6	Demonstration of the global 4 km AVHRR pathfinder project sea surface temperature product for the Indian Ocean	166
6.7	Example of GlobColour ocean colour data product for chlorophyll-a concentration	168
6.8	Typical activities in remote sensing image processing	172
6.9	Illustration of part of the NASO map collection for Nicaragua	175
6.10	Interpreted RADARSAT-1 SAR image and the resulting map of the aquaculture and fisheries structures	180
6.11	Chile Aquaculture Project Web portal - main page	183
6.12	Main benthic assemblages and bottom types at Laganas Bay, Greece, based on classification of a SPOT image (10 m resolution)	186
6.13	Sea surface temperature and chlorophyll-a concentrations for the southeast coast of Honshu Island, Japan	188
7.1	Comparison of three different map projections of Africa	194
7.2	The vector to raster and raster to vector conversion process	194
7.3	Examples of pre- and post-generalization in mapping	196
7.4	Line thinning at two levels of generalization	196
7.5	A comparison of three important methods of classifying data	198

7.6	Buffers formed around (a) points, (b) lines, and (c) polygons	199
7.7	Multiple buffers surrounding part of a stream network	199
7.8	Selected mapped layers for a specified area using points, lines, polygons, vectors and rasters	200
7.9	Illustration showing simple map algebra function	201
7.10	Overlay operation combines an input and overlay polygon	202
7.11	Raster GIS measurement showing diagonal distance (green); Manhattan distance (blue); and other random distances from start to finish (red or yellow)	203
7.12	Trapezoidal raster cells in an unprojected raster	203
7.13	The mean population centre of the United States of America (1790 to 2000)	206
7.14	An illustration of Thiessen polygons	207
7.15	Examples of the point-to-point and point-to-line proximity operations	207
7.16	Possible spatial distribution patterns in point data	208
7.17	The distribution of the invasive weed <i>Salvinia molesta</i> in fish ponds in the United States of America	209
7.18	Distribution of forest cover by county in the north central United States of America	210
7.19	Correct sample point strategy when using interpolation methods within a defined study area	212
7.20	Interpolation based on a sample appearing to show an exponential distribution	213
7.21	An inverse distance-weighted interpolation of the commercial values for groundfish in the New York Bight, United States of America	213
7.22	A trend surface to show the general trends of sampled water depths	214
7.23	Likely market area for city "G" based on calculations using a typical gravity model within a GIS	216
7.24	Illustration of the travelling salesman problem solved by the use of Google Maps in Optimap	217
7.25	The stream network in a portion of the central part of Panama	218
7.26	Screen shot of the RivEX GIS software for modelling stream networks	220
7.27	Illustration of GIS output using slope analysis in an area near Harlan, Kentucky, United States of America	221
7.28	Illustrating aspect for the same area shown in Figure 7.27	221
7.29	Hillshade obtained from a raster digital elevation modelling (DEM)	222
7.30	Visibility analysis showing areas (in green) visible from the located triangle	222
7.31	Raster elevation data in a hypothetical area	223
7.32	Predicted water flow direction across a section of the hypothetical area shown in Figure 7.29	223
7.33	The main river catchment and subcatchments identified by the GIS for the area shown in Figure 7.29	224
8.1	Framework for developing and using decision-support tools for determining recommendation domains for freshwater pond aquaculture	232
8.2	Overall suitability for pond aquaculture for the southern region of Malawi	232
8.3a	NASO map of China at an administrative level	233
8.3b	NASO map for part of Nicaragua at an individual farm level	234
8.4	Example image from Google Earth showing a fish farm off the coast of Greece	235
8.5a	Aquaculture zones 1 to 6	236

8.5b	Definition of severe, high and moderate impact for the SABBAC zone modelling. There are two rows of cages shown and different colours represent different amounts of waste flux (grams waste feed and faeces depositing on the bed per m ² per day)	236
8.6	Technical manual on GIS in fisheries management and planning	237
8.7	Implementation of the strategy process	238
8.8	The geographic distribution of GIS applications among countries	240
8.9	General modelling framework used in SPEAR ecosystem models	244
8.10	Screening model for carbon input to sediments from fish culture in Huangdun Bay under ambient current flow conditions (left), and for the same production level under slower hydrodynamic conditions (right)	245
8.11	Box layout of Sanggou Bay, China, and the location of FARM simulation area	245
8.12	The AkvaVis – Hardangerfjord grid for simulating current velocity	249
8.13	The AkvaVis site selection expert system	250
8.14	The Bay of Plenty, located on the north-east coast of New Zealand's North Island in the South Pacific Ocean	252
8.15	Development specific and environment specific factors influencing the potential for environmentally sustainable aquaculture within the marine environment	253
8.16	Assessed capacity for benthic habitats to assimilate the inputs from suspended bivalve aquaculture	254
8.17	Data layers and organizational structure (a) used to determine locations for sustainable aquaculture management areas (AMAs) and (b) output suitability index classes for suspended offshore bivalve aquaculture within the Bay of Plenty, New Zealand	255
8.18	Observed (a) and model predicted (b) surface chlorophyll-a concentrations on 19 November 2003, 110 days after model initialization	256
8.19	Modelled changes in chlorophyll-a concentration resulting from two mussel farms (% change from no mussel farm scenario)	257
8.20	Bivalve aquaculture induced chlorophyll-a depletion values	258
8.21	Schematic diagram of submodels showing the weights applied to each factor	263
8.22	Results of the submodels used in overall model building	265
8.23	Suitability classification for fish farming	266
8.24	Verification of models	267
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)	271
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	272
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	273
9.4	Stream reach and watershed areas in the Snohomish River, Washington, United States of America	274
9.5	Map showing the three recommended management zones based on opening dates for fishing for giant Eurasian trout in Mongolia	275
9.6	Flowchart of the processing steps, spatial analysis methods and products for creating resource habitat maps for river fish species	281

9.7	Illustration of the arrangement of feeding habitat along a river reach	282
9.8	Illustration of the process of creating a complementation map of stream fish habitats using the moving window analysis	283
9.9	Process for delineating potential subpopulation areas using an overlay of the daily activity areas map created with Chole software	284
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)	287
9.11	Map of catchment land use patterns for Udawalawe reservoir in southern Sri Lanka	288
9.12	Maps of the aquatic ecological classification hierarchy for four levels (4–7) in Missouri, United States of America	291
9.13	Predicted distribution maps for (A) a fish species, black redhorse (<i>Moxostoma duquesnei</i>), (B) a mussel species, round pigtoe (<i>Pleurobema sintoxia</i>), and (C) a crayfish species, golden crayfish (<i>Orconectes luteus</i>)	292
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	294
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	295
9.16	Map of 158 conservation-opportunity areas (COAs) selected by the aquatic resource professional team for Missouri, United States of America	295
10.1	Some typical distributions of marine parameters in the Gulf of Oman and the Arabian Sea	299
10.2	Main benthic habitats off Waikiki Beach, O’ahu, Hawaiian Islands, United States of America	300
10.3	Fish species richness in the same area as depicted in Figure 10.2	301
10.4	The interaction between anchovy and sardine stocks in South African coastal waters	302
10.5	Some modelling procedures for determining spawning habitats in the English Channel	303
10.6	Fishing effort in the south-west Portuguese crustacean trawl fishery as registered by VMS location data (2003)	304
10.7	Hours of fishing effort in 2003 in the Gulf of Maine, United States of America, and the location of marine reserves	304
10.8	Suggested marine protected areas (MPAs) in the Irish Sea	305
10.9	Extracts from the Marine Spatial Plan for California’s Channel Islands, United States of America, marine area	307
10.10	Ex-vessel values of four fisheries off the central California coast, United States of America	308
10.11	Distribution of the echinoderm <i>Echinocyamus pusillus</i> in the eastern English Channel, with inset showing the species	315
10.12	Collective perceptions of fishers from selected ports in south-east England and northern France as to where they fish for nine main commercial species	316
10.13	Areas selected for potential conservation in the eastern English Channel given a target of 40 percent of the total marine area	317
10.14	Area of distribution of Napoleon fish (within line). The species is closely associated to coral reefs within its range	319

10.15	Map showing the extension of the six surveyed areas in Indonesia analysed in this study	320
10.16	Distribution of humphead wrasse detected in UVS relative to the position of the reef edge shown in the satellite images	320
10.17	Section of barrier reef with an indication of the reef edge and 100-m buffer area (linear structures are not to scale)	321
10.18	Example of identification and manual vectorization of reef edges and automatic buffering on the reef edges in the Maratua Atoll, Indonesia	322
10.19	Grid of 279 Landsat-7 scenes used to calculate the humphead wrasse habitat areas in Indonesia, Malaysia and Papua New Guinea	323
10.20	3D bathymetry view looking west over the study area towards Cap Creus, Spain	325
10.21	Gear types used by fishers from the six main ports in the study area	327
10.22	Number of fishing methods (overlap value) deployed per cell in Cap de Creus waters, Spain	328
10.23	Relationship between the species communities most in need of conservation and the distribution of trammel nets in the Cap de Creus, Spain, marine area	328
11.1	Organization of sections 11.1 to 11.4 showing the sequence of materials covered	333
11.2	A comparison of world aquaculture production (1950 to 2010) with marine and inland fisheries production	337
11.3	A typical "aquapod" submersible finfish structure being used for mariculture	346
11.4	Predicted latitudinal shift of demersal marine organisms between 2005 and 2050 as caused by climate change (excluding areas > 2 000 m in depth)	353
12.1	Categories of challenge facing fisheries and aquaculture GIS	360
12.2	Varying time and/or space scales for selected physical and biological marine variables	362
12.3	4-dimensional image to show aggregated herring catches in northern Atlantic and Arctic Ocean waters from 2006 to mid-2010	365

Boxes

1.1	Factors contributing to the unsustainability of fisheries in less-developed areas	3
1.2	The operational characteristics of a modern GIS	9
1.3	Major application areas for GIS	11
1.4	Examples of early GIS innovation projects	12
1.5	Parallel developments that link to GIS	16
2.1	A quote giving the flavour of open source software	26
2.2	Why use Web-based GIS?	27
2.3	The present hierarchy and terminology of general computers	31
2.4	Suggested computer specifications for undertaking fisheries and aquaculture GIS work	31
2.5	Questions to ask of any open source software projects	46
3.1	Scales and levels of analysis for potential GIS applications to aquaculture	51
3.2	Main production functions applying to inland aquaculture	53
3.3	Some important spatially variable production functions influencing marine fisheries	54
3.4	The main spatially variable production functions influencing marine cage culture	55
3.5	Levels of measurement that can be assigned as an attribute of collected data	57
3.6	How to read a grid reference from a topographic map	63
3.7	Some important factors to consider regarding data quality	65
3.8	Some questions that should be asked of any data to be collected	67
3.9	FAO access portals to major marine, fisheries and aquaculture data providers	75
3.10	Online and mobile solutions to GIS mapping from the Environmental Systems Research Institute	77
4.1	Some common pitfalls contributing to the failure of GIS	82
4.2	Examples of questions to be asked in a feasibility study	86
4.3	Example of some costs involved in a recent (2009) implementation of GIS for aquaculture work in Bangladesh	87
4.4	The main sections of a "GIS system design" report	89
4.5a	Example of GIS implementation plan for a fisheries department	90
4.5b	Example of GIS implementation plan for county administration purposes	91
4.6	Checklist of important issues when implementing a GIS	93
4.7	Eason's principles for introducing new technology into an organization	99
4.8	Some main source categories for GIS guidance and support	100
4.9	Instruction manuals in ESRI's "Our World GIS Education" series	102
4.10	Some introductory textbooks covering general GIS	107
4.11	Examples of books published in the last decade on fisheries and/or aquaculture GIS	108
4.12	Journals and trade magazines having GIS applications in aquaculture	109
4.13	Web sites giving information on general and vendor-based GIS conferences	110

4.14	Examples of GIS user and discussion groups	111
4.15	Professional GIS organizations	112
5.1	Levels of abstraction in data modelling for a fisheries or aquaculture mapping scenario	121
5.2	Part of the database design for a 2007 fish census on the Lower Bridge River, British Columbia, Canada	123
5.3	Some advantages of using digital databases	124
5.4	The main functions of a database management system (DBMS)	125
5.5	Main characteristics of metadata as defined by the United States Federal Geographic Data Committee	127
5.6	Comparison of raster and vector data structures	140
5.7	Relative advantages of TIN and DEM surface models	145
6.1	Satellite orbits	151
6.2	Main types of optical and radar remote sensing systems	154
6.3	European Space Agency's Sentinel-2	156
6.4	Important questions to address in a scoping study	165
7.1	Examples of basic pre-processing functions available in most GIS or graphics programs	193
7.2	Transformations that may be directly applied to digital maps	193
7.3	Typical information shown on topographic maps at different scales	195
7.4	Method used by GIS to calculate the area of vector-based polygons	204
7.5	Examples of directed (oriented) network modelling relating to rivers or streams	219
8.1	Overview of major organizations carrying out aquaculture-related GIS research and projects	242
9.1	Main themes relating to GIS applications in inland fisheries	270
9.2	Overview of major organizations carrying out inland fisheries-related GIS research and projects	278
10.1	The main thematic areas in marine fisheries to which GIS is currently being applied	298
10.2	Overview of major organizations carrying out fisheries-related GIS research and projects	312
10.3	Observations made at the conclusion of the Symposium in GIS/Spatial Analyses in Fishery and Aquatic Sciences (Rio de Janeiro, Brazil, August 2008)	313
11.1	Main drivers affecting future spatial approaches to fisheries and/or aquaculture research and management	334
11.2	Some key current developments and issues with respect to GIS and remote sensing	338
11.3	The main emerging themes in fisheries and aquaculture to which GIS will be applied	342
11.4	Requirements of a global marine habitat classification system	355
12.1	Some challenges to gathering and assembling data	370