Spatial Analysis of Coastal Environments

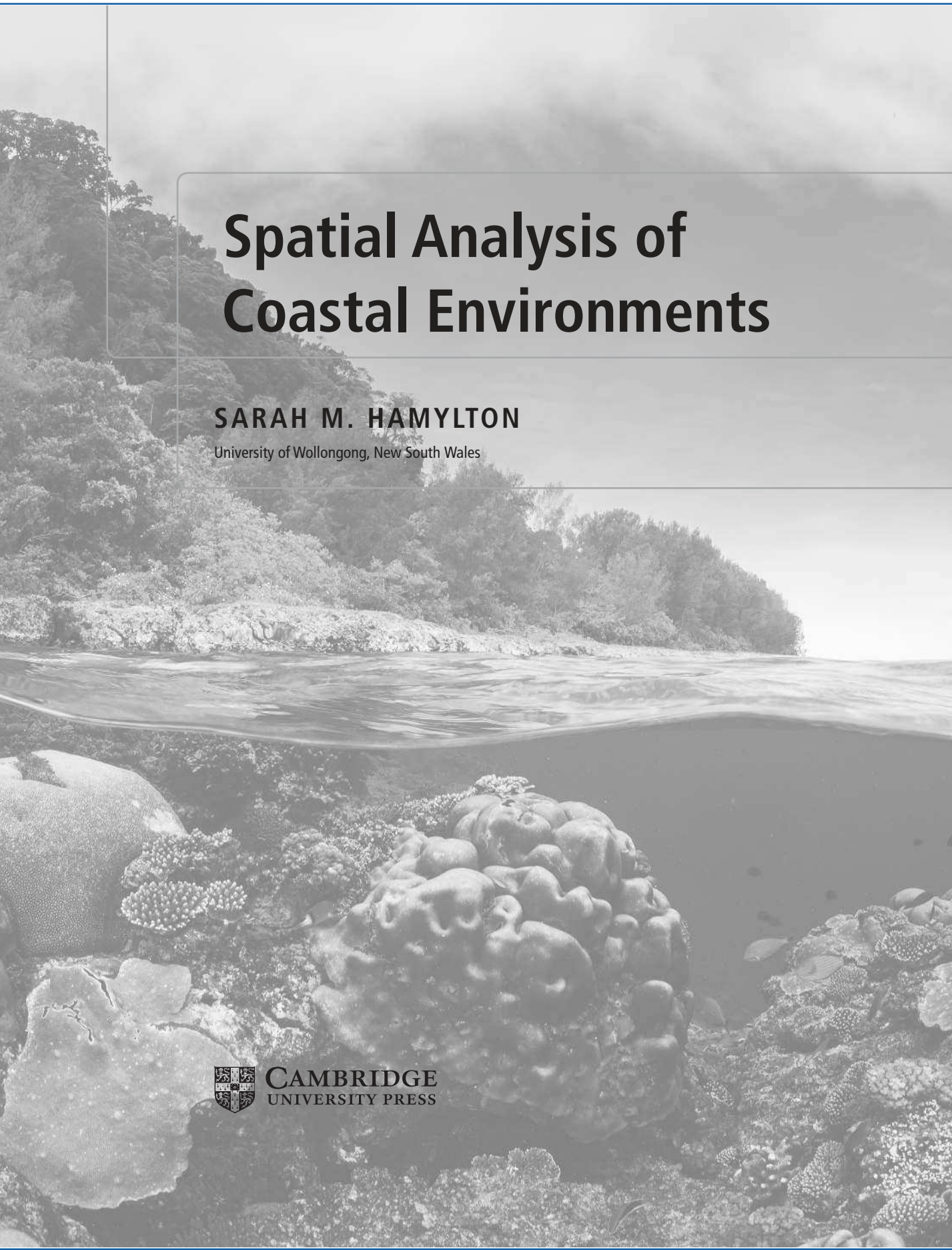
At the convergence of the land and sea, coastal environments are some of the most dynamic and populated places on Earth. This book explains how the many varied forms of spatial analysis, including mapping, monitoring and modelling, can be applied to a range of coastal environments, such as estuaries, mangroves, seagrass beds and coral reefs. Presenting approaches to modelling, which draw on recent developments in remote sensing technology, geographical information science and spatial statistics, it provides the analytical tools to map, monitor and explain or predict coastal features. With detailed case studies and accompanying online practical exercises, it is an ideal resource for undergraduate courses in spatial science. Taking a broad view of spatial analysis and covering basic and advanced analytical areas such as spatial data and geostatistics, it is also a useful reference for ecologists, geomorphologists, geographers and modellers interested in understanding coastal environments.

Sarah M. Hamylton is a Senior Lecturer at the University of Wollongong (Australia), where she specialises in the spatial analysis of coastal environments. Her research applies geospatial technology to tropical coastal environments. Her maps have helped establish marine protected areas, and her models of how climate change impacts coral reefs have informed national coastal policies.

'I wish this book had been around when I was a student! It ticks all the boxes: the primary focus on spatial analysis and interrogation of geospatial data is essential for sound, sustainable and evidence-based decision-making, and will give invaluable practical skills to students and practitioners alike; while the adoption of landscape ecology as the underpinning conceptual framework emphasises the need for joined-up, holistic and ultimately spatially-determined thinking in coastal science and management. The author shows a deep understanding of her subject matter, and her enthusiasm for, and love of, the coast stands out. Even the more complex ideas and methods are explained clearly and in an easily accessible, student-friendly manner. Although written for students of the coast, many of the concepts and methods introduced here will be readily transferrable to other areas of Earth Science specialism where geospatial expertise is needed.'
Darius Bartlett, *University College Cork, Ireland*

'*Spatial Analysis of Coastal Environments* is a rare and overdue resource that provides a comprehensive overview as well as an introduction to an array of important spatial analytical techniques and issues. Students and professionals new to coastal GIS will find the introductory coverage of data sources, mapping principles and analysis techniques easily accessible. Experienced researchers, coastal managers and planners, and instructors will take value from the coverage of advanced techniques such as geostatistics, modelling and characterising uncertainty. The book is richly and usefully illustrated with both conceptual and case study maps and graphics. I expect this book to fill an important void and, through its readers, further expand the scientific and practical application of GIS to coastal environments.'
Thomas R. Allen, *Old Dominion University, USA*

'It should become essential reading for students of coastal environments, demonstrating how spatial analysis methods, together with GIS, can enrich and bring new insights to the study of this important field.'
Robert Haining, *University of Cambridge, UK*



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For Gran, who was always interested.

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FOREWORD

As the noted econometrician and geographer Luc Anselin once said, 'Spatial is special'. Many of us without realising have probably first learned about spatial analysis at a very young age, perhaps as soon as we began to walk and to become fully aware of our geographic surroundings. More often than not, the first step in spatial analysis is understanding *where*. As a small child, you became aware of where you were, in the bedroom or in the kitchen. Your skills then started to expand into a second development phase, that of navigation. How do you go from one room to the next, and then how do you go from home to school? You didn't need to take a formal course in spatial analysis, but it was still becoming ingrained in your everyday life. Spatial analysis is a diverse and comprehensive capability that includes the simple visual analysis of maps and imagery, the determination of how places are related, the finding of the best locations and paths, the selection of the most appropriate site, the detection and quantification of patterns, and even advanced predictive modelling. The process of spatial analysis occurs every day in the human brain. However, over the last four decades, our ability to solve complex spatial problems has grown exponentially with technologies that include the global positioning system, real-time sensors, navigation algorithms, and the technology that brings them all together, the geographic information system or GIS. Spatial analysis has always been a hallmark of GIS, the 'numerical recipes' within, which set GIS apart from other forms of computerised visualisation and information management. With GIS we pose questions and derive results using a wide array of analytical tools to help us understand and compare places. One special place is the coast.

The coast is critical. Nearly 50% of the world's population lives within 60 km of a coast, and the United Nations estimates that by 2020 this will rise to 75%. This is because the coastal zone not only is a beautiful place to be, but also is critical for human life itself, with its provision of food and energy and its modulation of the weather. At the same time, the news is replete with stories of the hazards of sea level rise, hurricanes, tsunamis, rogue waves, coastal flooding, shark attacks, toxic spills, oxygen-poor 'dead zones', and even modern-day pirate attacks. With 60% of global coral reefs under immediate threat, 35% of global mangroves in dangerous decline, 80% of native oyster stocks in danger, and a bevy of other threats, the coast has become not only a desired destination but also a focus of intense restoration. Here spatial analysis is particularly needed for restoration site selection, long-term monitoring, and designing of 'greener' infrastructures, preferably with large doses of community involvement and political will.

Spatial is special. The coast is critical. When you combine both into a *textbook* aimed at second and third year undergraduates (rather than the customary edited

compilation of applied research papers), you have a unique book for raising awareness and inspiring action. This is because it is the next generation of coastal planners, conservationists, policy-makers, and well-informed 'citizens of the planet' that must be taught the basics of thinking spatially and critically about the coast, in rigorously manipulating and analysing spatial data, and in rapidly prototyping and delivering repeatable GIS solutions for a range of coastal applications. It is via spatial analysis that the next generation will see innovations in the problems they will be able to solve, in the stories that they will be able to tell, and the decisions that will help make their organisations and governments more successful. And it is within the classroom that students learn languages of many kinds, spatial analysis being one of those languages. This language consists of a core set of questions that we ask, a taxonomy that organises and expands our understanding, and a set of fundamental steps embodying how we solve spatial problems. Languages also have dialects, and *coastal* spatial analysis is one such important dialect.

This book is a great exemplar of not only *how* to conduct spatial analysis in coastal environments, but also why this is critically important. With this book, instructors and students will see that this is not just about eyeballs on a map, but about the invisible rubber bands of mathematical manipulation of different layers of data. With this book, you also possess an effective guide to coupling the appropriate data with the analysis to effectively communicate scientific results, and to transforming those results into actionable information, information that is useful in decision cycles for coastal restoration and resilience. The arrival of this text couldn't be more timely, as the time is *now* for governments, communities, NGOs, and, yes, universities to go beyond just an exploration and discussion of ideas. We need to teach our students to effectively use spatial analysis to help guide the planet towards a more resilient future … before time runs out.

Dawn J. Wright
Chief Scientist, Environmental Systems Research Institute (Esri)
Courtesy Professor of Geography and Oceanography, Oregon State University

PREFACE

Learning to think in spatial terms has changed my outlook considerably. Many research challenges, management problems and policy issues are geographical at heart. The application of spatial analysis has the potential to contribute insight through mapping, monitoring and modelling activities that express and develop our understanding of a range of phenomena. My primary motivation in writing this book is to raise awareness of the many and varied forms of spatial analysis that exist, and how these can be profitably applied to coastal environments.

Over the last 15 years I have conducted many different types of geospatial analysis working as a coastal environmental consultant or researcher. This includes work in Fiji, Thailand, the Philippines, Saudi Arabia, the Seychelles, Belize, the British Indian Ocean Territory (Chagos Islands), New Caledonia and Australia. Over this time I have experienced first-hand the profound ways in which maps and analytical results influence discussions around coastal policy or management decision-making. This book represents a timely and accessible consolidation of the learning outcomes from the projects I have worked on, intended for both students and people working in coastal environments.

While the applications described in this book have a coastal focus, the techniques are applicable across a wide range of different phenomena. For example, the tests described for the detection of point clusters of shark attacks in Chapter 3 were originally taught to me in the context of detecting hotspots of crime in cities or disease across countries. My aim is to provide a comprehensive outline of the *theoretical principles* underpinning the conduct of spatial analysis in coastal environments. This incorporates widely applicable basic spatial theory, skills and approaches that are helpful for any spatial analysis. While different software and statistical packages for conducting analysis may come and go, the theoretical and fundamental knowledge base upon which they are founded endures. Such a knowledge base is valuable and necessary for thinking creatively and critically to analyse phenomena in coastal environments. My intent is also to capture the state of the art in spatial analysis of coastal environments through carefully selected case studies that emphasise recently developed geospatial technology. For example, the use of unmanned aerial vehicles (drones) to map coastlines and the construction of interactive Web-based geographic information system (GIS) interfaces to deliver the mapped results of spatial analysis are both developments that have emerged relatively recently in the geospatial industry.

Another motivation for this book is to provide a text for the increasing number of undergraduate courses in the UK, USA and Australia that teach spatial sciences within a coastal context. In spite of a substantial growth in the application of geospatial technologies to coastal environments and a growing body of Higher Education

courses on the topic, no textbook exists that comprehensively covers the application of GIS to coastal environments. I hope that both students and practitioners wanting to learn more about how to collect and analyse spatial information on coastal environments will find this book useful. Although some of the topics covered are complex, they are introduced at a basic level and elaborated on in a user-friendly manner. A variety of pedagogical features have been included to facilitate comprehension and to guide learning, including real-life case studies demonstrating the application of analytical theory, a series of associated practical exercises offering the reader the opportunity to manipulate and analyse companion datasets, summaries of key points at the end of each chapter and a comprehensive glossary of important terminology.

This book covers all aspects of spatial analysis. It enables the reader to break down, interrogate and summarise patterns in coastal environments. Analytical methods draw from a range of disciplines, including ecology, geomorphology, geography and statistical modelling. The book builds in complexity, beginning with the collection of spatial data and basic geographical analysis of raster and vector data. Mapping and monitoring exercises are presented that draw on recent developments in remote sensing technology, geographical information science and spatial statistics to represent coastal features and assess how they have changed over time. The development of empirical geographical models to explain and predict coastal phenomena is described. Many processes in coastal environments produce patterns that are spatially autocorrelated, and a range of geostatistical techniques are presented for quantifying and characterising the spatial structure that underpins this autocorrelation. Methods for evaluating the uncertainty of spatial analysis are reviewed, along with techniques for the effective and responsible presentation and communication of spatial analysis results.

Chapter 1 defines the scope and structure of the book, providing introductory guidance on spatial analysis to the coastal researcher while also introducing coastal environments to the spatial analyst. Chapters 1, 2 and 3 provide an introductory foundation for carrying out spatial analysis, including an overview of different types of analysis, data considerations and basic analytical operations. A tripartite framework of mapping, monitoring and modelling activities is adopted for the application of increasingly complex levels of spatial analysis to coastal environments. This forms an organisational principle for Chapters 4, 5 and 7. Technical and analytical considerations are set out relating to each of these activities, including the use of remote sensing technology and the nature of datasets commonly employed for coastal mapping in both two and three dimensions, tools for observing coastal change over time, repositories of baseline data against which change can be measured and the development of both predictive and explanatory models. Chapter 6 introduces key spatial statistical principles that are often invoked in the process of model development. Any form of spatial analysis should be accompanied by an evaluation of the uncertainty associated with that analysis, and Chapter 8 presents a range of methods for achieving this. Finally, Chapter 9 provides advice on how to present and communicate the results of spatial analysis effectively, including through online Web viewers and factors to be considered in the organisational uptake of spatial analysis.

ACKNOWLEDGEMENTS

This book has taken shape over the last two years at the University of Wollongong, but has its roots in research that goes back around 14 years to Fiji. This is where I first dived on a coral reef and fell in love with coastal environments. At the time I was volunteering for Coral Cay Conservation, which set me (like many UK-based students of environmental science) on a long and enjoyable path of coastal research. Since then, I have had the good fortune to discover all the exciting prospects that spatial analysis offers for better understanding coastal environments. Particularly formative in this regard was Bob Haining's introduction to analysing and modelling with spatial data, principally the issue of spatial autocorrelation. Around this time, I spent an invaluable week at the University of Exeter, where Alastair Harborne taught me how to make maps from remote sensing images, a skill that has been central to my research since.

Several research fellowships have enabled me to undertake field-trips that have contributed to the examples described in the book. These include a Domestic Research Studentship (University of Cambridge), a Khaled bin Sultan Living Oceans Foundation Fellowship (for which I am particularly grateful to Prince Khaled bin Sultan and Captain Phil Renaud), an Australian Bicentennial Fellowship (King's College, London) and a Lizard Island Research Station Fellowship.

I have had the benefit of working with many excellent colleagues and research collaborators over the years. In particular, the examples set by Tom Spencer and David Stoddart, whom I am proud to call my academic father and grandfather, respectively, have inspired me to do research that makes a difference. The opportunity to publish this book with Cambridge University Press was created by Colin Murray-Wallace, whose interest and encouragement has been much appreciated. Similarly, Colin Woodroffe has provided invaluable help through intellectual discussions, proofreading and an unfailing generosity in supporting my growth as a researcher. Marji Puotinen, whose GIS course I inherited, provided me with excellent guidance as to the skills necessary for a well-rounded education in GIS, alongside the *'Geographic Information Science & Technology: Body of Knowledge'*. I am also indebted to Professor Noel Cressie, who provided general feedback on the manuscript, including the need for a more thorough discussion of directional spatial dependences in coastal environments.

I am grateful to the University of Wollongong for allowing me the time and intellectual space to see this book project through to completion. Many thanks are due to two anonymous reviewers for positive and productive comments on the initial book proposal. Parts of this book have been tested on undergraduate and postgraduate students at the Universities of Cambridge, Wollongong and Sydney, whom I thank for the opportunity to refine exercises and chapters. I am grateful to John Hedley,

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A number of individuals and organisations have given permission for me to use diagrams, and they are acknowledged in the captions of the appropriate figures. In particular, Matt Smith has generously allowed me to use his photographs, both as a front cover and throughout the book. Thanks are due to the following people for allowing me to use their data in case studies and examples throughout the book: Tom Spencer and Annelise Hagan (University of Cambridge) for the Aldabra vegetation change detection case study; Holly East (University of Cambridge) for the analysis of lagoon volumetric and shoreline planimetric change at Diego Garcia Atoll; Richard Barnes (University of Cambridge) for the invertebrates datasets in Moreton Bay; Eglantine Chapuis (Centre d'Estudis Avançats de Blanes) for the population data collected along the intertidal rocky shorelines of Catalonia; Rafael Carvalho (University of Wollongong) for the bathymetric soundings from the Shoalhaven Estuary; Javier Leon (University of the Sunshine Coast) for the idea of modelling uncertainty of tsunami inundation; John Hedley for the confidence interval map of Sykes Reef; and Rob Thieler (US Geological Survey) for the Nantucket shoreline change example.

Finally, thanks to my mother, father and brother, Kathryn, Gordon and Michael, who have given me such support over the years. And, of course, to my family – Valerie, Michael, Henry and Alexander – whose enthusiasm, tolerance and encouragement have helped immeasurably.