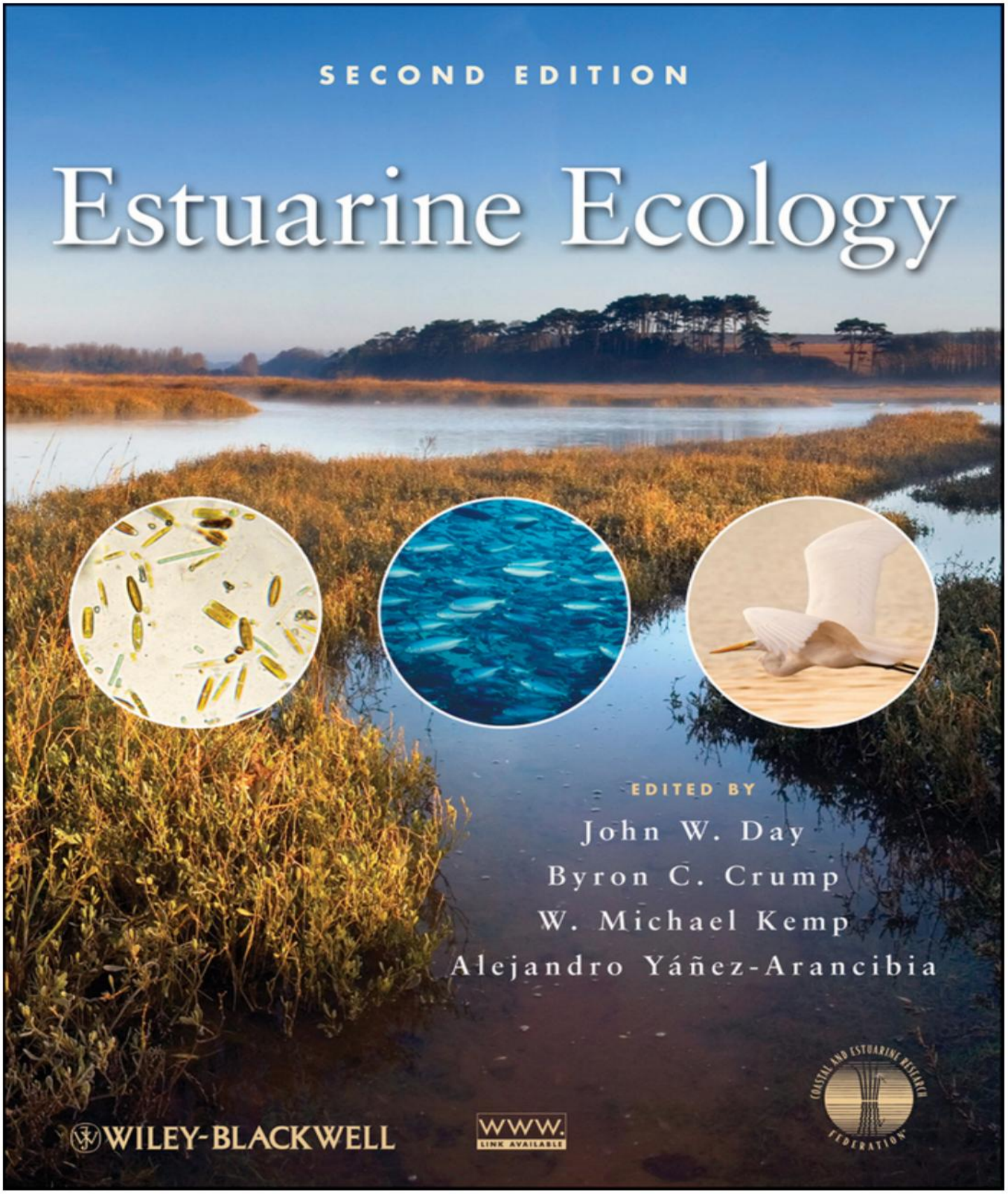
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EDITED BY
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Table of Contents

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The website includes:

- All figures from the textbook as Power Point slides for downloading
- Supplementary text material for Chapter 17
- Chapters 1, 10, and 20

ESTUARINE ECOLOGY

Second Edition

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This book is dedicated to our students and to all others around the world who are interested in understanding, using, managing, and protecting estuarine ecosystems in a sustainable manner for future generations.

In memory of Dr. Scott W. Nixon for his important contributions to the field of estuarine ecology.

Preface

This book is a textbook for a course in estuarine ecology designed to introduce students to the function and structure of estuarine ecosystems. It is designed primarily for an introductory graduate course, but it can also serve as a general resource book for estuarine ecologists. This book is the second edition of Estuarine Ecology; the first edition was published in 1989. Clearly there have been enormous advances since then, and this second edition has expanded from 13 to 21 chapters to cover these advances. Some topics, such as climate change, were of relatively minor interest prior to 1989, but have since become central to estuarine ecology. And there has been a dramatic increase in information about estuarine ecosystems, growing human impacts on these systems, and their value to society. This information is documented throughout the book. Another significant change is that we moved from a book in which most of the chapters were written by a small handful of authors to an edited volume with many authors. This was necessary because of the expansion of the bredth of estuarine science and the challenge of having a few authors adequately cover the subject. Thus, we reached out to a number of well-known experts to prepare individual chapters. But we endevoured to have them use a generally consistent format to ensure a comprehensive coverage of estuarine ecology.

The chapters in the book proceed logically through the science of estuarine ecology. The first chapter introduces estuaries and estuarine ecology, and describes some of the background, definitions, theory, and issues of estuarine ecology. The next two chapters deal with physical, geological, and chemical aspects of estuaries. The nature of estuarine ecosystems is to a great extent determined by a

complex and dynamic physical, geological, and chemical environment. Therefore, a basic understanding of these topics is essential for a comprehension of estuarine ecology. Then there is a group of chapters on primary producers of estuaries. Two new chapters are added compared to the first edition so that phytoplankton, seagrasses, coastal marshes, mangroves, and benthic algae are covered. After that are two chapters on microbes in estuaries covering estuarine microbial ecology and estuarine microbial food webs, the latter being a new chapter for the second edition. Four chapters follow that covering estuarine consumers including zooplankton, benthos, nekton, and wildlife. The next three chapters cover emergent, holistic properties of estuarine ecosytems including metabolism, food webs, and budgets. All of these chapters develop detailed information on taxonomy, physiology, life histories, ecological role, growth, metabolism, and interaction with abiotic factors. The last four chapters deal with fisheries, human impact and management, the effect of climate change on estuaries, and the role of modeling in estuarine science.

Our primary motivation for preparing this book was to update the first edition that is now very much out of date. In the intervening two decades since the publication of the first edition, many very good books have been written on estuarine science. But, we believe none of them really meets the need for an introductory text on estuarine ecology. Thus, we undertook this effort. We also hope that this book will become a “work in progress” that can be more easily updated on a regular basis because of the participation of many experts. The arduous task of preparing such a book by one or a few authors is part of the reason for the long delay in the second edition.

Baton Rouge, Louisiana
Cambridge, Maryland

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October 2011

Acknowledgments

Since estuarine ecology is such a dynamic science, we depended heavily on many of our colleagues in writing this book. Through discussions, suggestions and review of different chapters, many estuarine ecologists helped shape this book. Foremost among those are the authors of the different chapters. We acknowledge the intelletual stimulation of Howard and Eugene Odum. Their work, as well as that of their students and colleagues, is richly represented throughout this book. We also thank a number of individuals who helped with countless details involved in its production. These include Matt Moerschbaecher, Rhine Perrin, Anne Gauzens, Alan Joyner, and Paul del Giorgio. The Coastal and Estuarine Research Federation strongly supported and aided in the preparation of this book.

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Chapter One

Introduction to Estuarine Ecology

John W. Day Jr., Alejandro Yáñez-Arancibia, W. Michael Kemp,

and Byron C. Crump

1.1 Background, Theory, And Issues

We begin this description of estuaries and their functions by defining estuaries very broadly as that portion of the earth's coastal zone where there is interaction of ocean water, fresh water, land, and atmosphere. Large estuarine zones are most common in low relief coastal regions such as the broad coastal plains of Europe and the east coast of North America. They are much less common in uplifted coastlines such as the Pacific edge of North and South America. We begin our assessment as broadly as possible to include all portions of the earth that interact at the edge of the sea because these regions influence the smaller scale ecosystems sometimes more narrowly defined as estuaries proper.

From the vantage point of an orbiting satellite, several of the most basic attributes of estuaries are observable. Plumes of sediment-laden water float seaward on the ocean surface from the largest rivers, such as the Amazon, the Ganges, and the Mississippi. Color differences among

various water masses, representing waters of different histories and different biotic richness, are often apparent. Coastal waters in areas with significant riverine input and broad shelf areas generally appear more greenish brown than the deep blue waters adjacent to many other coastlines. There are also atmospheric features of importance to estuaries obvious from space. Clouds commonly form directly over the edges of continents as one manifestation of the atmospheric “thermal engine” that maintains the freshwater cycle on which estuaries depend. At the altitude of a satellite, the dense human populations that proliferate in coastal zones are outlined at night by their lights.

The two most recent geological epochs, collectively named the Holocene, could be called *the age of the estuary*, for estuaries are abundant today, even though they are geologically tenuous. All present day estuaries are less than about 5000 years old, representing the time since sea level reached near its present level following the last ice age. Human populations flourished during this same period, in no small measure owing to exploitation of the rich estuarine resources of the coastal margin. Most “cradles of civilization” arose in deltaic and lower floodplain areas where natural biota was abundant and where flooding cycles produced the rich bottomland soils and readily available freshwater supplies on which agriculture flourished (Kennett and Kennett, 2006; Day et al., 2007). Early centers of civilization that developed in estuarine or deltaic environments include those of the Tabascan lowlands of Mexico; the valley of the Nile; Tigris-Euphrates, Yellow, and Indus Rivers; and along the Andean coast of western South America where upwelling systems bordered estuarine systems.

Let us now continue our aerial survey of estuaries, but this time at a much lower altitude, about 1000 m, in a light

airplane following the course of a coastal plain river in the temperate zone from its headwaters to the ocean. The headwater river is narrow with rapids and falls, but changes near the coast to a larger meandering form with broad marshy areas where the actual edge of the river is not always clearly evident. The color of the water changes from clear blue to yellowish brown as the river picks up silt. As the river water nears the coast tidal currents become apparent and, moving seaward, the influence of tidal currents becomes greater.

Along the banks of the estuary, fresh and brackish water marsh plants grow at the edges of embayments. These marshes are often flanked by rows of houses and yards and spanned by narrow piers to provide access to deeper water. Among these marshes, a variety of wading birds may be observed stalking their prey at the water's edge. Where the water is shallow and relatively clear, dark-colored patches indicate the presence of submersed grass beds.

As we travel seaward, the tidal influence becomes more important and the intertidal zone becomes more extensive. Larger piers and bulkheads interrupt the banks of the estuary, and brown mud flats come into view, as well as greenish gray oyster reefs fringing the banks or dotting the mud flats. Various birds such as oystercatchers feed on the reefs, along with an occasional raccoon. The mud flats are peppered with mud snails, and just beneath the surface are teeming communities of small worms and crustaceans. Various shore birds are feeding at the water's edge, and skimmers fly along in quiet areas, plowing a furrow in the water with their lower bill as they fish for silversides and other small fish. The darker colored path of a deep shipping channel maintained by dredging is evident toward the middle of the estuary and contrasts with the lighter colored shallows.

The mouth of the estuary takes the form of a broad sound that opens up behind a barrier island. The sound is shallow, and we can see porpoises herding schools of juvenile menhaden, followed by gulls trying to get in on the action. Crab pot buoys and fishing boats are much in evidence. On either side of the barrier island are narrow passes with visible eddies and strange wave patterns, indicating rapid and complex currents.

Along the ocean beach, a number of shrimp boats raise long spiraling muddy plumes of sediment as they drag their trawls along the bottom. A kilometer or so offshore of the tidal passes the water changes color from dark brownish green to a lighter, less turbid green. Further offshore, it is a darker and bluer color.

On the landward side of most such barrier islands, there are flat intertidal areas colonized by salt marsh plants. The highest part of the island includes some oak trees. The beach may include a series of dunes, with the farthest from the ocean being covered with vegetation and the nearer dunes being less vegetated. The seaward side of the dune closest to the ocean has much less vegetation because the wave energy from storms makes it difficult for plants to survive. In parts of the beach–barrier system, vacation houses have replaced the dunes, and straight navigation channels have replaced twisting tidal channels.

In summary, from many elevations estuaries can be seen as complex, dynamic, and biotically rich environments dominated by physical forces and impacted by human activity. Their study requires a consideration and knowledge of geology, hydrology, chemistry, physics, and biology. Ideally, we can integrate knowledge gained through these specific disciplines using what we call systems science. This book is an introduction to the specifics of estuarine science and their integration into a coherent view of estuaries as ecosystems. We show how estuaries are different from one

another and how they are similar, and why we need to preserve them while enhancing their value to society.

We will begin by describing a very generalized estuary, to provide the reader with an introduction to the geology, physics, chemistry, and biology of estuaries. This is done with a certain danger because, as the rest of the book shows, estuaries are characterized as much by differences as by similarities. Nevertheless, in this chapter, we attempt to describe a generalized estuary. But before we proceed further, we will define an estuary.

1.2 Definitions, Terms, and Objectives

1.2.1 Definitions of Estuary and of Ecology and Difficulties in Applying These Definitions to Real Estuaries

The term *estuary* comes from the Latin *aestus* meaning heat, boiling, or tide. Specifically, the adjective *asetuarium* means tidal. Thus, the *Oxford Dictionary* defines estuary as “the tidal mouth of a great river, where the tide meets the current.” *Webster's Dictionary* is more specific: “(a) a passage, as the mouth of a river or lake where the tide meets the river current; more commonly, an arm of the sea at the lower end of a river; a firth. (b) In physical geography, a drowned river mouth, caused by the sinking of land near the coast.”

Perhaps the most widely quoted definition of an estuary in the scientific literature is given by Pritchard (1967): “An

estuary is a semienclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage.” Certainly, one of the most characteristic attributes of most coastal areas is the action of the tide. Pritchard's definition makes no specific mention of tide, although the mixing of seawater and fresh water implies this. There are, however, many nontidal or minimally tidal seas, such as the Mediterranean Sea and the Black Sea, where fresh and salt water mix.

There are also estuaries in semiarid regions that may not receive any fresh water for long periods; sometimes, as in the Pacific coast of California and Mexico, Western Australia, and several parts of Africa, the estuary may become blocked by longshore sand drift, so that it is ephemerally isolated from the sea for months to even years. In other regions, the tidal limit, sometimes with a tidal bore, may reach 100 km or more above the limits of salt water intrusion. So Pritchard's definition of estuary excludes some coastal areas where estuarine ecology is studied today.

In an attempt to address the limitations of Pritchard's definition, Fairbridge (1980) gave a more comprehensive definition of an estuary: An estuary is an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors: (i) a marine or lower estuary, in free connection with the open sea; (ii) a middle estuary subject to strong salt and fresh water mixing; and (iii) an upper or fluvial estuary, characterized by fresh water but subject to daily tidal action. The limits between these sectors are variable and subject to constant changes in the river discharge.

Fairbridge's definition excludes some coastal geomorphic features such as lagoons, deltas, and sounds and also nontidal estuaries. The distinctions among these different terms are treated in detail in Chapter 2, but characteristic