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Coastal Wetlands: Alteration and Remediation

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Preface

This volume of *Coastal Research Library* (*CRL*) deals with the general topic of coastal wetlands but specifically from within the purview of impacts that are deleterious to wetlands and kinds of restorative efforts that are deployed in attempts to correct wrongs resulting from human action. To this end, the volume is divided into three main parts: Part I, Impacts of Urbanization, Agricultural Occupation, Pollution, Climate Change, and Coastal Marine Influences; Part II, Impacts of Coastal Engineering and Environmental Degradation; and Part III, Restoration Techniques, Ecological Aesthetics, and Ecosystem Conservation (Sustainability and Biodiversity). These general subject area parts are in turn subdivided into chapters that are exemplars of degradation impacts or vignettes illustrating various approaches to restoration, either conceptually or in principle, and examples of new methodologies.

The geographical scope of this volume ranges from tropical to high-latitude coastal zones with various types of wetlands such as mangroves and salt marsh. A wide range of ecological considerations focuses on fisheries, intertidal benthic fauna, macrobenthic communities, and wildlife management. This selection of wide-ranging topics provides insight into the interconnectedness of various aspects of coastal wetlands. Provided here is a plethora of examples of successes and failures in attempts to correct the errors of human action when it comes to dealing with coastal wetlands. Sadly, many coastal wetlands around the world have been subjected to unwanted or unintended adverse impacts associated with urbanization, industrialization, and commercialization. With half of the world's coastal wetlands destroyed by such activities, it is imperative to absorb what is reported here in the following chapters that outline potential remediation efforts to save, conserve, or protect what is left of these valuable coastal ecosystems that are almost continually under threat from development.

Part I contains eight chapters that are examples of coastal wetlands adjacent to or overtaken by urbanization and agricultural occupation, which in turn result in degradation or destruction of coastal ecosystems. This dismal situation is further exacerbated by pollution, usually associated with urban development and/or agriculture, that compromises the integrity and in some cases the very survival of the remaining wetlands. Chapter 1 ("The Florida Everglades: An Overview of Alteration and Restoration"), by Charles W. Finkl and Christopher Makowski, discusses how urbanization, agriculture, and flood control destroyed about half of the Florida Everglades (a wetland of international importance [Ramsar Convention] and an international biosphere reserve [UNESCO]) and indicates failures of the world's most expensive reclamation effort that amounts to more than US$ 8 billion. Chapter 2 ("Recent Agricultural Occupation and Environmental Regeneration of Salt Marshes in Northern Spain"), by Ane García-Artola, Alejandro Cearreta, and María Jesús Irabien, deals with the reclamation of more than 50% of the original salt marshes that were degraded since the seventeenth century. This chapter illustrates how global temperate coastal wetlands with abundant sediment supply can be regarded as a soft adaptation measure that militates against consequences of climate change in the coastal zone. Chapter 3 ("Impact of Urbanization on the Evolution of Mangrove Ecosystem of the Wouri River Estuary [Douala, Cameroon]"), by Ndongo Din, Vanessa Maxemilie Ngo-Massou, Guillaume Léopold Essomè-Koum, Eugene Ndema-Nsombo, Ernest Kottè-Mapoko, and Laurant Nyamsi-Moussian, illustrates the deleterious effects of the urban environment on mangrove depletion around cities due to wood harvesting, sand extraction, and petroleum exploitation, in addition to coastal erosion and climate change. Unfortunately, the prognosis for a change in perception of mangrove degradation in this region is poor due to the absence of implementation of specific regulations to protect the mangrove forests. Chapter 4 ("Impacts of Coastal Land Use Changes on Mangrove Wetlands at Sungai Mangsalut Basin in Brunei Darussalam"), by Shafi Noor Islam and Umar Abdul Aziz Bin Yahya, continues in a similar vein by showing how increasing population pressure and economic development are detrimental to mangroves and salt marshes. Similar to the Everglades, there is the specter of conversion of water bodies and loss of open space where clearing of coastal mangroves and salt marshes result in a wide range of environmental issues and risks, not the least of which is severe pollution. This situation happens because the local authorities are unable to cope with the rapidly changing situations, internal resource constraints, and management limitations. Chapter 5 ("Land Use and Occupation of Coastal Tropical Wetlands: Whale Coast, Bahia, Brazil"), by Sirius O. Souza, Camara C. Vale, and Regina C. Oliveira, reports similar impacts in Brazil where coastal tropical wetlands are often compromised by the gradual expansion of population and economic cycles. Better planning proposals for land use and occupation are suggested for implementation. Chapter 6 ("Degraded Coastal Wetlands Ecosystems in the Ganges-Brahmaputra Rivers Delta Region of Bangladesh"), by Shafi Noor Islam, Sandra Reinstädtler, and Albrecht Gnauck, is perhaps the premier example in the world of population pressure on coastal wetland resources where 36.8 million people are living in the coastal region delta and who are dependent on coastal water resources. Unwanted impacts on the delta, tidal flats, mangrove forests, marches, lagoons, estuaries and other natural resources are elucidated in the light of ecosystem development and management strategies that are supposed to ensure communities with livelihood and sustainable development. Chapter 7 ("Handling High Soil Trace Elements Pollution: Case Study of the Odiel and Tinto Rivers and Accompanying Salt Marshes [Southwest

Iberian Peninsula]"), by Sara Muñoz Vallés, Jesús Cambrollé, Jesús M. Castillo, Guillermo Curado, Juan Manuel Mancilla-Leytón, and M. Enrique Figueroa-Clemente, verifies that salt marshes are one of the most prolifically heavy-metal polluted systems in the world. The interesting aspect of this chapter is its explanation of how key native halophytes are able to phytoextract or phytostabilize trace elements leading to the recovery of native prairies of low tidal marshes. Chapter 8 ("El Yali National Reserve: A System of Coastal Wetlands in the Southern Hemisphere Affected by Contemporary Climate Change and Tsunamis"), by Manuel Contreras-López, Julio Salcedo-Castro, Fernanda Cortés-Molina, Pablo Figueroa-Nagel, Hernán Vergara-Cortés, Rodrigo Figueroa-Sterquel, and Cyntia E. Mizobe, like the preceding chapters discusses adverse impact of human activities on coastal wetlands, in this case in central Chile, but additionally brings in the effects of natural disasters such as earthquakes, tsunamis, ocean swells, and ENSO. Field monitoring is also discussed with the objective of eventually implementing ecological restorations.

Part II contains five chapters and deals with direct impacts of coastal engineering and environmental degradation. The chapters here focus on clearly established and obvious links between construction works and degradation of coastal wetlands that are induced by ancillary effects. Chapter 9 ("Physical and Morphological Changes to Wetlands Induced by Coastal Structures"), by Germán Daniel Rivillas-Ospina, Gabriel Ruiz-Martinez, Rodolfo Silva, Edgar Mendoza, Carlos Pacheco, Guillermo Acuña, Juan Rueda, Angélica Felix, Jesús Pérez, and Carlos Pinilla, focuses on procedures that are used to better understand the relationship between modifications of coastal processes and the response of a coastal environment, in the case of civil works in the development of a new port in Barranquilla, Colombia. The interest here is to ascertain what changes in physical conditions will produce negative effects on the stability of natural systems in coastal wetlands. Chapter 10 ("Long Term Impacts of Jetties and Training Walls on Estuarine Hydraulics and Ecologies"), by Alexander F. Nielsen and Angus D. Gordon, probes inlet instabilities caused by the construction of jetties that in turn adversely impact the distribution of seagrass, salt marsh, and mangrove forests on the east coast of Australia. Chapter 11 ("Mangrove Degradation in the Sundarbans"), by Ashis Kr. Paul, Ratnadip Ray, Amrit Kamila, and Subrata Jana, investigates aspects of mangrove degradation in the Sundarbans and identification of contributing factors via extensive fieldwork, geospatial techniques, and factor analysis. This chapter shows hypersalinity, storm effects, fishery development, land erosion, and sediment deposition parameters are mainly responsible for mangrove degradations. Chapter 12 ("Assessment of Anthropogenic Threats to the Biological Resources of Kaliveli Lake, India: A Coastal Wetland"), by Krishnan Silambarasan and Arumugam Sundaramanickam, focuses on various threats to Kaliveli Lake, which is one of the largest wetlands in peninsular India and considered a wetland of international importance by the International Union for Conservation of Nature and Natural Resources (IUCN). Anthropogenic activities such as infringement from agricultural lands, wildlife poaching, loss of surrounding forests, increased salt pan and aquaculture farming, and recreation constitute important threats to the well-being of this wetland. This chapter also explores measures for conservation and protective management. Chapter 13 (“Egyptian Nile Delta Coastal Lagoons: Alteration and Subsequent Restoration”), by Ayman A. El-Gamal, identifies causes of wetland degradation in the Egyptian Mediterranean coastal region to be pollution, deterioration of water quality, eutrophication, habitat loss, overfishing, siltation, and climate change. Field studies are being conducted in efforts to determine management practices that will improve the resilience of these coastal lagoons.

Part III covers restoration techniques, ecological aesthetics, and ecosystem conservation with particular emphasis on sustainability and biodiversity. Although some of the previous chapters include discussion of remediation, this section highlights restoration efforts that promote sustainability and biodiversity in the broadest sense. This section is thus a logical follow-up to the previous two sections that primarily identified threats or risks to coastal wetlands. Determination or identification of the problem is obviously the first step in remediation; otherwise, it is impossible to remedy causes of unwanted conditions or situations. These chapters are examples of efforts in a diverse range of ecological setups where management strategies are proffered as means of conservation and protection within the realm of restoration and remediation. Chapter 14 (“Coastal Wetland Restoration: Concepts, Methodology, and Application Areas Along the Indian Coast”), by Ramasamy Manivanan, features a new concept that uses natural restoration techniques for coastal wetland restoration using the Chilika wetland ecosystem as a prototype. The idea here is to create conditions under which coastal ecosystem processes can withstand and diminish the impact of stressors. Chapter 15 (“Ecological Aesthetics Perspective for Coastal Wetland Conservation”), by LeeHsueh Lee, posits a new approach to the conservation of coastal wetlands where it is suggested that aesthetic preference provides a critical connection between humans and ecology. Promoted here is the prospect-refuge theory and the preference matrix of the bioevolutionary hypothesis, based on aesthetic experience, that could drive landscape change and pull with it ecological quality. Chapter 16 (“Estuarine Ecoclines and the Associated Fauna: Ecological Information as the Basis for Ecosystem Conservation”), by Mário Barletta, André R.A. Lima, Monica F. Costa, and David V. Dantas, is based on the definition of ecocline as a “gradation from one ecosystem to another where there is no sharp boundary between the two” where there are relatively heterogeneous communities influenced by gradual changes between river-dominated and marshlike waters. This chapter explains how to generate descriptors of reference conditions taking into account how human impacts affect coastal systems while providing steps to guarantee the sustainable use of estuarine resources. Chapter 17 (“Alteration and Remediation of Coastal Wetland Ecosystems in the Danube Delta: A Remote-Sensing Approach”), by Simona Niculescu, Cédric Lardeux, and Jenica Hanganu, demonstrates advantages of using remote sensing techniques to classify coastal wetland vegetation in the Danube Delta (a Biosphere Reservation), which was altered by human intervention in over one quarter of the entire delta surface. The random forest supervised classification algorithm was used to advantage for the Sentinel-1 and Sentinel-2 data collection. Chapter 18 (“Implementation of a Wildlife Management Unit as a Sustainable Support Measure Within the Palo Verde Estuary, Mexico: An Example of the American Crocodile [*Crocodylus acutus*]"), by Omar Cervantes, Aramis Olivos-Ortiz, Refugio Anguiano-Cuevas, Concepción Contreras, and Juan Carlos Chávez-Comparan, is a species-specific study in the Palo Verde Estuary (a Ramsar site) that recognizes that pollution, fragmentation of ecosystems, and habitat destruction due to human action incite the need for strategic management practices to encourage harvest sustainability. This chapter represents an opportunity to reconcile human activities with the environment based on an analysis made from the perspective of the conceptual Driving Forces-Pressure-State-Impact-Response model. Chapter 19 ("Mangrove Inventory, Monitoring, and Health Assessment"), by Ajai and H.B. Chauhan, identifies threats to mangroves from human activities (reclamation of mangrove areas for human habitation, aquaculture, agriculture, and port and industrial development) and shows how the use of remote sensing data can be used to develop a model for mangrove health assessment. The model developed here is demonstrated through a case study in India. Chapter 20 ("How Can Accurate Landing Stats Help in Designing Better Fisheries and Environmental Management for Western Atlantic Estuaries?"), by Mário Barletta, André R.A. Lima, David V. Dantas, Igor M. Oliveira, Jurandyr Reis Neto, Cezar A.F. Fernandes, Eduardo G.G. Farias, Jorge L.R. Filho, and Monica F. Costa, discusses fishery management in Brazilian estuaries while pointing out the need for better statistics to help avoid the impacts of overfishing. The main thrust of this chapter is the explanation of the need to improve fishery management by compliance of ecological data and biological research, obtaining robust data for landing stats, and establishing a social profile of the fishery community to build better rules of comanagement. Chapter 21 ("Returning the Tide to Dikelands in a Macrotidal and Ice-Influenced Environment: Challenges and Lessons Learned"), by Laura K. Boone, Jeff Ollerhead, Myriam A. Barbeau, Allen D. Beck, Brian G. Sanderson, and Nic R. McLellan, deals with the lessons learned from the design, implementation, and monitoring of salt marsh restoration in the upper Bay of Fundy, Canada. They found that the bioengineering species saltwater cordgrass (*Spartina alterniflora*) performed well and could be used again in similar situations. Chapter 22 ("Macrobenthic Assemblage in the Rupsha-Pasur River System of the Sundarbans Ecosystem (Bangladesh) for the Sustainable Management of Coastal Wetlands"), by Salma Begum, investigates a non-forestry product (benthic invertebrates) of the Sundarbans (the world's largest mangrove forest) and found that the combined effects of environmental and biological parameters influence relative species abundance. Chapter 23 ("Ecological Services of Intertidal Benthic Fauna and the Sustenance of Coastal Wetlands along the Midnapore [East] Coast, West Bengal, India"), the last chapter in the book, by Susanta Kumar Chakraborty, shows the value and functional contribution of benthic biodiversity (macrobenthos and meiobenthos) for the continuation of the Sundarbans mangrove estuarine complex. These bioindicators are indicative of the health of this disturbed coastal environment.

What is presented in this volume is but a snippet of the global situation confronting coastal wetlands today, which entails a universal threat from human action. The chapters illustrate the status of coastal wetlands from the geographical spread ranging from the tropics to high-latitudes via studies in Florida, Spain, Cameroon, Brunei Darussalam, Brazil, Bangladesh, Chile, Colombia, Australia, India, Egypt, Romania, Mexico, and Canada. These vignettes carry the common theme of coastal wetlands under stresses of variable types ranging dominantly from human action and less so from natural causes related to climate change. With about half of the world's coastal wetlands already destroyed by either urban expansion or the development of industrial and commercial infrastructure, the remainder are seriously threatened by a range of human activities (e.g., wood harvesting and loss of surrounding forests, sand extraction, petroleum exploitation, infringement from agricultural lands, wildlife poaching, increased salt pan and aquaculture farming, fishery development, land erosion, sediment deposition, and recreation) that usually fall under the radar of governing bodies that either turn blind eyes to what is happening or do not have the available resources to control the deterioration of the wetland ecosystems.

The other main theme of the various chapters is that the remaining coastal wetlands worldwide that have or continue to receive protection usually cannot remediate the damage that has already incurred. Although large areas have come under the "protection" of various types of statuses (e.g., Ramsar Convention, International Biosphere Reserve [UNESCO], International Union for Conservation of Nature and Natural Resources [IUCN]), this does not guarantee proper management by local authorities. Although the intent is laudable, the practicalities of the present world situation is that population growth is out of control in many regions that contain coastal wetlands. Human pressure on wetland resources is immense, and constructive efforts to protect, preserve, and conserve coastal wetland ecosystems are currently too weak to achieve goals that will maintain this valuable resource base for posterity. Several chapters point to new research that is being conducted into innovative ways of understanding and comprehending how these ecosystems function so they can be better managed. But the research and implementation of its findings are generally too slow compared to population growth with the result that coastal wetlands remain under threat from a wide range of human activities that eventually harken the death knell. What is required are more stringent protective measures that will secure a sustainable and unfettered future for the world's mangrove forests, fresh- and saltwater marshes, lakes, estuaries, and lagoons. All of the chapters in this book indicate in one way or another the present status and probable conditions of coastal wetlands as we look to the future.

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Chapter 10
Long Term Impacts of Jetties and Training Walls on Estuarine Hydraulics and Ecologies

Alexander F. Nielsen and Angus D. Gordon

Abstract Data and theory show that the inlets of several large estuaries on Australia's eastern seaboard that appeared to be stable within a range of entrance conditions are demonstrating unstable scouring modes and have been doing so for decades, if not centuries, since entrance jetties had been constructed. Jetties have increased the hydraulic conveyance of the entrance channels by removing sand bars and extraneous littoral currents that impeded ebb tide discharges. Field data comprising comprehensive water level monitoring in the bays, enabling the definition of tidal planes to a high resolution, have shown that the spring tidal ranges of these bays has been increasing steadily for decades with high tide planes rising and low tide planes falling. The field data have indicated that these changes show no signs of stabilizing and Escoffier analyses have indicated that it could take centuries for these inlets to reach new stable hydraulic regimes. Implications have included extensive scour in the entrance channels requiring channel erosion protection works, subsidence of road bridges, collapse of foreshores including buildings, sedimentation in the bays and on adjacent beaches and permanent changes to fringing marine ecologies and fisheries. Changes to the distribution of seagrass, saltmarsh and mangrove forests have been observed to coincide with and confirm the expectations of impacts on marine ecology that could derive from jetty construction. While jetties have improved flood conveyance significantly the increases in ebb tide velocities have resulted in navigational hazards for recreational boating.

Keywords Tidal constituents • Amplitude • Phase • Prism • Inlet • Equilibrium area • Escoffier stability analysis • Jetties • Training walls • Marine ecology

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10.1 Introduction

Continuously, natural inlets on littoral drift shores comprising entrance bars, shoals and channels are in a state of flux, changing in response to variations in the controlling hydrodynamic forces such as floods, variations in the spring-neap tidal range, varying wave climates and rates of littoral drift transport. Typically, they scour during flood events but, subsequently, trend towards closure as littoral drift reforms the entrance bars and shoals, potentially closing the inlet. For much of the time the wetlands associated with natural inlets are subjected to small tidal ranges, reflecting shoaled entrances, which control the extent and diversity of the wetland ecology.

The sensitivity of estuarine responses to such variations depends primarily on the size of the estuary. The most noticeably sensitive estuaries are the small bays and lagoons, the ocean entrances of which, generally, are closed but can be opened abruptly to wave and tidal forcing following floods. Such small estuaries are the least stable when open (Brown 1928; Bruun 1978; Gordon 1990). On the other hand, large estuaries, while open to the ocean for much, if not all, of the time and, hence, exposed to a greater range of variable hydrodynamic forcing, often have a tidal discharge and a channel cross-sectional area that appear to fluctuate about stable average values.

For the larger estuaries, such as those commonly used for recreational boating or commercial fishing, ever-changing bars, shoals and channels present uncertainty and risks to navigation. Further, shoaled entrances can result in the backup of floodwaters causing inundation of waterfront properties. Often the response to navigational and flooding issues has been to construct entrance channel improvements such as training walls and jetties. In most cases these works have achieved their intended results, often spectacularly, but many have been implemented without an understanding of the potential long term impacts. Training walls and jetties can alter estuarine hydraulics significantly, increasing hydraulic conveyance, inducing scouring of the channels, changing tidal planes and, hence, changing the environmental conditions of the associated wetlands.

Large estuaries respond slowly to perturbations at their entrances and the signature of any change to their stability may go undetected for many years to decades. However, once set in motion, a change to the dynamic stability of a large estuary, which may have been occasioned by jetty construction, for example, or from a rising mean sea level, will be difficult to predict both in the degree of change and time to reach a new state of dynamic equilibrium.

As a result of technological advances in water level data loggers there is now a large and growing body of empirical data that allows for a closer examination and definition of estuarine hydraulics and inlet stability. Hourly water level recordings allow the determination of high-resolution, objective, statistical estimates of the tidal constituents on an annual basis that can be used to define accurately the relevant parameters of tidal range, phasing, prism and levels that are used in estuary stability theories. Examining the time histories of amplitude and phase of tidal constituents within estuaries where jetties have triggered unstable scouring modes, along with classic estuary stability theory, informs the hydraulic and ecological impacts of jetty and training wall construction and their future prognosis.

This chapter outlines theories related to the hydraulics of tidal channels and bays in communication with the ocean, the impacts of training walls and jetties on estuarine hydraulics, sediment transport, channel stability and the subsequent impacts on the marine ecology of the associated estuaries. The impacts are illustrated with three well-documented examples from two large and one smaller estuary on the Australian eastern seaboard.

10.2 Estuary Characteristics

10.2.1 Conceptual Model

The particular situations described herein apply only to specific estuary types and do not include large drowned river valleys or long narrow rivers that, generally, are not as susceptible to these processes. The natural elements that characterize the behavior of the estuaries of interest include an infinitely large water source (the ocean) with a periodic tide of reasonable amplitude connected to a relatively large coastal bay or lagoon that has the potential to generate a large tidal prism, by a relatively narrow and shallow erodible sandy channel; the ocean entrance of the channel being exposed to waves and the ingress of littoral drift.

In their natural state, on shores experiencing relatively high rates of littoral drift transport and in the absence of any significant precipitation, such estuaries trend towards closure (Brown 1928; Bruun 1978; Gordon 1990). However, flood events and, sometimes, large spring tides may scour the surf zone bars, the entrance channel and shoals, thereby removing the littoral drift that had been deposited over time and had choked the flow. The resulting reduction in hydraulic impedance at the entrance produces greater tidal discharges and, hence, the tidal ranges in the bay increase for a time. However, during ensuing dry periods, waves and currents re-establish the entrance bars and move littoral drift back into the entrance, resulting in the reformation of the marginal shoals, thereby increasing the impedance to the penetration of the tidal wave with the resulting loss of hydraulic efficiency to drive flows to and from the bay. The tidal range in the bay reduces progressively until either the entrance closes or the tidal flushing and occasional rainfall events are sufficient to keep a channel open, albeit in a shoaled state.

The action that alters fundamentally the natural cycle described above is the construction of entrance jetties that both increase depths over the offshore bars and limit or eliminate the ingress of littoral drift to the entrance channel. This produces a more hydraulically-efficient entrance allowing greater penetration of the tidal wave into the estuary. This increase in hydraulic conveyance depends upon the degree to which the works modify the behavior of the entrance bar. Experience on the Australian eastern seaboard has shown that a single jetty tends to have only a

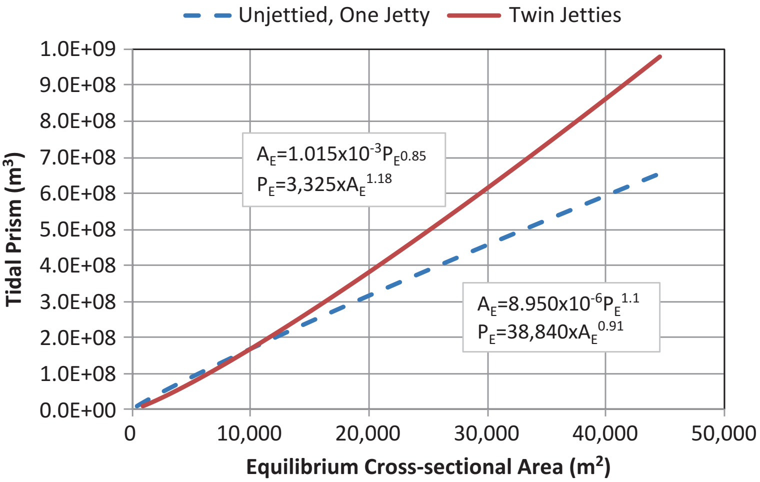

Fig. 10.1 Tidal prism vs. channel cross-sectional area for Pacific coast inlets (After Jarrett 1976). The boxes present the original equations (in metric units) with an inverted format presenting the equilibrium tidal prism as the dependent variable plotted on the ordinate. For the larger cross-sectional areas the tidal prisms for twin-jettied inlets is always larger than those with one or no jetty

modest impact on improving the overall hydraulic efficiency of an entrance. This is because a component of the gross littoral drift can enter the entrance channel from the unprotected side. However, twin jetties that intersect the surf-zone increase the hydraulic conveyance significantly. Such differences are found also on both the USA Atlantic and Pacific coasts where, for the same cross-sectional areas, twin jetties generate larger tidal prisms than do single jetty entrances or inlets without jetties (Jarrett 1976; see Figs. 10.1 and 10.2).

With the reduction of hydraulic impedance at the entrance due to twin jetty construction, the channel connecting the ocean to the bay begins to scour under steepened hydraulic gradients that increase channel velocities (Nielsen and Gordon 1980, 2008, 2011, 2015). This establishes a positive feedback loop; as channel depths increase, channel friction reduces and hydraulic gradients become steeper resulting in ever greater tidal discharges and velocities. Finally, but after a long time, the process begins to slow down as progressively increasing bay tidal ranges and reducing bay tidal phase lags begin to reduce hydraulic gradients and, hence, scour potential. As channel velocities approach the equilibrium velocity (O'Brien 1931, 1969; Jarrett 1976), channel scour ceases and a new stable hydrodynamic regime is reached. The larger the bay the longer it will take to reach a new equilibrium. Constraints to this runaway situation created by the construction of twin jetties can include bedrock controls, bank protection works or the imposition of relatively large structures, such as bridge abutments or a marina, in the entrance channel.

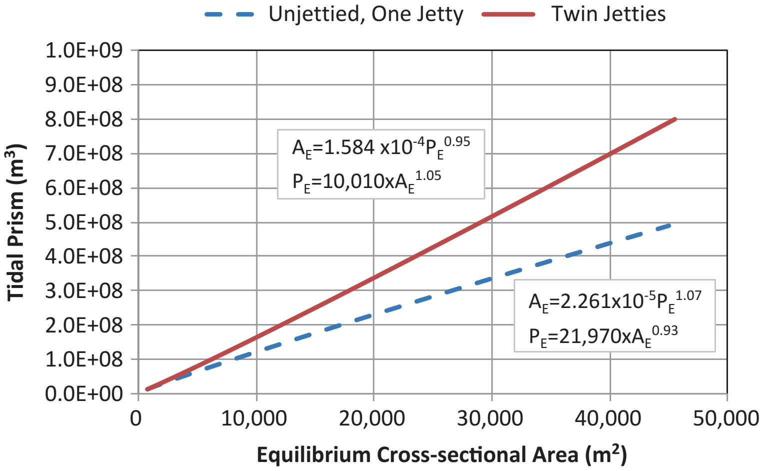

Fig. 10.2 Tidal prism vs. channel cross-sectional area for Atlantic coast inlets (After Jarrett 1976). The boxes present the original equations (in metric units) with an inverted format presenting the equilibrium tidal prism as the dependent variable plotted on the ordinate. For the larger cross-sectional areas the tidal prisms for twin-jettied inlets is always larger than those with one or no jetty

10.2.2 Tidal Constituents

The tidal signature in a waterway is a characteristic, sinusoidal oscillation comprising either two main cycles per day (semi-diurnal tides), one cycle per day (diurnal tides), or a combination of the two (mixed tides).

The underlying principle of tidal analysis is that a time series of tidal oscillations can be deconstructed into a series of regular sinusoids, usually represented by the cosine function, each having the period of oscillation of the celestial forcing that gives rise to it. The tidal harmonic constants comprise the amplitude and phase of the individual cosine waves, each of which represents a tidal constituent identified by its period.

While there may be scores of tidal constituents computed for a tidal harmonic analysis, the following are the major contributors to the astronomical tidal stage variation:

M2 – principal lunar semi-diurnal constituent
S2 – principal solar semi-diurnal constituent
K1 – luni-solar declinational diurnal constituent
O1 – lunar declinational diurnal constituent.

Empirical and analytical formulations for estuary hydraulic analyses rely on good estimates of the estuary's tidal planes, either to determine accurately the spring tidal prism or to determine accurately the bay-to-ocean tidal range ratio. The spring

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tidal range, mean high water springs (*MHWS*) minus mean low water springs (*MLWS*), is defined as:

$$MHWS - MLWS = 2 \times \left(M2_{amplitude} + S2_{amplitude} \right) \tag{10.1}$$

Accurate and consistent estimates of these tidal constituent parameters can be obtained only from long-term continuous tide recordings. Usually, such data are available only from government-operated sites, often managed by hydraulic laboratories.[1]

10.2.3 Channel Flow and Training Walls

Training walls may be constructed along the banks of an entrance channel, often to manage bank erosion. Such works can change the hydraulic characteristics of a channel and, invariably, increase its hydraulic conveyance by reducing the impedance to flow.

The basic equation for open channel flow is termed the Manning (or sometimes Strickler's) equation thus, in metric units (for example, see Henderson 1966):

$$v = \frac{R^{\frac{2}{3}} \times S^{\frac{1}{2}}}{n} \tag{10.2}$$

where:

v = channel velocity (m/s)
R = hydraulic radius (m)
 $= A_C/P$
A_C = channel cross-sectional area (m^2)
P = wetted perimeter (m)
S = energy or water surface slope (-)
n = Manning's bed roughness coefficient (-).

The instantaneous channel discharge, q, is the product of the average channel velocity, v, and the cross-sectional area, A_C, thus:

$$q = v \times A_C \tag{10.3}$$

Figure 10.3 presents schematic diagrams of three channel types; a natural channel in sand with typical side bed-slopes of 1:10 (vertical:horizontal), a channel in

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[1] The field data upon which the research herein was based was provided generously by the NSW Government Public Works Department Manly Hydraulics Laboratory. The authors take responsibility for its analysis and interpretation.

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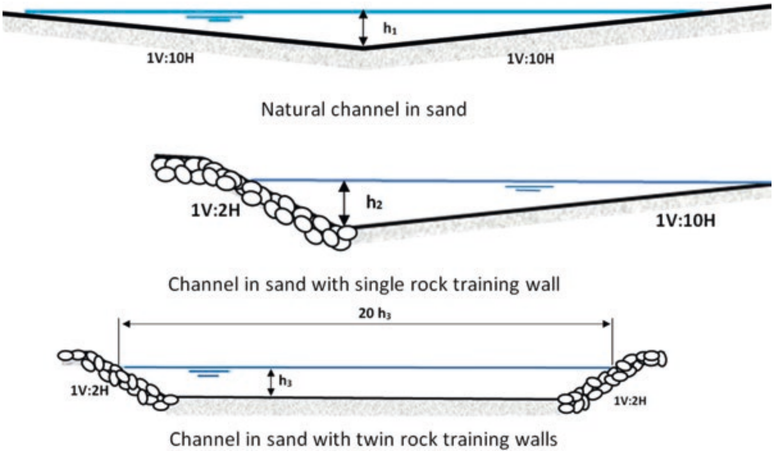

Fig. 10.3 Schematic diagrams portraying (1) a typical channel in sand (*top*); (2) a typical channel in sand with a single rock training wall (*middle*); (3) a typical channel in sand with twin rock training walls (*bottom*). Fundamental equations for channel hydraulics applied to these sections with equal areas demonstrate that training walls enhance hydraulic conveyance

sand with a single rock training wall of side slope 1:2, and a channel in sand with twin rock training walls. It can be demonstrated using Eqs. 10.2 and 10.3 that, for channels with equal cross-sectional areas, bottom roughness and water surface slopes, the channel with a single training wall would discharge 16% more water than the natural channel and the channel with twin training walls would have a 20% higher discharge than the natural channel. Thus, training walls alone improve significantly the hydraulic conveyance of tidal channels, without taking into account the impact that jetties may have on altering littoral drift processes.

10.2.4 Inlet Stability Theory

The understanding of estuary inlet hydraulics and stability is based on the synthesis of empirical and analytical formulations.

Empirical formulations (O'Brien 1931, 1969; Jarrett 1976; Bruun 1978) comprise the identification of relevant parameters, such as tidal prism, entrance cross-sectional area and rate of littoral drift transport to the inlet, relating cause and effect, and the development of relationships between these parameters using coefficients derived empirically from many field observations.

Analytical approaches comprise the development of generalized formulae from mechanism understanding relating bay tidal range (tidal prism) and lag, entrance channel area and velocity, channel head losses, friction and the forcing ocean tidal range (Brown 1928; Escoffier 1940; Keulegan 1951, 1967; O'Brien and Dean 1972; Czerniak 1978; van de Kreeke 1992; Seabergh 2003).

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10.2.4.1 Empirical Formulations

From empirical data, O'Brien (1931) proposed that the stable inlet cross-sectional area could be determined from the tidal prism using the relationship (in metric units):

$$A_E = 9 \times 10^{-4} P_E^{0.85} \tag{10.4}$$

where:

A_E = equilibrium cross-sectional area below mean sea level (m^3)
P_E = equilibrium spring tidal prism (m^3).

Many other similar relationships with different constant and exponent values have been developed for various sites and differing entrance jetty configurations (Jarrett 1976; van de Kreeke 1992; Seabergh and Kraus 1997).

Of particular interest are the data from Jarrett (1976) on inlet configurations comprising twin jetties, a single jetty and/or no jetty, presented in Fig. 10.1 for the US Pacific coast and Fig. 10.2 for the US Atlantic coast, which show that estuaries with twin jetties invariably have larger tidal prisms than do those with a single jetty or no jetty, implying that twin jettied entrances have greater hydraulic conveyance.

These relationships between the spring tidal prism and the channel cross-sectional area of stable inlets imply that equilibrium channel velocities can be determined for inlets on various coasts with differing tidal regimes and with differing entrance configurations. If the form of the discharge curve can be assumed to be sinusoidal, the tidal prism can be related simply to the peak ebb tide discharge and, hence, the peak (maximum) channel velocity. Therefore, the equilibrium velocity for any stable inlet can be determined from these relationships thus:

$$P_E = \frac{v_{E_{\max}} A_E T}{\pi} \tag{10.5}$$

where:

P_E = equilibrium tidal prism (m^3)
v_{Emax} = maximum equilibrium channel velocity (m/s)
A_E = equilibrium channel cross-sectional area (m^2)
T = tidal period (s)

Combining Eqs. (10.4) and (10.5), for semi-diurnal tides – tidal periods of 12.42 h – the following relationship between the equilibrium flow area and equilibrium maximum channel velocity is derived from O'Brien's (1931) equation (in metric units):

$$v_{E_{\max}} = 0.269 A_E^{0.176} \tag{10.6}$$

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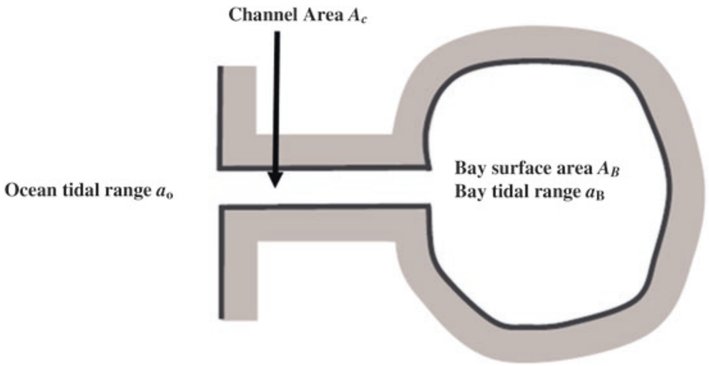

Fig. 10.4 Idealized estuary for Escoffier inlet analysis. The analysis assumes short regular entrance channels without surf zone bars and shoals

Similar equations can be derived from the myriad of prism/area relationships that have been developed since that of O'Brien (1931). For example, from Jarrett (1976) for twin jetties on the Pacific coast, the relationship is (in metric units):

$$v_{E_{\max}} = 0.509 A_E^{0.081} \tag{10.7}$$

Bruun (1978) presented a simple empirical relationship, based on the ratio of the tidal prism to the rate of littoral drift transport to the entrance, which determined whether an estuary may be prone to closure or may remain open. Low values of the ratio denoted an unstable shoaling mode (in the terminology of O'Brien and Dean 1972). However, this method does not predict an unstable scouring mode or a stable channel cross-sectional area. Further, the method does not apply to entrances where the littoral drift transport to the inlet has been interrupted by jetties.

10.2.4.2 Analytical Formulations

Brown (1928) and Escoffier (1940) presented a generalized analytical approach for a simple idealized estuary system, as shown in Fig. 10.4, relating the bay tide phasing and amplitude to that of the ocean tide through the hydraulic characteristics of the entrance channel. The method is applicable to small and large tidal inlets on shorelines where the rates of littoral drift transport are small. It favors estuaries with relatively short and regular entrance channels connecting the bay to the ocean.

Through the construction of an Escoffier Diagram, the status of an inlet at any point in time can be examined and, theoretically, the ultimate stable cross-sectional area of the entrance channel can be predicted. The method is outlined as follows (after O'Brien and Dean 1972).

Keulegan (1951, 1967) developed the relationships between the tidal phase lag, the ratio of the bay-to-ocean tidal amplitudes (a_B/a_O) and what is termed the

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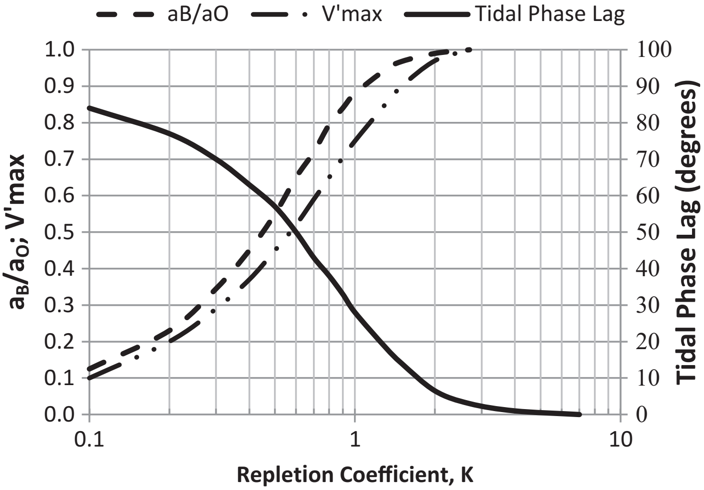

Fig. 10.5 The relationship between the Repletion Coefficient, *K*, and the ratio of the bay tide to ocean tide, a_B/a_O, the tidal lag and the dimensionless maximum velocity, v', in the entrance channel (From Keulegan 1951, 1967). Increasing *K* values denote more efficient repletion or filling of the bay storage volume as channel velocities increase, bay tidal ranges increase and tidal phase lags decrease, the high tide level in the bay being reached sooner

Repletion Coefficient (*K*; increasing *K* implies a more efficient repletion or filling of the bay storage volume), as shown in Fig. 10.5. Keulegan (1951, 1967) presented also the relationship between the repletion coefficient and the dimensionless maximum velocity in the inlet (v'_{max}), shown in Fig. 10.5, where the maximum velocity through a specific inlet is given by:

$$v_{\max} = v'_{\max} \frac{2\pi}{T} a_O \frac{A_B}{A_C} \tag{10.8}$$

The Repletion Coefficient, *K*, may be expressed as a function of the hydraulic and geometric properties of the estuary as follows:

$$K = \frac{T}{2\pi a_O} \frac{A_C}{A_B} \sqrt{\frac{2ga_O}{k_{en} + k_{ex} + \frac{fL_c}{4R}}} \tag{10.9}$$

where:

T = tidal period (s)
a_o = amplitude of the ocean tide (m)
A_C = inlet cross-sectional flow area (m^2)
A_B = surface area of the bay (m^2)
g = gravitational constant (m/s^2)

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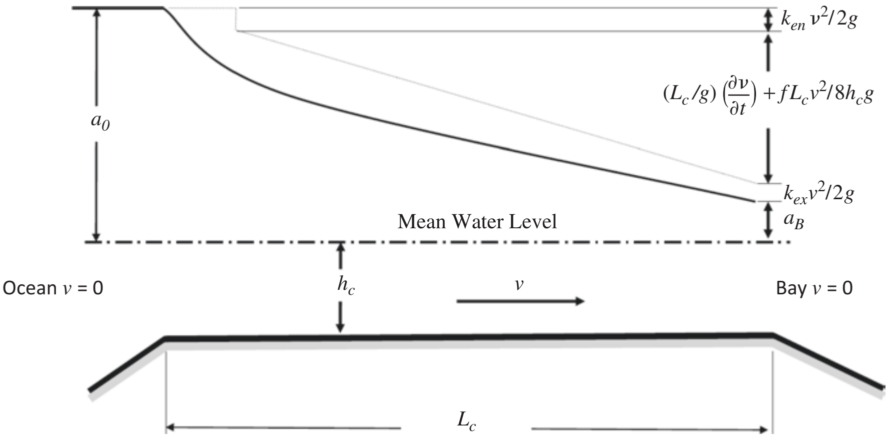

Fig. 10.6 Idealized entrance channel head losses assumed in the Escoffier inlet analysis depicting channel entrance (k_{en}) and exit (k_{ex}) losses and friction losses along the channel length for a channel velocity v. No entrance bar losses are assumed

k_{en}, k_{ex} = channel entrance/exit head loss coefficients (Fig. 10.6)
f = friction factor (-)
= $0.113(k_s/R)^{1/3}$ (Henderson 1966)
k_s = height of surface roughness (m)
R = hydraulic radius of entrance channel (m)
L_c = friction length (m; Fig. 10.6)

Where Eqs. 10.8 and 10.9 and Fig. 10.5 are used together, a range of inlet hydraulic conditions can be calculated in terms of the maximum velocity versus cross-sectional flow area. The inlet mechanics are portrayed by the inlet stability curve or Escoffier Diagram (Fig. 10.7).

It can be seen from this diagram that an induced change in the cross-sectional flow area of an hitherto hydraulically stable inlet, which has a flow area (A_E) in equilibrium with the tidal prism (P_E), will result in either a change in inlet current velocity that will work to return the inlet towards its equilibrium flow area by appropriate deposition or scour or, if the induced area change is so large as to reduce the cross-sectional area below the critical flow area, A'_c, making the inlet hydraulically unstable. An hydraulically unstable inlet is characterized by increasing friction with decreasing cross-sectional area or vice versa. The result is that if any natural or man-induced change in flow area occurs, this is accompanied by a change in the flow velocity that will, by inducing scour or deposition, perpetuate the induced area change. Since area changes are perpetuated, an hydraulically unstable inlet will either scour continuously until a stable flow area is achieved (unstable scour mode) or it will shoal continuously until inlet closure (unstable shoaling mode).

Other interpretations of the Escoffier Diagram place significance on the first (or lower) intersection of the "closure" curve with the equilibrium P_E/A_E relationship, classifying unstable inlets as only those having cross-sectional areas smaller than

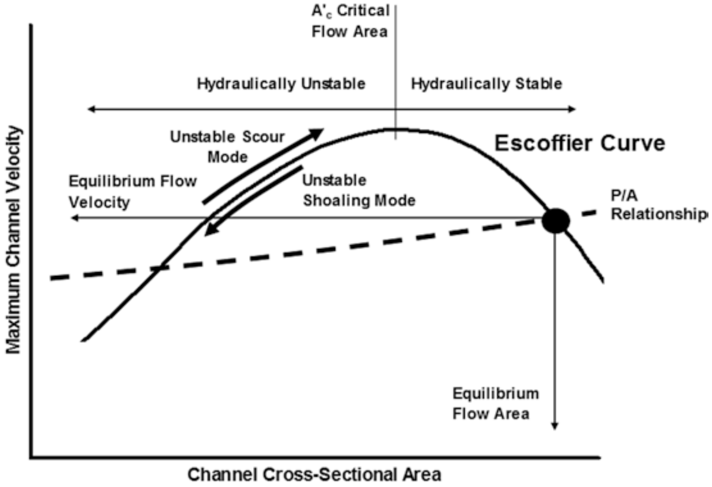

Fig. 10.7 Inlet stability curve or Escoffier diagram. An hydraulically stable inlet will strive to have a tidal prism/channel cross-sectional flow area as determined by the equilibrium *P*/*A* relationship. Natural tidal inlets with shoaled entrances may be induced to either scour to reach the equilibrium flow area or shoal to closure

that value (van de Kreeke 1992). Escoffier (1940) dismissed any relevance of this lower root.

Seabergh (2003) discussed approaches other than those using an equilibrium P_E/A_E relationship for determining the stable equilibrium condition on the Escoffier Diagram. Mota Oliviera (1970) proposed that the stable point may be reached when the Repletion Coefficient reached a value between 0.6 and 0.8. This was based on calculations that included the consideration of tidal stage with maximum ebb tide scour velocities, which occurred on low waters rather than on the Keulegan (1967) assumption of average depth. Another approach of Skou (1990) proposed that the most optimum situation for an inlet to remain stable was where the cross-sectional area coincided with the maximum gradient of the Escoffier curve.

When constructing the Escoffier Diagram for a particular estuary the following approach can be used (after Czerniak 1978):

- a_B/a_O is calculated from existing data and K is determined from Fig. 10.5
- Equation 10.7 is solved for L_c using K and known values of A_c, R, T, a_O, A_B, f, k_{en} and k_{ex}
- The hydraulic stability curve is computed using Eqs. 10.6 and 10.7 and Fig. 10.5 (for v'_{max}) with only A_c (and, consequently, R and, hence, f) varying over the entire range, maintaining the ratio of channel width to depth used in the calibration.

In Eq. 10.7, four head loss parameters (k_{en}, k_{ex}, f, L_c) are used to describe the total impedance of the entrance channel to the flow. A typical value for $k_{en} + k_{ex}$ is 1.3 (O'Brien and Dean 1972) with $f = 0.02$ being adopted for the calibration conditions adopted herein, thereafter f varying with R as indicated in Eq. 10.9.

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There are two major sources of head loss between the forcing function, a_O (the amplitude of the ocean tide) and the bay response, a_B. These are the head loss over the entrance bar and the losses associated with the hydraulic characteristics of the entrance channel. As the forcing function is applied immediately outside the inlet, a_o is not a true ocean tidal amplitude unless entrance bar losses are negligible. Otherwise, bar losses need to be accommodated in the analysis (Nielsen and Gordon 1980).

Many limitations of the generalized analytical modelling approach are documented in Bruun (1978). A significant limitation of the approach is that it is an inaccurate predictive tool in situations where significant perturbations are to be made to the inlet impedance, such as those associated with the construction of entrance jetties (Nielsen and Gordon 1980). This is because the estuary stability relationship (entrance channel velocity versus cross-sectional area) cannot be constructed accurately if the inlet and channel head losses vary significantly from the “natural” calibrating condition. Difficulties can arise also where the dimensions of an entrance channel vary significantly along its length, where there are multiple channels or where significant abrupt head-losses are encountered at severe bends, constrictions and bridge crossings; that is, where the basic assumption of a short regular entrance channel in unconsolidated sediment is violated. Further difficulties can arise also where changes are introduced to channel conveyance through rock armoring and groin construction. Finally, the method can assess only the potential for change; it cannot, of itself, indicate whether or not an estuary is in a process of change.

Nevertheless, the development of these empirical and generalized analytical formulations for estuary stability presents a sound basis for an understanding of inlet tidal hydraulics. Of particular note is that the spring tidal prism is a common and most important parameter to all of these stability criteria. This can be defined accurately, objectively and consistently from the tidal constituents.

10.2.5 Marine Ecology

Estuarine macrophytes (saltmarsh, mangrove, seagrass) grow within the sub-tidal and inter-tidal zones where their presence is affected by physical, chemical and hydrodynamic conditions (Kailola 1993). Estuarine macrophytes are fundamental building blocks of estuarine ecology as they create new tissue from sunlight and, hence, initiate estuarine food chains, they provide habitat for fish, crustaceans and molluscs in which to shelter from predators as well as forage for food. Most of the commercially and recreationally important fish species on Australia’s eastern seaboard are dependent at some stage of their life cycle on estuarine habitats.

A generalized schematic diagram of the distribution of macrophytes around the fringes within tidal estuaries is presented in Fig. 10.8. Rising tidal planes within estuaries are likely to impact these fringing ecologies. Saltmarsh habitat is very sensitive to tidal levels and increasing levels are likely to result in excessive flooding and loss of saltmarsh habitat, which would then be colonized by mangrove species.

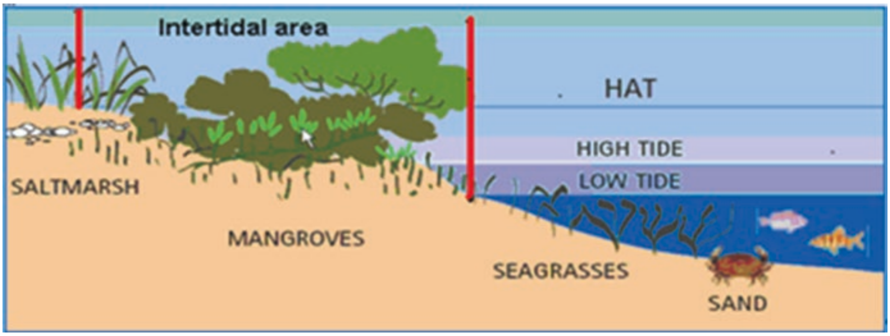

Fig. 10.8 Common fringing habitat zones in an estuary (Kailola 1993). HAT is highest astronomical tide. Saltmarsh is sensitive particularly to tidal levels. Various seagrass species are sensitive to water depth

Alternatively, if the topography is favorable, saltmarsh communities may migrate upstream into tributaries as may mangroves.

10.3 Impacts on Estuarine Hydraulics

10.3.1 *Introduction*

An estuary experiencing an unstable scouring or shoaling mode will have a tidal prism, channel cross-sectional area and hydraulic radius that are all varying with time, even if the banks are fixed by training walls, in which case the bed of the channel is the variable parameter for cross section and hydraulic radius. While it may be possible using the Escoffier inlet stability theory to identify that an estuary may be prone to such instability, it is not possible always to predict if an estuary is unstable, what the ultimate stable configuration may be and when that may be reached.

Should the amplitudes of the major tidal constituents measured within an estuary be increasing, this would be an indicator of increasing tidal prism. Similarly, should the phase lags of the major tidal constituents be decreasing, this would be an indicator also that the tidal wave is penetrating the estuary more efficiently, implying increasing tidal prism or improved efficiency of the tidal conveyance in the entrance channel. Conversely, should the amplitudes of the major tidal constituents be decreasing and/or their phase lags increasing, this would be an indicator of decreasing tidal prism and, possibly, an unstable shoaling mode. The rates of change of these parameters may be used to estimate the time it may take to reach a stable state.

In the following, the time histories of the variations in the spring tidal constituents of three estuaries with jettied entrances in New South Wales, Australia are examined; two are relatively large and the other an order of magnitude smaller. The

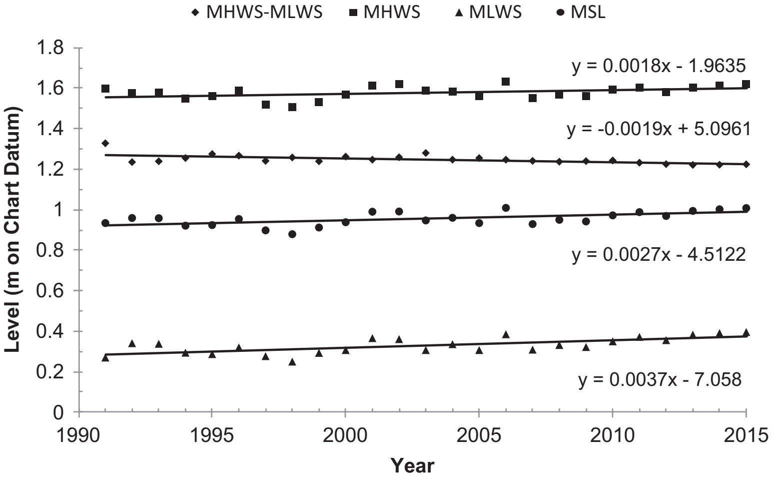

Fig. 10.9 History of ocean tidal planes at Sydney 1990–2015 (Data from NSW Public Works Manly Hydraulics Laboratory). These data are relevant to compare with changes to the tidal planes examined in the estuaries of interest exemplified herein. For the 25 years since 1990 the mean sea level (MSL) has increased at an average rate of 2.7 mm/a whereas the spring tidal range (MHWS-MLWS) has decreased at an average rate of 1.9 mm/a as measured in Sydney Harbor

data have been used to develop Escoffier analyses for each and to investigate if the time to reach stable configurations can be estimated.

10.3.2 Ocean Tidal Constituents Control Data

If the tidal constituents in the ocean vary over time then it could be expected that those within estuaries would follow suit. Therefore it is important to normalize the basis for tidal analysis. For the NSW estuaries exemplified herein, the selected control data set for the histories of amplitude and phase of the major ocean spring tidal constituents was that represented by the Sydney Harbor tidal data, a large, relatively deep, drowned river valley estuary with a reliable and stable tidal gauging station. The baseline information from the Sydney gauge is presented in Figs. 10.9 and 10.10.

Figure 10.9 shows that for the period 1990–2015, mean sea level (*MSL*) rose over the period at an average rate of 2.7 mm/a and, while mean low water springs (*MLWS*) rose at a higher rate of 3.7 mm/a, mean high water springs (*MHWS*) rose at a slower rate of 1.8 mm/a, resulting in an average decrease in the ocean's spring tidal range of 1.9 mm/a over that period. This reduction in ocean spring tidal range is an important consideration when comparing it with the increases in spring tidal range of the estuaries exemplified herein.

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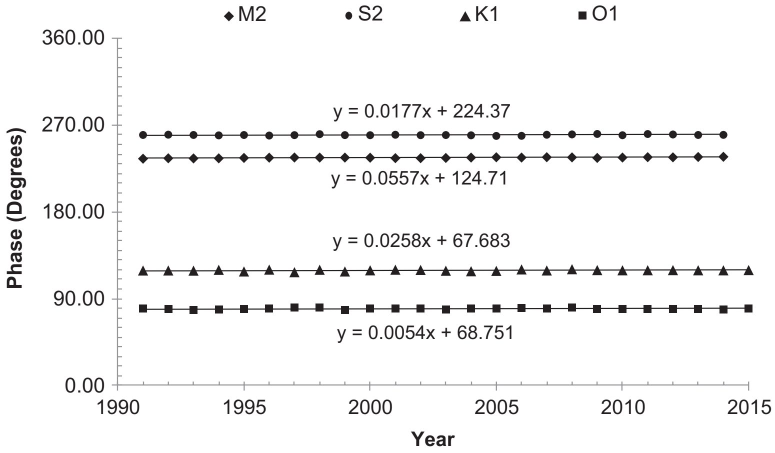

Fig. 10.10 History of major ocean tidal constituent phases at Sydney 1990–2015 (Data from NSW Public Works Manly Hydraulics Laboratory). For the 25 years since 1990 the phases of the major ocean tidal constituents as measured in Sydney Harbour have all increased

Figure 10.10 shows that over that period the phase of all of the major tidal constituents increased at average rates varying from 0.005 to 0.05°/a, with the major tidal constituent, *M2*, increasing at an average rate of 0.017°/a.

As the ocean tidal signature is the main forcing agent of the estuarine hydraulics, these data form an important control data set with which the tidal signatures within the case study bays are compared.

10.3.3 Wallis Lake

The Wallis Lake estuary on the mid-north coast of NSW is a complex system of bays and rivers with inter-connecting channels that separate the towns of Tuncurry and Forster, located adjacent to the ocean inlet (Fig. 10.11). The bay has a plan area of some 100 km^2 (Fig. 10.12) and has a mean spring tidal range of around 0.15 m. On very large spring ebb tides near solstices, peak velocities through the entrance channel between the jetties, which are 100 m wide, exceed 3 m/s, presenting challenging conditions for recreational boaters. The tidal prism on these higher spring tides has a discharge in the order of the annual average flood (Nielsen and Gordon 1980).

Prior to any training wall and jetty construction, the ocean entrance to the Wallis Lake estuary was choked with littoral drift (Fig. 10.13). The ruling depth on the ocean bar was 0.6 m (2 ft) on low waters. The estuary was reported to have been closed for many years in around 1831 (Pennington 1877). Over the time of recorded history only fresh water floods kept the inlet open until jetty construction modified the entrance.

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Fig. 10.11 The Wallis Lake Estuary entrance at Forster/Tuncurry, looking west (Photo courtesy NSW Government). Tidal communication between the ocean and the bay (Wallis Lake) is effected through a myriad of channels. The piling foundations for the road bridge in the foreground have been compromised severely by channel scour

The southern (Forster) jetty was constructed in 1898. While it improved the tidal conveyance somewhat, often entrance navigability was compromised still so, in 1966, the southern jetty was extended some 90 m and a 460 m long jetty was constructed on the northern (Tuncurry) side.

Dramatic changes to the Wallis Lake estuary ensued. These were attributed to the increased hydraulic conveyance of the inlet occasioned by the construction of the northern jetty (Nielsen and Gordon 1980). Since 1990, when consistent and reliable data became available, the bay's spring tidal range, as measured at Tiona (Fig. 10.12), has continued to increase at a rate of 1.8 mm/a ($R^2 = 0.89$) and, by the year 2015, the ratio of the bay range to that of the ocean had risen from 0.09 to 0.14, a 55% increase, at a rate of 0.0016/a ($R^2 = 0.92$) and showing little signs of abating (Fig. 10.14).

The history of the major spring tidal constituent ($M2$) phase lag (bay phase minus ocean phase) from 1990, presented in Fig. 10.15, shows a weak decreasing trend indicating increasing efficiency in tidal wave penetration of the estuary.

An Escoffier Diagram (Fig. 10.16) was constructed for Wallis Lake following the method of Czerniak (1978), assuming the most constricted width of the inlet channel (Seabergh and Kraus 1997) of 100 m at the entrance with a channel depth of 5 m. This gave an effective friction length for the channel of 3,400 m. It was assumed also that the tidal discharge curve was sinusoidal with period 12.4 h to enable the

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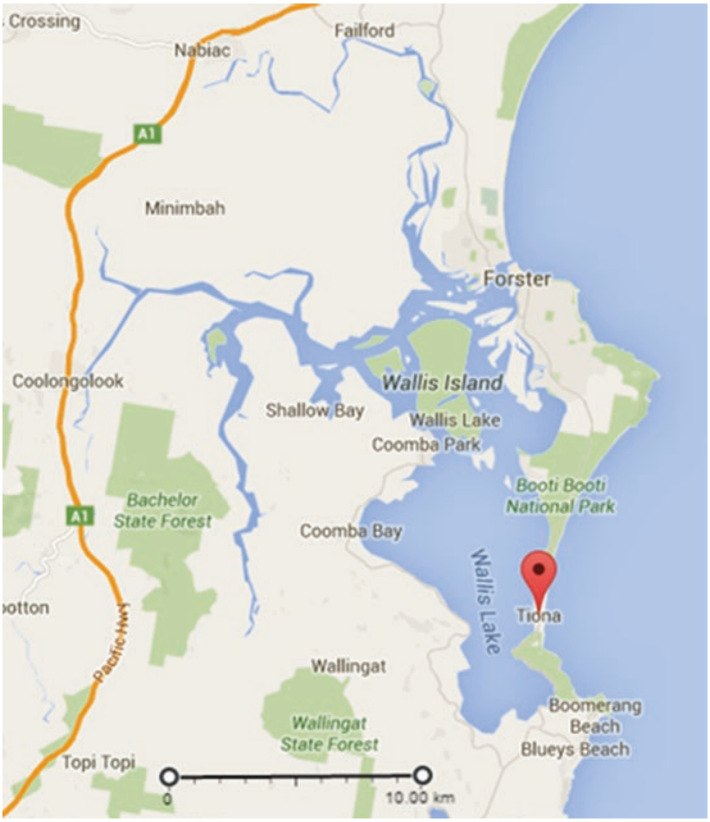

Fig. 10.12 A plan of the Wallis Lake estuary showing the ocean entrance at Forster and the location of the bay (Wallis Lake) tide gauge at Tiona (Courtesy Google maps). To note are the rivers that kept the natural entrance open by debauching flood waters. Historically, the inlet had closed during periods of prolonged drought

stable equilibrium flow velocities to be determined from the O'Brien (1969) and Jarrett (1976) prism-area relationships.

The Escoffier Diagram (Fig. 10.16) indicated that the estuary channel was in an unstable scouring mode. In accordance with O'Brien (1931), an equilibrium condition would be reached when the flow area reached some 6,000 m^2, a tenfold increase. By that stage the bay-to-ocean spring tidal range ratio (a_B/a_O) would have reached 1.0, increasing from 0.14. At an average rate of increase for a_B/a_O of around 0.0016/a (Fig. 10.14), it would take some 540 years for the equilibrium cross-sectional area to be reached. However, taking the approach of Mota Oliviera (1970), where stability could be reached when K reached a value between 0.6 and 0.8, a_B/a_O would have a value of between 0.65 and 0.78 and it would take some 300 to 400 years for the equilibrium cross-sectional area to be reached. It is noted that as scour progresses, the Escoffier diagram indicates that the rate of change may increase, which would reduce the time estimated to reach equilibrium.

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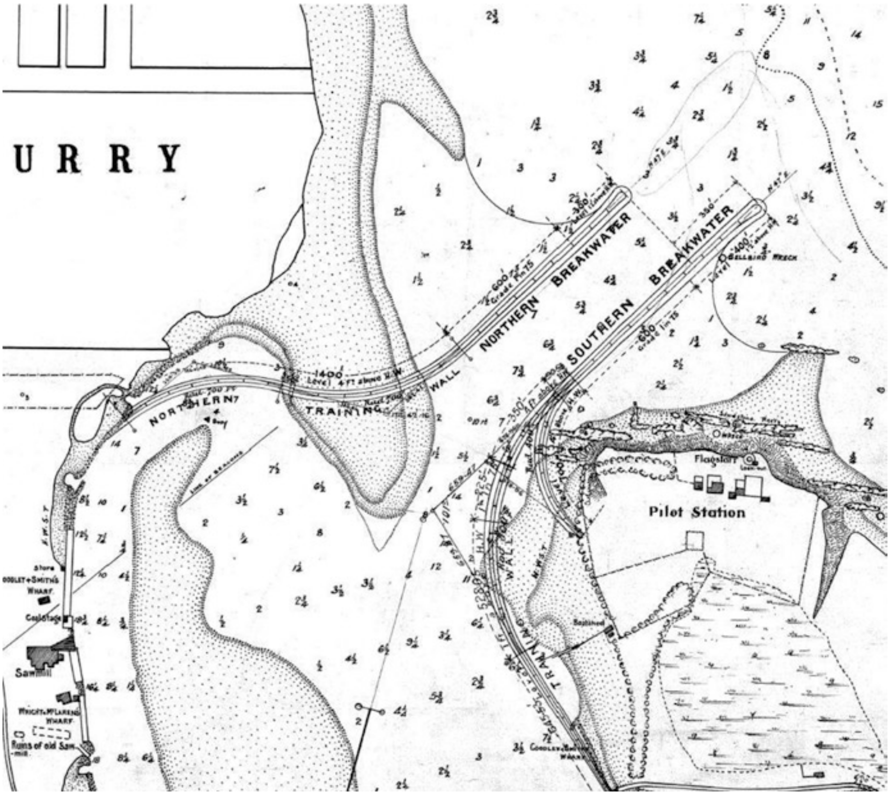

Fig. 10.13 Wallis Lake inlet prior to training wall and jetty (breakwater) construction and showing proposed jetties (water depths given in feet to Indian Springs Low Water – ISLW; Survey Plan courtesy of NSW Government)

These changes are difficult to contemplate as they assume that the jetty lined entrance can scour sufficiently to accommodate the additional flow. At present the field data give no hint of stabilization and the changes in tidal range and channel scour continue unabated.

10.3.4 Lake Macquarie

Lake Macquarie is on the NSW central coast some 25 km south of Newcastle (Fig. 10.17). The bay has a plan area of around 110 km^2 and is connected to the ocean by an irregular 4,700 m long Swansea Channel (Fig. 10.18) of average depth around 2.0 m, average width around 400 m and with various forms of rock bank protection along much of its length. It has dual highway bridges crossing the entrance channel that constrain the tidal flow. The bay spring tidal range is around

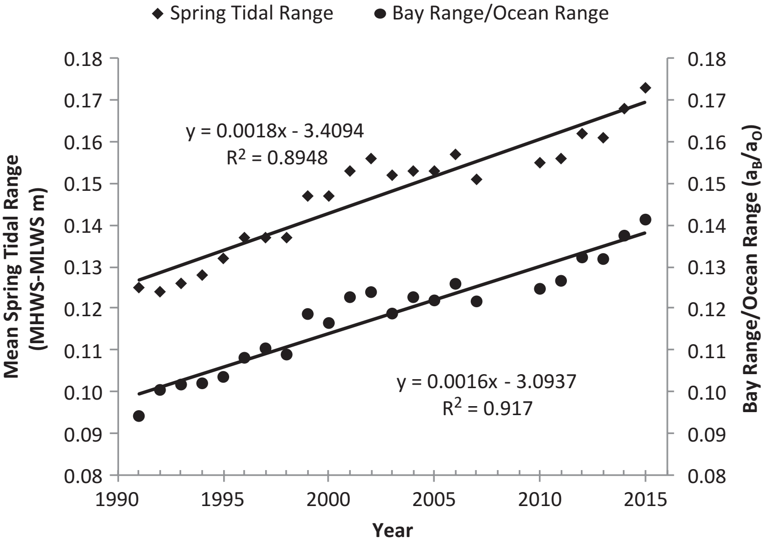

Fig. 10.14. Change history of the mean spring tidal range in Wallis Lake and its ratio to the ocean range. The trends are strong (R^2 = 0.9) showing no signs of abating. With the bay area some 100 km^2, the increase in the spring tidal range of 1.8 mm/a equilibrates to an annual increase in the spring tidal prism of 180,000 m^3

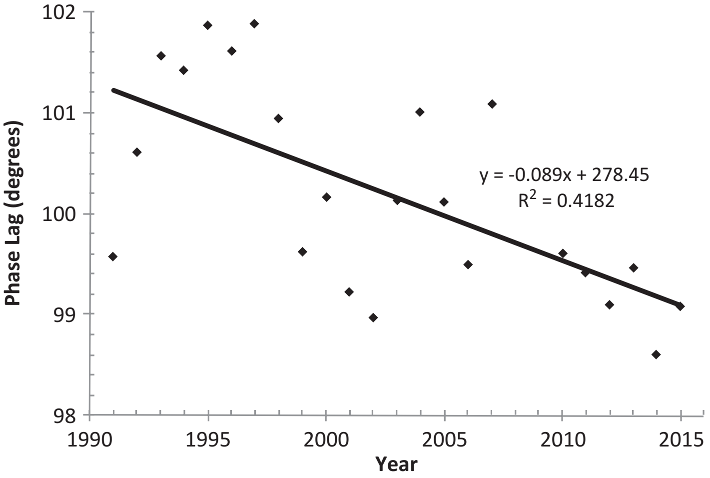

Fig. 10.15 Change history of the phase lag (bay phase minus the ocean phase) of the major spring tidal constituent (M2) in Wallis Lake. There is a weak reducing trend (R^2 = 0.4) indicating high tide arriving sooner in the bay

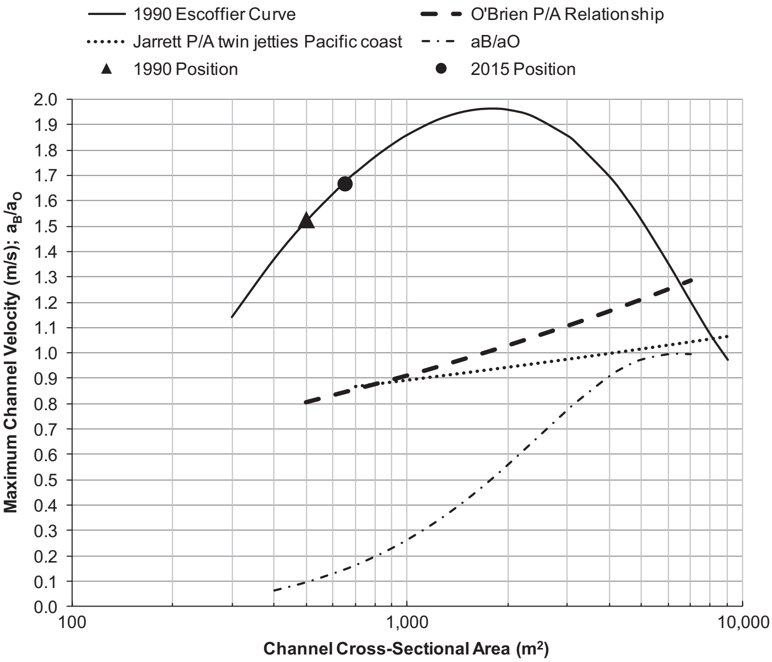

Fig. 10.16 Escoffier diagram for Wallis Lake indicating an unstable scouring mode. The O'Brien and Jarrett *P/A* relationships indicate a tenfold increase in channel area for the estuary to reach equilibrium

0.13 m and the maximum spring tide channel velocities are around 1 m/s (Watterson 2010).

Jetties were constructed from 1878 to 1887 (MHL 1994). Utilizing the available tidal records since 1990, the spring tidal range in the bay has increased steadily at an average rate of 1.7 mm/a ($R^2 = 0.96$; Fig. 10.19) with the bay-to-ocean spring tidal range ratio increasing steadily at a rate of 0.0015/a ($R^2 = 0.94$).

Figure 10.20 shows a decreasing trend in the phase lag of the major spring tide constituent of 0.5°/a. These data are strong indicators of an unstable scouring mode. If it is assumed that the tidal range grew steadily between 1887 and 1990 to reach 0.09 m from an initial value of zero, assuming the inlet being closed in 1887, the average rate over that period could not have been greater than 0.9 mm/a, suggesting that the current rate represents an increasing trend.

An Escoffier Diagram for Lake Macquarie is presented in Fig. 10.21, which indicated an unstable scouring mode. Without geomorphologic and/or anthropogenic constraints, based on the O'Brien (1931) equilibrium cross section, the channel area could continue to scour, increasing some fivefold, allowing for the tidal range in the bay to reach around 80% of the full ocean tidal range. At current rates of change, this could take a further some 450 years. However, taking the approach of Mota Oliviera (1970), it would take 350 to 400 years for the equilibrium cross-sectional

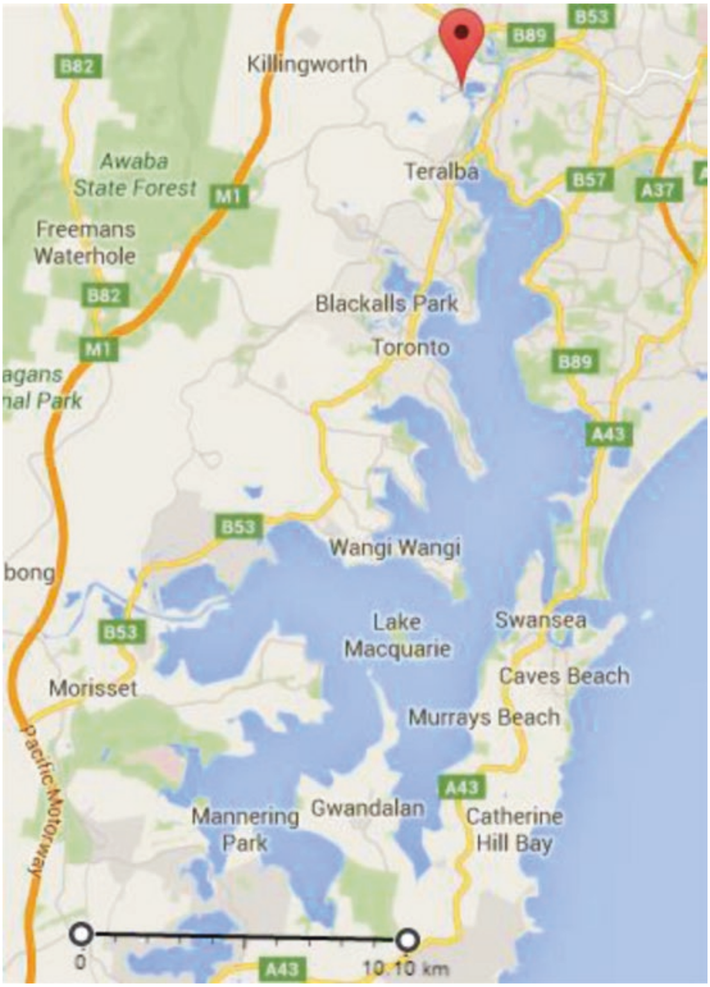

Fig. 10.17 Plan of Lake Macquarie (Courtesy Google maps) showing the location of the bay tide gauge. The ocean inlet is at Swansea. The plan area of the bay is 110 km^2

area to be reached. However, other factors such as a coal seam in the entrance channel and the constraints posed by the two bridges will produce an increasing relative roughness as velocities increase and, hence, the final equilibrium of the system may occur within a shorter timeframe.

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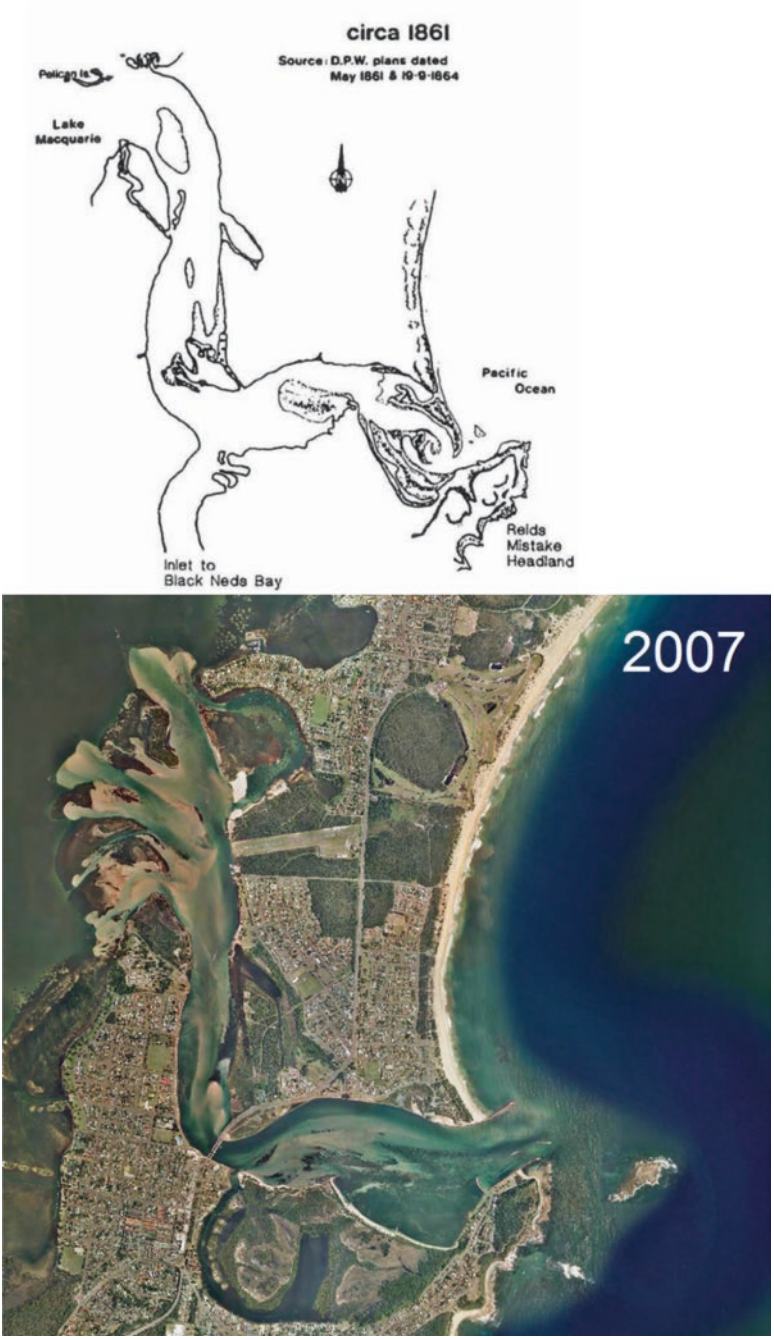

Fig. 10.18 Lake Macquarie entrance, Swansea Channel; *top* 1861; *bottom* 2015 (Watterson 2010). In 1861 the inlet virtually was closed with littoral drift choking the entrance. The beach on the southern side of the channel near the entrance is shown to have eroded significantly. There has been considerable extension of the flood tide delta northward into the bay

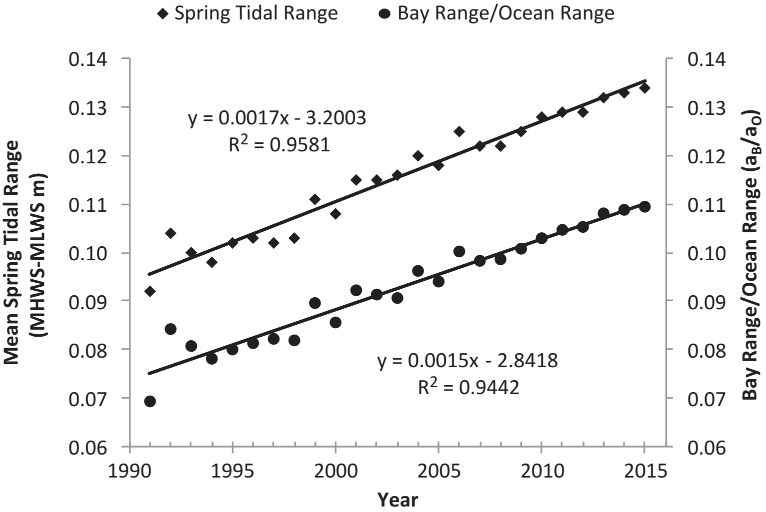

Fig. 10.19 Change history of the mean spring tidal range in Lake Macquarie and its ratio to the ocean range. The trends are strong ($R^2 > 0.9$) showing no signs of abating. With the bay area some 110 km^2, the increase in the spring tidal prism of 1.7 mm/a equilibrates to an annual increase in the spring tidal prism of 190,000 m^3

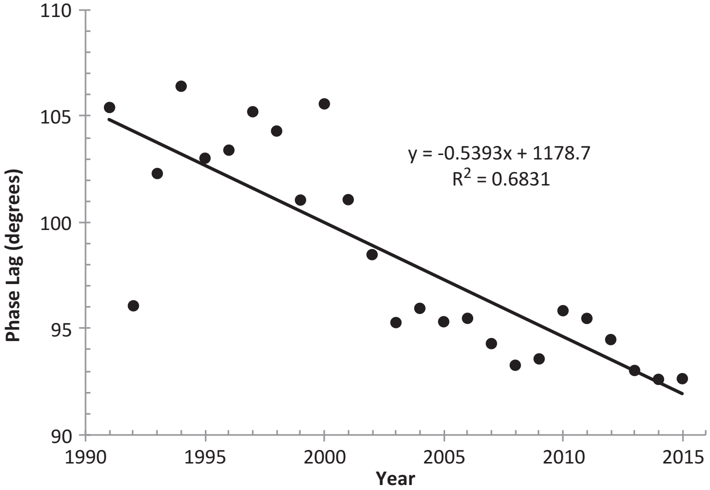

Fig. 10.20 Change history of the phase lag (bay phase minus the ocean phase) of the major spring tidal constituent (*M2*) in Lake Macquarie. There is a clear reducing trend ($R^2 = 0.7$) indicating high tide progressively arriving sooner in the bay

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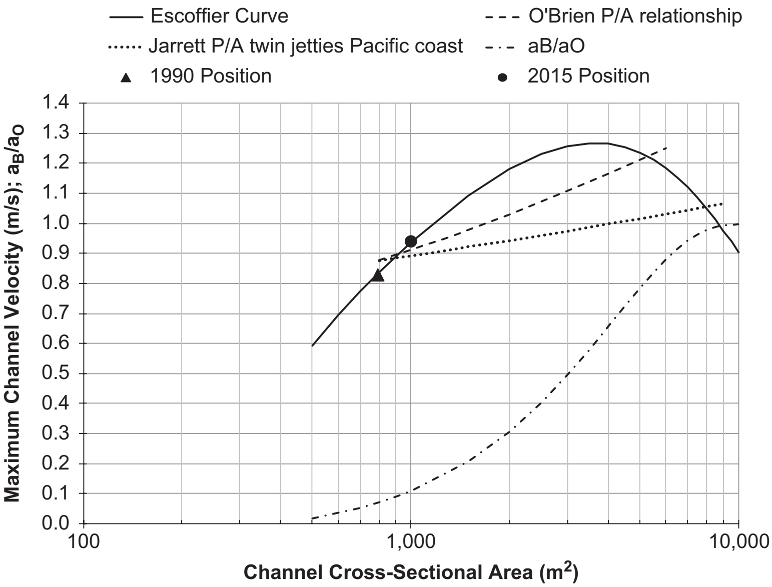

Fig. 10.21 Escoffier Diagram for Lake Macquarie indicating an unstable scouring mode. The O'Brien and Jarrett *P/A* relationships indicate a sixfold increase in channel area for the estuary to reach equilibrium

Fig. 10.22 Lake Wagonga, Narooma NSW (Courtesy Google earth). The plan area of the bay is 7 km^2. The jetties intersect the surf zone, the channel appears deeply scoured and there are significant flood tide sand deltas entering the bay

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10.3.5 Lake Wagonga

The Lake Wagonga estuary is situated at Narooma on the NSW south coast (Fig. 10.22). Twin entrance jetties were constructed in 1976–1978, primarily to improve entrance navigability for the commercial fishing fleet (MHL 1994). The estuary comprises a steep-sided bay of area around 7 km^2 (MHL 2001); an order of magnitude smaller than Wallis Lake and Lake Macquarie. A regular 3,250 m long entrance channel has a depth around 2.0 m, an average width of around 100 m and has intertidal training walls constructed of rock rubble. The spring tidal range in the bay is around 0.7 m and on the higher spring ebb tides the peak channel velocities approach 2 m/s (MHL 2001).

Regular tidal stage measurements are available from 1997. As shown in Fig. 10.23, the spring tidal range has increased steadily over the period of record at an average rate of 3.0 mm/a ($R^2 = 0.84$) and the bay-to-ocean spring range ratio has been increasing annually at an average rate of around 0.0033/a ($R^2 = 0.91$). The change history of the major spring tidal constituent phase lag is in Fig. 10.24, indicating a steady reduction of around 0.2°/a ($R^2 = 0.80$).

The regular features of this estuary allow for a considered derivation of an Escoffier Diagram, which is presented in Fig. 10.25. The Escoffier Diagram confirms the trend in the field data, indicating that the estuary channel is in an unstable scouring mode.

Without limitations, such as the influence and behavior of the channel training walls, the indications are that the channel could scour to more than double its present cross-sectional area, leading to the bay achieving almost full ocean tidal range. At current rates and without constraint, full ocean tidal range in the bay is predicted to be achieved within 120 years. However, taking the approach of Mota Oliviera (1970), at an average rate of increase for a_B/a_O of around 0.0033/a (Fig. 10.23), it would take some 20 to 50 years, rather than 120 years, for the equilibrium cross-sectional area to be reached.

The trends, based on the relatively short 18 years' record, currently are linear with no indications of any decreasing rates of change to the amplitudes or phase lags of the major spring tidal constituents. However, as indicated by the Escoffier Diagram, once the critical flow area has been exceeded, the channel velocities are predicted to decline and the rate of change of the tidal range in the bay also may decline, extending the time required to reach stability.

10.4 Impacts on Coastal Processes

10.4.1 Wallis Lake

Prior to training wall and jetty construction, the entrances exemplified herein were plagued with shifting sand shoals and, occasionally, were closed to navigation. Jetty construction intersected the surf zone bars and eliminated the marginal flood tide

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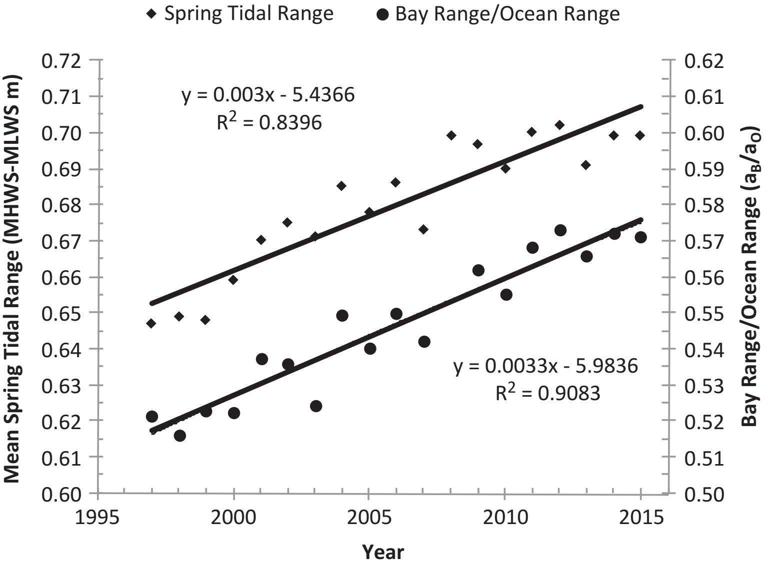

Fig. 10.23 Change history of the mean spring tidal range in Lake Wagonga and its ratio to the ocean range. The trends are strong ($R^2 = 0.8–0.9$) showing no signs of abating. With a plan area of 7 km^2, the rate of increase in the spring tidal prism of 3 mm/a equilibrates to an annual increase in the spring tidal prism of 20,000 m^3

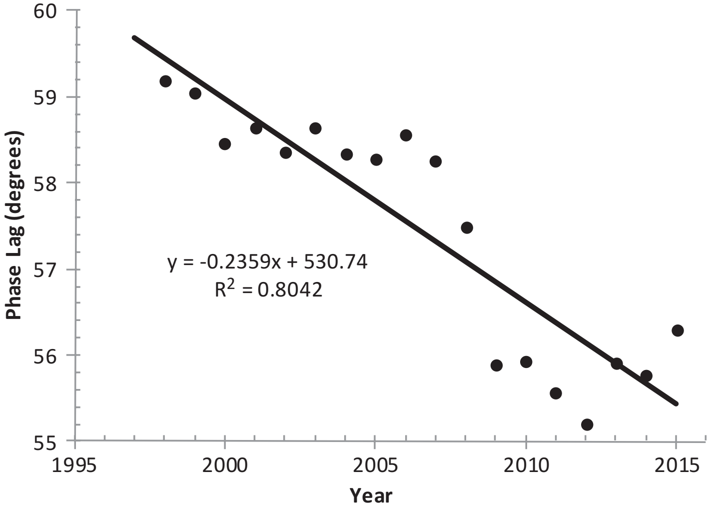

Fig. 10.24 Change history of the phase lag (bay phase minus the ocean phase) of the major spring tidal constituent (M2) in Lake Wagonga. There is a strong reducing trend ($R^2 = 0.8$) indicating high tide arriving sooner in the bay

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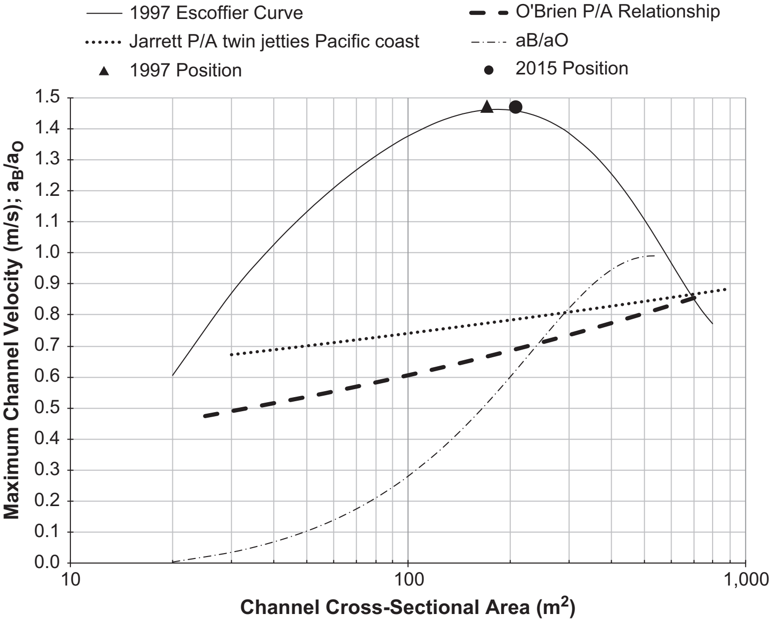

Fig. 10.25 Escoffier Diagram for Lake Wagonga indicating an unstable scouring mode. The O'Brien and Jarrett *P/A* relationships indicate a threefold increase in channel area for the estuary to reach equilibrium. The rate of change of the bay spring tide amplitude is likely to decrease as the equilibrium area is approached

channels and shoals. In each case, jetty construction has occasioned scouring of channels and changes to tidal planes, the reasons for which are exemplified in the case study of the Wallis Lake entrance improvements (after Nielsen and Gordon 1980).

Prior to the construction of the northern (Tuncurry) jetty at Wallis Lake entrance, the asymmetrical nature of the ebb jet expansion resulted in the development of shallow ocean shoals. A large ebb tide separation eddy had developed on the northern side of the inlet resulting in an inlet-directed current through the northern marginal flood tide channel during ebb tide (Fig. 10.26). This opposing current carried sediment into the entrance channel on ebb tides and induced a significant head loss to the ebb tide flow. The effect was enhanced during the flood tides as sand, which was entrained into the flow by wave action on the asymmetric entrance bar and beach on the northern (Tuncurry) side of the entrance, was transported into the entrance channel. This encouraged the southward growth of the spit on the non-jetty side, thereby tending to close the inlet.

The construction of the northern jetty intersected the marginal flood tide channel extending southwards along the beach. As indicated in Fig. 10.27, this eliminated the ebb tide separation eddy and reduced significantly the rate of littoral drift transport into the entrance channel, which would have had a major impact on keeping the inlet open (Bruun 1978). Further, this focused all of the tidal flows onto deepening

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Wallis Lake Inlet 1952 (Photograph courtesy NSW Government)

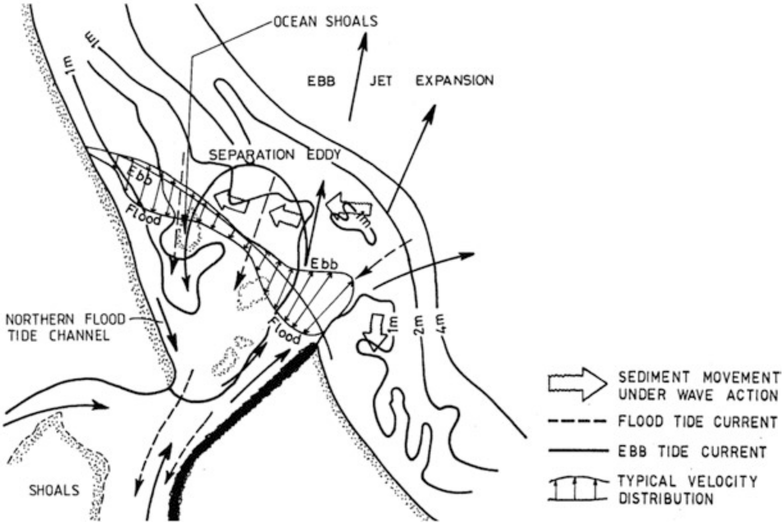

Fig. 10.26 Schematic representation of the hydrodynamics at a typical asymmetrical entrance (Nielsen and Gordon 1980). The entrance asymmetry created by a single jetty induces a separation eddy on the ebb tide discharge creating an inlet directed current along the beach, which constricts the ebb tide flow and contributes littoral drift to the entrance channel. Flood tide flow across the surf zone bars contributes a considerable amount of suspended sediment to the entrance channel. Wallis Lake Inlet 1952 (Photograph courtesy NSW Government)

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Wallis Lake Inlet 1974 (Photograph courtesy NSW Government)

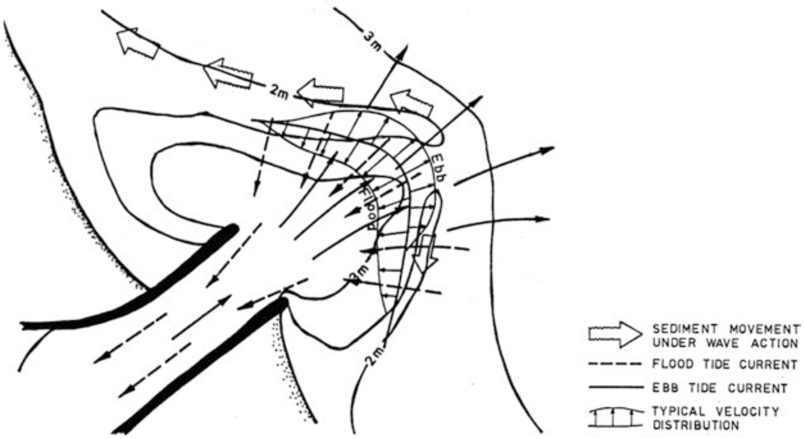

Fig. 10.27 Schematic representation of the hydrodynamics at a typical symmetrical entrance (Nielsen and Gordon 1980). The symmetrical jettied entrance configuration has improved hydraulic conveyance and reduces the sediment feed into the entrance channel. Wallis Lake Inlet 1974 (Photograph courtesy NSW Government)

the entrance bar and it eliminated the processes maintaining the shallow marginal ocean shoals. The resulting symmetrical and deeper entrance bar and channel reduced significantly the head loss for both the flood and ebb tide flows. The reduction in head loss across the entrance bar has improved the hydraulic efficiency of the entrance and has enhanced tidal propagation into the estuary. This has increased the

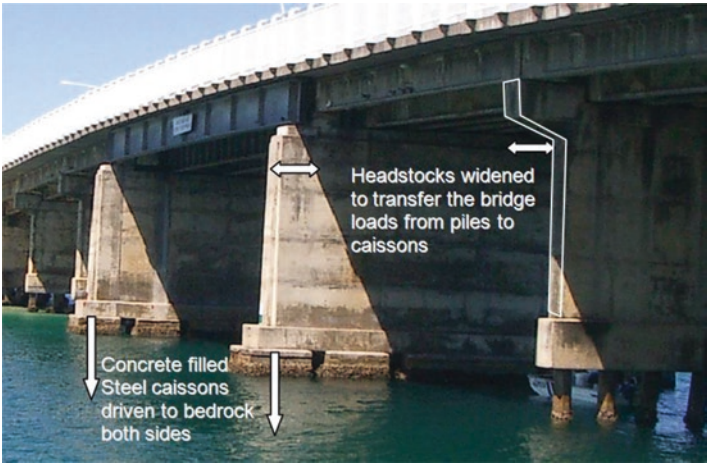

Fig. 10.28 Underpinning of the Forster-Tuncurry Bridge piers following channel scour. The channel piers had subsided almost 0.5 m. The headstocks were underpinned with steel caissons driven to bedrock and the headstocks were widened to transfer the bridge loads to them

velocities and sand transporting capabilities of the tidal streams in the estuary channels, leading to their scour and to the deposition of sand on the flood tide deltas leading into the bay as well as exporting sand onto the adjacent ocean beaches, thereby nourishing them and adding sand to their sediment budget. The scouring and progressive deepening of the entrance bar has increased further the effective tidal forcing, creating a positive feedback loop which, in turn, deepens the entrance bar, leading to more channel scour.

Interestingly, the study linking jetty construction to channel scour was initiated by an investigation that, by happenstance, used a main road bridge across the entrance channel as a measuring station for flow velocities and cross-sectional areas. When the channel cross-section was plotted on the works-as-executed drawing of the bridge it was found that the channel had scoured almost to the toes of the bridge piles, which had been designed as friction piles in sand, rendering the bridge potentially to become unstable. Subsequent surveys showed that the bridge pile supports in the main Forster Channel had settled some 475 mm and, at significant expense and disruption, led to underpinning the headstocks with steel caissons driven deep to bedrock (Fig. 10.28). Fortunately, the roadway deck had been simply supported, which allowed for considerable tolerance in settlement and for the subsequent jacking up of the roadway bridge deck to its original levels following underpinning.

10.4.2 Lake Macquarie

Since the jetties were constructed at Lake Macquarie, the Swansea Channel has been scouring and its foreshores have been eroding, necessitating groin and revetment construction, some of which is collapsing. Detailed bathymetric surveys undertaken in 1996 and 2008 (Fig. 10.29) indicated that the channel was scouring over that period at an average rate of around 25,000 m^3/a, with the bay's flood tide

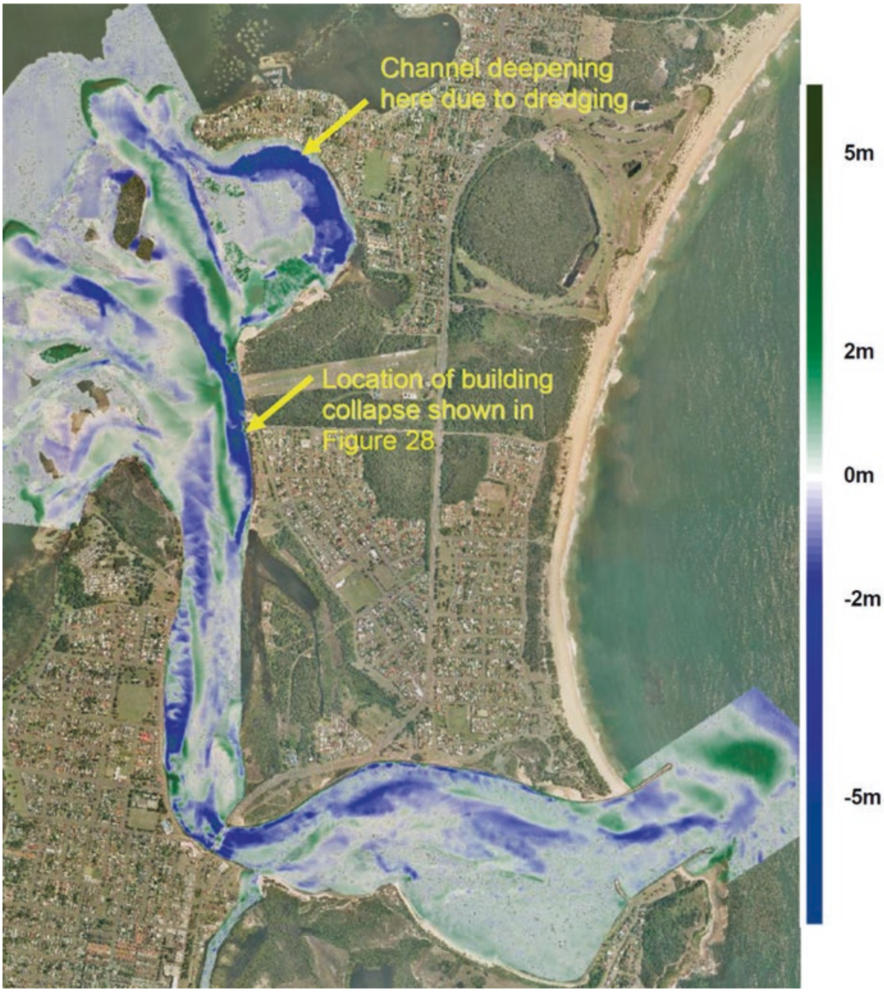

Fig. 10.29 Bed level changes in Swansea Channel 1996–2008 (Watterson 2010; courtesy Lake Macquarie Council). Up to 5 m of sand accretion has been measured on the leading edges of the flood tide deltas entering the bay and the ebb tide delta at the ocean entrance. Sand has come from channel deepening and erosion of the beach on the south side of the channel near the ocean entrance

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Fig. 10.30 Collapse of Swansea Channel foreshore building comprising restaurant, offices and residences on 8 February 2016 (Photo: Fire and Rescue NSW). The location is shown in Fig. 10.29. Particularly severe erosion has occurred along a revetment constructed to protect the western end of the airstrip. The revetment has attracted the channel thalweg, which has led to further scour both upstream and downstream, undermining the pile foundations of the building

deltas growing at an average rate of around 12,000 m^3/a, the remainder being deposited on the ocean bar and, subsequently, as nourishment, onto the ocean beach (Watterson 2010). The piling foundations of the main road bridge spanning the entrance channel at Swansea village have been compromised by the channel scour, necessitating the placement of large volumes of rock scour protection, which requires frequent maintenance. In accordance with Sect. 10.2.3, it appears that a revetment constructed to protect the nearby airstrip has attracted the thalweg of the channel, increasing velocities there. This, along with the three-dimensional flow induced by the "cross-over" downstream, has induced additional scour and, hence, a deepening of the channel at that location.

The changes have been progressive over many decades, if not centuries. At Lake Macquarie, the data indicated that the rate of change may be accelerating. The acceleration of an unstable scouring mode may be caused by a sea level rise. However, that the rate may be increasing is predicted by the Escoffier Curve. The implication is for continued scouring of Swansea Channel. Progressively, this is threatening other assets as shown by the collapse of the foreshore marina building due to undermining of the pile foundations (Fig. 10.30), perpetual scour to the Swansea Bridge foundations, progressive failure of the marginal rock rubble revetments and groins. That this is occurring still some 125 years after the major perturbation of jetty construction indicates that the time for large estuaries to reach stabilization can be considerable and in the order of centuries.

10.5 Impacts on Marine Ecology

10.5.1 Wallis Lake

In Wallis Lake, trends in seagrass colonization between 1988 and 2002 have been mapped using satellite imagery (Fig. 10.31). The seagrass trend in Wallis Lake seems to be an overall decline in the shallow water seagrass *Zostera* with deeper water *Posidonia*, *Ruppia* and *Halophila* seemingly stable with no gross changes in the 14 year period (Dekker et al. 2003).

Of particular note is the entire loss of *Zostera* in the channels between the entrance to Wallis Lake and the ocean. We have attributed this to channel scour and deepening. Here there was some gain of *Posidonia*, which colonizes deeper waters. There was a slight increase in *Posidonia* also in the northern channel areas where we would predict channel deepening. Large areas of *Zostera* were lost also within Wallis Lake but no reasons for this were given in Dekker et al. (2003).

10.5.2 Lake Wagonga

Long term changes to the distribution of aquatic flora have been identified and mapped in the Wagonga estuary (Burrell 2012; Duchatel et al. 2014). These studies have shown that Lake Wagonga has experienced a significant decrease in the distribution of macrophytes over the 25 year period between mapping campaigns (Duchatel et al. 2014). Figure 10.32 shows seagrass mapping in the entrance

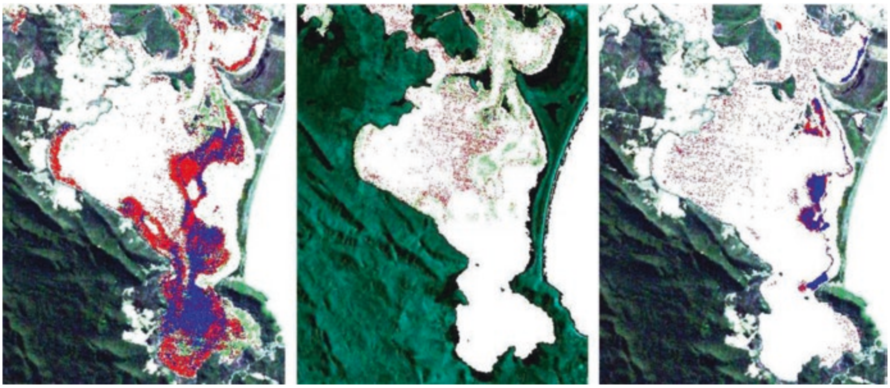

Fig. 10.31 Changes in Wallis Lake to aquatic flora (from *left* to *right*) *Zostera*, *Posidonia* and *Ruppia*/*Halophila* from 1988 to 2002 with *red* = loss, *green* = gain and *blue* = no change; *white* pixels within the lake indicate a class not identified as seagrass (Dekker et al. 2003). Channel scour between the lake and ocean has resulted in loss of *Zostera*. Some of the deepened areas have been colonized by *Posidonia*

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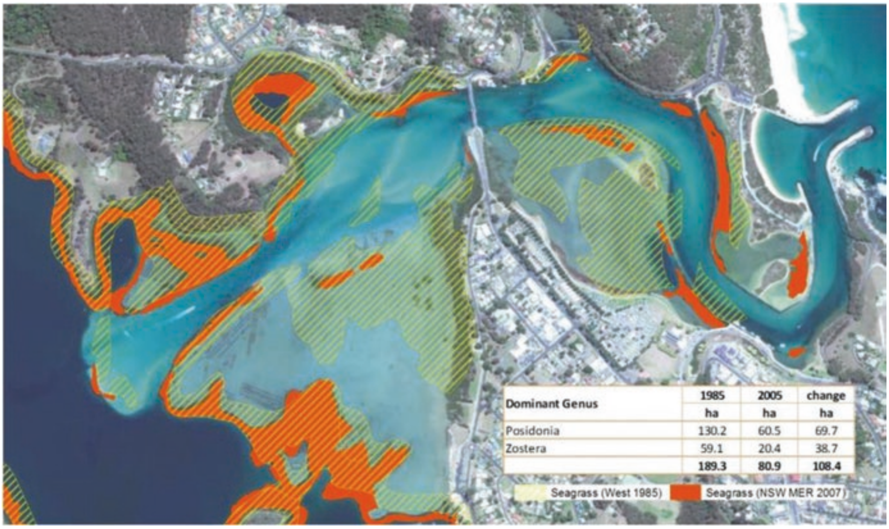

Dominant Genus	1985 ha	2005 ha	change ha
Posidonia	130.2	60.5	69.7
Zostera	59.1	20.4	38.7
	189.3	**80.9**	**108.4**

Fig. 10.32 Change in the extent of seagrass at the entrance to Lake Wagonga 1979–2005 (Duchatel et al. 2014). Loss of seagrass in the channel has been attributed to channel scour whereas on the flood tide delta it has been attributed to sand inundation

channel, where changes to seagrass distribution and abundance has occurred as a result of increased tidal velocities causing channel bed scour and accreting flood tide deltas causing seagrass smothering. The data indicated that the total abundance of all seagrass throughout the estuary decreased by 57% (from 189.3 to 80.9 ha). Approximately 64% of this loss was *Posidonia* and the remaining 36% predominantly *Zostera*. In this case some of the Posidonia beds were covered as the delta spread into the bay. Over 33% of the total seagrass loss occurred within the channel with approximately 72% of that being the loss of *Zostera.*

Since 1957, throughout most of the Wagonga estuary the mangrove communities were found to be either stable or expanding with expansion occurring through incursion up-slope into the saltmarsh communities, laterally along the foreshore and down-slope onto prograding deltas and sandbars (Burrell 2012). The data from Burrell (2012) showed that the rate of change had increased threefold since the jetties were constructed in 1978 (Fig. 10.33) with the greatest increase occurring in the upper part of the estuary.

Since 1957, saltmarsh has decreased throughout the estuary. Foreshore reclamation for a caravan park, urbanization and draining of wetlands has accounted for the most significant loss of saltmarsh within the Inlet (Burrell 2012). Taking into account those major impacts, the data from Burrell (2012) indicated that the natural rate of saltmarsh loss increased threefold since the jetties were constructed (Fig. 10.34).

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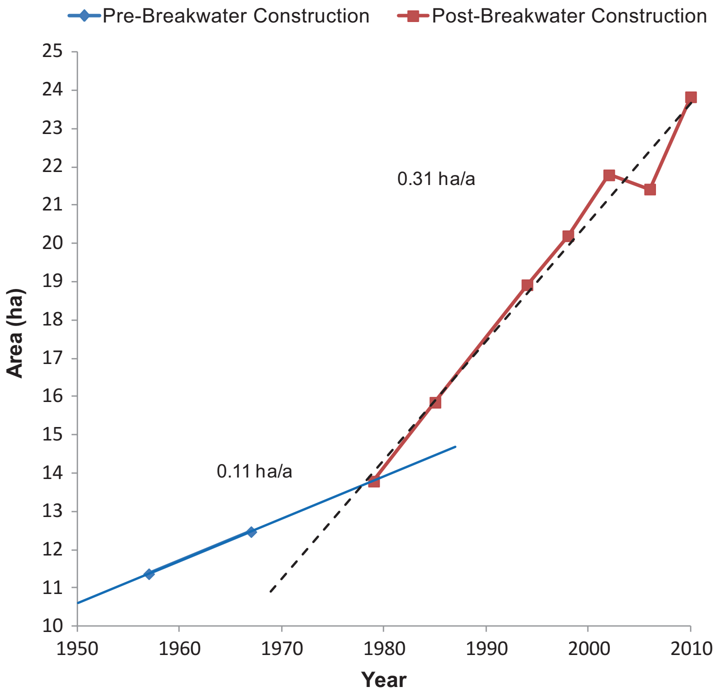

Fig. 10.33 Change in area of mangrove and natural rates of change at Lake Wagonga inlet prior to and after entrance jetty construction (Data from Burrell 2012). Marked differences in the rates of change coincide with jetty construction in 1978

10.6 Implications

The construction of training walls and jetties at the ocean entrances to coastal bays and lagoons has the potential to alter fundamentally estuarine hydraulics, inducing changes to channel flows, morphology and tidal planes. While in the case studies exemplified herein these works have improved flood conveyance and inlet navigability considerably, as intended, they have induced channel scour compromising roadway bridge foundations and bank stability. The subsequent requirements to protect foreshore assets with further training walls and revetments have exacerbated the scouring processes with additional unintended adverse impacts. Implications have included the continual maintenance of scour protection to prevent further loss of foreshore assets, including buildings, and scour protection for and underpinning of bridge pylons. The prognosis is that it may take decades to centuries for these estuaries to attain ultimate inlet stability, implying long term maintenance costs.

Such major long-term changes to estuarine hydrodynamics have significant potential to alter marine ecologies. The changes to the distribution of aquatic flora within the bays of Wallis Lake and Lake Wagonga are likely to have resulted from a combination of many factors. Nevertheless, they are consistent with and as would be expected from the changes to the geomorphology, tidal planes and flows that

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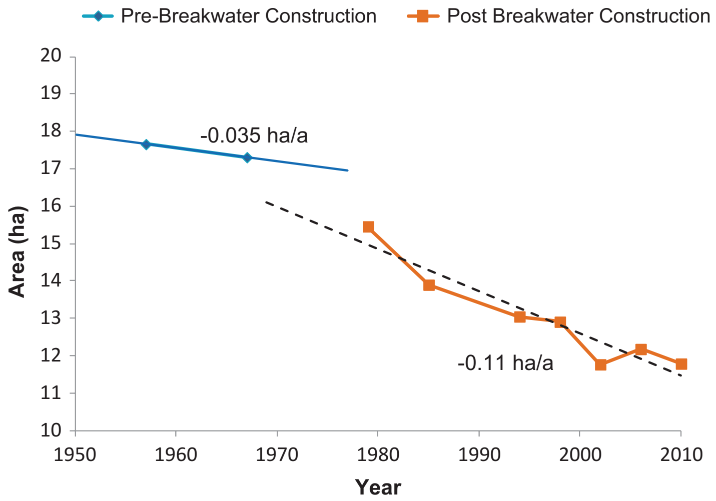

Fig. 10.34 Change in area of saltmarsh and natural rates of change at Lake Wagonga inlet prior to and after entrance jetty construction adjusted for shore-based land-use changes (Data from Burrell 2012). Marked differences in the rates of change coincide with jetty construction in 1978

have been induced by the construction of the jetties at the ocean entrances. Increasing tidal ranges induce wetland communities to migrate into tributaries and upland shorelines (Duchatel et al. 2014). However, often there will be limits to this occurring in the form of natural topographic features and anthropogenic constraints, such as shore protection works, foreshore roads, weirs, levee banks and flood gates constructed to limit salt water incursion into farm lands. The loss of these wetland areas has adverse impacts on fisheries and the overall health and water quality of estuaries.

It is vital to understand how estuary tidal planes may be modified by the construction of training walls, revetments and entrance jetties; such an understanding being the basis for designing and implementing necessary compensatory actions to secure assets and to retain wetlands in jetty protected estuaries.

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