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Groundwater in the Coastal Zones of Asia-Pacific

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Groundwater in the Coastal Zones of Asia-Pacific

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Foreword

Humankind has an overwhelming desire to live, work, and vacation near the ocean. More than 1.2 billion people live within 100 km of shoreline and 100 m of sea level; this coastal zone has an average population density nearly three times higher than the global average. Each year more than 50 million people move to the coastal zone worldwide. The coastal populations swell seasonally by hundreds of millions of tourists that flock to local beaches. Coastal zones also have some of the largest and most industrialized cities, many of which have grown from historic ports and centers of shipping and trade.

This strong and growing human footprint in coastal zones has put an enormous pressure on many sensitive ecosystems and limited natural resources. Among the most vulnerable are coastal freshwater resources, including the critically important water resource beneath land surface – groundwater.

Groundwater is an essential part of the global hydrologic cycle and the largest distributed store of freshwater. Groundwater supplies fresh drinking water to almost half the world's population and supports and sustains many streams, lakes, wetlands, aquatic communities and ecosystems, economic development and growth, irrigated agriculture, and food production worldwide. The demand for groundwater has threatened its sustainability. Coupled socioeconomic and climate stresses have led to groundwater depletion and reduced water quality in many aquifers around the world.

Aquifers in coastal zones are particularly vulnerable because of the additional threat of seawater intrusion from over-pumping and abstraction, sea-level rise, and storm surges. The mitigation and remediation of seawater intrusion within coastal aquifers is prohibitively expensive, necessitating the prevention of seawater intrusion to become a primary goal for many coastal groundwater managers. Because of competing stakeholder needs and uncertain scientific findings and recommendations, particularly regarding climate change and the timing and magnitude of sea-level rise, coastal managers and policy makers must often make complex and controversial decisions to best use local groundwater while protecting against seawater intrusion. However, many coastal management decisions are made without clear groundwater sustainability goals or development plans.

Such coastal groundwater issues are becoming increasingly important in the Asia-Pacific region of the western Pacific Ocean. The Asia-Pacific region has many islands and continental, low-lying shorelines that support major population centers, but are susceptible to wave erosion, seawater inundation, and storm surge. The projected global sea levels will likely exacerbate these hazards and have a wide ranging socioeconomic consequence for the region, especially for coastal groundwater resources.

Groundwater resources support a tremendous range of development across the Asia-Pacific region, from densely populated megacities to sparsely populated, rural and developing areas. For example, the North China Plain aquifer and many other coastal aquifers help support nearly 60 % of China's more than 1.3 billon people that live in the 12 coastal provinces along the western Pacific Ocean. The Asia-Pacific megacities, defined as metropolitan areas with populations in excess of ten million, include Karachi, Calcutta, Bangkok, Jakarta, Hong Kong, Manilla, Osaka, and Tokyo. Groundwater beneath these megacities is often contaminated and over-abstracted, which led to land subsidence in Tokyo and Osaka during the mid-1900s. Subsequent groundwater-pumping regulation led to groundwater levels that recovered to historical levels, but created new problems with the rising groundwater levels causing buoyancy of underground structures such as subway stations. Along the eastern Pacific Ocean, approximately 80 % of California's more than 35 million residents live within 50 km of the coast – a region that has localized seawater intrusion from over-pumping of groundwater to meet strong economic demands for groundwater-fed irrigated agriculture and drinking-water supply.

The Asia-Pacific region also has nearly 1,000 populated, small tropical and sub-tropical islands, many of which are underdeveloped or developing countries. Many of these small island developing states (SIDS) face severe constraints in terms of freshwater resources. Many SIDS lack any substantial surface storage for water and thus are highly reliant on groundwater. Groundwater beneath low-lying atolls and coral islands is often present as thin lenses of freshwater floating on seawater. Groundwater lens beneath small islands are particularly vulnerable to seawater intrusion from natural tidal fluctuations, climate variability and change, storm surges, over-pumping, and point and non-point source contamination from human activities and livestock. Conflicts surrounding land ownership, inadequate governance, and inadequate knowledge, including a lack of well-trained hydrogeologists, groundwater engineers, and managers are central problems that enhance the vulnerability of groundwater lens to seawater intrusion across the Asia-Pacific region.

To address these important questions in the Asia-Pacific region, this volume provides a valuable overview and collection of case studies about the current state of research to better understand seawater intrusion and other important processes that affect groundwater resources in aquifers of the continental shoreline and island settings. Results and findings from this volume will help groundwater scientists, engineers, managers, and policy makers develop strategies toward sustainable groundwater resources under continued population growth and uncertain consequences of climate variability and change.

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Contents

Part I
Understanding the Movement of Groundwater in the Coastal Zone

Chapter 1
Groundwater in the Coastal Zones of the Asia–Pacific Region—A Threatened Resource Needing Integrated Management

Chris Wetzelhuetter

Abstract Groundwater management and conservation are becoming an increasingly important issue in the heavily urbanized coastal zones of the Asia–Pacific region. This volume of papers is intended to support groundwater managers in their planning, and offer potential solutions for decision makers.

This chapter provides a comprehensive overview of the general concept of this volume. It describes the composition, content and objectives of the different chapter contributions. Furthermore, it also, outlines how the status of coastal groundwater research is presented and illustrates how this volume offers an integrated view of groundwater processes in coastal aquifers in the Asia–Pacific region. It includes a discussion of the methodologies and technologies used to assess processes associated with coastal groundwater development. A summary of the case studies and local examples aims to provide the reader with a broader understanding of the diversity of costal aquifers and their groundwater resources.

1.1 Introduction

The coastal zone is marked by significant biological diversity, and of great importance for fisheries and urban populations. In the Asia–Pacific Region it is under ever increasing pressure due to population growth and activities related to industry and tourism.

The groundwater in coastal zones faces many new threats. For example, wells can be destroyed when being overrun by waves. They can also become contaminated with saline water or other pollutants during flood events or by leaching from saline ponds or the soil after flooding. Groundwater pollution is caused by the spreading of waste, sewerage, and/or chemicals, and the inland

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migration of the fresh water–saline water interface. The volume of freshwater on small islands can be reduced by ‘natural’ marine incursion, e.g. during storms, and/or as the result of over-exploitation. Last but not least, the movement of a fresh water–saline water interface upriver, either in response to sea-level rise or surface water abstraction, might have significant impacts on the ecosystem.

Groundwater is an important freshwater resource. In order to deal with potential threats to this resource it is therefore important to gain an understanding of the fresh water–saline water interface between marine levels that vary due to tidal effects and fresh groundwater moving along the coastal zone. The hydrogeochemical changes resulting from the movement of the interface are complex and must also be understood to enable preservation/conservation of the limited freshwater resource. It will also allow integration and the development of innovative management solutions for the sustainable management of coastal zone groundwaters.

The purpose of this chapter is to provide an overview of topics related to coastal groundwater with a focus on the Asian–Pacific Region. The chapter content closely follows the same order as the book content. It summaries and discusses the results of the different approaches and concepts by the contributing authors. The aim of this book is to lead to disseminate the concepts applied in coastal groundwater research, and allow researchers and managers to choose methods and find solutions to meet specific project requirements. The reader will acquire the knowledge needed to develop specific project plans for a sustainable management of coastal aquifers and the near-shore marine environment.

1.2 The Structure of the Book

The book consists of four parts.

Part 1 (Chaps. 1, 2, 3) deals with the fundamentals and principal concepts of hydrogeology in the coastal zone. It provides the basis of an understanding of groundwater flow, the hydrochemistry of ground- and seawater, and aquifer properties in coastal zones.

Part 2, is a seven part series (Chaps. 4, 5, 6, 7, 8, 9, 10) dedicated to descriptions of typical methodologies and applications for groundwater investigations in coastal zones. These include geophysical methods and numerical modeling, and provide the reader with an overview of well-established methods and the latest technologies developed and applied in case studies.

Part 3 (Chaps. 11, 12, 13, 14) is about various projects and cases studies that focus on impacts on groundwater in the coastal zone. These chapters are examples of assessments undertaken to investigate threats to groundwater, including sea-level rise, pollution resulting from flooding and/or over-exploitation of groundwater resources.

Part 4 is a series of three chapters (15, 16, 17 inclusive) dealing with water management issues and gives a general overview of the situation in the region. It includes examples of the different ways of groundwater management.

Of the 17 chapters:

- The majority was written by researchers summarizing the latest results of their work in coastal research. Some include descriptions of methodologies that are commonly used for research or assessments, or describe a new technology or unique approach. They address readers who are not experts in these disciplines, and provide the principles and information required for further understanding. Students of marine and environmental studies, geology and/or hydrology, or related topics, will find these details helpful.
- Some chapters provide an overview of an actual topic such as sea-level rise, climate change or saltwater intrusion, or a more general discussion on the current state of groundwater research in coastal zones in the Asia–Pacific Region. The region is large area and almost every country in it has a different potential and issues for groundwater research and coastal management. Hence, these chapters reflect specific local requirements.
- The principal features of the chapters are: being structured like a scientific report, including abstract, introduction, methodology, discussion of results, and summary. All of the chapters are related to the region and include a case study—except for Chaps. 1 and 15—where the discussion in general relates to groundwater management in the Asia–Pacific Region.
- The Asia–Pacific Region, as referred to in or by all of the chapters, covers an area from the Indian Ocean in the west to the Pacific Ocean in the east. The region incorporates the smaller adjacent seas and bays along the shores of Iran, India, Indonesia, Papua New Guinea and China, such as the Arabian Sea, the Bay of Bengal, and the South and East China Seas (Fig. 1.1).

1.3 Locations of Case Studies

The case studies dealt with in this book cover this vast area from as far west as the coast of Africa to the islands of Hawaii in the central Pacific in the east. Authors from Australia contributed five case studies, two are from by India, and one each from China, USA (Hawaii), Malaysia, France (Mayotte), Thailand, UAE and Indonesia. The locations pertaining to these case studies relate cover a wide range of different climates and geomorphological settings, including tropical islands, high-density populated urban areas, river banks and estuaries, agricultural plains, deserts, and temperate woodlands and swamps in the coastal zone (Fig. 1.2).

1.4 Content and Objectives

Chapter 2 (by H. Li et al.) deals with mud beaches and mangrove swamps in the Dongzhaigang National Nature Reserve. This is the largest mangrove forest nature reserve in China. The author explains how changes in the hydrogeology and

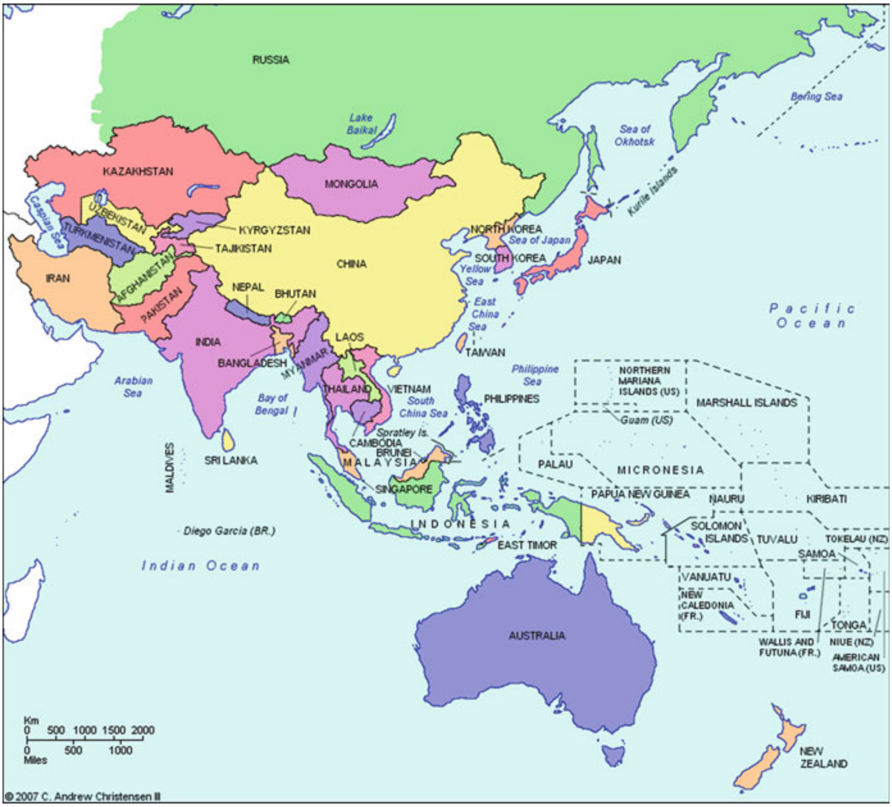

Fig. 1.1 The Asia–Pacific region (from C. Andrew Christensen III, www.worldmonitor.info, Regions, Asiapacific, March 2006)

hydrochemistry along the two transects could have ecological implications for the restoration, protection and management of mangrove ecosystems. The intertidal zones of a mangrove transect and a 'bald beach' transect with similar topography and tidal actions were selected for a comparative study. The chemistry of water sampled along the transects was compared and variations in the water table investigated.

Chapter 3 (by P. Swarzenski et al.) is an examination of coastal groundwater discharges and associated nutrient loadings at selected coastal sites in Hawaii (USA). The suite of tools used to evaluate groundwater discharge included selected U/Th-series radionuclides, a broad spectrum of geochemical analytes, multi-channel electrical resistivity, and *in situ* oceanographic observations. The data derived from this investigation will extend our basic understanding of the physical controls on coastal groundwater discharge, and provide an estimate of the magnitude and physical embodiments of submarine groundwater discharges and the associated trace metal and nutrient loads conveyed by this submarine route.

Fig. 1.2 Locality map: Case studies reported in relation to research in groundwater in the coastal zones of the Asia Pacific Region (Modified from Google Earth)

Chapter 4 (by L. Surinaidu et al.) demonstrates how geophysical and hydrochemical tools were applied to identify the source of salinity in an aquifer and to assess the extent of saline water intrusion in the Godavari Delta in the Bay of Bengal (India). The author shows how hydrogeologists carry out site characterization and present the results in maps and provides an overview of the benefits of using a combination of electrical resistivity tomography and hydrochemistry.

Chapter 5 (author S.C. Singh) is a discussion of some geophysical techniques and refers to the Kasai–Subarnarekha River Basin, West Bengal (India). Downhole geophysical logging and different types of surface electrical resistivity surveys were employed to investigate complex hydrogeological settings. The study demonstrates the way in which sound hydrogeological investigations can support the development of a groundwater resource.

Chapter 6 (by A. Davis et al.) presents relevant research used to characterize a coastal aquifer system on the Eyre Peninsula, South Australia, using surface-based nuclear magnetic resonance (NMR). This technique enables direct detection of groundwater in the subsurface. The chapter will give a better understanding of the potential level of connectivity between the Uley Basin and the Southern Ocean, and enable consideration of whether new groundwater resources could be tapped in this coastal aquifer.

Chapter 7 (by C. Schamper et al.) provides a detailed description of the airborne electromagnetic method. It includes a discussion of the processing and inversion of the data produced, giving the reader an excellent introduction of the method. The results from an investigation are demonstrated by a case study from the volcanic island of Mayotte, where key geological structures and saline intrusion were mapped successfully. While the location of this case study is closer to Africa than Asia, it is relevant as an example for many island settings in the Asia–Pacific Region that have similar environments, geology and hydrogeology.

Chapter 8 (by H. Duerrast and J. Srattakal) deals with an investigation of salt water intrusions in the coastal aquifer of Songkhla in Southern Thailand. Seismic reflection and refraction, and vertical electrical sounding (VES) were employed to investigate the deeper aquifers, and contribute to the understanding of the aquifer and groundwater conditions for groundwater management

Chapter 9 (by A.D. Werner and L. Dung Dang) deals with the development of a three-dimensional seawater intrusion model of the Uley South Basin, South Australia, using a numerical model with code derived from MODHMS. The modelling enables simulation, for the first time, of the current extent of seawater intrusion in the aquifer, the temporal salinity variability, and the susceptibility of the aquifer to seawater intrusion. As such, the model is a significant step beyond results of modelling attempts, and provides important insights into salinity distribution and mobility.

Chapter 10 (by L.K. Morgan et al.) presents the application of a rapid-assessment method for seawater intrusion vulnerability via a case study in the Willunga Basin, South Australia. This study provides guidance for both well installation and future data collection, and will be of significant interest and value to groundwater managers.

Chapter 11 (by A. Zaharin et al.) deals with the impacts of ecotourism on groundwater on small tropical islands in Malaysia. The author demonstrates how hydrochemical investigations can provide information for sustainable groundwater development and management, and how groundwater must be considered in order to avoid the effects of its over-exploitation hindering the growth and development of ecotourism.

Chapter 12 (by J.P. Terry et al.) investigates into the groundwater resources of atolls that are at risk of storm-generated marine flooding. The chapter includes a case study on the Pacific island of Pukapuka with a summary of the findings of an investigation of the effects on freshwater lens profiles of storm waves washing over and across atoll islets, and the subsequent patterns of recovery over time. Both field and modelling approaches are used.

Chapter 13 (by M. Sherif et al.) discusses the employment of MODFLOW and MT3D to simulate groundwater flow and assess the saline intrusion problem in Wadi Ham, UAE, and possible mitigation measures. The study provides important information about management of the local coastal aquifer. The impacts of excessive pumping and artificial recharge are investigated.

Chapter 14 (by T. Laattoe et al.) is about the impacts of sea-level rise (SLR) and any associated saline (salt water) intrusion (SWI). Variable-density numerical modelling is used to examine the implications of transgression for a range of SWI scenarios, based on simplified coastal aquifer settings. The findings of this study suggest that modelling analyses that neglect the effects of transgression in SLR–SWI investigations may underestimate the rates and extent of SWI significantly.

Chapter 15 (author K. Villholth) deals with the current level of knowledge of coastal groundwater systems in continental and island settings in the Asia–Pacific region, their utilization and vulnerabilities, and the hazards arising from various sources. It is proposed that an integrated framework approach could be used to show how sustainable and resilient groundwater management can be promoted and enhanced. The work described is partially based on the tsunami event of December 26, 2004 in eastern Sri Lanka and the immense challenges generated by that. The opportunities for local and higher level groundwater management are also noted.

Chapter 16 (author S.B. Kusumayudha) demonstrates the way in which hydrogeological investigations can be used to support the development of a Geopark. Discharges of groundwater from springs along a coastal stretch in Indonesia are evaluated as resources for drinking water supply and tourist attractions.

Chapter 17 (author L. Leonhard et al.) exemplifies the use of groundwater models as tools for groundwater management. The study demonstrates that it is essential to ensure that the required quantity and quality of groundwater can be sustained through extensive periods of zero recharge for alluvial aquifer systems. The modelling outputs are combined with the results of regular measurement of both groundwater level and salinity obtained from a network of observation bores, to ensure the sustainability of the water supply.

1.5 Conclusions

With its discussions of a broad range of studies related to groundwater in coastal zones of the Asia–Pacific Region, this volume offers a critical tool for coastal researchers, geoscientists in related fields, water engineers, groundwater managers and decision makers. It illustrates human and environmental impacts on coastal groundwater resources, their relationship to coastal zone management strategies, and the development of sustainable management approaches.

Acknowledgments The Editor gratefully acknowledges all contributors to this book, especially Charles W. Finkl and the Coastal Education & Research Foundation for their promotion. Many thanks go to all the supporters and reviewers who made publication possible and offered their help in editing, Bernd Striewski and Jeremy Joseph.

Reference

C. Andrew Christensen III, www.worldmonitor.info, Regions,Asiapacific, March 2006

Chapter 2
Hydrogeology and Hydrochemistry Along Two Transects in Mangrove Tidal Marshes at Dongzhaigang National Nature Reserve, Hainan, China

Hailong Li, Yuqiang Xia, and Xiaolong Geng

Abstract Dongzhaigang National Nature Reserve is the largest mangrove forest nature reserve in China, holds the most abundant mangrove species, and has been giving the best preservation. However, bald mud beaches were found among the mangrove marshes in the reserve. In order to investigate the environmental characteristics behind this phenomenon, the intertidal zones of a mangrove transect and a bald beach transect with similar topography and tidal actions were selected for comparison study. Several monitoring wells were installed along the two transects for in-situ measurements of pH, ORP, salinity and temperature of groundwater. Groundwater samples were collected for lab analysis as well. The results showed that pH values of the mangrove transect were higher than that of the bald beach transect, ORP measurements indicated that the mangrove transect had an oxidizing environment and the bald beach transect has a reducing environment. Lab analysis showed that the concentrations of anions (Cl^-, SO_4^{2-}, Br^-) and cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) of water sampled from the bald each transect were much higher than that of the mangrove beach transect. Along both transects, observed water table variations were significant in the high and low intertidal zones and negligible in the middle intertidal zones. The observed groundwater salinity was significantly smaller along the mangrove transect than along the bald beach

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transect. Previously published analysis concluded that the two transects have a mud-sand two-layered structure: a surface zone of low-permeability mud and an underlying high-permeability zone that outcrops at the high and low tide lines. The freshwater recharge from inland is considerable along the mangrove transect but negligible along the bald beach transect, this may explain the lower concentrations of salt and regular ions along the mangrove transect than along the bald beach transect. This comparative study of hydrogeology and hydrochemistry along the two transects would provide ecological implications on the restoration, protection and management of mangrove ecosystems.

2.1 Introduction

As one of the most important salt marsh ecosystems, mangrove marshes typically occur along tidal estuaries and coastlines in tropical and subtropical regions (Chapman 1977; Kjerfve et al. 1990; Spalding et al. 1997). They are important for coastal ecology and play an important and irreplaceable role in the maintenance of coastal biodiversity (Field et al. 1998; Bosire et al. 2008). However, mangrove forests are also one of the world's most threatened tropical ecosystems with an obvious global degradation (Valiela et al. 2001; Duke et al. 2007; Gilman et al. 2008).

Dongzhaigang National Nature Reserve is the largest mangrove forest nature reserve in China, holds the most abundant mangrove species, and has been giving the best preservation. Most mangroves are distributed along the broad shallow beach such as Sanjiang plain and the coastal area of Tashi, other mangrove forests are situated along rivers (e.g., Yanfeng River, Fig. 2.1). However, bald beaches without any vegetation were found among mangrove marshes. In order to investigate the hydrogeological and hydrochemical characteristics critical to mangrove development, a mangrove transect and a bald beach transect were selected to conduct a comparison study (Fig. 2.1). The mangrove transect is located in the Changningtou tidal marsh, and adjacent to the estuary of Yanfeng River. The bald beach transect is situated in a tidal beach without any vegetation and abuts the Shanweitou Village and Dongzhaigang Bay. Along each transect, eight or nine observation wells were installed (Fig. 2.2), and the water level, salinity, pH, ORP and temperature in the wells were measured for 3 days with intervals of 1–3 h. Water samples were also collected for lab analysis of water quality.

2.2 Study Sites

The Dongzhaigang National Nature Reserve is the first mangrove forest reserve in China founded in 1980. It is located in Dongzhaigang Bay bordering the administrative regions of Qiongshan City and Wenchang City, in north eastern Hainan

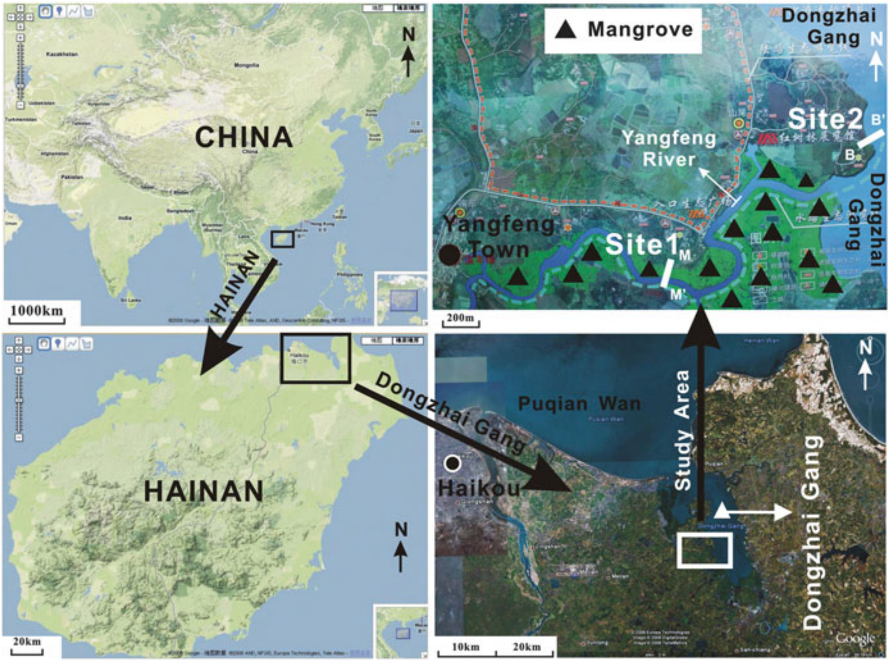

Fig. 2.1 Location maps of Dongzhaigang National Nature Reserve, China and the mangrove transect M–M′ and the bald beach transect B–B′

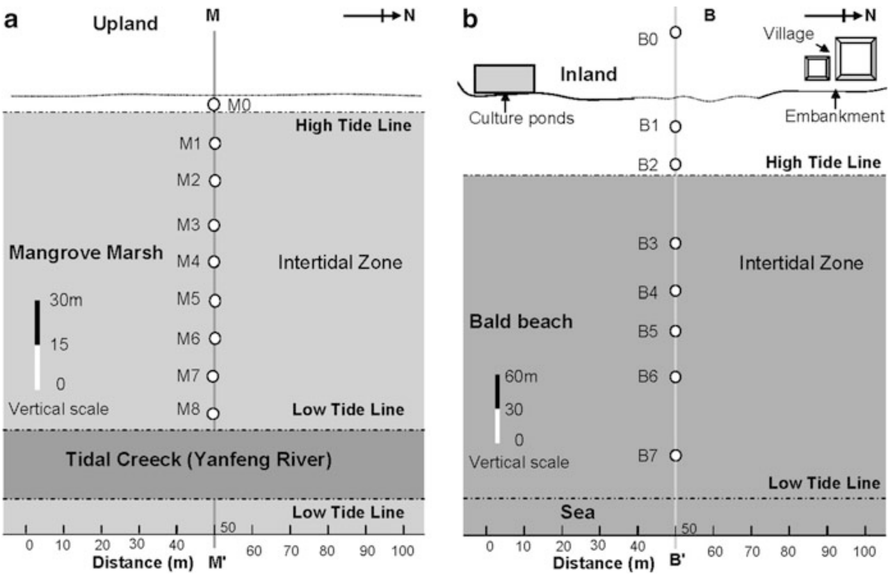

Fig. 2.2 The bird-eye’s view of the two transects

Province. Its geographical coordinates are 19°57′–20°01′N, 110°32′–110°37′E (Fig. 2.1). The area trans-bounds the tropical and sub-tropical zones of southern China and has a correspondingly diverse transitional fauna and flora with the southern sub-tropical species dominant. The transitional climatic and hydrological conditions, specific topographic features (estuarine ecosystems) and its rich biodiversity ensure its global significance as a wetland of international importance. Its relatively large area of mangrove forests and wide inter-tidal sands and mudflats provide migratory water birds and fish with rich feeding grounds and breeding habitats (Chen et al. 1999).

The Dongzhaigang estuary has an irregular rectangle shape with a south–north orientation. It is the largest bay in Hainan Province with a total area of nearly 100 km^2. The estuary is a shallow water bay formed by continental sink during the 1605 Great Qiongzhou Earthquake, and has a typical subtropical monsoon marine climate (Xia and Li 2012). The estuary forms a nearly closed lagoon having only two narrow channels connected it to the South China Sea in the north. Beigang Island, situated at the mouth between the two channels, is large enough to block the effects of strong storms from the South China Sea. The eastern side of the estuary consists of an alluvial plain and the western side is bordered by low hills. The base rocks in this area are mainly basalt and olive basalt and these are the origin of overlying soils. Typical acid red soils have been developed under the sub-tropical and tropical climate. The soil layer is generally between 1 and 1.5 m thick and the acidity is pH 5–6. The soils under the mangroves are mainly saline marsh soils (Chen et al. 1999).

The Dongzhaigang National Nature Reserve has a tropical monsoon marine climate with an average rainfall range of 1,700–1,933 mm (data during 1973–1986) with 80 % of the precipitation occurring during May to October and a mean annual temperature of 23.3–23.8 °C. The region is usually affected by typhoons during the summer months (Fu 1995; Xia and Li 2012).

Four rivers enter into the Dongzhaigang Bay, they are Yanzhou River, Sanjiang River, Yanfeng River and Xi River. During the rainy season, the four rivers carry large amount of silts which are largely deposited within the bay to create the extensive inter-tidal mudflats. It is the mudflats that provide a suitable environment for mangrove growth in this area. The annual average temperature of the surface sea water is 24.5 °C within the estuary, while the highest mean water temperature from May to July is 31.5 °C and the lowest is 17.7 °C in January (Chen et al. 1999). Tides in this area are mixture of diurnal and semidiurnal components. The tidal range is about 1.92 m during spring tides and 0.38 m during neap tides (NMDIS 2008).

With 2,065 km^2 of mangrove forests distributed in the shoals of the tidal zone, Dongzhaigang National Nature Reserve accounts for 44.51 % of mangrove forests of Hainan Island and is the largest mangrove forest nature reserve in China, holds the most abundant mangrove species, and has been giving the best preservation (Xia and Li 2012). Dongzhaigang mangrove forest has 26 “true” mangrove species belonging to 12 families, and 40 semi-mangrove and mangrove-associated species belonging to 22 families (Chen et al. 1999). The mangrove marshes in

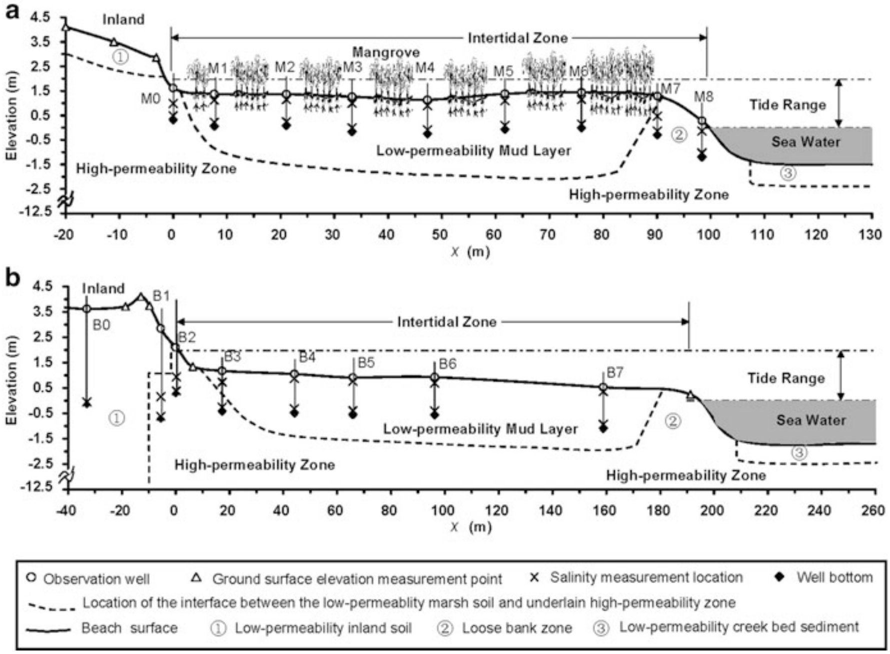

Fig. 2.3 The cross-section of (**a**) the mangrove transect M–M′ and (**b**) the bald beach transect B–B′. The intertidal zone is located within 0 m $\leq x \leq$ 100 m for the mangrove transect and 0 m $\leq x \leq$ 190 m for the bald beach transect, where x is the seaward distance from the high tide mark. The detailed information about monitoring wells is presented in Tables 2.1 and 2.2

Dongzhaigang National Nature Reserve mainly distribute in three coastal areas: Tashi, Yanfeng and Sanjiang Plain (Fig. 2.1).

Two transects were selected for field investigations in Yanfeng and their distance is about 1.8 km (Fig. 2.1b). The first (mangrove transect) is located in Changningtou mangrove tidal marsh, and adjacent to the estuary of Yanfeng River. Mangrove plant species in this site mainly include *Aegiceras corniculatum*, *Bruguiera sexangula*, *Bruguiera gymnorrhiza*, *Kadelia candel*, *Ceriops tagal* and *Acanthus ilicifolius* (Ye and Lu 2001). Nine monitoring wells (M0–M8) were installed along the mangrove transect (M–M′ in Figs. 2.1b, 2.2a, 2.3a) perpendicular to the high tide mark. Well M0 is located at the intersection of mangrove marsh and inland hill. The width of intertidal zone is about 100 m. The second (bald beach transect) is situated in a tidal beach without any vegetation. It abuts the Shanweitou Village and Dongzhaigang Bay. The beach sediment is mainly mud. Eight monitoring wells (B0-B7) were set up in the bald beach transect perpendicular to the high tide mark (B–B′ in Figs. 2.2b, 2.3b). The width of the intertidal zone is about 190 m. More information about the selection of transects can be found in Xia and Li (2012).

2.3 Methods

2.3.1 Field Measurements

Boreholes were drilled with Hand Auger (AMS Inc., USA) to install observation wells. Each well was made up of inner and outer PVC pipes, the inner pipe was put inside the outer one, the outer and inner pipes were wrapped by fine plastic screen, and the space between the two pipes was filled with coarse sands. All these measures were taken in order to prevent the fine beach sediments from entering wells and to guarantee good hydraulic connection between the beach groundwater and the water inside the well. Installation details of the observation wells were described in Xia and Li (2012).

Wells were installed during 12–17 December 2007, which provided 7–13 days for the disturbed groundwater level, salinity profiles and other characteristics to recover to natural status. The elevations of wells and the topography of study profiles were geometrically leveled using an Electronic Total Station (TOPCON, Japan) which has a measurement accuracy of ±2 mm. The data are summarized in Tables 2.1 and 2.2. The sediments around B0–B3 are dominated by sandy loam with gravel, and mud sediments are extensively distributed on the tidal platform (B4–B7). The sediments in the intertidal zone of the mangrove transect are almost uniform (mainly mud). The soil properties along the mangrove transect is much simpler than those along the bald beach transect (Xia and Li 2012).

Water level and salinity in each well were measured by using an electronic dipper system and the Salinity Handheld meter (JENCO Inc., USA), respectively. The values of pH, ORP, and temperature of water samples in the wells were detected by the pH/ORP/Temperature Handheld meter (JENCO Inc., USA). The observation period was from 25 December 2007, 08:00 to 28 December 2007, 08:00. There was no rainfall during the 3 days. Water samples were collected at

Table 2.1 Locations and depths of wells at the mangrove transect M–M′

Locations	Distance (m)	Elevation (m)	Well length above surface (m)	Well length below surface (m)	Elevations of salinity measurement (m)		Thickness of mud layer (m)
					Shallow	Deep	
M0	0.000	1.615	0.67	1.33	0.985	0.485	0.8
M1	7.679	1.367	0.65	1.35	1.117	0.217	2.5
M2	21.081	1.366	0.68	1.32	1.146	0.246	2.5
M3	33.291	1.259	0.53	1.47	0.989	−0.011	2.6
M4	47.331	1.133	0.57	1.43	0.903	−0.097	3.0
M5	61.719	1.375	0.52	1.48	1.095	0.095	3.5
M6	75.985	1.435	0.51	1.49	1.145	0.145	3.7
M7	90.096	1.284	0.38	1.62	0.464	−0.136	0.4
M8	98.378	0.273	0.49	1.51	−0.137	−1.037	0.0

Table 2.2 Locations and depths of wells at the bald beach transect B–B′

Locations	Distance (m)	Elevation (m)	Well length above surface (m)	Well length below surface (m)	Elevations of salinity measurement (m)		Thickness of mud layer (m)
					Shallow	Deep	
B0	−33.000	3.611	0.23	3.77	/[a]	−0.059	/
B1	−5.568	2.839	0.44	3.56	0.149	−0.621	2.0
B2	0.000	2.094	0.19	1.81	1.112	0.562	0.0
B3	17.284	1.166	0.38	1.62	0.726	−0.254	0.9
B4	44.078	1.048	0.43	1.57	0.878	−0.322	2.5
B5	65.835	0.907	0.50	1.50	0.757	−0.393	2.5
B6	96.196	0.921	0.47	1.53	0.691	−0.409	2.5
B7	158.884	0.527	0.33	1.67	0.357	−0.943	2.5

[a]/ means not available

shallow and deep depths in each well using a sterile syringe and then filtered through 0.45 μm (or smaller) filters. The collection vial was rinsed three times with filtrate before being filled brimful of sample filtrate. Samples were stored cold until they could be processed. Samples collected in well M7 were broken.

2.3.2 Laboratory Analysis

Water samples were analyzed by ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectroscopy) for cation elements like Ca, Mg, Mn, Fe, Zn, Na, K. ICP-AES systems consist of several components such as the sample introduction system, the torch assembly, and the spectrometer. The sample introduction system on the ICP-AES consists of a peristaltic pump, Teflon tubing, a nebulizer, and a spray chamber. The fluid sample is pumped into the nebulizer via the peristaltic pump. The nebulizer generates an aerosol mist and injects humidified Ar gas into the chamber along with the sample. This mist accumulates in the spray chamber, where the largest mist particles settle out as waste and the finest particles are subsequently swept into the torch assembly. Approximately 1 % of the total solution eventually enters the torch as a mist, whereas the remainder is pumped away as waste. In the ICP-AES a plasma source is used to make specific elements emit light, after which a spectrometer separates this light in the characteristic wavelengths. Sequential (monochromator) spectrometers were used in ICP-AES analysis for this study. Generally 10 mL of solution was used for estimation of basic elements, and blank solution for each batch of samples was also provided.

The ion chromatography was used for analysis of water samples for common anions such as Cl^-, SO_4^{2-}, and Br^-. Ion chromatography is a form of liquid chromatography that uses ion-exchange resins to separate atomic or molecular ions based on their interaction with the resin (Weiss and Weiss 2005). Water samples were filtered prior to evaluation with an ion chromatograph to remove sediment and other particulate matter as well as to limit the potential for microbial alteration before the sample is run. The minimum sample required for analysis is approximately 5 mL, with no maximum limits.

2.4 Results and Discussions

2.4.1 Variations of Salinity, pH, ORP and Temperature

Figure 2.4 depicts the observed salinity, pH, ORP and temperature of groundwater in shallow and deep depths of monitoring wells along the mangrove and bald beach transects. It is obvious that the shallow water and depth water show a considerable difference along the mangrove transect, while they are close to each other along the

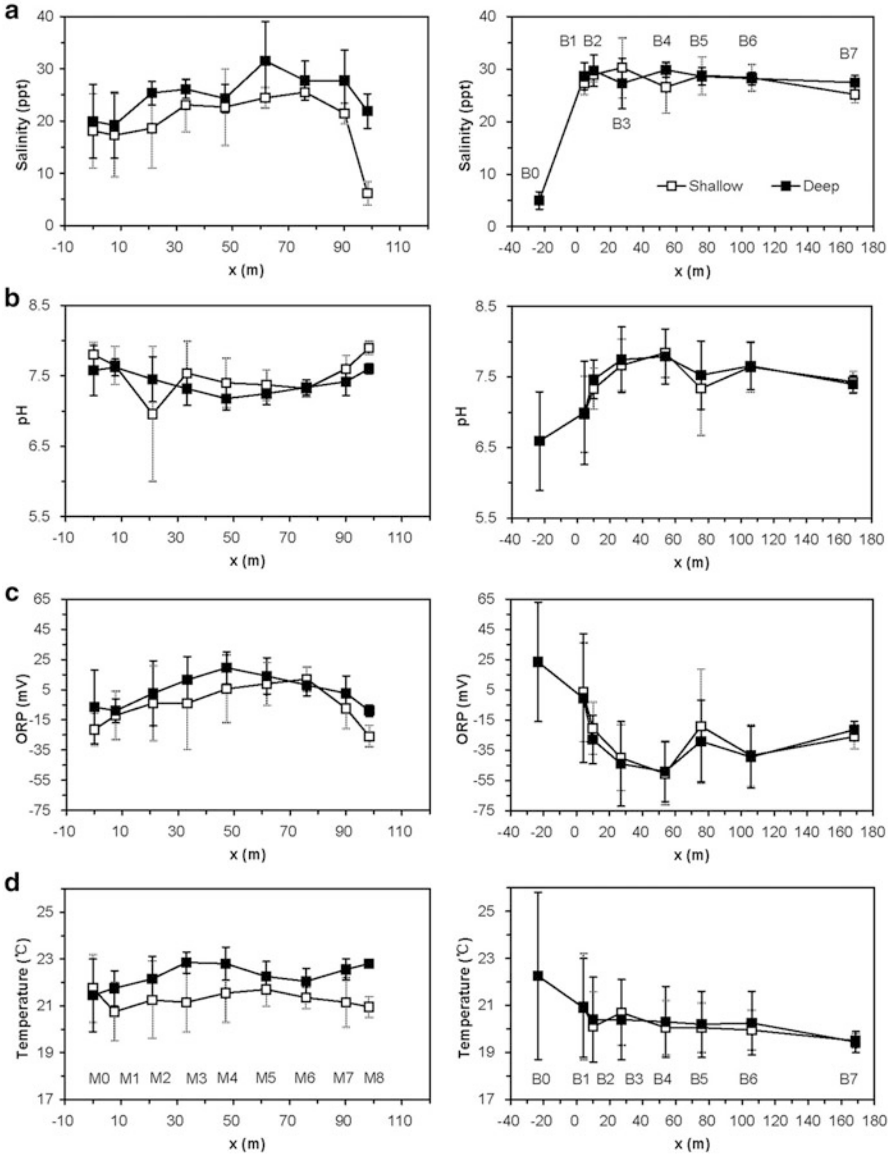

Fig. 2.4 Observed pH, salinity, ORP and temperature of the mangrove (*left panel*) and bald beach (*right panel*) transects. The average is indicated by *symbols*, and the maximum and minimum are indicated by the upper and lower ends of the *vertical bars*, respectively. The shallow and deep locations for each well were indicated in Fig. 2.3 and given in Tables 2.1 and 2.2

bald beach transect, indicating a different subsurface environment between them (Xia and Li 2010).

Figure 2.4a reports the groundwater salinity over the 3-day observation period at two depths of each well in the intertidal zones of the mangrove and bald beach transects. The salinity distribution along the two transects shows a significant difference. The averaged salinity in each well along the mangrove transect is significantly lower than that along the bald beach transect, particularly in the high intertidal zones and near the low tide lines of the two transects. Further calculations showed that the average salinity of all the wells is 23.0 ppt for the mangrove transect and 28.5 ppt for the bald beach transect. The salinity varies significantly along the mangrove transect implies a strong saltwater and freshwater exchange there. In addition, in each well of the mangrove transect, salinity at shallow location is always lower than that at deep location. As documented by the observations of both water table and salinity and numerical simulations of the water table that were conducted by Xia and Li (2012), the salinity discrepancy between the two transects was most probably caused by the difference of freshwater recharge conditions between them.

Figure 2.4b shows that in the mangrove transect, pH values of the high intertidal zones and near the low tide lines were higher than that of the middle intertidal zone, indicating that the vegetation has an effect of decreasing the pH value of groundwater in the rhizosphere. On the contrary, in the bald beach transect, pH values of the high intertidal zones and near the low tide lines were lower than that of middle intertidal zone, indicating that the biogeochemistry dominated by the fauna in the intertidal zone has an effect of increasing the pH value of groundwater.

The ORP in the intertidal zone of the mangrove transect is significantly higher than that of the bald beach transect as depicted in Fig. 2.4c. Along the mangrove transect, the averaged ORP values in almost all the wells were positive. Along the bald beach transect, most of the averaged ORP values were negative. The above observations indicate that the mangrove transect has an oxidizing environment (particularly between M2 and M7 of the mangrove transect where the rhizosphere of the mangroves is located) and the bald beach transect has a reducing environment.

The temperatures of groundwater demonstrated in Fig. 2.4d further indicate a different subsurface environment along the two transects. The temperature along the mangrove transect shows a significant variation with depths (increasing of temperature with depth). The temperature along the bald beach transect is almost constant with depths. These phenomena may be explained by the fact that in winter the temperature of surface water is lower than that of the groundwater.

2.4.2 Water Quality

In order to identify the difference of hydrochemistry characteristics between the mangrove and bald beach transects, we compared the concentrations of common anions and cations of groundwater sampled approximately at the same time from