1 Estuarine and Coastal Hydrography and Sediment Transport

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1 Introduction

This chapter provides an introduction to the handbook and summarises some of the more recent fieldwork on estuarine and coastal research topics and the instrumentation deployed. The handbook deals with numerous methodologies that are currently in use to study the physical behaviour of estuaries, their coastal plume areas and the coastal zone in general. It is clearly impossible to provide detailed accounts of all the methods used and their various laboratory and field procedures; rather, what we hope to provide in this book is a source of material that can be used both as an introduction to the methodologies and a starting point from which to follow up, in much greater detail, the various techniques that are briefly described here.

The chapters deal with physical properties such as bathymetry, water circulation and waves, and sediment properties and behaviour. Other ECSA handbooks are planned that will deal with the biology and chemistry of estuarine and coastal systems. Holistically, many, if not all, of the ‘life’ systems and processes and their interactions with suspended and deposited sediments and water-column and particulate chemistry within estuaries and coastal waters are strongly dependent on physical processes, whether they are associated with horizontal transport, vertical and horizontal mixing or the erosion and deposition of sediments. Although the handbook is largely focused on physical processes, biological effects are not ignored. For example, Chapters 6 to 9 consider several properties of the suspended and deposited sediment, including its particulate organic content and other biologically relevant variables, and Chapter 10 outlines methods that are used to deal with and mitigate the biofouling of moored instrumentation.

The estuarine and coastal-waters system is of great importance to us; most of the world’s major cities and most of our most populous areas are near the coast (e.g., Huntley et al., 2001). Water-borne effluents and wastes derived from industries, cities and river catchments are transported by rivers and estuaries to the coastal zone. Sediment movements are particularly difficult to predict because of the complications of resuspension, settling and deposition, and particle flocculation. Observations of the pertinent processes are an important part of our effort to model these processes and provide essential data for model validation, interpretation and understanding. The instrumentation and methodologies described and presented in this handbook form a key part of the armoury of estuarine and coastal oceanographers in their attempts to obtain these data.

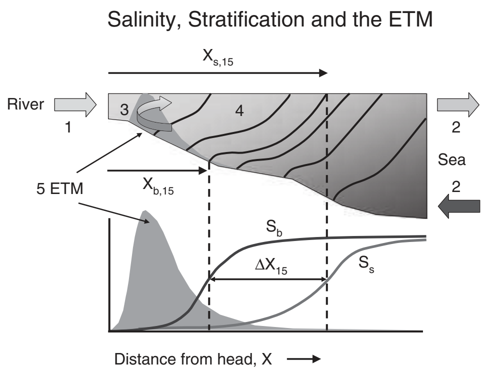

Figure 1-1 A qualitative, indicative schematic illustrating a partly mixed estuary and showing: (1), river inflow at the head; (2), the residual exchange-flow of waters from, and to, the sea at the mouth; (3), the residual estuarine circulation null-point near the bed and close to the head; (4), some salinity isohalines that exhibit stratification due to freshwater buoyancy, which leads to the surface isohalines, S_s, located at distance X_s, being displaced down-estuary relative to the bed isohalines, S_b, located at distance X_b ($X_{s,15}$ and $X_{b,15}$ and their separation ΔX_{15} are shown for the 15 isohaline); (5), SPM concentrations that maximise near the head within the ETM and then fall dramatically progressing closer to the head and the nontidal river. Tidal oscillations are superimposed on this depiction of residual properties, leading to intratidal variations in salinity intrusion, mixing, stratification and ETM location and magnitude.

In his introduction to the earlier handbook, Dyer (1979) summarised the tidally averaged (residual) estuarine physical processes as they were known at that time. These focused on the classic concept of estuarine circulation (or buoyancy or gravitational current) and the classic classification scheme of tidally averaged circulation and salinity stratification. We do not attempt to update this knowledge here, although it is worthwhile to mention these topics very briefly and illustrate some of the most fundamental concepts (a partially mixed estuary is shown schematically in Figure 1-1). The inflow of freshwater and buoyancy to an estuary generates an estuarine circulation (reviewed by MacCready and Banas, 2011), which, in a tidally averaged sense, is down-estuary near the surface and up-estuary near the bed. This in turn leads to an exchange flow at the mouth; a null-point in the residual circulation in the upper estuary; greater or less salinity stratification (surface salinity less than bed salinity, dependent on freshwater inputs and mixing); and, depending on the nature and extent of sediment supply, the potential for an estuarine turbidity maximum (ETM) to form in the upper reaches (Figure 1-1). This simple picture is greatly complicated by tides, winds and sediment behaviour, and one of the consequences of the development of new technologies and associated instrumentation in the intervening years since the first handbook was published has been the ability to study, in great detail, the influences of tidal variability and turbulence on estuarine and coastal dynamics.

We start with the handbook's raison d'être and then provide a preview of the chapters and their contents. In an attempt to highlight the current state of knowledge and general direction of travel of research efforts in the topics covered by the handbook, a summarised description of some of the latest (generally 2010–2016) research work that has been undertaken using the methods and instrumentation described in these chapters is then given. We conclude with some final comments on the relevance of the topics covered and a note of caution about ensuring the timely use of the knowledge base.

2 The Handbook's Raison d'Être

To give just a few examples, the technology behind the acoustic Doppler current profiler (ADCP), the HF (high frequency) ocean surface current radar (OSCR) and, more recently, X-Band radar, the optical backscatter (OBS) sensor, and airborne and space-borne remote-sensing technology, were either not available or in their infancy when the previous handbook was published (Dyer, 1979). Since that time, these and other advances in instrumentation, such as accurate, handheld global positioning system (GPS) readout units, have produced a huge advance in our ability to observe spatial and temporal variations in estuaries and coastal waters.

Satellite and airborne remote sensing are continually providing new insights that are invaluable to research programmes that investigate estuarine and coastal phenomena, e.g., understanding key processes, as well as aiding studies of estuarine and coastal water quality. Airborne remote sensing, utilising light aircraft, can provide very high spatial resolution images, typically of the order of metres or less, and OSCR has provided highly resolved maps of surface currents in the coastal zone.

Given these huge advances since 1979, we felt that it would be valuable to provide an updated version of the handbook, generally following the earlier version in overall coverage of the research topics considered therein, but concentrating on the instruments and methods that have evolved since. This does not render the earlier version obsolete because many of the methods described there are still useful, although there are inevitably some overlaps with the updated handbook when older methods have been considered too important to omit; e.g., the fundamental technique of gravimetric determination of suspended solids concentration is described in Chapter 7.

3 Preview of Chapters

The handbook begins with a description of the modern techniques used in hydrography, followed by those utilised in hydrodynamics for the measurement of waves, conductivity, temperature, salinity and density, depth and water velocity. The instrumentation and methodology required to measure properties of the deposited sediment and the suspended primary and flocculated sediment and transported sediments and particulate matter within estuaries and the coastal zone are then covered. Finally, there are discussions on the methodologies currently used to capture remotely acquired data from moored observation platforms and from satellite and aircraft images.

3.1 Hydrography

Abbott describes the modern methodologies that are used to measure estuarine and coastal bathymetry and tides in Chapter 2. The chapter includes topics such as the recording of vertical tidal movements and the processing of data; global reference frames and positioning on the Earth's surface, including satellite positioning; the technologies, methodologies and types of survey platform utilised for the determination of bathymetry and the associated uncertainties; and finally the approach taken to plan survey field work, including safety aspects. In Chapter 3, Jones, Abbott, Manning and Jakt continue this theme and describe the applications of sidescan sonar to seabed imaging, geological mapping and habitat mapping, which developed from early 12-kHz systems through to the modern 900-kHz and 1600-kHz systems. Chapter 3 covers swathe bathymetric systems, using multiple echo sounder transducers, interferometric bathymetric swathe sounding and Multiple Beamforming Echo-Sounder (MBES), Lidar, subbottom profilers, and survey planning and seabed classification.

3.2 Hydrodynamics

3.2.1 Temperature, Salinity, Density and Velocity Measurement Techniques

Technologies for velocity measurements in estuaries and coastal waters, especially acoustic Doppler instruments (velocimeters – ADVs, and profilers – ADCPs), are described by Souza in Chapter 4. He describes the underlying physical principles of operation of these instruments and highlights their great operational flexibility; e.g., their use when mounted on moving platforms, for which the ship's velocity is removed using either the bottom-tracking of the same ADCP in shallow waters or else calculated from the ship's GPS. He then goes on to describe the use of ADCPs and ADVs for the estimation of turbulence production and dissipation, pointing out the simplicity and versatility of the ADCP instrument, which allows the user to obtain full water-column estimates of turbulence production and dissipation and even directional wave spectra and suspended particulate matter (SPM) concentrations with appropriate calibrations. Nevertheless, turbulence measurements from bottom-mounted moorings are usually obtained using the ADV, which rapidly samples the three components of velocity in a small sampling volume. Remote sensing techniques are also mentioned because of their sea-surface descriptions of ocean winds, waves, temperature, ice conditions, suspended sediments, chlorophyll, eddy, and frontal locations.

Also described in Chapter 4 are modern measurement techniques for the determination of temperature, conductivity and hence both salinity and, with SPM concentrations, water-column density, along with an historical review of these measurement methodologies. Although modern measurements of temperature and salinity are usually carried out using conductivity-temperature-depth (CTD) sensors, temperature alone is also measured using thermistors. The main operational difference between CTD sensors, aside from accuracy and stability considerations, resides in whether they use inductive or conductive sensors and the configuration of sensors on the instrument. Other advances include reliable self-recording systems that can be either moored or mounted on ships and AUVs (automated underwater vehicles) and gliders and the availability of communication technologies that provide real-time estimates of density. Measuring sea-surface temperatures from space is well established although the measurement of salinity from space is still not routine, despite the fact that techniques using passive microwave radiometry have been under development for more than 20 years.

3.2.2 Wave Measurement Techniques

Tides and buoyancy due to freshwater inflows and surface heating generally dominate the hydrodynamic behaviour of estuaries and coastal systems, although wind is often an important influence, both as a driver of currents and surface waves. A description of linear wave theory and its various definitions in coastal and estuarine waters is given by Wolf (Chapter 5) to provide an introduction to modern measurement techniques for the observation of waves in shallow waters and the determination of surface wave properties. Several types of instrumentation are documented, including directional wave buoys, arrays of current meters and pressure sensors, and satellite, aircraft and land-based, remotely deployed instrumentation, which sense wave characteristics such as surface roughness using microwave radar or optical systems.

Wolf points out that wave-following buoys can be difficult to deploy in shallow estuarine and coastal waters, so that combined current meter and pressure-sensing instrumentation are frequently used (the PUV – pressure and two orthogonal components of horizontal velocity – method). ADCPs, adapted to capture wave data, have been used for this PUV method. The ADCP's vertical profile configuration is used for wave measurements and high-frequency data are recorded at several Hertz to resolve the periodicities of surface gravity waves. Remotely sensed instrumentation includes ground-based radar systems using radar ranging from structure-mounted instruments, X-Band radars that measure waves via analysis of the backscattered radar energy from the sea's surface, and HF radar that can simultaneously observe waves and currents over a spatial grid of many kilometres. Other methods covered include ultrasound (>20 kHz) tide and wave gauge instruments and the laser altimeter (LiDAR), which can be used from a satellite, plane or helicopter.

Chapter 5 also includes an overview of wave modelling techniques for the nearshore zone, which includes the spectral (phase-averaged) approach and the SWAN model, which has been a landmark development in spectral wave modelling for the coastal zone.

3.2.3 Sediment Measurement Techniques

Solving important practical problems that involve sediments, e.g., estuarine and coastal erosion and accretion, accretion within harbours and ports and the maintenance of navigational channels, requires a quantitative understanding of the transport and behaviour of sediment. Fine sediments, which are an attribute of many large, strongly tidal estuaries, cause an additional water quality issue because of their high adsorptive capacity for dissolved pollutants. Currently, the numerical prediction of sediment transport phenomena largely involves the computation of physically based relationships, although the relevance of biological effects is increasingly acknowledged. These physical relationships are predominantly empirical in nature and rely on the accurate measurement of sediment properties and processes in the field and in the laboratory.

The sampling and analysis of estuarine deposited sediments are discussed by Spencer in Chapter 6. The nature and composition of the surface layer of deposited sediments (the surface or surficial sediments) within an estuary are characteristic of present conditions, whereas analysis of sediment cores can provide information on the deposited sediment at depth within the sediment column, which may indicate past estuarine conditions.

Various methods of collecting surface sediment samples are described in Chapter 6. These range from the manual deployment of scoops or lightweight grab samplers in very shallow waters, to the use of ship-borne mechanical winches for the deployment of heavy grab samplers. Similarly, core samplers range from handheld polycarbonate or PVC tubes that are pushed into the sediment, suitable for use on, e.g., exposed salt-marshes, to gravity and piston corers, vibro- and percussion corers, and box corers. References are made to the instruments and methods that attempt to sample sediment at the thin sediment–water interface.

Other topics covered in Chapter 6 include survey design and frequency of sediment sampling, the storage, preparation and pretreatment of samples, which may include washing, removal of biogenic calcite and organic matter, dispersion and drying. Frequently, particle sizes of the coarse-grained sediment fraction are determined by sieving. The fine-grained sizes are usually determined by sieving, gravimetric techniques or automated methods such as laser diffraction (granulometry). Other methods of size analysis are described, including electro-resistance using the commonly employed Coulter Counter. A discussion is given of other key sediment properties, such as particle shape, sediment structure, porosity and density.

Methodologies for the sampling and analysis of SPM, which encompasses suspended minerogenic sediment, are described by Mitchell, Uncles and Stephens in Chapter 7. They discuss various kinds of sampling platforms, from ships to bridges, and various sampling methods, from pumping to bucket collection, as well as land-based, moored platform-based, and boat-based surveys to determine SPM concentrations; the benefits of working tidal-cycle stations and utilising moored instrumentation are mentioned. Chapter 7 provides a description of the various methods that are currently used for measuring SPM concentrations, including gravimetric analysis and optical and acoustic measurements. The optical sensors that are discussed include the older Secchi Disc and Transmissometer instruments, as well as newer sensors such as the OBS sensor and those operating remotely from satellites and aircraft; acoustic sensors include the ADV and ADCP as well as the acoustic backscatter (ABS) sensor. Also discussed are the calibration requirements of these various instruments.

In addition to the sampling process, Chapter 7 also covers techniques to measure several important properties of the SPM; these include particle mineralogy, the particle size distribution and the effect of organic material and aggregation on particle size, in situ settling velocity of the SPM, and its specific surface area (SSA). Other properties covered are loss-on-ignition (LOI) and the particulate organic carbon (POC), chlorophyll-*a*, and extracellular polymeric substances (EPS) components of the SPM.

Fine, cohesive SPM plays an important role in muddy, strongly tidal estuaries and is greatly affected by floc formation, which is induced by turbulent mixing and stresses. Measurement methodologies that quantify these processes are described by Manning, Whitehouse and Uncles in Chapter 8. Flocs may settle as individual aggregated particles, or when suspended sediment concentrations are large, they may be subjected to 'hindered' settling. Chapter 8 begins with a discussion of clay mineralogy and the composition of biological material within muddy sediments, followed by the influences of SPM concentration and turbulence, salinity and organic matter on the flocculation of muddy SPM as well as the behaviour of mixed-sediment SPM.

Chapter 8 then provides a review of instrumentation and devices for floc measurements and floc sample collection. These include settling tubes and sensing instruments such as the Lasentec (which uses rapidly scanning laser light), the LISST (laser in situ scattering and transmissometry), and InSiPid (in situ particle imaging device). Simultaneous measurements of floc size and settling velocity are made using instruments such as INSSEV (a video-based floc camera system), LabSFLOC (a laboratory-based derivation of INSSEV), and PICS (a particle imaging camera system). The analysis and processing of floc data are described, together with theoretical results for turbulence and shear stresses and sediment deposition.

Sediment transport methodologies are discussed by Black, Poleykett, Uncles and Wright in Chapter 9. The topics include the direct measurement of sediment fluxes, using both classical vertical profiling techniques as well as ADCPs that estimate the SPM concentrations from acoustic backscatter intensity. Direct quantification of sediment bedload transport is difficult to achieve, and the use of mechanical traps and bedform migration rates for measuring this transport are described. An alternative methodology, particle tracking, is discussed as a method with which to determine the movement of suspended and bedload sediments through space and time. Recently, a dual signature sediment tracer has been introduced that combines a fluorescent colour signature with a paramagnetic signature. Sediment erosion methodologies are discussed, including the use of high-resolution recording altimeters for fine-scale deposition–erosion measurements and benthic flumes as a means of assessing seabed stability in terms of erosion thresholds and erosion rates.

3.3 Autonomous Sampling Platforms and Remote Sensing

The use of autonomous sampling platforms is discussed by Fishwick and Turton in Chapter 10. The emphasis of their chapter is on moored data buoys, although recent autonomous technologies are also covered. They include the platform design of moored data buoys and stress the legal obligations associated with the deployment of such buoys in the sea. Power generation and battery considerations are discussed, including solar charging, power generation from buoy motion and wind turbines. An example is given of such systems, using the Western Channel Observatory data buoy in the English Channel. Data handling and control considerations are discussed together with buoy communications via radio, GSM (Global System for Mobile communications), satellite and wireless Ethernet communications. Various types of data-buoy measurement capabilities are covered in Chapter 10, including those for temperature, conductivity, salinity, density, turbidity, optical (apparent and inherent optical properties) and ADCP-derived variables, as well as meteorological and sea-state measurements.

Satellite and aircraft remote sensing, primarily focusing on derived variables such as surface water level, temperature, salinity and suspended particulate matter is discussed by Lavender (Chapter 11). A discussion is given of the use of the electromagnetic spectrum for optical remote sensing and the topics of atmospheric correction, optical theory applications to the derivation of water constituents, and the use of algorithms to derive quantitative variables, as well as the remote sensing of bathymetry. Thermal imagery is discussed together with, as examples, the derivation of biogeochemical constituents and the mapping of water surface temperatures from satellites and aircraft. In addition, microwave remote sensing is discussed, and its use for water level measurement is illustrated.

4 Some Recent Observational Work, Its Instrumentation and Results

In support of the general rationale behind the handbook, we now seek to place it in the context of current ongoing research work in the field. It is clearly not possible to provide an exhaustive review here, but it is nevertheless important to stress the relevance of the handbook within the ongoing scientific debates on coastal and estuarine matters. Some of the more recent work on estuarine research topics and the instrumentation deployed are briefly summarised here, generally for the period 2010–2016. An attempt is given to provide a 'flavour' of the research conclusions for each topic; however, it is recognised that this brevity cannot do full justice to the work discussed. The types of instruments used and their product names are given for completeness, although this does not imply recommendation of these products by us or the publisher.

In the following text, the abbreviation SPM refers to suspended particulate matter, which includes suspended, inorganic mineral sediment; however, the abbreviation SSC is widely used to refer to suspended sediment concentration or suspended solids concentration, without reference to the organic content, which can vary widely within and between estuaries (Uncles et al., 2015). In this section the concentrations of SPM, which includes inorganic suspended sediment, e.g., suspended sand grains, are referred to by the abbreviation SSC (suspended solids concentration(s)).

4.1 Currents: Tides, Density, Winds and Turbulence

Generally, estuarine tides are forced by those in the adjacent coastal sea, and the associated currents are mainly horizontal because tidal wavelengths are very long compared with water depths. The shallow depths of most estuaries can also lead to the development of overtides and tidally induced residual currents (reviewed by Li, 2011) and, occasionally, tidal bores (Figure 1-2a and b). Cross-estuary spatial variations in the longitudinal tidal and residual currents are influenced by the cross-estuary channel shape (reviewed by Valle-Levinson, 2011); for example, the estuarine circulation

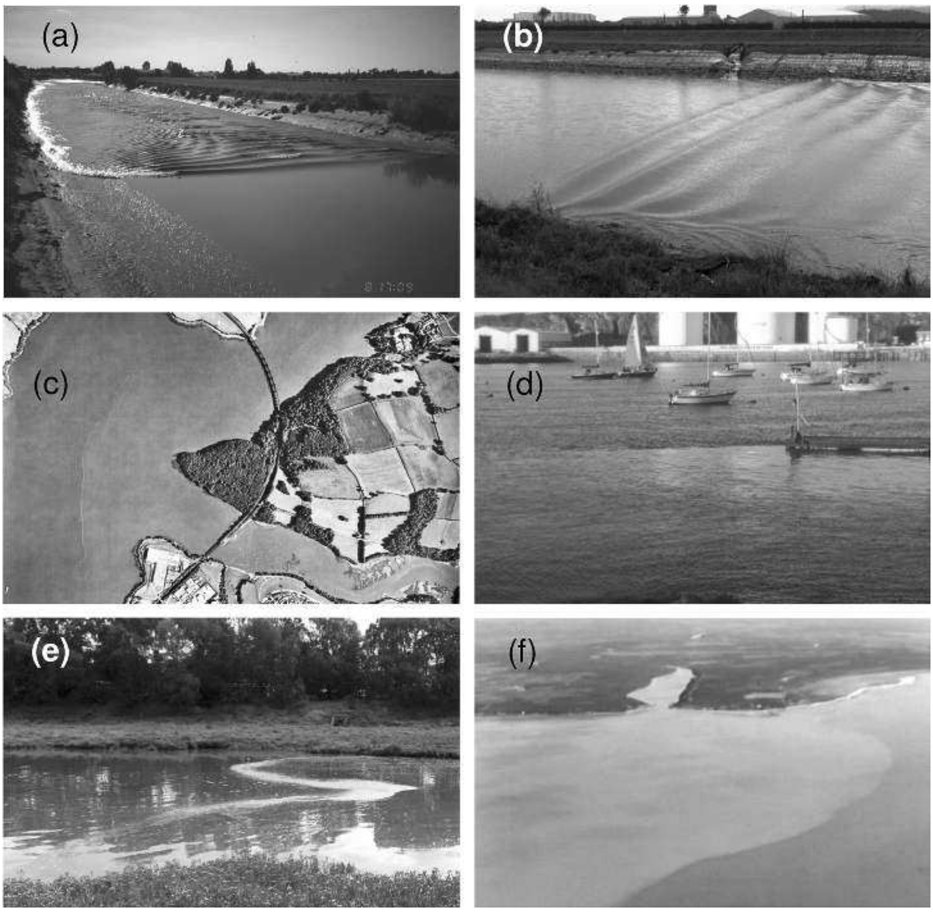

Figure 1-2 Some examples of fronts and tidal bores: (a), a spring-tide tidal bore in the upper Humber-Ouse Estuary, UK; (b), a spring-tide tidal bore in the upper reaches of the Dee Estuary, northern English–Welsh border region, UK; (c), a front separating waters with different colours between the Tamar Estuary's main channel (to the left) and the shallows closer to the mouths of the two subestuaries (to the right); (d), an ebb-tide spring-tide front separating shallower, near-shore (smooth surface) and deeper (ruffled surface) waters caused by flow separation at the end of a pontoon (right of centre) in the Plym Estuary, UK; (e), a tidal intrusion front during a late flood-tide spring tide in a small creek off the Dee Estuary, UK; (f), an ebb-tide river plume off Penang, Malaysia. Photographs: R. J. Uncles, except (c), which is cropped from an aerial photograph that is © Cornwall Council and is reproduced with permission. Photograph (f) is reprinted from Uncles (2011) with permission from Elsevier.

(Figure 1-1) has both vertically and horizontally sheared flows, with inflow at depth and outflow along the estuary sides (not depicted in Figure 1-1) and at the surface.

Wind stress on an estuary's surface generates waves (Chapter 5), surface currents and turbulence (reviewed by O'Callaghan and Stevens, 2011). Remote, nonlocal wind stresses generated by along-shelf winds cause an Ekman setup of water levels that can then propagate into an estuary. Currently, there are few reported measurements that highlight and quantify the interaction between waves and currents at estuary mouths and in tidal inlets. A review of the theoretical and modelling aspects of wave dynamics is given by Wolf et al. (2011).

Stacey et al. (2011) review sheared, stratified turbulence with applications to estuaries, plumes and coastal seas and explain that water-column stratification acts to decrease turbulent mixing, current shear acts to increase it, and turbulence acts to reduce both shear and stratification. They show that the total kinetic energy (KE) can be separated into the mean KE and the turbulent KE (TKE) using the Reynolds' decomposition (Chapter 4).

4.1.1 Tides, Overtides and Bores

O'Donncha et al. (2015) used HF radar (Coastal Ocean Dynamics Applications Radar – CODAR) measurements to describe surface flows in Galway Bay, Ireland. Two HF radars continuously measured radial water velocity components at a frequency of 25 MHz; the effective depth of measurement was 0.48 m, the sampling range 25 km, and the spatial resolution 0.3 km. Two radar systems were used to determine the water velocity because one system measures only the radial component of velocity along a line originating from its antenna (Chapter 4). Barotropic model simulations and HF radar data demonstrated good agreement for tidal currents, although the comparison with residual currents was much less satisfactory.

Sound transmission experiments, designed to measure tidally influenced river currents, were carried out by Zhu et al. (2012) in a freshwater, tidal-bore reach of the Qiantang River, China. Two coastal acoustic tomography (CAT) transceiver nodes were installed on opposite tidal-river banks to form a 3-km-long section diagonally across the Qiantang River. The broadband transducer (Neptune Sonar, Model T170) – operated for sound transmission and reception – was suspended at a depth of 3 m. The transducer's central frequency and bandwidth were 5 kHz and 2 kHz. The CAT was able to successfully monitor the abrupt fluctuations in river flow that resulted from the passage of a tidal bore. It also estimated steady river flows, in the absence of bores, which were well correlated with measured water-level data.

Bonneton et al. (2015) investigated the physics of tidal bores. In the Garonne Estuary, France, pressure sensors were deployed in shallow water, and two 1.2-MHz ADCPs (RDI), with vertical bin sizes of 0.2 m and 0.05 m, and one acoustic wave and current profiler (AWAC, Nortek) with a 0.5 m vertical bin size, were deployed along the estuary axis. The pressure sensors sampled at 10 Hz and other instruments (OBS-3A, Campbell Scientific; ALTUS Altimeters, IFREMER and MICREL, France) at 2 Hz. A seabed-mounted 1.2-MHz ADCP with a 0.1-m bin size, and an ADV (Nortek), which sampled at 2 and 32 Hz, respectively, were deployed in mid-channel, and three pressure sensors that sampled at 10 Hz were deployed over the river cross-section. Field data showed that the dimensionless tidal range was the parameter that governed bore intensity and that the waves associated with a bore in a rectangular channel were significantly different from those associated with undular bores in natural estuaries (e.g., Figure 1-2a and b).