# Chapter 5 : Knysna Estuary — Meeting Place of River and Sea

### John Largier & Lucienne Human

## 5.1 Introduction

Boundaries like the land-sea interface provide critical ecological habitats as well as increasingly desirable human habitat. This is nowhere more evident than where rivers meet the coast, and where people can access both the benefits of rivers and the sea. Generally known as estuaries, these intersection points host diverse and productive ecosystems at the same time as attracting humans who value the resources and aesthetics of these special places. While larger estuaries like Chesapeake Bay (USA) or Mar del Plata (Argentina) may receive more attention globally, smaller systems like the Knysna Estuary are regionally important, providing significant services and value to local communities — and they may punch well above their weight as small islands of critical habitat that promote regional biodiversity.

Companion chapters in this book outline the history, evolution, and ecology of Knysna — all of which relate to the water motion and water properties in this estuarine basin where the waters from the land meet and mix with the waters from the sea. With the passing of seasons and interannual fluctuations (droughts and floods), the waters in the basin may at times be more like a river and at other times be more like an 'arm' of the ocean — but always a meeting place, where river waters and ocean waters interact. And always there is an incessant rise and fall of the tide that alternately pulls in ocean waters and pushes out estuarine waters — the "breath of the bay"[1], akin to humans breathing in ambient air and breathing out air that has been modified by reactions in our lungs. The essence of the Knysna Estuary is a tidal interplay of freshwater and seawater, which characterizes the water filled Knysna basin that extends from Charlesford Weir to the rocky Heads (see Chapter 1 for photos of these estuary features).

In the Anthropocene, input of material to estuaries has been altered by direct human activity, with river water properties being altered by land use and human activities in the watershed, as well as discharge of wastewater and runoff of stormwater directly from developed areas to the tidal estuary. Human-driven loading combines with natural loading from the watershed and ocean as inputs to the physical mixing and biogeochemical reactions that occur within the estuary. Physical aspects of the estuary can also be altered by development, restricting flows or promoting seawater intrusions through embankments or dredging, respectively. And in the modern era, human-driven global climate change has become an additional modifier of estuary processes, including sea-level rise, ocean acidification and deoxygenation, and changes in precipitation patterns and land runoff (see Chapter 10 for details).

The water motions and water properties in the Knysna Estuary reflect much of what is expected in an estuary, including recent human modifications. But at the same time, it is special and there is no estuary quite like it. There are estuaries that exhibit similar character, however, and we can compare Knysna to global paradigms and other estuaries. For example, for much of the time Knysna can be considered a "low-inflow estuary" relative to its size[2]. As with other basins not carved out by river action alone (Knysna basin lies in a valley between fossil dune fields — see Chapter 4), the inflowing river is small compared with the size of the basin; in Knysna the average river inflow of 3 $m^3$ per second would take months to fill the basin. Also comparable with mountainous coastal watersheds in the Western Cape or in the Tsitsikamma region to the east of Plettenberg Bay, the unmodified river delivers a low nutrient load and low concentrations of suspended particles.

In contrast to prevailing textbook paradigms, the estuary is primarily fueled by material imported from the ocean shelf[3], which is biogenically rich and accounts for high productivity, biogeochemical cycling, and biodiversity. However, like too many estuaries in the world, pollution is significant and in some parts of Knysna it is severe enough to alter the food web, with phytoplankton/algal blooms, turbid water, and hypoxia replacing clear waters and seagrass habitats[4].

In this Chapter we outline the movement of water in Knysna Estuary and characterize water properties including nutrient, oxygen and phytoplankton levels, in addition to the abiotic properties of salinity and temperature. These physical dynamics

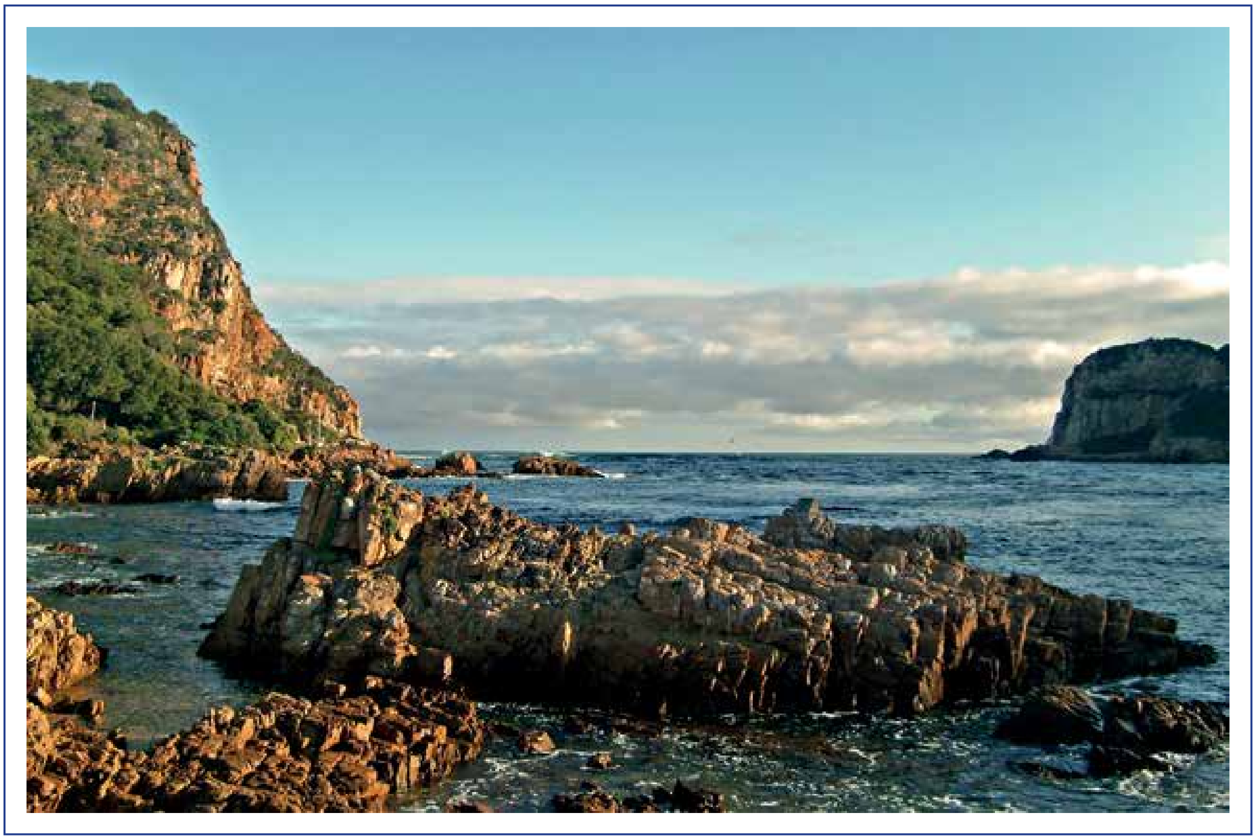

**Figure 5.1** Rocky shores at The Heads shelter Knysna Estuary from ocean waves (Photograph: © Fultonsphoto).

provide the stage on which various ecological dramas can play out. While some may still wish to debate whether Knysna is an estuary, there is not much to be gained from that and more is gained from exploring the diverse phenomena that play out in estuaries, whether they are called estuaries, lagoons, rias, bays, vleis, coastal confluences, transitional waters, or whatever. Of these the most common term is estuary, which is increasingly used in an inclusive way to refer to all places where river waters meet the sea, often in a defined basin.

The adjective 'estuarine' introduces some nuance as estuarine circulation may disappear in the dry season when marine salinity prevails and some estuarine species may move into the upper reaches of the system. This intermittency in estuarine features and processes is increasingly recognized as a common phenomenon in many of the world's estuaries. Whether intermittent or not, the two fundamental physical characteristics that shape estuaries are variations in salinity (meeting of river and ocean waters) and the importance of tides (currents, import/export, fluctuations in water level), which are addressed in sections 5.3 and 5.2, respectively. In turn, these water motions advect parcels of water around the estuary and account for mixing between water parcels, in which biogeochemical reactions are happening simultaneously — together accounting for differences in water properties across space and time. Specifically, we address nutrients (section 5.4), phytoplankton (section 5.5), dissolved oxygen and pH (section 5.6), and pollutants (section 5.7). Finally, we address critical changes in parts of the estuary where the food web is changing due to severe anthropogenic nutrient loading (section 5.8)

## 5.2 Water flows and water levels

Along the coasts of the world, water level rises and falls in response to multiple celestial forces tugging on the great body of water that forms the ocean. This tidal 'heaving' results in water flooding into confined estuary basins as the water level rises in the ocean and some hours later water ebbs out of the basin as the water level drops in the ocean. The rise and fall of water level, the cycle of wetting and drying of intertidal land surfaces, and the strength of tidal currents filling and emptying the estuary are a fundamental characteristic of most estuaries.

While many smaller estuaries on mountainous coasts in South Africa and globally may be shut off

**Figure 5.2** Flood tide entering the broad and permanently open Knysna Estuary mouth, with the western Head visible on the far side (Photograph: © Ava Peattie).

from the sea by wave-built sand berms, the mouth of Knysna Estuary remains permanently open despite low river inflow. Not only do rocky headlands at the mouth provide shelter from wave action (Figure 5.1), but they also limit the longshore supply of sand from proximal coasts so that a beach does not form adjacent to the mouth and cannot build across the mouth as for most other estuaries in the region, e.g. Swartvlei Estuary. While there may be some wave-driven sand supply and accretion in or near The Heads, the open-mouth nature of Knysna Estuary is maintained by strong currents due to the large volume of water that moves into and out of the estuary on every tidal cycle.

This large tidal prism is more common in mesotidal or macrotidal regions of the world, but in microtidal areas like South Africa the tidal prism can also be large where there is an extensive tidal area, as in Knysna. Comparable wave-sheltered, open-mouth estuaries in micro/mesotidal California are Bolinas Lagoon and Bodega Harbor with tidal areas of 450 ha and 1 280 ha, respectively, and comparable with the 1 690 ha tidal area in Knysna. Large estuaries with a permanently open mouth and small river inflow are sometimes called embayment estuaries or estuarine bays. Such systems have many characteristics similar to the sea but are calmer and warmer than waters along the adjacent open coast — these are rare in South Africa (e.g. Langebaan Lagoon) but common elsewhere such as in the estuaries of northwest Spain (i.e. the rias in Galicia).

With a relatively deep and broad open mouth, ocean water flows strongly into Knysna on flood tides (Figure 5.2). Tidal currents attain speeds of 1 m per second at The Heads and 0.5 m per second adjacent to Thesen Island[5]. These currents transport sand into the estuary, accounting for flood-tide shoals between The Heads and Leisure Isle (see Chapter 4 for details). Marine sand also contributes to tidal shoals further landward, although the railway embankment has throttled these dynamics and altered tidal morphology.

The tide propagates into Knysna Estuary as a long-period wave that develops non-linear characteristics such as a short flood tide with fast currents and a long ebb tide with slower currents. This tidal asymmetry is most noticeable in shallow waters, where fast flood-tide currents move sediment landward that then settles out during slow ebb-tide

**Figure 5.3** Tides are responsible for the daily inundation and exposure of plants and sediments in littoral areas around the Knysna Estuary (Photograph: © Alan Whitfield).

currents, maintaining the very shoals that account for this process. No surprise then that extensive shoals are found either side of the channel. These shoals, in turn, constrict most tidal transport to the channel that acts like an artery connecting the outer, middle and inner estuary.

Near the mouth, water levels can also fluctuate rapidly due to waves or slowly due to wind surge effects. Although waves are sufficiently dissipated at the mouth (Figure 5.1) to preclude beach building, some wave energy propagates through the mouth and plays a role in maintaining beaches in the outer estuary, assisted by short-period waves generated by winds in the estuary (e.g. north-easterly winds that produce waves on the shore between Brenton-on-Lake and The Heads). In addition to swell waves (periods of 5 - 20 seconds), long-period infragravity waves (periods of minutes) can enter from the ocean. These small fluctuations do not last long and are largely unnoticed, but they can be seen to move material quickly over short distances and may be important in exchange between open water and marshes.

In contrast, wind-driven surges in the ocean are noticed in Knysna Estuary because they are larger (they can account for a 0.5 m change in water level, comparable with the neap-tide range) and more persistent (a few days, allowing water to rise slowly even in the furthest recesses of the basin). The wind-driven surge may be due to local winds along the coast, but at times it is a propagating surge, generated by winds further west — these 'coastal trapped waves' propagate eastward along the south coast[6]. The long-period disturbances do not result in significant water velocities and are not expected to be important for changes in morphology nor transport of biogenic material into the estuary. However, they can account for persistently high water levels with significant impact on marshes and adjacent areas, some of which have now been developed by humans. As sea level rises and flooding becomes more of a threat, it is the concurrence of a wind surge and high tide, with high river flow, that is the worst-case scenario for flooding of low-lying developments around the Knysna Estuary.

Tides also account for pelagic-littoral coupling, moving waters on/off seagrass covered shoals and in/out of saltmarsh habitats (Figure 5.3). This lateral exchange of waters between the arterial channel and productive littoral habitats is aided by

**Figure 5.4** Aerial photo showing the clarity of estuarine water in the outer estuary (Photograph: © Duran De Villiers).

infragravity waves near the mouth and by local wind-driven water motions that raise water levels locally, pushing water into tidal creeks that drains out when the wind subsides. Inflowing channel waters can be expected to supply marshes and littoral habitats with nutrients, and in turn export organic material during ebb tides (known as 'outwelling').

Water velocities in the upper estuary driven by river inflow are only important during high river flow events. Tidal currents still dominate in mid - and outer estuary where even high river flows account for velocities no more than about 0.1 m per second. However, river flows are important in that they bring low-density freshwater into the basin, resulting in stratification and a mode of circulation in the vertical plane that is critical to water exchange in the inner and mid-estuary (this phenomenon, known as 'estuarine circulation' is outlined in Section 5.3).

While an estuary is a continuum and functions as an integrated system linking river to ocean, there are clear changes in the hydrodynamic character moving longitudinally through the basin. For shallow low-inflow estuaries like the Knysna system, there is a river-dominated inner estuary, an ocean-dominated outer estuary, and a low-energy mid-estuary[7]. Specifically, for Knysna, Largier et al[5] identified and described these zones, identifying hydrographic regimes that migrated tidally. They referred to the inner estuary as the estuary regime, the outer estuary as the bay regime, and the mid-estuary as the lagoon regime. While shifting with the tides, the estuarine regime is generally landward of White Bridge (the main road bridge) and the bay regime is generally seaward of the Railway Bridge.

A primary consideration for water properties addressed in subsequent sections is residence time: how long water remains in an estuary or part of it before being displaced out of the estuary. If the residence time is short, then there is little time for biogeochemical reactions (or surface heating) to alter water properties. However, if residence time is longer than reaction time, then the water properties will be largely determined by these biogeochemical reactions. For example, nutrients imported by tidal inflow or river inflow are typically flushed from Knysna before there is enough time for a phytoplankton bloom to occur, accounting for the clear waters (Figure 5.4). While residence time is a

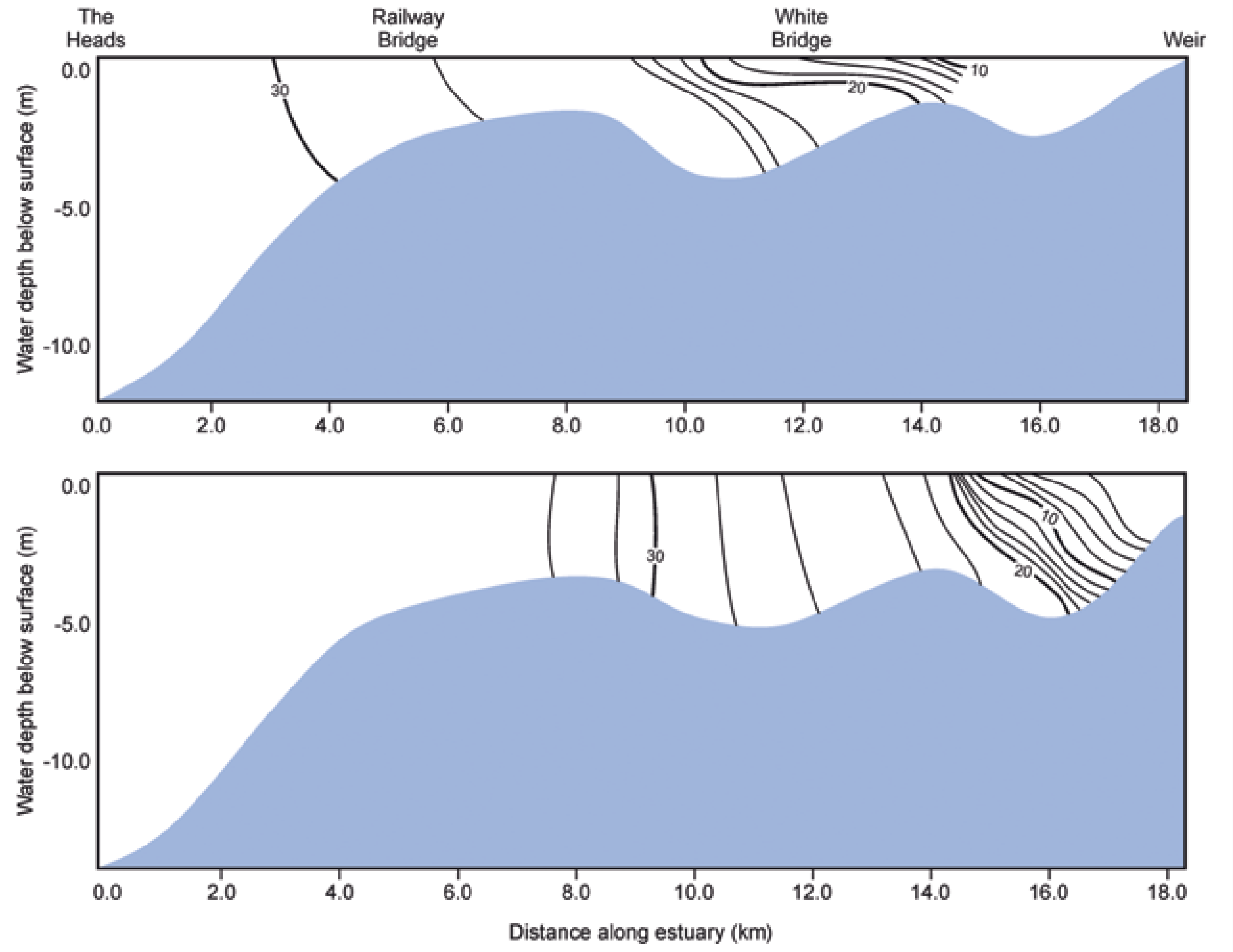

**Figure 5.5** Salinity sections at low tide (upper panel) and high tide (lower panel) during average river inflow (2.8 m$^3$ per second on 5th May 1997), showing salinity stratification in the middle estuary at low tide and compression of low salinity water into the upper estuary during high tide[5].

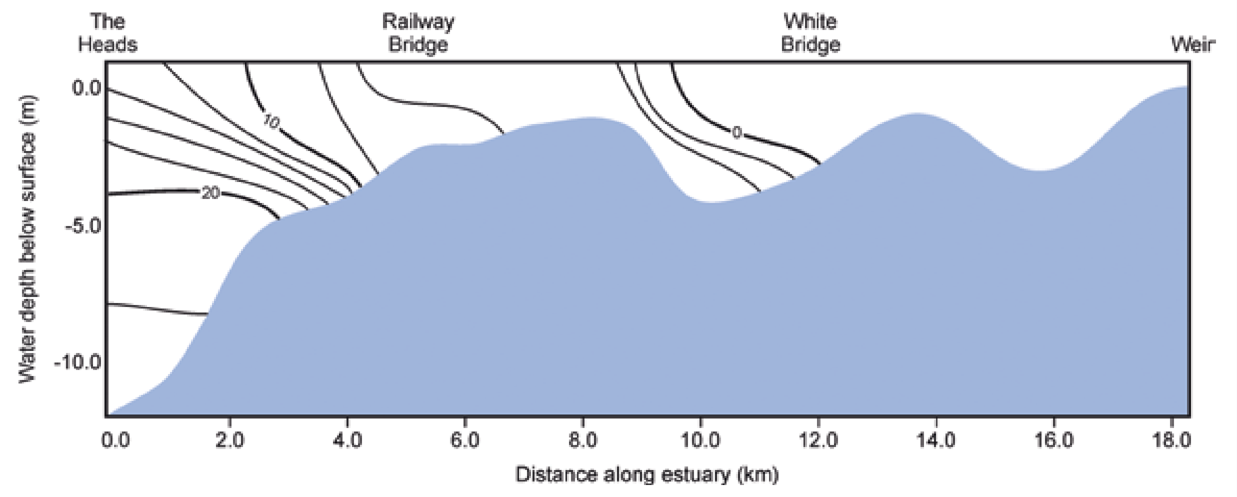

**Figure 5.6** Salinity profiles along the Knysna Estuary on the 25th October 1996 during a 50 m$^3$ per second flood event. Note the absence of any saline water between 12 km and 18 km from the estuary mouth[5].

nuanced concept[8] and best calculated with a computer simulation model, rough estimates can be made by considering the volume of interest and the flow rate that could flush it. For example, if one expected that the whole estuary (volume 32 million $m^3$) was flushed by the river (average 3 $m^3$ per second), then the basin-wide residence time would be approximately four months.

However, if one focused on the inner estuary (volume landward of White Bridge is 2.7 million $m^3$), the residence time is just 10 days — and if one considers that estuarine circulation rate can be several times larger than river flow rate, then residence times may be just a few days. At the same time, the outer estuary is readily flushed by tidal flows: during spring tides the 18.5 million $m^3$ tidal prism[9] (intertidal volume) can fill the basin from The Heads to just beyond the Railway Bridge so that the outer estuary residence time is less than a day during spring tides, being rapidly flushed by tidal action. Between the river-flushed inner estuary and the ocean-flushed outer estuary, however, waters in the mid-estuary may be resident for longer periods. Long residence is also found in dead-end or constricted channels like Ashmead Channel.

While the tidal volume between Railway Bridge and White Bridge (12 million $m^3$) is comparable with the tidal prism volume that passes Railway Bridge, waters moved seaward on ebb tide are not exported to the ocean and likely returned to mid-estuary on the next flood tide with little loss. The long residence of waters in the mid-estuary are evident in the high temperatures (discussed below). However, there are reports of only marginal hypersalinity in open-water[10], which is expected to occur with residence times of about 10 days during periods of low river flow[7]. When river flows are below 0.5 $m^3$ per second, evaporation can remove this freshwater in the upper estuary, thus resulting in negligible freshwater input to the mid- or lower estuary.

## 5.3 Salinity and temperature

The primary water property in an estuary is salinity, which is conservative (i.e. is not changed by biological or chemical processes) and thus tracks the interplay of zero-salinity freshwater flowing from the river and high-salinity seawater flowing in from the sea (ocean salinity about 35 ppt). In most estuaries, variations in salinity account for variations in density and thus for density-driven estuarine hydrodynamics, specifically estuarine circulation. However, in Knysna and other low-inflow estuaries adjacent to marine upwelling regions, water temperature differences may also be important in accounting for density differences that influence circulation patterns within the estuary.

Differences in water density account for stratification (layers of different density with limited mixing). Stratification can develop where stirring is weak enough, but where tidal currents (or winds) stir strongly enough, mixing precludes the formation of layers. In Knysna, the presence and importance of stratification changes spatially and temporally, in response to changes in river inflow and tidal flow speeds[5]. Knysna Estuary exhibits all stratification types on the continuum from completely mixed to highly stratified (Figure 5.5). Stratification tends to increase with increases in river flow during the rainy season and decreases during drought and other times of weak inflow — or rather the spatial extent of the stratified estuary portion shrinks towards the freshwater source at Charlesford Weir.

Stratifcation also changes with the tides, being stronger during neap tides with weaker currents and thus weaker mixing , and weaker during spring tides. The sweet spot for estuaries is when layers form but stratification is mild enough to allow cross-layer mixing; in this case, one gets 'estuarine circulation' with a tidal-mean inflow of dense seawater in the bottom layer and a tidal-mean outflow of low-density estuarine water in the upper layer. The cross-layer mixing pulls the dense water upward into the outward flowing upper layer, completing a conveyor-belt-like circulation in the vertical plane. This is what ventilates estuaries, continuously importing nutrients and other biogenic material from land and ocean watersheds and continuously flushing out material derived from biological production and decomposition.

During low inflows, Knysna is well mixed and the longest residence times are expected in the inner/mid-estuary, however for average inflow (Figure 5.5) the inner estuary is classified as partially mixed (i.e. modest stratification) and a robust estuarine circulation is expected (notably the circulation flow rate is several times larger than the river inflow rate). Estuarine circulation extends into mid-estuary during higher inflows, but highly stratified conditions (no mixing) can occur in the inner estuary during these periods, as the inflowing freshwater 'lifts off' and flows over a long-residence bottom layer. During highest flows, all saline water is flushed from the inner estuary (e.g. 25 October 1996, Figure 5.6), although stratification may be observed in the mid- and outer estuary.

Water temperature varies seasonally in Knysna Estuary (even more so in Knysna River), yielding significant estuary-ocean temperature differences.

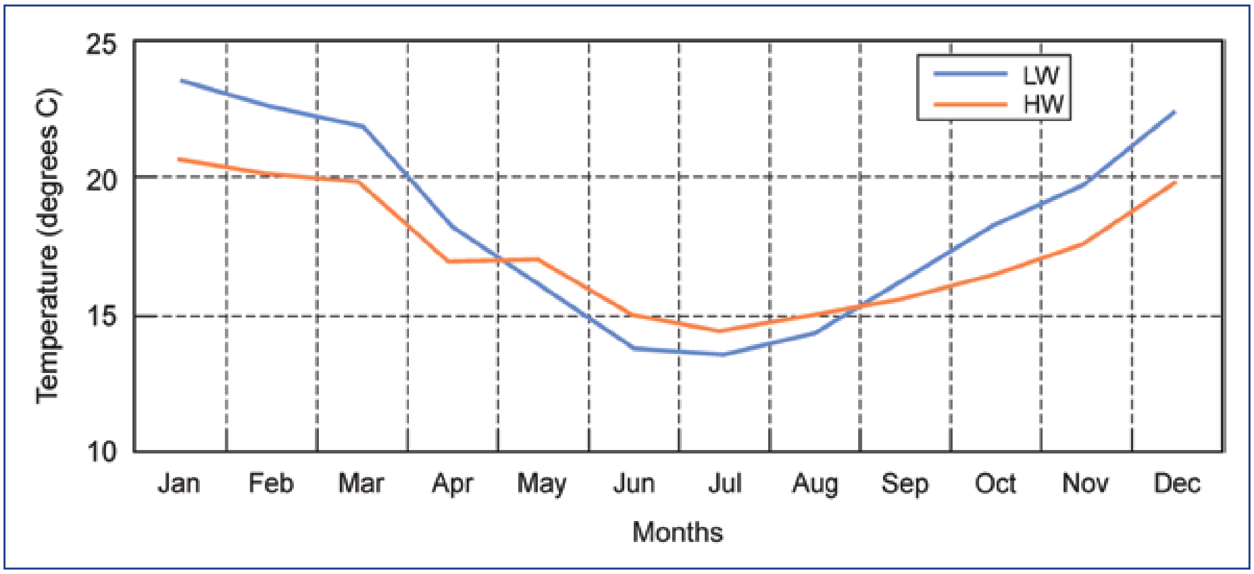

**Figure 5.7** Mean monthly water temperature at low tide and at high tide in the outer estuary[10]. Temperatures were measured at Thesens Island Quay (Figure 1.4). River and inner estuary waters are colder than ocean and outer estuary waters during winter (June-August). In summer estuary waters are warm, typically over 20°C (December-March).

Summer temperatures are generally above 20°C in the estuary with lower temperature near the mouth owing to the influence of the sea, while winter temperature ranges from 12 to 15°C throughout the estuary (Figure 5.7). The estuary-ocean temperature difference is maximal in summer when ocean waters are coldest during coastal upwelling events, while estuary waters are warm[5,6]. Cold, upwelled water intrudes as a dense lower layer, analogous to a salt wedge, and may drive a thermal estuarine circulation in the outer estuary. Detailed descriptions of temperature fluctuations, and specifically of seawater intrusions as cold as 10°C extending as far as Railway Bridge, have been published[5,6]. Not only does temperature change dramatically in the outer estuary during these intrusions, but also oxygen, pH, nutrients and other water properties which can stress benthic organisms. In addition, dense fog sometimes develops over the coast and outer estuary as warm air moves over cool ocean waters entering the estuary during periods of upwelling along the coast (Figure 5.8).

The three zones identified in Knysna Estuary exhibit distinctively different thermohaline character and stratification. The outer estuary (bay regime) is characterized by high salinity, cool waters that are generally mixed and only stratify transiently during cold-water intrusions following coastal upwelling or during very high river flow rates. The inner estuary (estuary regime) is characterized by low salinity and stratification, with temperature that varies strongly between winter and summer. The mid-estuary (lagoon regime) is partially mixed with moderately high salinity and temperatures that are often higher than elsewhere in the estuary, particularly during summer. Fringing marshes may exhibit hypersalinity during dry periods with high evaporation, but residence time in the channel is typically insufficient for this to develop. However, residence in mid-estuary is sufficient for substantial warming of the waters. In summer, mid-estuary water can be more than 10°C warmer than one would expect from a simple mixing of river and ocean waters. Expecting a warming rate of about 1°C per day in waters a few meters deep, this indicates residence times of order 10 days.

## 5.4 Nutrients

The concentration of nutrients in the water controls photosynthesis (primary production), including phytoplankton, drift algae, fixed algae and submerged aquatic vegetation. New nutrients are brought into Knysna Estuary by inflowing river waters and inflowing ocean waters, with the importance of the ocean input being more significant in Knysna Estuary than in textbook estuaries (specifically during intrusions of cold, nutrient-rich water upwelled along the open coast).

In recent decades, the discharge of nutrient-rich wastewater and stormwater has become a third source of new nutrients for Knysna Estuary, especially in side-channels that were previously well removed from ocean or river nutrient inputs. While

**Figure 5.8** The Heads shrouded in fog which develops as warm air moves over cool ocean waters entering the estuary during periods of upwelling along the coast (Photograph: ©Vladimira Pufflarova).

**Figure 5.9** Note the dense intertidal filamentous algal mats (upper half of the picture) that have developed in the Ashmead Channel as a result of nutrient pollution in this region of the Knysna Estuary (Photograph: © Alan Whitfield).

the supply of nitrate exerts overall control on productivity, nutrients are also recycled within the estuary and localized high concentrations of ammonium may result in filamentous algal blooms (Figure 5.9). Accumulated organic material in the sediment results in an important sediment-to-water flux of remineralized nutrients, including outwelling from marshes and shallow, muddy littoral habitats. The anthropogenic accumulation of organic material in Ashmead Channel over the last few decades (i.e. legacy pollution) ensures a continuous supply of nutrients to the water column even in the absence of discharge events, thus sustaining high concentrations of phytoplankton and benthic algae[4].

Nutrient concentrations at a given location depend on the transport and mixing of nutrient-bearing waters as well as biogeochemical reactions in the water and sediment-water nutrient fluxes. The essential nutrients required for primary producer growth are inorganic nitrogen and phosphorus, with nitrogen typically the limiting nutrient for algal growth in Knysna Estuary and other coastal waters.

Mixing diagrams have been used to describe nutrient cycling in the Knysna Estuary[3,9]. These are scatter-plot diagrams in which nutrient concentration is plotted as a function of salinity (Figure 5.10). If the nutrient is conservative, as is salinity, data points fall on a straight line between river and ocean source waters, i.e. nutrient reactions are negligible, and concentration is controlled by the physical processes of transport and mixing. Deviations from the 'mixing line' can be used to quantify nutrient uptake (downward curvature) or nutrient production (upward curvature). During high river inflow through the Knysna Estuary, nutrients behave conservatively — they are rapidly flushed from the upper and middle estuary via freshwater throughflow, and a combination of high flow and tidal flushing quickly removes these nutrients from the outer estuary. The short residence time in the estuary also limits the biogeochemical influence of nutrients on benthic, littoral, and pelagic primary producers. This rapid mixing and removal of high-nitrate river water from the estuary before it could fuel phytoplankton blooms is illustrated by data collected during high river flow on 16 November 2000 (Figure 5.10): data points fall along a mixing line between freshwater inflow with concentration 350 µg per litre and seawater with concentration 100 µg per litre.

In contrast, during periods of low river flow estuarine waters are resident long enough for nutrients to be taken up, contributing to significant photosynthesis and algal growth in the upper/mid-estuary. However, nutrient influx is low during low river flows, influencing only the inner estuary, and ocean-derived nutrients are more important in the

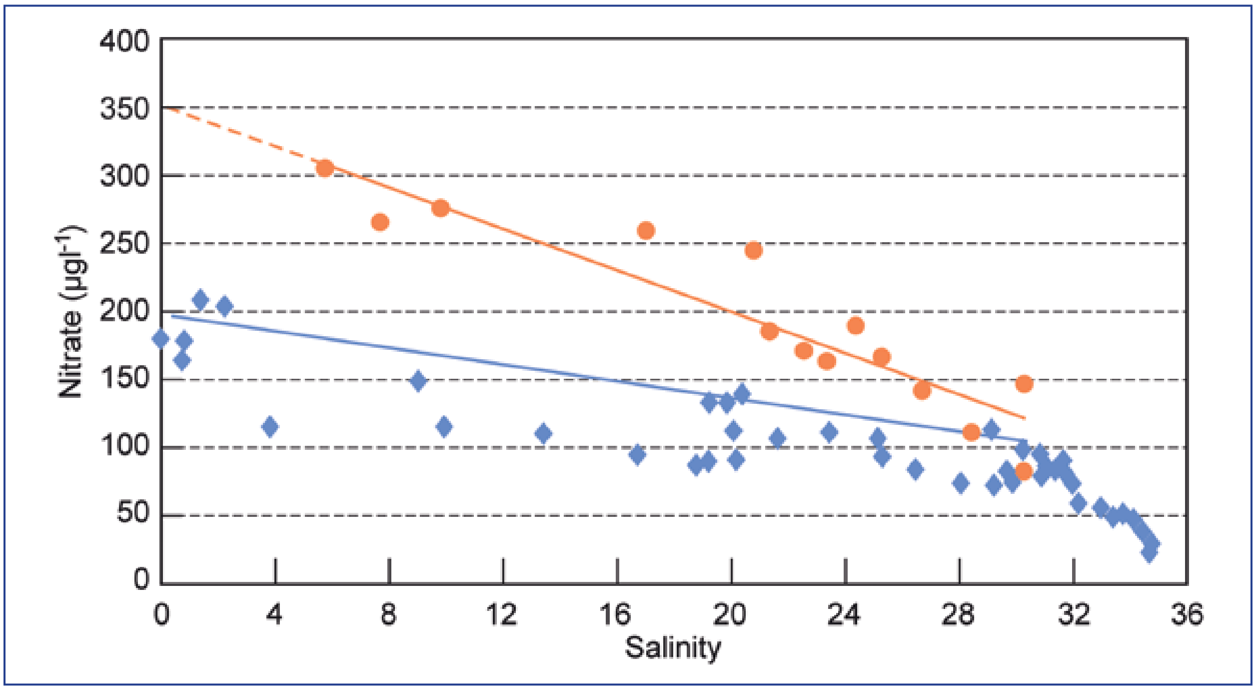

**Figure 5.10** Mixing diagram for nitrate and salinity data from November 2000[9]. Blue symbols are for 13-14th November when water residence time is longer and nitrate values are lower than expected, i.e. biological uptake is important. Orange symbols are for 16th November during a high river flow event when elevated nitrate concentrations were transported through the estuary with weak uptake.

**Figure 5.11** Nutrient rich effluent from the Knysna Waste Water Treatment Plant entering a reed bed prior to discharge into the estuary (Photograph: © Alan Whitfield).

outer and mid-estuary. Most commonly, the mixing diagram for nitrate in Knysna Estuary shows downward curvature corresponding to lower than expected concentrations in the mid-estuary between higher concentrations associated with both ocean and river inflows[3,11]. This shown in data collected on 13 - 14 November, when river flow was lower and flushing was slower relative to a few days later (Figure 5.10): while mixing alone would yield nitrate concentrations between freshwater values of 200 µg per litre and outer estuary values of 100 µg per litre, observed values remain around 100 µg per litre in waters with salinity between 2 and 32 (i.e., inner and mid-estuary), implying that 50 to 100 µg per litre nitrate has been taken up by photosynthesizing plants and plankton in the estuary.

In summer, pulses of cold high-nitrate ocean water associated with upwelling can intrude into the estuary[9]. For example, an upwelling event that began on 27th February 2002 resulted in a 7-fold increase in nitrate concentration as estuarine waters with concentration 2.5 µmol per litre were replaced by ocean waters with concentration 17.5 µmol per litre. When conditions are rapidly changing, data collected at multiple locations within the basin may not exhibit a single mixing-line relationship between nutrient concentration and salinity, as found for the dry winter of 1996/7 when concentrations of $NH_4$ and $NO_xN$ in the estuary were generally below 3 µg per litre[3].

In addition to ocean inputs, nutrient influx via the Ashmead Channel explains higher concentrations of $NH_4$ and $NO_x$ nitrogen in the outer estuary. A wastewater treatment plant that discharges into this channel (Figure 5.11) has experienced multiple failures over the years, which has led to excessive algal growth and hypoxia, i.e. eutrophication[4]. The long residence time in this channel allows for remineralization of legacy organic matter (i.e. accumulated material from prior inputs), resulting in the persistently high $NH_4$ concentration recorded in the Ashmead area. Conditions are amplified during dry periods (e.g. 2016-2017) when flushing events are minimal.

Dissolved reactive phosphate (DRP) concentrations in the estuary remain low (<30 µg per litre) for both high and low inflow periods. However, once again, higher concentrations are recorded in the Ashmead Channel area due to wastewater inputs and remineralization of legacy organic matter[4]. High concentrations of DRP are also found in the upper estuary during dry phases, derived from desorption of P from fluvial particulate phases[9].

## 5.5 Phytoplankton levels

Primary production in estuaries occurs through phytoplankton, benthic algae, seagrass meadows, and littoral marshes. While primary production is generally controlled by the availability of nutrients (described above) and the availability of light, the accumulation of phytoplankton biomass also depends on residence time in the estuary as a phytoplankton bloom (and floating macro-algae) can be flushed out of the estuary before it fully develops. Thus, in either low-nutrient systems and/or rapidly flushed systems, phytoplankton can be low, and waters can be clear, as in Knysna. This allows light to reach the bottom and promotes the growth of benthic algae and seagrasses that are fixed in place. Extensive seagrass meadows are documented for the Knysna Estuary (see Chapter 6 for details). However, if insufficient light reaches the bottom, these bottom-fixed plants and algae do not fare as well.

In general, phytoplankton biomass is tracked by measuring water-column concentration of chlorophyll a (Chl-*a*), the photosynthetic pigment in microalgae. Higher phytoplankton bio-mass is expected in more nutrient-enriched estuaries where dense phytoplankton blooms may exhibit concentrations over 20 µg per litre. In Knysna Estuary, Chl-*a* is generally below 3 µg per litre[3,12,] which is low compared with other South African estuaries[12]. While DWA documented typical low levels of 3.5 µg per litre in July 2007[10], high-concentration phytoplankton blooms can develop following intrusion of nutrient-rich upwelled waters or inflow of nutrient-rich river waters, as in August 2008 when DWA found localized peaks over 15 µg per litre in the vicinity of White Bridge. This was a period characterized by high nutrient availability, low turbidity, and favorable residence time. Phytoplankton biomass can also be high in the inner estuary during summer, such as in February 2008 when moderately high chlorophyll concentrations of 7.5 µg per litre were recorded.

It is likely that localized high-phytoplankton events will become more frequent in the estuary with increasing nutrient loading[9] — in specific areas with long residence times (e.g. side channels). In the inner estuary, a reduction in river flow (reduced flushing) or an increase in nutrient loading will result in the formation of denser phytoplankton blooms, which in turn are likely to lead to anoxic conditions in the lower layer of the upper estuary. In the canals in Knysna Quay, extreme Chl-*a* (over 100 µg per litre) and Secchi disk readings less than 0.5 m have already been measured. Rather than a broad increase in the average algal biomass throughout the estuary, it is expected that high-concentration events will occur more frequently, with high-concentration ‘hot spots’ becoming more widespread.

Phytoplankton levels may also change if river flow is reduced for Knysna Estuary, resulting in longer residence times in mid-estuary. In low-inflow estuarine bays in California, phytoplankton production is driven by ocean-derived nutrients, exhibiting peak Chl-*a* concentrations mid-estuary in the dry season as the outer bay has insufficient retention and the inner bay has insufficient nutrients[14]. Knysna Estuary is shorter than the California bays and river inflows are sufficient to preclude sufficient retention time in the inner estuary — however, if retention time increases in Knysna, a similar phytoplankton maximum may develop mid-estuary. In addition, further work is needed to quantify the rate of nutrient removal by seagrass meadows in the outer/mid-estuary as seagrass-mediated depletion of ocean derived nutrients may preclude this scenario in Knysna Estuary.

Elevated water turbidity is an important control on light availability for submerged aquatic plants. Turbidity may be due to high concentrations of phytoplankton or due to suspended sediments resulting from turbid river inflows, wave-driven sediment resuspension at the mouth, or resuspension of bottom material by tidal currents. While there are occasional turbid events, in general light can reach the bottom across most of Knysna Estuary (Figure 5.4). Traditionally, the Secchi-disk depth has been used to estimate the depth of light penetration (i.e. a measure of turbidity), which varies both spatially and seasonally. Light penetrates deepest in the outer estuary (Secchi depth ~2.3 m) while the middle and inner estuary are characterized by Secchi depths of ~1.5 and ~1.7 m, respectively. During marine dominated states, estuary waters are clearest with Secchi depths of ~2.5 m, ~2.0 m and ~2.25 m in the outer, middle, and inner estuary, respectively. In contrast, transparency decreases markedly during strong river inflow, with Secchi depth averages of ~2 m, ~1.5 m and ~1 m in the outer, middle, and inner estuary, respectively.

When light does not penetrate the entire water column, benthic primary production cannot occur, but phytoplankton can still photosynthesize if trapped near-surface by stratification. So, while seagrass in the outer/mid-estuary may deplete nutrients and limit phytoplankton concentrations, it is also possible that if phytoplankton concentration increases, it will limit growth of new seagrass plants and thus remove this nutrient control, resulting in a positive feedback and phytoplankton blooms with even higher concentrations, i.e. there is likely a tipping point in relation to anthropogenic nutrient inputs to the Knysna Estuary which would result in conversion from the present seagrass-dominated, clear-water state, to a future turbid-water state dominated by phytoplankton and macro-algae.

## 5.6 Oxygen and pH

Aquatic organisms require sufficient levels of dissolved oxygen (DO) to survive. For this reason, it is often used as an indicator of estuary health. In the Knysna Estuary, typical saturated DO values vary between 7 and 11 mg per litre and most commonly are between 8 and 10 mg per litre. Where there is a net biological oxygen demand (BOD) owing to uptake by respiration (dominant at night) and decomposition of organic material, oxygen levels can fall below 100% saturation. Conversely, where photosynthesis exceeds respiration and decomposition (common during the day), oxygen levels can be above 100% saturation, with small bubbles of oxygen from seagrass beds floating to the surface.

In South Africa, oxygen concentrations below 3 mg per litre are considered hypoxic, signaling the need for management intervention. The Knysna Estuary is well flushed and there is therefore insufficient time for severely deoxygenated waters to develop. However, just as anoxic levels occur naturally in the bottom waters of Swartvlei lake, so too can lower DO levels occur in the trapped, high-salinity lower layer in the upper Knysna Estuary (when stratification persists). This exacerbates a spatial trend of lower DO values with distance from the ocean; with lower DO recorded at Red Bridge than at Old Bridge, which in turn had lower levels than White Bridge, which were like those in the well-mixed water column closer to the ocean[3,11]. Lower DO in the inner estuary (above White Bridge) is attributed to higher BOD in this section of the estuary, as well as vertical stratification preventing effective re-aeration of the lower layer.

Seasonal differences in DO are primarily related to seasonal changes in water temperature, with higher DO levels occurring when waters are colder in winter (cooler waters have higher DO saturation values). While warm ocean water in summer may have a lower DO, these waters are seldom deoxygenated and tidal intrusions of ocean water bring well-oxygenated waters into the outer estuary and even the outer parts of the mid-estuary, with significantly higher DO when cold upwelled waters intrude during summer.

Net photosynthesis in seagrass beds can be a local source of oxygen-rich waters to the estuary, as recorded by Allanson et al.[3] in the Ashmead Channel at a time when photosynthesis in these beds was enhanced by nutrients from stormwater and wastewater inflows. However, more recently there has been a decline in DO in Ashmead Channe[14], particularly where wastewater delivers a high load of organic matter that accounts for BOD high enough to exceed local photosynthesis — resulting in a net uptake of oxygen and the observation of low DO values (hypoxic events). As outlined in sections 5.4 and 5.5 above, wastewater also delivers excess nutrients that lead to phytoplankton blooms, which contribute to additional BOD and lower DO as the bloom decays in a classical example of cultural eutrophication (see section 5.8 below).

As with salinity, the pH in the estuary is a function of its receiving waters — lower pH is associated with greater freshwater influence during low tides and higher pH is associated with greater seawater influence during high tides. Although pH levels also may rise in response to net photosynthesis or fall in response to net respiration, this effect is dominated by the large difference in the pH of source waters for the Knysna Estuary. Freshwater properties are determined by both the catchment geology and vegetation. The Knysna River drains Table Mountain Sandstone, which has a low carbonate content and contains acidic colloidal material, resulting in pH levels of about 5. Decomposed fynbos and forest plants contribute to the formation of humic acid, with the dissolved humates also giving rise to tannin-stained water (Figure 5.12).

In contrast to the Knysna River water, seawater is alkaline with pH levels about 8.5 due to the presence and buffering capacity of bicarbonate and carbonate compounds. This difference results in a pH gradient from the top of the estuary to the mouth, with values typically ranging between 5.5 and 8.3, and the lowest pH recorded in the freshwater-dominated waters in the upper estuary. During high river flow, low-pH waters can extend through much of the estuary, e.g. during the major 1996/97 flood the pH dropped below 7.0 (salinity <5 ppt), only increasing to 8.2 near the mouth (where seawater salinity was recorded).

## 5.7 Human modifications

Knysna Estuary has not only changed over geological time scales (Chapter 4), but also historically as humans have gathered on its shores and developed

**Figure 5.12** Humate stained estuarine water adjacent to an eelgrass bed near the White Bridge. When salinities are above 17 ppt and the pH is above 8, the dissolved humic material precipitates out of the water column and the estuary then loses its tannin stain (Photograph: © Alan Whitfield).

the watersheds that drain into the lagoon. Two primary effects of socio-economic development are changing water quality (i.e. pollution) and the changing landscape (e.g. bridges, causeways and seawalls). The estuary is also changing in response to global climate change.

Pollution of estuaries is a global problem and there are many forms, including toxigenic pollution (pollutants that are toxic), pathogenic pollution (pollutants that spread disease), and biogenic pollution (pollutants that stimulate algal growth and oxygen depletion). There are few data on toxigenic pollution for Knysna Estuary, however past studies concluded that Knysna was not polluted at that time[12,15]. While there is no long-term record of metal data in the estuary, more recent data show elevated copper and zinc levels in stormwater[16] (above detection limits of 5 and 25 µg per litre, respectively), suggesting that more attention is needed. Similarly, there are few data on polyaromatic hydrocarbons and other toxic organics which are produced during processing of timber, including creosote seeping[3]. In addition, there is a need for data on pathogen concentrations in Knysna Estuary, specifically in locations where people have contact with the water.

Biogenic pollution of Knysna Estuary is better known, primarily in the form of nutrient pollution originating in river catchments and in wastewater from adjacent urban areas. In the Knysna catchment, indigenous Afromontane forest has been replaced with plantations over a third of the total area (133 km$^2$). During the last two decades there has been a marked increase in the use of fertilizers in the forestry industry and on cattle farms in the area. Fertilizer is transported to the estuary by runoff following heavy rains[9]. In addition, high-nutrient wastewater is discharged into the estuary -via the Ashmead Channel, accounting for algal blooms in this poorly flushed channel[14,17]. In the summer of 2014/2015 a bloom of green macroalgae covered the water column and mudflats of the channel — a clear sign of eutrophication[18,19]. When the filamentous or foliose green algae genera *Ulva* and *Cladophora* accumulate in such large abundance, it is known as a 'green tide'. Legacy sediment and organic matter which has accumulated in the channel are also a contributing factor, with high fluxes of nutrients from the sediment into the water column of 100-300 μmol per m$^2$ per day nitrogen and 15 μmol per m$^2$ per day phosphorous[20]. Water column concentrations of $NH_4$ and DRP in the Ashmead Channel are significantly higher where wastewater enters the channel (145 μmol $NH_4$; 5 μmol DRP) than where the channel joins the main body of the estuary (20 μmol $NH_4$; 1 μmol DRP). This is a significant change from concentrations recorded 20 years ago[4,9] and may be partially attributed to lower oxygen levels.

During periods of hypoxia, remineralization results in higher benthic flux of nutrients from sediment to water[17]. While such eutrophication is only currently recorded in the Ashmead Channel, it is unclear how much longer dilution by tidal flushing can maintain the oligotrophic/clear waters that characterize the outer estuary. Indeed, the green waters and low oxygen levels in Ashmead Channel are a forewarning of changes that could happen elsewhere if a more concerted effort is not made to manage biogenic pollution and maintain the ecological health of the estuary. Such changes would lead to a loss of seagrass habitats and a wholesale transformation of the ecosystem, including fish and bird populations.

Knysna Estuary is crossed by multiple bridges and causeways, including roads to Thesen Island and Leisure Isle and other smaller alterations have also been made through small-scale channel dredging and seawalls. The most significant change to the morphology of the estuary is the railway crossing that serves to demarcate the outer and mid-estuary (Figure 1.4), although impact studies on the

**Figure 5.13** Historical aerial photograph from 1936 showing the railway bridge several years after construction. A long bridge section straddles the main channel in the upper left of the photograph while a narrow culvert-bridge straddles a secondary channel below it.

functioning of the system are lacking. Built in the mid-1920s, the railway crossing is a combination of embankments and short-span bridges that together constrain the flow of water in the estuary (Figure 5.13). During large river floods the constriction is likely to account for elevated water levels in the mid- and inner estuary, which may contribute to flooding of low-lying lands. And if the bridge blocks outflow during river floods it also reduces peak flow velocities in both the mid-estuary and the outer estuary where peak-velocity events are critical for scouring the channel through the flood-tide shoals. Also, by controlling outflow it slows the draining of high marshes that scours channels and maintains marsh-estuary connectivity.

Perhaps more significantly is the alteration of tidal flows that pass through narrow breaks in the embankment, specifically on the south west side where the railway crosses intertidal flats and marshes. On the north east side, the bridge constriction is likely to speed up tidal currents in the main channel, increasing scour of the channel in the vicinity of the bridge and accounting for more mixing that reduces stratification. Although the constricted flow will result in enhanced along-estuary exchange and reduced residence in the mid-estuary due to tidal pumping[1], this is countered by a reduction in the conveyor-belt-like estuarine circulation related to stratification. Most evident is the effect of the bridge on increased sedimentation on either side of the channels, accounting for shoals and precluding small channels that would feed the marshes adjacent to Brenton-on-Lake.

Climate change effects on Knysna Estuary are addressed in Chapter 10. In relation to estuary hydrology, the foremost change is the rise in sea level that will make high tides higher, increasing flooding of low-lying lands and slowly drowning shoals and marshes that cannot build up fast enough through sedimentation. Shoals in the outer estuary are supplied with marine sediments, worked by tides, and it is expected that they will elevate as sea level rises, but marshes and mudflats in the mid-estuary are unlikely to receive sufficient sediment given the low sediment loading and small inflowing rivers. With little low-lying space for landward expansion of intertidal marshes (and mostly already occupied by humans), it is expected that there will be a loss of marsh habitat in the estuary. Climate change will also result in warmer waters and potential for stronger estuary-ocean thermal gradients that could enhance stratified intrusion of high-nutrient seawater. In addition, climate change is expected to change precipitation patterns, which in turn impact the pulses of freshwater inflow to the estuary and therefore the hydrodynamics of the system.

## 5.8 Conclusions

Knysna Estuary is characterized by low freshwater inflow and a large tidal prism, which account for the water column being generally well mixed and extensive sand shoals in the outer estuary. Significant stratification is only found in the inner estuary or during events when there is high river inflow or intrusions of cold upwelled water from the ocean. Similarly, phytoplankton blooms occur as events separated by periods of low concentration and clear water that have allowed extensive seagrass meadows to form. Comparable with other low-inflow estuaries connected to coastal upwelling, the Knysna Estuary is primarily driven by the ocean. It is an unusual estuary in South Africa due to the combination of a permanently open mouth and low nutrient input from the land.

Knysna Estuary is threatened by increasing nutrient input through wastewater/stormwater discharges and the accumulation of organic-rich sediments in Ashmead Channel and other poorly flushed side channels. The Knysna Estuary offers direct value to humans, as well as being an important habitat for wildlife — all of which is founded on the present ecological state that is derived from its open-mouth, low-nutrient status.

## Dedication

We dedicate this chapter to Brian Allanson, our mentor, colleague, and friend who passed away as we were writing this chapter. We will miss him deeply. Not only did we gain many insights into Knysna Estuary from Brian, but he is responsible for recruiting both of us to work on this special estuary. We enjoyed many hours talking about Knysna, learning from him and developing a common purpose of understanding the estuary and sustaining it.

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Low tide view over intertidal flats towards The Heads (Photograph: © Dreamstime.com).