SECTION 6:
SCIENTIFIC AND ENGINEERING ASSESSMENT

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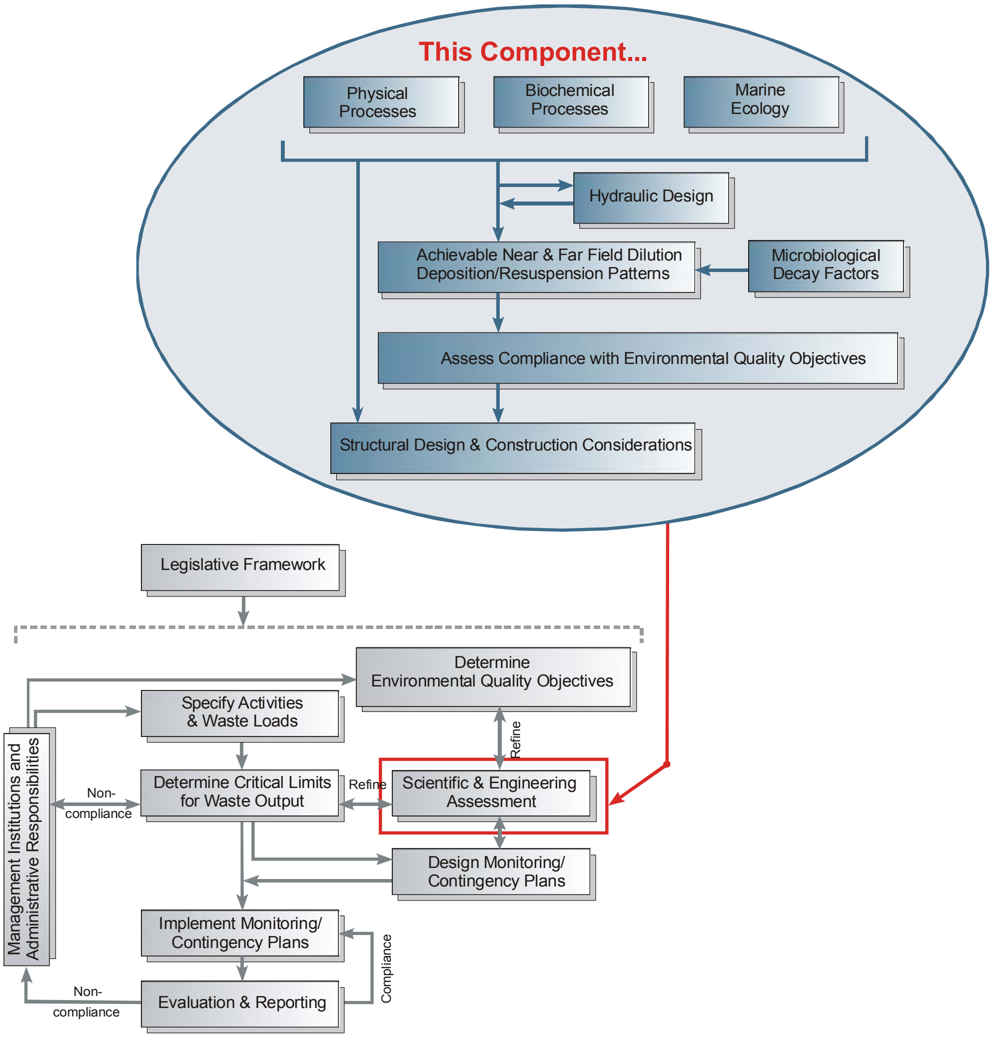


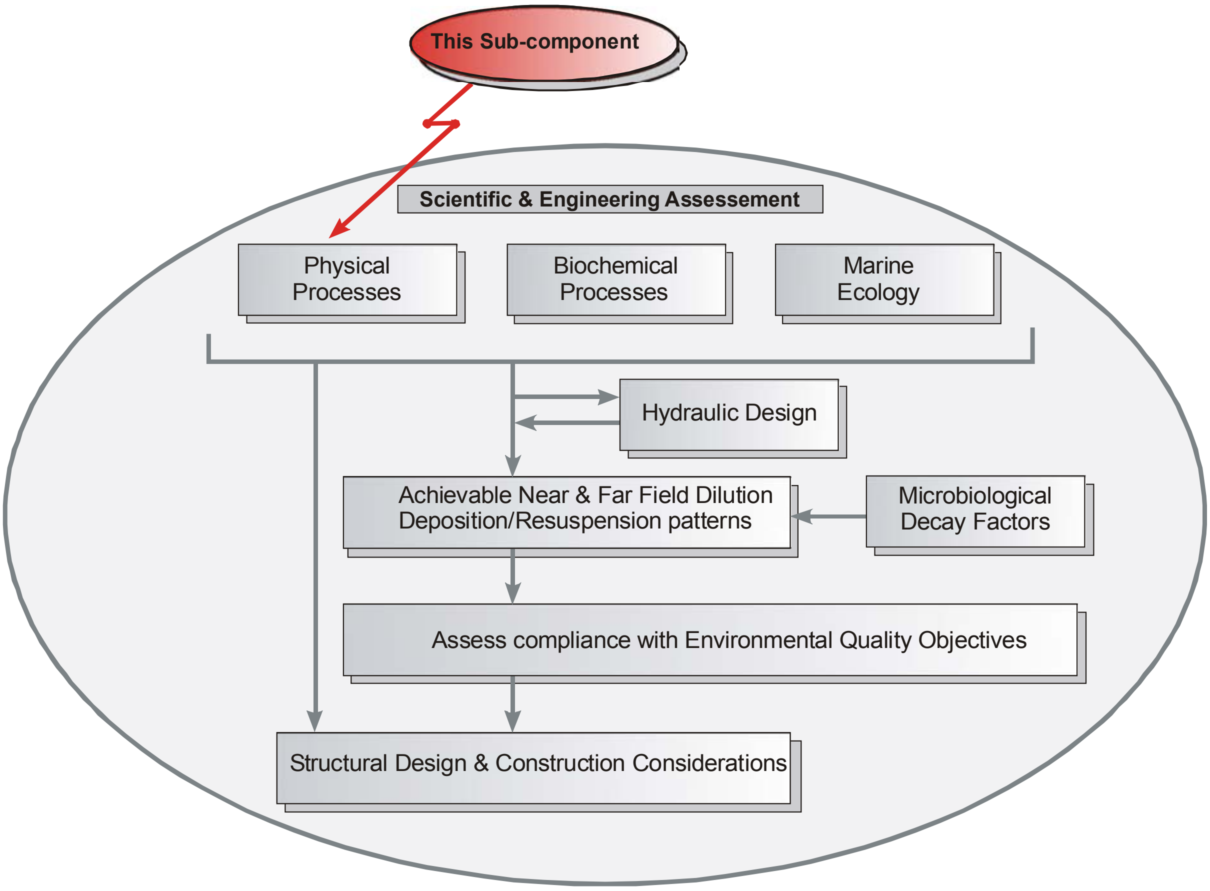
PURPOSE:

The objective of this component is to refine the environmental quality objectives and establish if a waste disposal practice will comply with the environmental quality objectives set for a particular marine environment. This is achieved through the following steps:

- ***Characterise physical and biogeochemical processes and the ecological functioning***
- ***Conduct the hydraulic design of the (offshore) outfall based on preliminarily required dilution estimates and taking into account the characteristics of the waste load (volume and composition)***
- ***Determine the achievable near and far field dilution and the deposition/re-suspension patterns of the proposed wastewater discharge. Also assess possible synergistic or cumulative effects, taking into account other anthropogenic influences in the study area.***
- ***Assess for compliance with environmental quality objectives. Where non-compliance with environmental quality objectives is evident, the hydraulic design of the outfall needs to be adjusted. Where compliance cannot be achieved through adjustment of the hydraulic design, either the critical limits for the waste load need to be reduced (e.g. through additional pre-treatment prior to discharge) or the environmental quality objectives need to be re-defined (i.e. only in extreme situations, e.g. in cases where economic/social gains justify such environmental sacrifice).***
- ***Define the structural design and the construction considerations of a marine outfall to meet requirements as determined by the above***

Where applicable, a distinction is made between requirements for* Pre-assessments *and for* Detailed Investigations *(with reference to* Section 3.1: Licence Authorisation Process*).

6.1 PHYSICAL PROCESSES



PURPOSE:

The purpose of this component is to gain an understanding of the hydrodynamic and geophysical characteristics and processes in the study area by:

- ***Producing a geo-referenced map of physical features, such as coastline configuration, topography, bathymetry and geological characteristics of the sea bottom***
- ***Assessing hydrodynamic processes (i.e. currents, water column stratification, water temperature variability and turbulence) for a range of environmental conditions (i.e. for various tides, waves, winds and air-sea fluxes as experienced in the marine environment).***

An additional purpose is to provide a basis to be used in the hydraulic design, as well as the assessment of achievable near and far field dilutions and deposition/re-suspension patterns of particles.

6.1.1 Overview

i. Bathymetry

A bathymetric survey is carried out to provide water depth contours, indicating the slope of the sea-floor and irregularities such as protruding reefs and offshore sandbars (Figure 6.1).

During a bathymetric survey, seawater depths at a large number of sites are determined using an echo-sounder operated from a survey boat. Depths are recorded as the boat travels at predetermined parallel lines perpendicular to the coast. In order to obtain a review of the area, lines spaced about 100 m apart are adequate whereas along the pipeline route itself, line spacing of 25 m or less is required. Corrections for tidal height and swell interference must be undertaken. The use of an integrative survey software package, providing accurate position fixing, bathymetric data and corrections for tide/swell, is necessary for the production of accurate contour plots and profiles.

NOTE:

Anthropogenic perturbations of marine water and sediment quality are usually perceived to be the result of biogeochemical modifications. However, developments that modify circulation dynamics, such as harbour structures and marina developments, can also modify sediment and water quality characteristics of the marine environment.

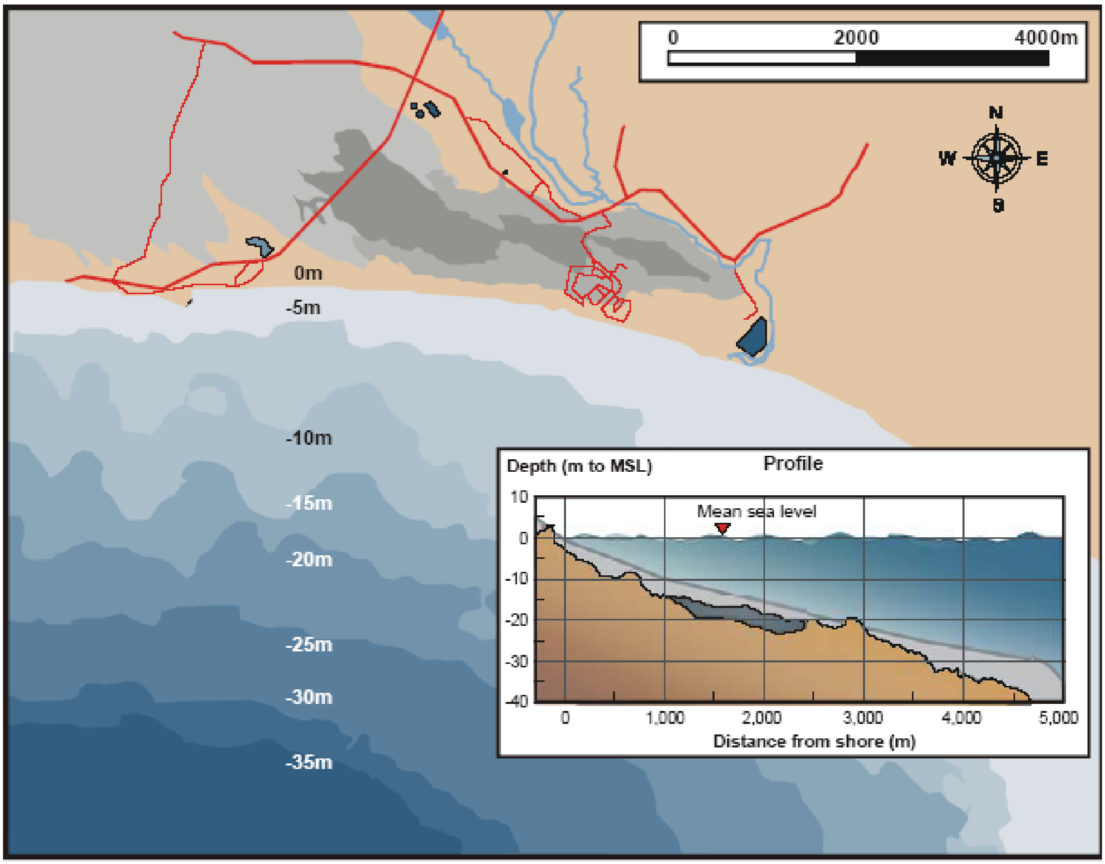


FIGURE 6.1: Example of bathymetric contour map and typical profile

ii. Seabed physiography

The physiography of the seabed not only determines the method and cost of construction of the outfall but also indices the type of biological communities that may be present along the proposed outfall route based on the nature of the seabed type. For example, biological communities generally are more diverse on rocky reefs than on sandy seabeds. Reefs thus should be avoided if at all possible.

A side scan sonar survey is conducted to provide a graphic picture ('aerial photo') of the seabed in order to define the location of reefs, gravel and boulder beds and sandy areas, and the height and direction of sand waves and ripples as well as obstructions such as wrecks, anchors or other pipelines or cables (Figure 6.2).

A side scan sonar transmits a very narrow sound beam to either side of a sound source unit (normally called a "side scan fish"), towed at a predetermined depth behind a survey vessel. Projections and irregularities on the seabed, such as reefs, sand waves and wrecks, reflect the sound back to the sensing transducers on the unit and the magnitude of sound energy reflected is recorded on a continuous graph. As the unit is towed along a co-ordinated survey line, the seabed is mapped in a strip up to 250 m wide on either side of the unit's path. Diver observations complement the sonar records by the 'calibration' of the side scan images with collected bed material. Probing by divers will confirm the depth of sand cover over rocky material. Underwater videos and photographs can also complement the survey, not only for the planners and designers, but also to enable the public to study real observations along the outfall route and conditions prior to, and after, construction of the outfall.

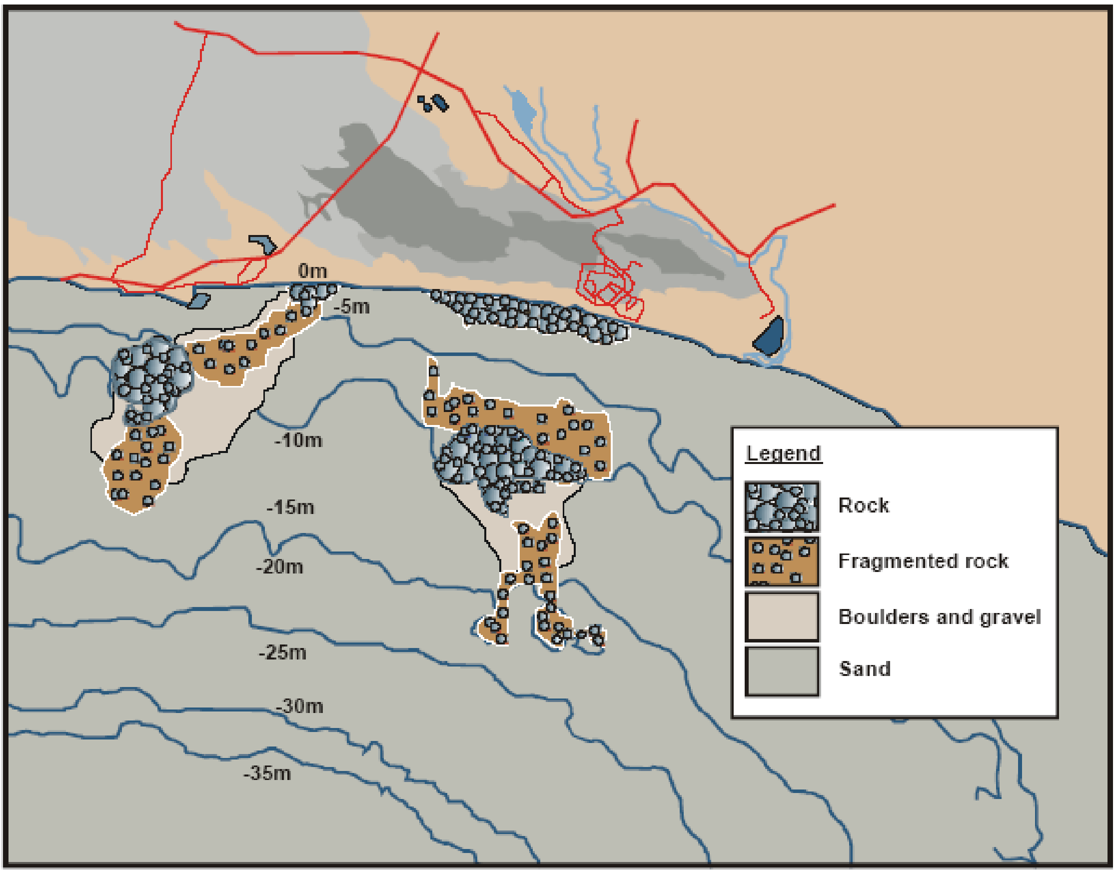


FIGURE 6.2: Example of a side scan sonar survey providing a graphic picture of the seabed characteristics

iii. Sub-seabed conditions

An outfall may be required to be installed in a trench. The trench may have to be excavated several metres into the seabed at certain locations along its length. The method and cost of trenching will depend on the sub-seabed composition. Normally, seabed conditions beyond the surf zone are reasonably stable and consist of either sandy sediments and/or gravels, which can be excavated relatively easily, or rock, which is difficult and costly to excavate. It is possible for both extremes to be present along the length of an ocean outfall.

Seismic surveys are conducted to obtain information from beneath the sea-floor, using a sound source or transducer towed behind the survey vessel either on a surface float or below the surface. The transducer beams sound down through the seabed, and sub-bottom features reflect a fraction of the sound energy that are received on a hydrophone array that is towed behind the boat. The magnitude of the sound energy reflected depends on the interface between layers with different acoustic properties, including changes in rock type, degree of weathering or major fissures and interfaces (Figure 6.3). The received sound is then transmitted from the hydrophone to a plotter on the survey boat as the boat travels along a predetermined path.

Exploratory drilling is required to verify the results of the seismic survey. Further geotechnical investigation for the detailed design will be required:

- Soil analysis – classification, cohesive and shear strengths, angle of repose (internal friction), density properties
- Rock analysis – classification, hardness
- Seismic stability.

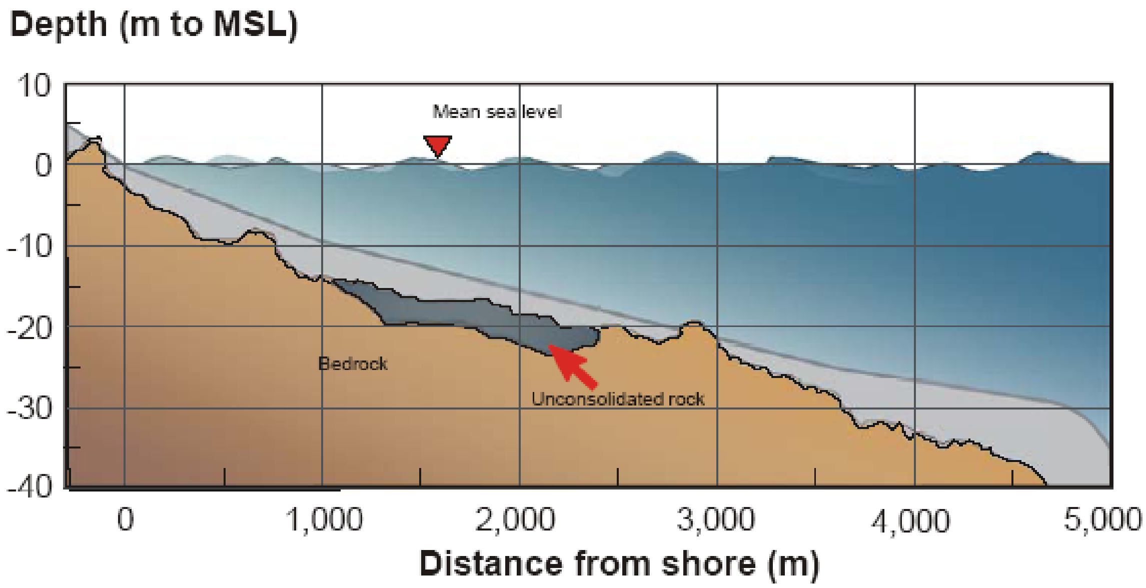


FIGURE 6.3: Sub-bottom profile derived from a seismic trace

iv. Sediment movement (erosion and sedimentation)

In the surf zone, wave wave-induced turbulence and currents can result in large seasonal changes in the depth of sand, especially during storms. An outfall is normally installed in a trench extending across the shore and surf zone, which is then backfilled so that after completion, the outfall is not exposed. Thus the lowest depth of the sand across the beach and surf zone has to be determined, i.e. the profile resulting from storm erosion, so that the outfall can be securely installed below this level. An example of an 'envelope of variability', that is, the maximum (accretion) and minimum (erosion) levels over time is shown in Figure 6.4.

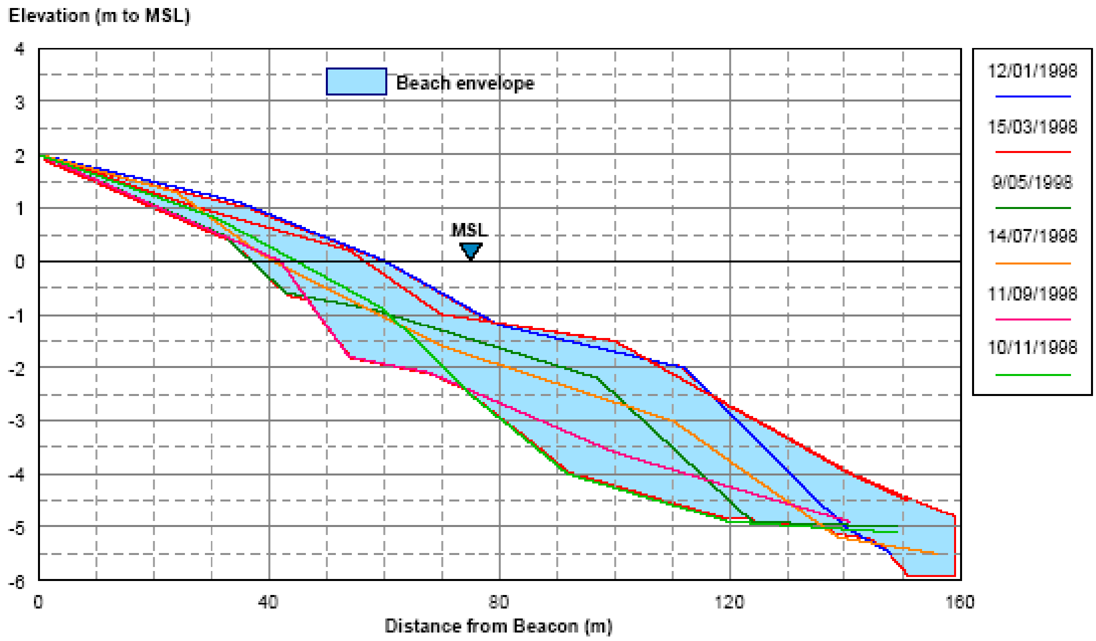


FIGURE 6.4: Example of beach profile envelope, showing maximum and minimum profiles

The degree (rate) of sediment transport and the probability of scouring have to be determined using historical data and supplemented with appropriate numerical modelling outputs, if required.

v. Waves

Although wave data is not crucial with regard to the behaviour of the wastewater plume, it is critical for the initial deposition and redistribution of 'solid' phase particles. Wave energy is also the major consideration for the detailed (structural) design of an outfall with regard to the construction phase as well as to the forces to which exposed parts of the outfall will be subjected during its lifetime. Waves are also the crucial factor in determining the sediment dynamics in shallower water and in the shoreline geomorphology. In the case of surf zone discharges, the mixing, transport and dispersion of the wastewater plume are controlled by the breaking waves and the currents generated by waves approaching the shoreline.

Waves are defined in terms of:

Wavelength (λ in metres):	Distance between two wave crests or two wave troughs.
Wave height (H in metres):	Vertical measure between the bottom of a trough and the peak of the crest.
Wave period (T in seconds):	Time required for two crests to pass a fixed point. The period is also expressed as a frequency (Hz) = 1/T.
Wave celerity (c in m/s):	Where c $= (g\lambda/2\Pi)^{1/2}$

In the ocean, 'waves' are generated by numerous processes and can range from a period of 1 second (wind chop) to several days (lunar and solar tidal components). The type of waves that are significant for the structural design of an outfall, for the nearshore geomorphology and the hydrodynamics related to the transport and dispersion of the wastewater plume in shallow water are the wind-generated waves or swell, which are generated by the drag of the wind on the sea surface. Along the South African coastline, the wave/swell period is typically in the range of 8 to 14 seconds. The water itself does not proceed with the wave, but moves in circular orbits, clockwise in the direction of the wave (Figure 6.5). The diameter of the orbits reduces with depth until the orbital motion ceases at a depth equal to approximately half the wavelength. In water depths less than half the wavelength, the circular orbits becomes elliptical and wave action starts to act as shear forces on the seabed material or exposed structures such as pipelines. When the orbiting pattern collapses, breakers are formed. Smaller waves with long wavelengths on a gently graded beach slope will spill and lose energy during the run-up, whereas steeper (high, short-wavelength) waves will tend to plunge with a subsequent strong backwash, causing erosion.

The above description of waves refers to a regular wave train. However, the wave regime in the sea is highly irregular and it is very unlikely that two consecutive waves will have exactly the same characteristics with regard to height, length and period. Numerous waves (different frequencies), superimposed on one another, can also occur at the same time and location. Therefore, statistical measures/procedures have to be applied to a wave condition for a certain length of time in order to describe the wave conditions in terms of significant wave height and period. Typically, the statistical parameters to describe wave conditions relate to a recording period at least 20 minutes long:

H_S	= Significant wave height. The average height of the highest 1/3 of the waves in a recording period
T_S	= Significant wave period. The average period of the highest 1/3 of the waves in a recording period
H_{max}	= Maximum wave height. Maximum trough to crest height in a recording period

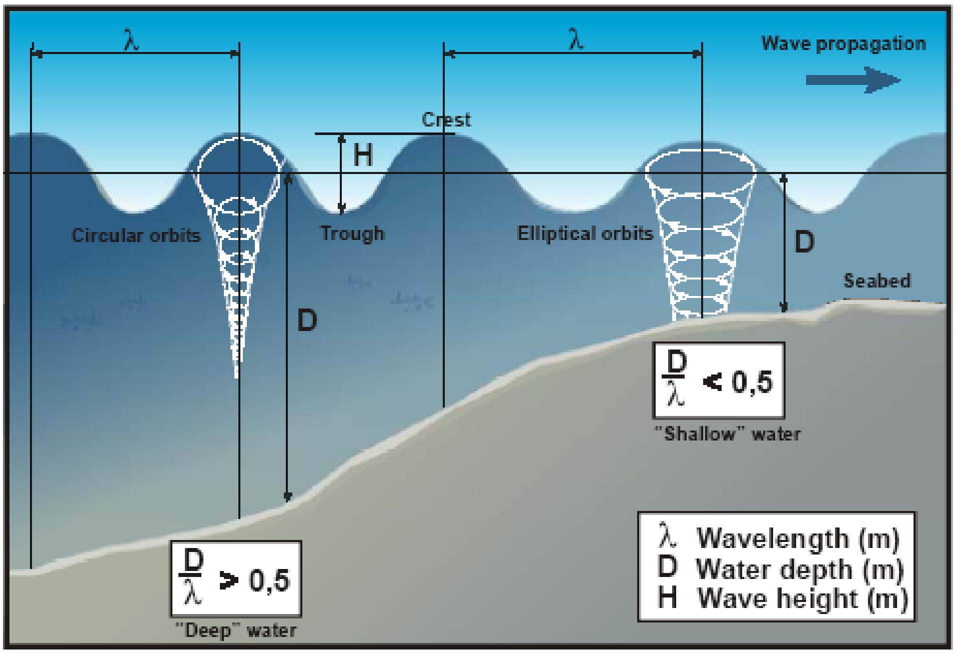


FIGURE 6.5: Description of a wave

Energy based parameters (Rossouw, 1984), which are the standard deviation of sea-surface elevation of all the data values obtained from the digital spectral analysis, are:

H_{mo} = characteristic wave height (m)
= $4.m_o^{1/2}$ which is equivalent to $4.\sigma$

where m_o = the area under the wave spectrum
σ = square root of the variance

T_p = Peak energy wave period (s)
= $1/f_p$ where f_p is the peak energy frequency (Hz)

Confusion can arise when H_S and H_{Mo} values are ulitised. CERC (1984) describes this relationship between H_S and H_{Mo} with regard to the influence of water depth on the wave profile. In deep water, H_S is approximately equal to H_{Mo}, but can be at least 30% greater in shallow water for breaking waves. A wave height H for a monochromatic wave train with the same energy as an irregular wave train with a height of H_{Mo} is given as:

$H = H_{Mo}.2^{1/2}$

Wave data are typically presented as time-series plots of wave height and period, occurrences and exceedances for wave height and period and persistence of calms and storms. For the structural design of an outfall, maximum wave heights for return periods of 1, 10, 50 and 100 years must be determined with the associated wave periods and wave directions. The persistence curves are important for construction planning and scheduling, as the probability of seasonal durations of calm or storm conditions can be estimated from these curves. To determine seasonal variations, at least one full year's data from the site are needed for correlation with other available long-term data. A standard procedure for measuring wave height is the mooring of a wave measurement buoy (e.g. Waverider) at a representative location along the pipe route. The buoy samples the relative elevation of the sea surface on which it floats at 0.5-second intervals, normally for 20-minute periods each day (at six-hour intervals). The data are transmitted by the buoy to shore station receivers, where they are digitally recorded. Acoustic-Doppler-Current-Profilers (ADCP) are rapidly becoming the norm for measuring wave data as these instruments are also able to measure other parameters, such as temperature and current velocity and direction, through the water column.

Examples of wave data outputs required are provided in Figures 6.6a to 6.6e. Directional wave data can be displayed in a manner similar to the wind rose in Figure 6.11.

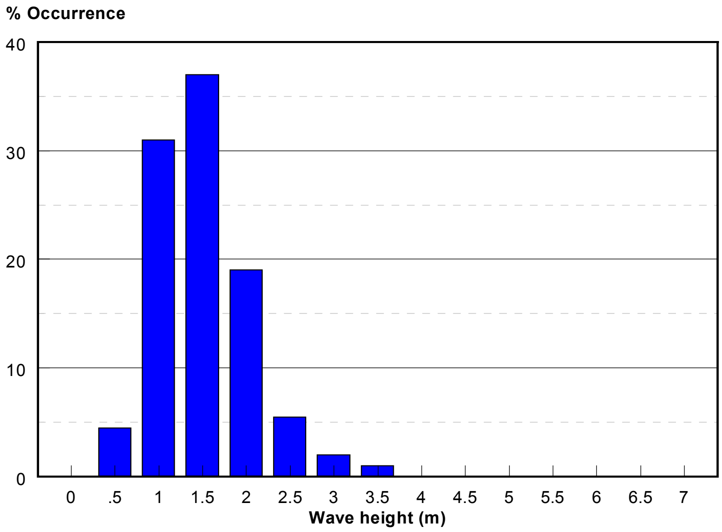


FIGURE 6.6 a: Example: Annual wave height occurrence (%)

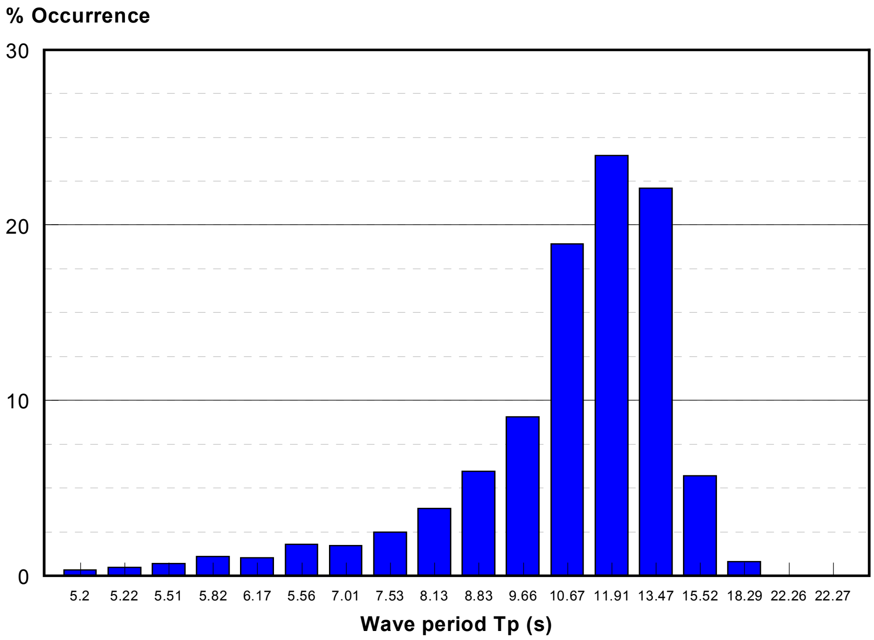


FIGURE 6.6 b: Example: Annual wave period occurrence (%)

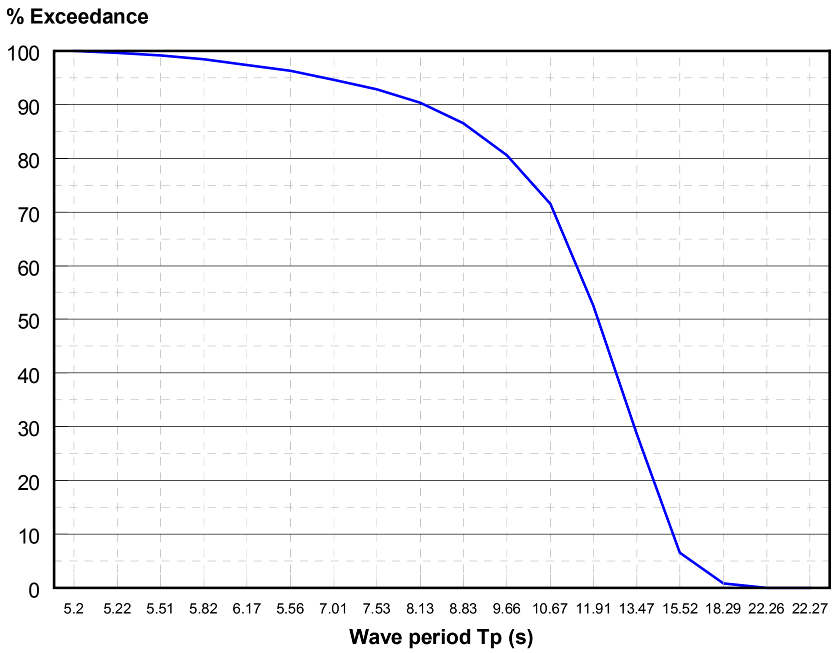


FIGURE 6.6 c: Example: Annual wave period exceedance (%)

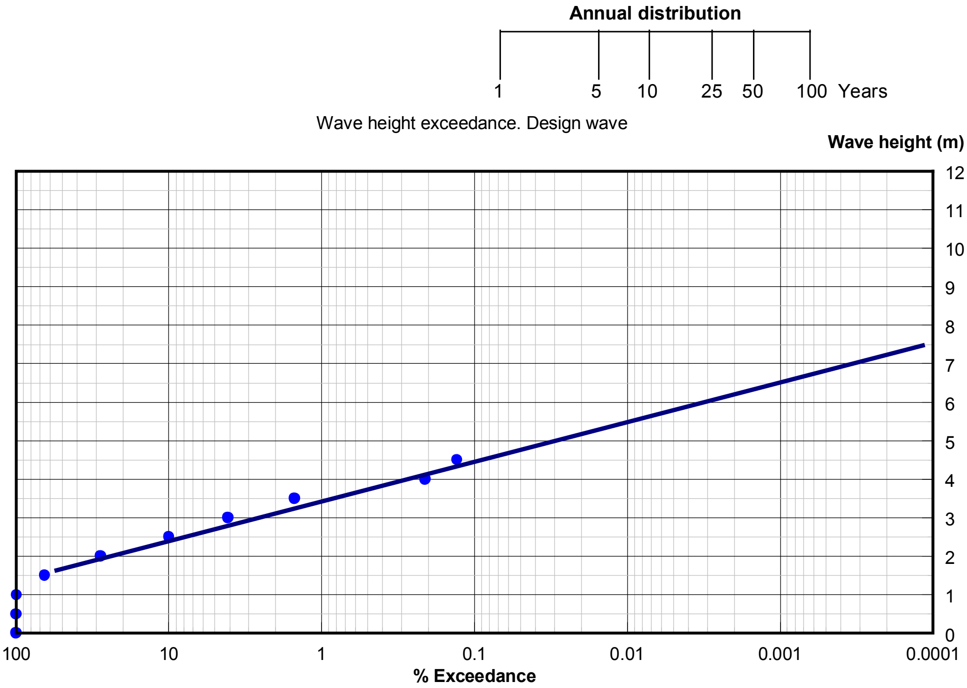


FIGURE 6.6 d: Example: Design wave heights

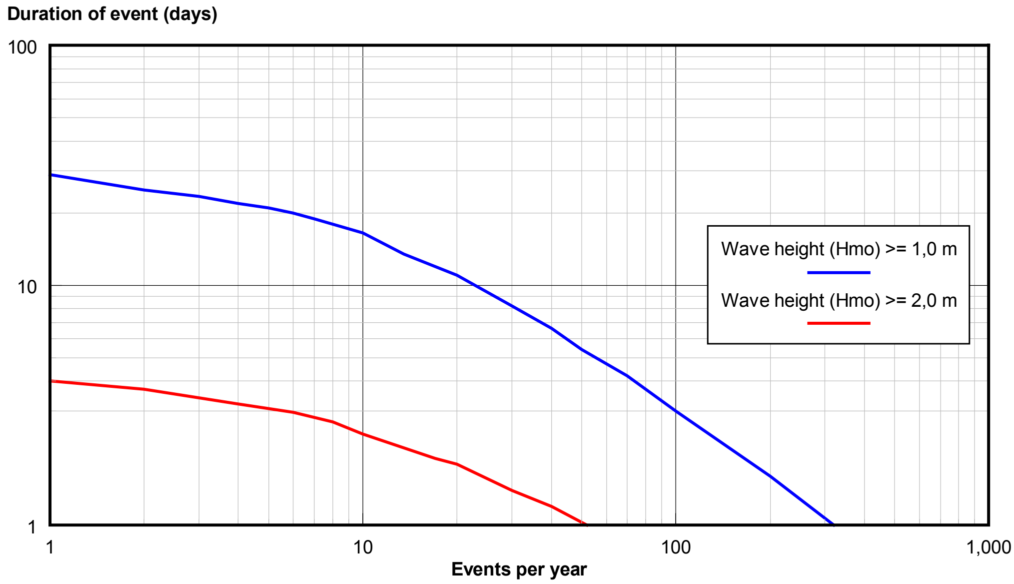


FIGURE 6.6 e: Example: Persistence of storms

A summary of all available wave data along the coast of South Africa up to 1984 was summarised by Rossouw (1984) and is listed in Table 6.1. The variation of wave height along the South African coastline is illustrated in Figure 6.7.

TABLE 6.1: A summary of all available wave data along the coast of South Africa up to 1984 (Rossouw, 1984)

LOCATION	SIGNIFICANT WAVE HEIGHT (H_s in metres) FOR DIFFERENT % EXCEEDANCES			WAVE PERIOD (T_P in seconds) FOR 50% EXCEEDANCE
	0.01%	0.1%	1.0%	
Oranjemund	7.5	6.0	4.4	
Saldanha Bay	7.7	6.3	4.8	
Koeberg	8,3	6.5	4.8	12.8
Slangkop	9.3	7.5	5.6	12.5
Gans Bay	8.1	6.4	4.6	
Mossel Bay	6.0	5.0	3.9	
Durban	5.8	4.7	3.5	
Richards Bay	5.5	4.5	3.4	11.4

Source: Rossouw (1984)

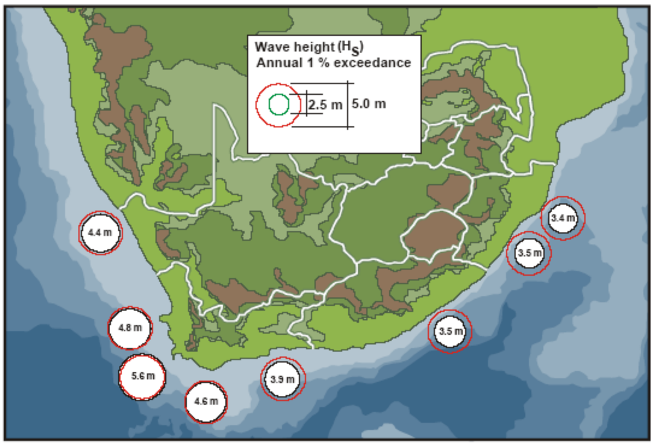


FIGURE 6.7: Wave heights (1% exceedance) along the South African coastline

vi. Wind

Wind is an important phenomenon in that the wind-field can govern the behaviour of surface currents and the subsequent transport (speed and direction) of a buoyant wastewater plume to distant locations. Winds exert a stress on the water surface that is down through the water column by shear between the moving surface water and the lower layers. In the absence of stronger ocean currents, wind-driven currents dominate. Most of the time, the only available long-term data records at a study site are for wind. Long-term wind data records is therefore used to verify the representativeness of detailed, short-term data set measured during the study period, not only short-term wind data, but also other data influenced by wind such as currents. It is important to understand the interaction between the wind and the ocean processes, especially the nearshore circulation characteristics, in the study area.

In the offshore region, the surface wind-induced current vector is approximately 45 degrees left of the wind direction in the Southern Hemisphere, deflecting more to the left as the depth increases (at approximately 10 m depth the direction can be 90 degrees to the left of the wind direction). This phenomenon is related to the earth's rotation and is known as the Coriolis force (Neumann, 1968). In shallower water, the Coriolis effect reduces with subsequent reduction of the deflection of the current direction from the wind direction. This phenomenon is included in 3-D numerical models used for detailed investigations. For pre-assessment studies, the wind-induced surface current can be taken as 3% of the wind speed (Williams, 1985). For the transport of floatable material on the surface, a value of 7% can be used.

In the case of shallow outfalls (e.g. surf zone discharges), the diurnal land and sea breezes (resulting from the difference in temperature between the land and the sea) will result in diurnal changes of the transport (onshore/offshore) of surface waste fields (Figure 6.8). During the day the land temperatures will be higher than the sea temperatures, causing the air to rise over the land and cooler air from the sea to flow towards the land. The maximum temperature difference between the land and the sea will occur at approximately 15h00, with the sea breeze at its maximum velocity (Hydrographic Office, 1994). During the summer, the onshore wind will prevail from early morning to midnight, the season and the time of day when the South African beaches are heavily utilised for recreation. During the winter, the sea breeze will occur from noon to early evening. Typical conditions in Algoa Bay are illustrated in Figure 6.9 (Hydrographic Office, 1994).

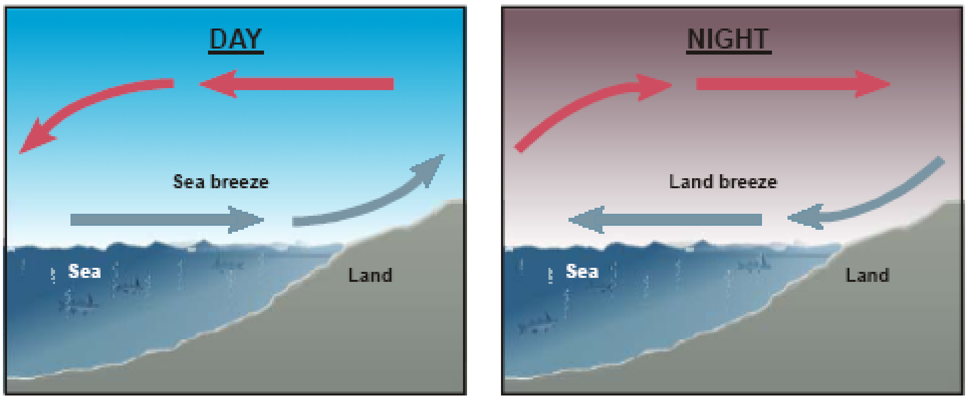


FIGURE 6.8: Land and sea breezes (Hydrographic Office, 1994)

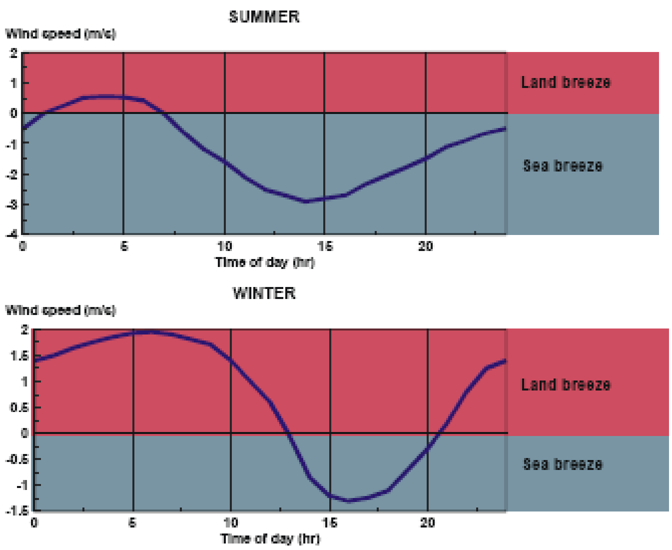


FIGURE 6.9: Typical diurnal land- sea breeze variations (Hydrographic Office, 1994)

Wind speed and direction are measured by automatic wind recorders connected to data loggers. Wind speed and direction at almost any predetermined sampling interval can be digitally recorded, transferred to a computer and processed. The coastal topographic features may have a local effect on the prevailing wind-fields and, in the case of a complex coastline configuration, several such recorders should be operated around a proposed outfall area to avoid biased results that may be brought about by sheltering or deflection of winds by topographic features.

Typical data outputs include annual and seasonal wind speed and directional occurrences as shown in Figure 6.10. An example of a wind-rose is shown in Figure 6.11. Exceedance data are presented in a similar manner to that for waves (refer to Figures 6.6a to 6.6e).

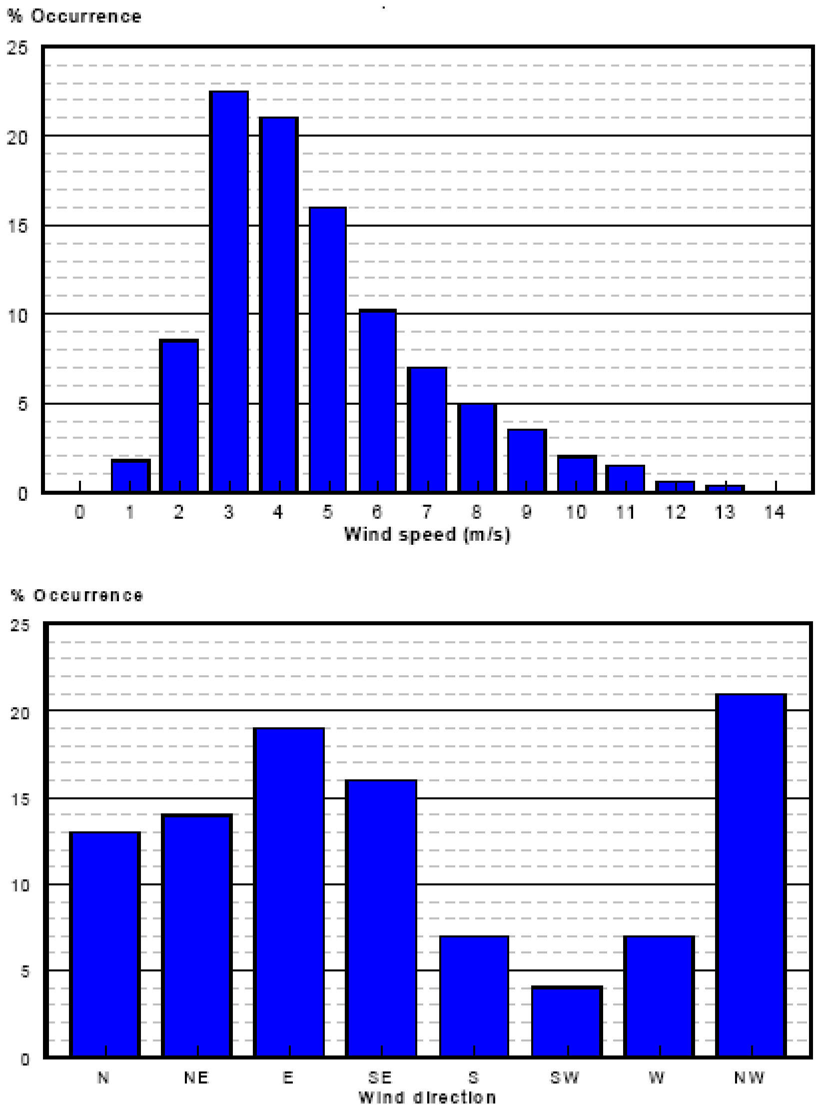


FIGURE 6.10: Example of graphs showing speed and direction occurrence of wind

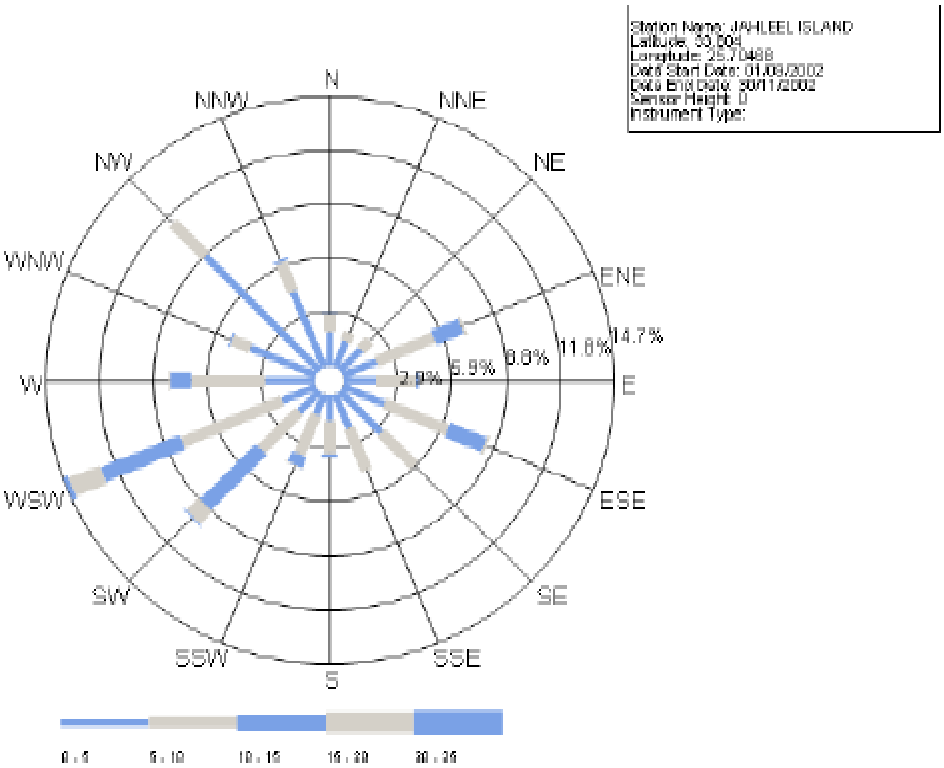


FIGURE 6.11: Wind-rose, showing the typical wind direction and speed at a particular site

The Hydrographic Office (1994) provides monthly wind direction occurrences for a number of coastal locations, based on more than 20 years of data. The mean annual occurrences of wind direction and speed for selected locations are presented in Table 6.2 and illustrated in Figure 6.12.

TABLE 6.2: Mean annual occurrences of wind direction and speed for selected locations along the South African coastline

LOCATION	***PERCENTAGE OCCURRENCE FOR WIND DIRECTIONS***									***MEAN SPEED (m/s)***	
	N	***NE***	***E***	***SE***	***S***	***SW***	***W***	***NW***	***Calm***	***8h00***	***14h00***
Port Nolloth	*3*	*1*	*2*	*5*	*32*	*5*	*2*	*8*	*43*	*2.1*	*5.7*
Cape Columbine	*7*	*6*	*2*	*12*	*42*	*10*	*4*	*10*	*7*	*4.6*	*6.2*
Cape Town	*7*	*3*	*0*	*10*	*28*	*10*	*3*	*16*	*23*	*3.1*	*6.2*
Cape Point	*4*	*6*	*3*	*33*	*9*	*14*	*10*	*13*	*8*	*9.3*	*8.2*
Agulhas	*1*	*10*	*17*	*12*	*6*	*16*	*23*	*8*	*7*	*4.6*	*6.2*
Mossel Bay	*3*	*5*	*9*	*12*	*8*	*29*	*10*	*15*	*9*	*4.1*	*6.2*
St. Francis	*2*	*5*	*20*	*3*	*3*	*9*	*40*	*5*	*13*	*5.1*	*7.2*
Port Elizabeth	*2*	*6*	*15*	*5*	*5*	*23*	*20*	*3*	*21*	*3.6*	*7.2*
East London	*5*	*16*	*11*	*4*	*7*	*18*	*17*	*7*	*15*	*3.6*	*6.2*
Port Shepstone	*7*	*27*	*3*	*2*	*5*	*25*	*5*	*12*	*14*	*3.6*	*6.7*
Durban	*7*	*19*	*6*	*3*	*13*	*15*	*2*	*2*	*33*	*2.1*	*5.7*
St.Lucia	*9*	*22*	*4*	*10*	*11*	*14*	*6*	*17*	*7*	*5.7*	*7.2*

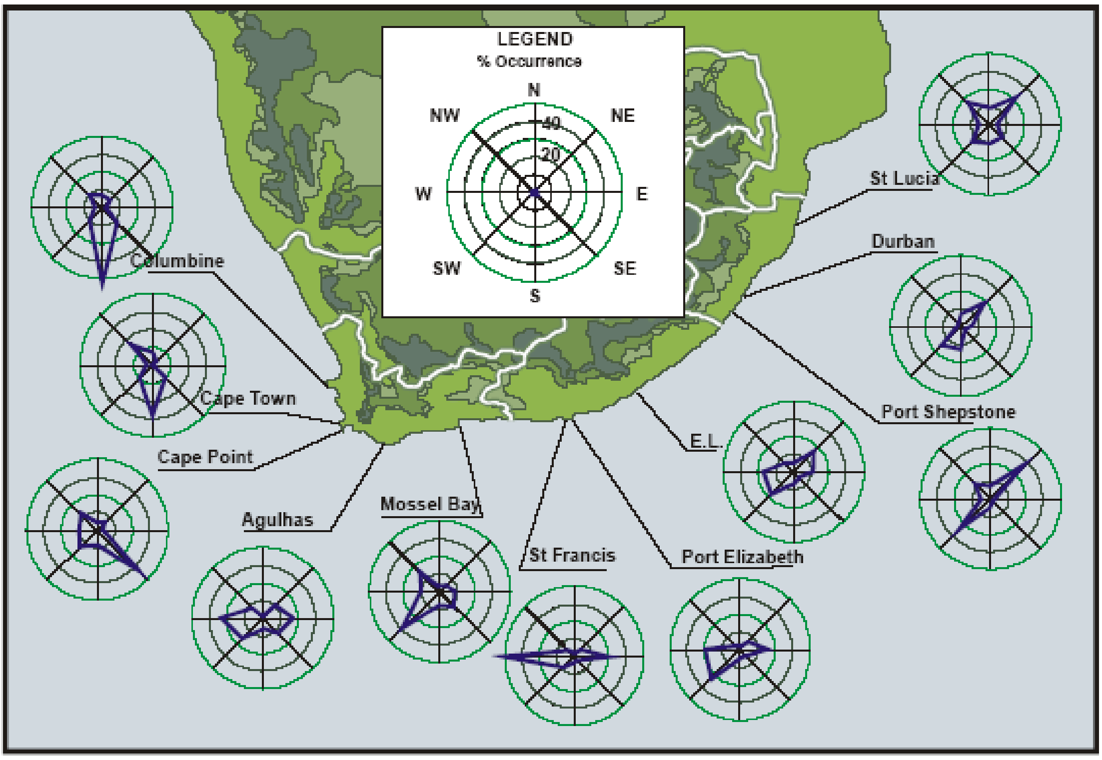


FIGURE 6.12: The coastal wind regime (Hydrographic Office, 1994)

vii. Tides

The astronomical tides together with the nearshore bathymetry and the coastline configuration are amongst the most influential and significant factors governing the nearshore hydrodynamics and the hydrodynamics of estuaries and bays. Tidal variations (ranges) also have to be taken into account in the hydraulic design with respect to the available head (pressure or gravity) required to discharge the wastewater.

The dominant tide is semidiurnal (period of approximately 12 hours and 20 minutes). Differences between high and low water can range from 2 m during spring tide (full moon and new moon) to 0,5 m at neap tide. The lowest and highest astronomical tides predicted for South African coastal towns, based on 19 years of data, are given in Table 6.3 (SAN, 2003). These levels can be exceeded when extreme meteorological conditions coincide with the neap and spring tides.

TABLE 6.3: Approximate spring tide ranges for the main South African coastal towns

PLACE	*LOWEST ASTRONOMICAL TIDE (LAT) (m)*	*HIGHEST ASTRONOMICAL TIDE (HAT) (m)*
Port Nolloth	*0*	*2.41*
Saldanha Bay	*0*	*2.03*
Cape Town	*0*	*2.02*
Simon's Town	*0*	*2.09*
Hermanus	*0*	*2.07*
Mossel Bay	*0*	*2.44*
Knysna	*0*	*2.21*
Port Elizabeth	*0*	*2.12*
East London	*0*	*2.08*
Durban	*0*	*2.30*
Richards Bay	*0*	*2.47*

A typical tidal record for South African conditions is illustrated in Figure 6.13.

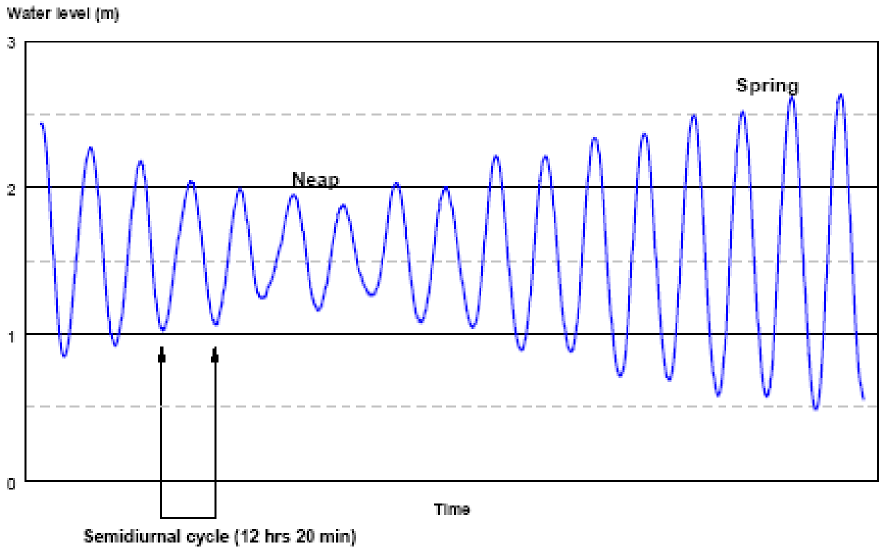


FIGURE 6.13: Typical tidal record for South African conditions measured at Knysna

viii. Coastal currents

The South African coastline is bounded by two major circulation systems, these are the 'warm' south-bound Agulhas Current along the east and south coast and the 'cold' north moving Benguela System along the west coast (Figure 6.14). The Agulhas Current is powerful: at the surface it can reach maximum speeds of 2 m/s (Gyory *et al.*, 2000). As the Agulhas Current reaches the southern tip of Africa, it begins to turn toward the southwest. Once it reaches the Southern Ocean, the current retroflects, or turns back on itself, and flows eastward as the Agulhas Return Current.

The Benguela Current is the eastern boundary current of the South Atlantic subtropical gyre (Shannon, 1985). It begins as a northward flow off the Cape of Good Hope, skirts the western African coast equator-wards to about 24°S-30°S from where it moves further offshore. The sources of the Benguela System include Indian and South Atlantic subtropical thermocline water; saline, low-oxygen tropical Atlantic water; and cooler, fresher sub-antarctic water. Shannon (1985) gathered all available information on surface current speeds from previous studies and calculated the mean speed of the Benguela System to be 17 cm/s. Wedepohl *et al*. (2000) found that the mean speeds of the current vary from less than 11 cm/s to a maximum of 23 cm/s. Apparently the highest speeds occur in the south during summer and in the north during winter, a pattern that corresponds with seasonal wind fields. The prevailing winds are responsible for strong Ekman transport and the resulting coastal upwelling of cool, nutrient-rich water that stimulates primary productivity (Boyer *et al*. 2000; Skogen 1999).

Although the main ocean currents along the east coast of South Africa are much more dynamic than the currents along the west coast, the inshore circulation (less than 40 m water depth) is mostly tidal and wind driven. This was demonstrated by using drogues to determine surface current velocities at various locations along the South African coastline between 1980 and 1992 (CSIR 1986, CSIR 1988, CSIR 1991b, CSIR 1992). Data gathered for a minimum of one year at each location are presented in Table 6.4.

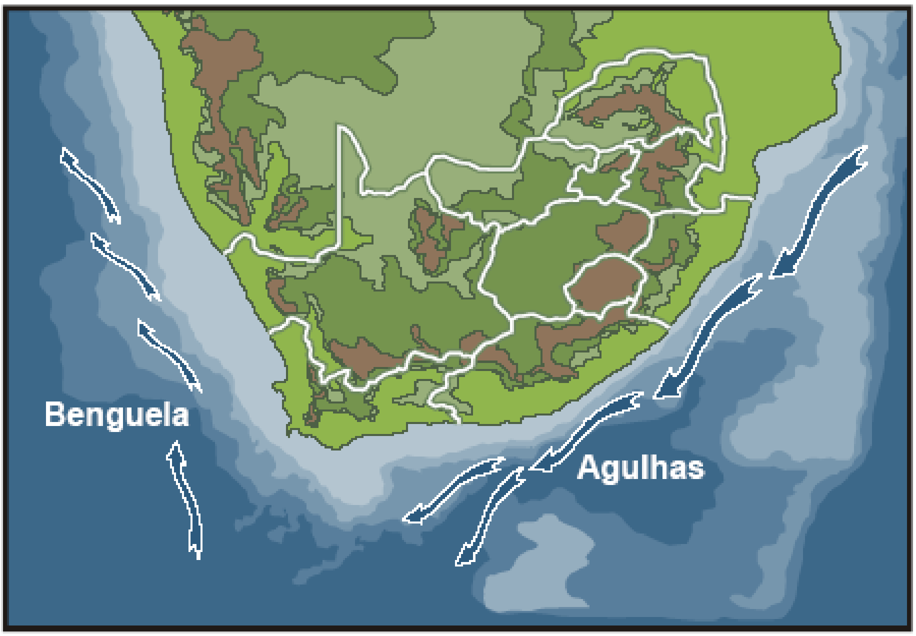


FIGURE 6.14: South Africa's major coastal circulation systems

TABLE 6.4: Measured surface current velocities at various locations along the South African coastline based on drogue tracking between 1980 and 1992 (minimum 1 year)

LOCATION	*DISTANCE FROM SHORE*	*AVERAGE CURRENT SPEED (cm/s)*	
		SURFACE	*SUB-SURFACE (-5 m)*
North West Bay (north of Saldanha)	*2 km* *6 km*	*20* *30*	- -
Hout Bay	*1 km*	*16*	*11*
False Bay	*2 km* *5 km*	*17* *15*	*9* *9*
Mossel Bay (Dana Bay)	*1 km* *2 km*	*18* *21*	*12* *15*
East London			
Tongaat	*1,2 km* *1,9 km*	*18* *23*	*15* *20*

<u>Offshore</u>. The offshore circulation characteristics (speed and direction of currents) are the main oceanographic processes that would influence the initial dilution of a buoyant wastewater stream and its subsequent transport and dispersion to distant locations. The seasonal variation in current speeds also influences the selection of the appropriate method of construction and the structural design of the outfall.

The net (resultant) current which will transport and disperse a waste field is the result of a complex of numerous driving forces. These forces include the local wind forcing, ambient continental currents (for example the Agulhas current), surf zone long-shore and rip currents generated by waves, tidal currents and density differences. In the nearshore zone, the circulation is strongly influenced by the seabed topography and the configuration of the coastline.

Measurement of currents at sea is complicated because of the varying spatial and temporal nature of currents. The ultimate (resultant) current measured is a composite of numerous driving forces. Instantaneous measurements cannot be compared directly with the various generating forces because, for example, currents measured during a particular wind condition may be unrelated to that condition since they may still be subject to the inertia of a previous wind forced circulation. All these and other effects require that any current measurement programme be carefully designed to avoid bias.

Eulerian measurements are continuous recordings of current data collected at pre-determined time intervals by the use of moored current meters at fixed points in the study area. Eulerian data provide the basis for statistical estimates of occurrence and persistence of current speed and direction. Typically the information is measured and recorded by the instrument at 15-minute or 30-minute intervals. Moored current meters use a variety of methods for sensing speed and direction and it is important to understand the limitations and performance of each type of meter when designing a current recording programme. Current profilers, lowered to a specific depth from an anchored platform or vessel, can also be used. If the survey vessel is allowed to drift during the current measurement, accurate position fixing (using global positioning fixing (GPS) techniques) must be recorded as the drift vector must be vectorially subtracted from the measured velocity to produce the true ambient current vector.

Lagrangian measurements include spatial studies with drogues, drifters, or dye, in which the path and velocity of a particle are determined. Surface and subsurface current recordings can be made by the tracking of the movement of floats (Lagrangian) in the current field at the outfall location. Floats consist of either drogues or drift cards. Dye patch observations are also sometimes used.

Drogues are surface or subsurface floats, identified by a flag number, which drift with the current. Drogue pairs (surface and subsurface) are released at pre-determined locations around a proposed pipeline/diffuser to detect the probable path of the surface wastewater plume. A survey vessel equipped with GPS is used to track the drogues. The actual surface and subsurface current vectors for the particular day of observation can be obtained. Vectors from various drogues are then combined to produce a reliable indication of the general current pattern on that particular day. These results can also be used for the spatial calibration of a far field numerical model.

Radio drogues that transmit a signal to the shore at a predetermined frequency can also be used for larger scale spatial observations. At three shore stations, directional receivers are tuned to receive the signal and thereby provide an accurate fix of the drogue’s location.

In the design of drogues, the influence of the wind on the above-water part and the influence of the current on the nylon line connecting the float has to be minimised to ensure that current measurements are not seriously affected (Botes, 1988).

Drift cards are plastic cards, typically 10 x 15 cm in dimension, that are dumped in lots of 200 at a time at specific locations. The fate of the cards is recorded by the location and time of their deposit on the shoreline. This is used as a crude but effective way of predicting what the fate of a surface wastewater release at the same location would be. Cards of various colours can be dropped from different proposed outfall locations. The results are meaningful but cannot be used for quantitative assessments.

Dye patches provide another method of recording surface current patterns. A quantity of concentrated dye (such as Rhodamine-B dye) is released at a specific location or at several locations in the study area. The movement and spreading of the dye patch is then monitored by aerial photography or by tracing the perimeter of the patch using a survey vessel equipped with GPS.

Typical graphical output data for understanding the nearshore circulation processes for the optimisation and assessment of the potential impact of marine discharges include:

- Time series data for current velocities, directions and vectors (Figure 6.15)

- Current roses or a scatter diagram summarising the directional behaviour (refer to Figure 6.16)
- Current profiles showing the vertical variation in current velocities in the water column (Figure 6.17)
- Tracer (e.g. Rhodamine-B) data demonstrating the spatial behaviour of a wastewater plume under specific current conditions (Figure 6.18)
- Radio-buoy tracks recording the direction and speed of surface and sub-surface currents in a study area (Figure 6.19).

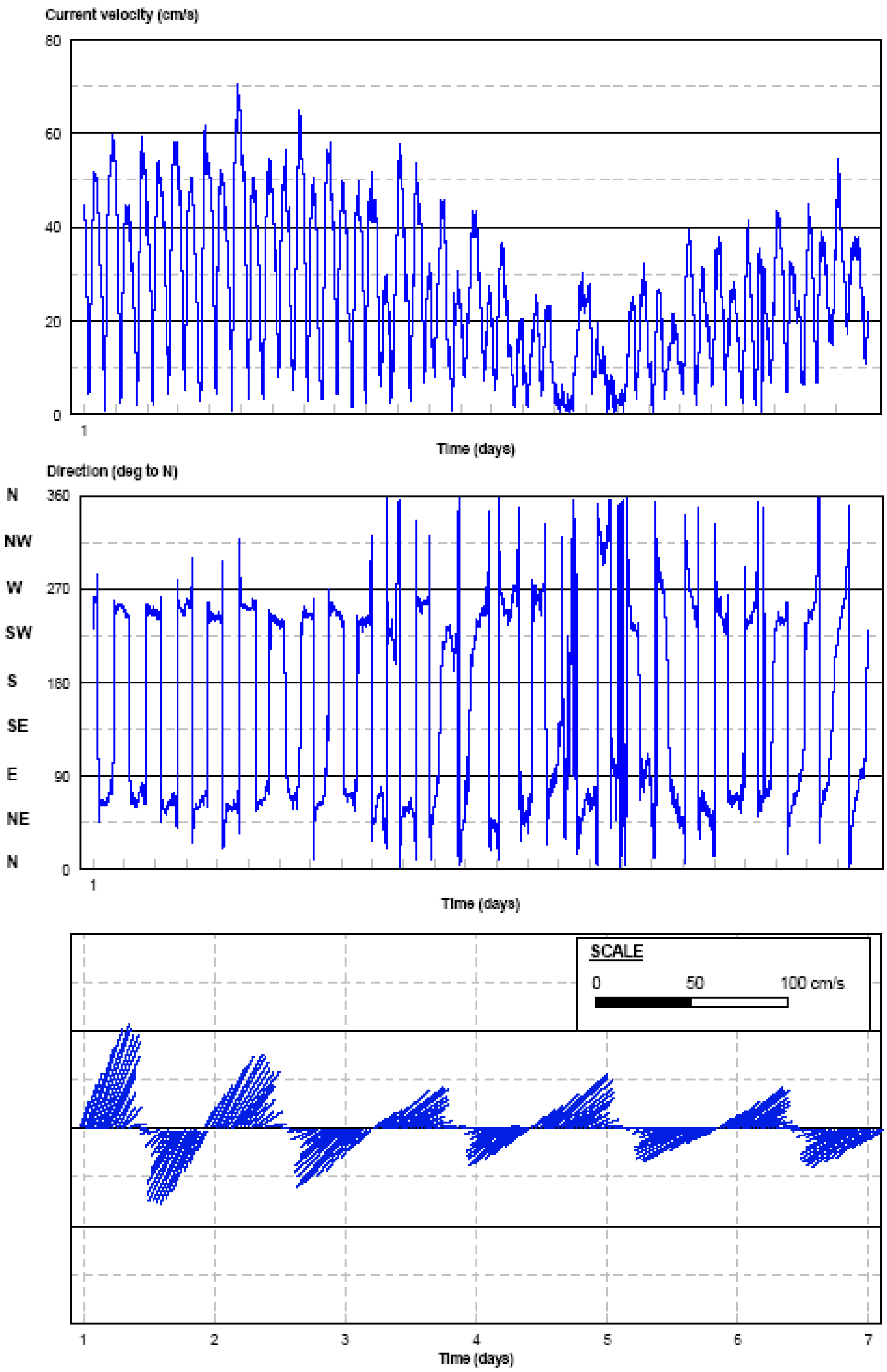


FIGURE 6.15: Time series data for current velocities, directions and vectors

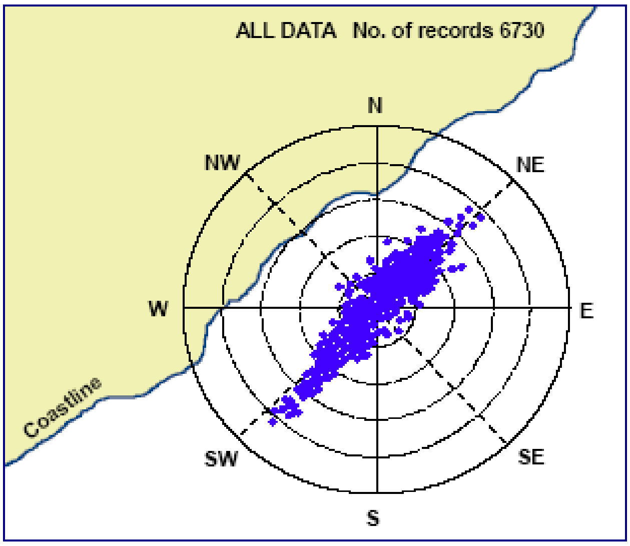


FIGURE 6.16: Current scatter diagram

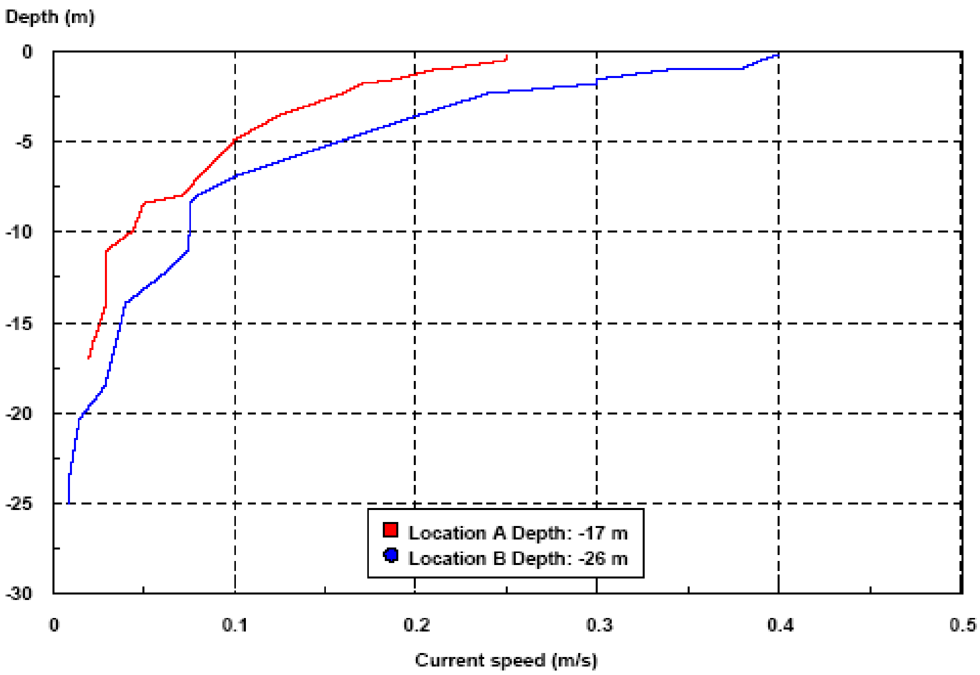


FIGURE 6.17: Example: Current Profile

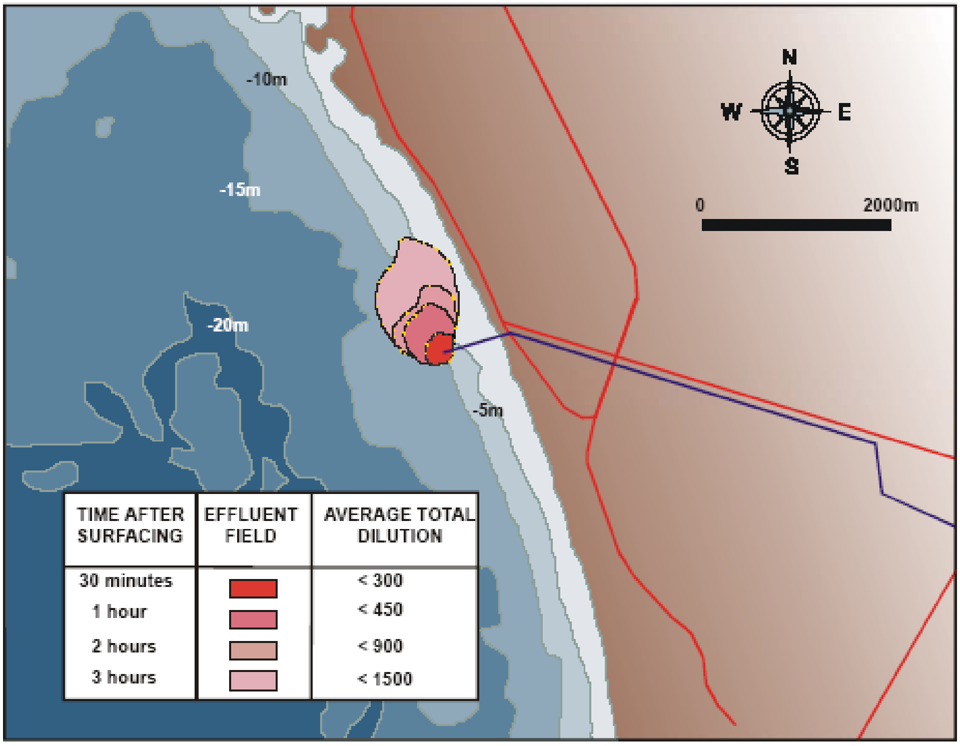


FIGURE 6.18: Prototype tracer studies

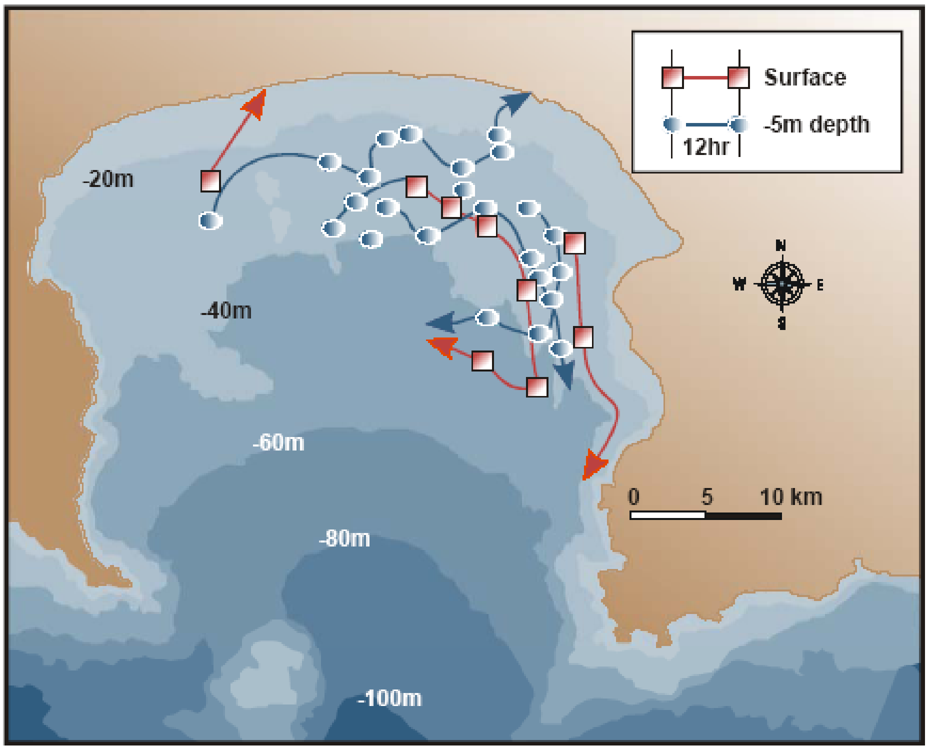


FIGURE 6.19: Circulation patterns recorded over three days in False Bay using radio-buoy tracking (Botes, 1988)

Surf zone. Currents in the surf zone (littoral zone) are wave-dominated, and initial mixing is rapid due to the vigorous processes of which long-shore and cross-shelf transport are the most dominant. Long-shore transport is driven by the momentum flux of shoaling waves approaching the shoreline at an angle, cross-shelf transport is driven by the shoaling waves, while water is transported out of the surf zone by rip currents, which will result in the diffusion of surf zone water into the offshore waters. For wave fronts parallel to the coast, symmetrical circulation 'cells' will be formed and the surf zone width will be determined by factors such as the wave height/period and the beach slope. For example, along the Kwazulu-Natal coastline average cell widths of 600 m, with rip currents 30 to 60 m wide and offshore velocities varying between 0.3 m/s and 1 m/s, have been recorded (NTRPC, 1969). Results showed that some of the rip current water is forced back into the cells by the onshore wave transport. Observations along the Kwazulu Natal coastline indicate a typical offshore flow of approximately 400 m (NTRPC, 1969). In the case of oblique waves, the circulation 'cells' will be asymmetrical and the tendency is for the rip currents to flow to the downstream cell only. Some of the water expelled beyond the surf zone may be transported back into the surf zone by the next set of waves. It is important to note that onshore winds and the incoming tide will tend to keep water in the surf zone, whereas offshore winds and the outgoing tide will contribute to the transport of water away from the shoreline.

Estuaries. There are about 250 estuaries in South Africa that fall within the definition of an estuary (see *Glossary of Terms*) (Whitfield, 1992). The water movement (hydrodynamics) and related processes in South African estuaries will depend on the status (open or closed) of the estuary mouth. About 75% of South Africa's estuaries are temporarily open/closed systems.

In permanently open estuaries, the flow in the estuary and the subsequent exchange of water between the estuary and the sea is dependent on the diurnal and semi-diurnal differences in water levels in the estuary and in the sea (due to tidal variation), the 'size' (cross-sectional area) of the estuary mouth and the volume and timing of source inflows (e.g. river inflow). Salinity distribution patterns in the estuary also affect hydrodynamic behaviour associated with the density difference between saline and freshwater. Usually, in deeper estuaries, the more dense seawater creates a salt wedge along the bottom, resulting in strong vertical stratification. In a shallower system, however, the strong tidal currents are usually sufficient to break down any vertical stratification, resulting in a well-mixed system. Each estuary has a unique salinity regime, which continuously changes according to the state of the tide and freshwater inflows. The fresh and saline water structure of a 'partially-mixed' estuary is illustrated in Figure 6.20.

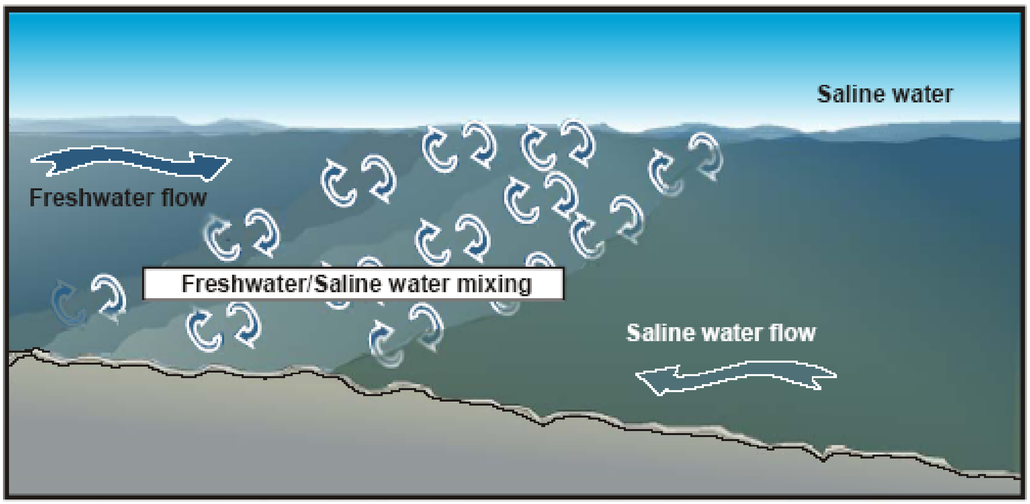


FIGURE 6.20: Illustration of vertical mixing in an estuary

In temporarily open/closed estuaries, in which the mouth is closed for periods when there is little or no river inflow, the water movement will depend mainly on wind stress. Elevated water levels resulting from river inflows and possible seawater input from waves overtopping the sandbar at the mouth during storms and spring tides, also play a role in the water movement within these systems. The only exchange to the sea then will be through seepage. When the mouth is open, the dynamics will be similar to those of permanently open estuaries. However, as the river inflow declines, the volume of water exchanged through the estuary mouth is reduced. Ultimately, the estuary mouth will be closed by sand transported by a combination of wave and tidal energy.

ix. Stratification

Stratification is the term used to describe the phenomenon of denser sea water underlying lighter sea water thereby causing a vertical density gradient in the water column, depending on the vertical temperature gradient between warmer upper water layers and colder deeper water (thermocline) and the salinity gradient (halocline). Seawater density is a function of temperature, salinity and pressure (depth). An example of the relationship between temperature, salinity and depth is shown in Figure 6.21.

Density stratification is the major factor that influences the rising of a buoyant wastewater plume and thus determines whether the discharge from an ocean outfall remains beneath the surface as a submerged field or continues to rise to become a surface field.

The conversion formula to calculate the density as a function of temperature, salinity and depth (ρ_{STP}) is as follows:

$$\rho_1 = 999.842594 + 0.06793952T - 0.00909529T^2 + 0.0001001685T^3 + -0.000001120083T^4 + 0.000000006536332T^5$$

$$\rho_2 = \rho_1 + S(0.824493 - 0.0040899T + 0.000076438T^2 - 0.00000082467T^3 + 0.0000000053875T^4) + (-0.00572466 + 0.00010227T - 0.0000016546T^2) \times S^{3/2} + 0.00048314S^2$$

$$K_1 = 19652.21 + 148,4206T - 2.327105T^2 + 0.01360477T^3 - 0.00005155288T^4$$

$$K_2 = 3.239908 + 0.00143713T + 0.000116092T^2 - 0,000000577905T^3$$

$$K_3 = 0.0000850935 - 0.00000612293T + 0.000000052787T^2$$

$$K_{ST0} = K_1 + S(54.6746 - 0.603459T + 0.0109987T^2 - 0.00006167T^3) + (0.07944 + 0.016483T - 0.00053009T^2).\ S^{3/2}$$

$$A = K_2 + S(0.0022838 - 0.000010981T - 0.0000016078T^2) + 0.000191075S^{3/2}$$

$$B = K_3 + S(-0.00000099348 + 0.000000020816T + 0.00000000091697T^2)$$

$$K_{STP} = K_{ST0} + A \times D/9.81 + B \times (D/9.81)^2$$

$$\rho_{STP} = \rho_2 / [(1-D/9.81)/K_{STP}]$$

Where:

T = Temperature (^oC)
S = Salinity (ppt)
D = Water depth (m)

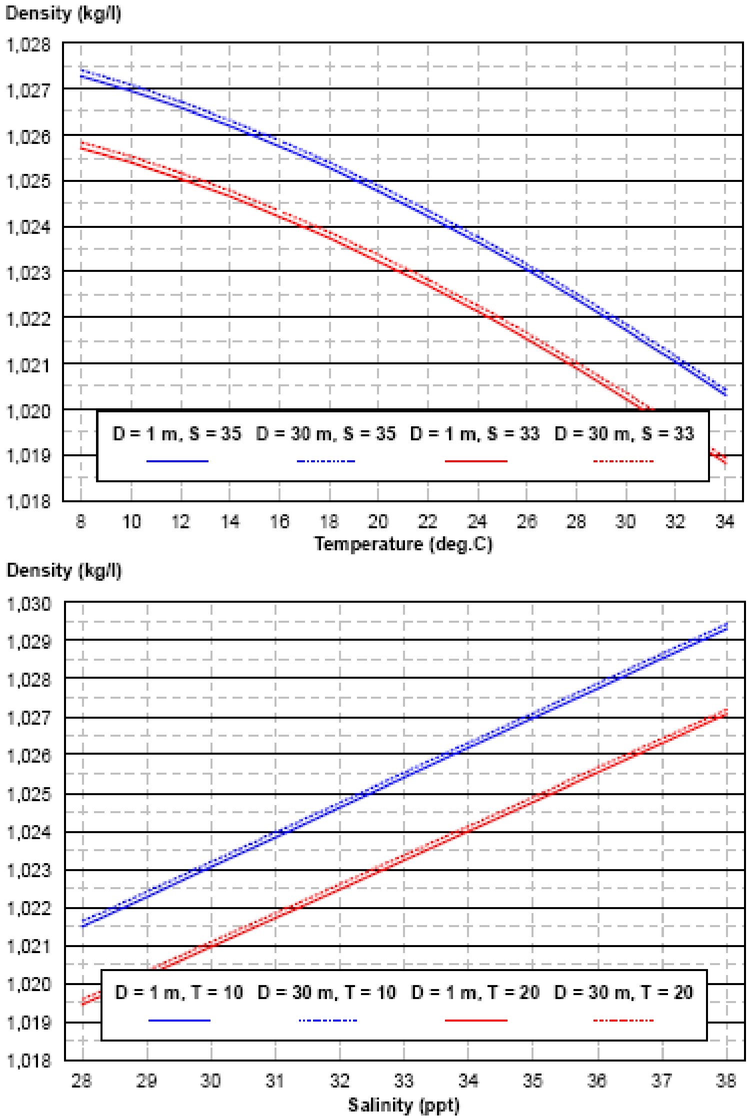


FIGURE 6.21: Seawater density versus temperature and salinity

Warming of the surface waters as a result of solar radiation, upwelling of colder deep ocean water (particularly on the west coast) and the movement of warmer (less dense) water towards the coast because of ambient ocean currents (an east coast phenomenon), typically cause stratification along the South African coast. An overview of the winter and summer sea surface temperatures along the South African coast is shown in Figure 6.22 (Hydrographic Office, 1994).

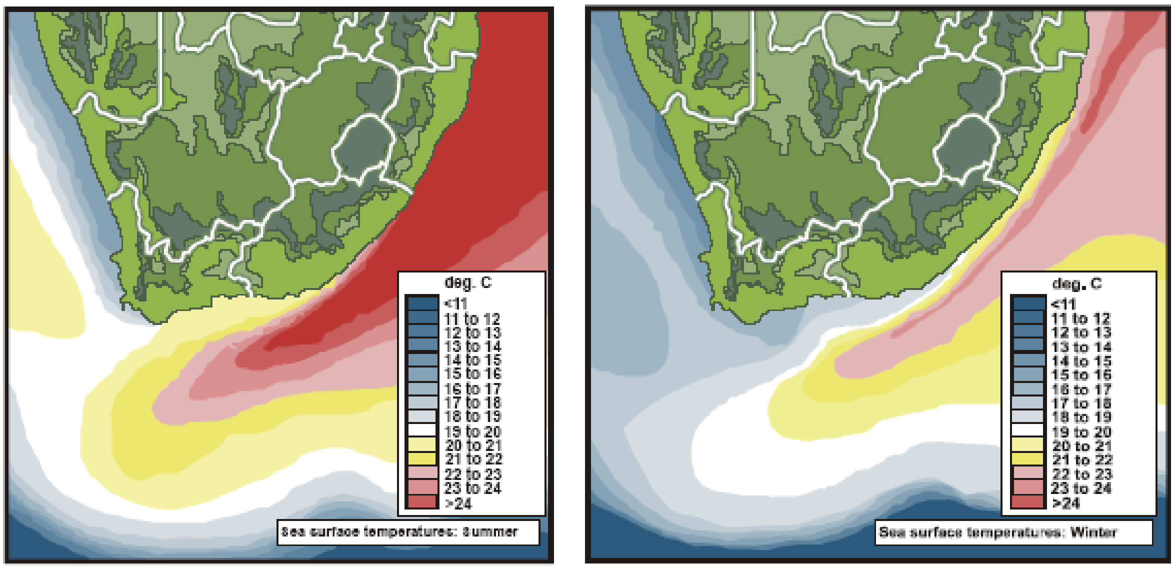


FIGURE 6.22: Typical sea surface temperatures along the South African coast for summer and winter (Hydrographic Office, 1994)

Between 1980 and 1992, temperature and salinity profiles were measured for a minimum of a year at various locations along the South African coastline (CSIR 1985, CSIR 1986, CSIR 1988, CSIR 1991b, CSIR 1992). These are summarised in Table 6.5.

TABLE 6.5: Temperature (in °C) and salinity (in ppt) profiles measured at various locations along the South African coastline based on drogue tracking between 1980 and 1992 (minimum 1 year)

LOCATION	DISTANCE FROM SHORE (km)	WATER DEPTH (m)	TEMPERATURE (SURFACE)			TEMPERATURE (BOTTOM)		
			Maximum	Minimum	Average	Maximum	Minimum	Average
North West Bay	2	30	15.5	9.3	12.3	11.4	9.4	10.3
	4	35	15.3	9.3	12.5	13.0	8.8	10.6
Hout Bay	1	30	16.6	10.4	14.0	15.9	9.7	12.2
False Bay	2	20	21.1	13.8	17.8	20.3	12.4	15.9
	5	30	21.0	14.5	17.7	16.1	12.0	14.3
Mossel bay	1	20	21.6	15.2	18.0	21.0	13.6	16.7
	2	40	21.2	15.7	18.0	18.2	11.3	15.6
Tongaat	1,2	26	24.8	18.5	21.17	24.2	16.4	20.7
	1,9	34	24.7	18.7	21.3	24.2	16.1	21.0

LOCATION	DISTANCE FROM SHORE (km)	WATER DEPTH (m)	SALINITY (SURFACE)			SALINITY (BOTTOM)		
			Maximum	Minimum	Average	Maximum	Minimum	Average
North West Bay	2	30	36.25	34.86	35.28	35.35	35.03	35.13
	4	35	37.44	34.60	35.29	36.52	34.20	35.23
Hout Bay	1	30	35.45	33.80	35.06	35.75	33.60	35.10
False Bay	2	20	35.78	34.50	35.46	35.74	35.00	35.46
	5	30	35.96	34.50	35.36	35.67	35.00	35.32
Mossel Bay	1	20	35.40	35.02	35.20	35.48	35.50	35.34
	2	40	35.48	35.00	35.19	35.04	35.15	35.38
Tongaat	1,2	26	35.45	33.6	35.01	35.45	34.43	35.1
	1,9	34	35.39	33.57	34.94	35.72	34.35	35.08

In order to detect stratification in the water column, both temperature and salinity profiles should be measured since seawater density is a function of both properties. The stratification measurements should also be done on a similar grid as that used for the current measurements. It is convenient to attach the small temperature and salinity probes to the current profiler to maximise the information obtained from each measured profile.

Stratification is calculated from measured (recorded) vertical profiles of temperature and salinity. Conductivity-Temperature-Depth (CTD) profilers can be used for measurements from a survey boat. For input data to numerical models, continuous records (pre-determined time intervals) are required and can be obtained from the deployment of a thermistor string, consisting of temperature and conductivity/salinity probes, located at regular depth intervals through the water column.

Normally, stratification in the surf zone area will be insignificant because of the vigorous movement and the consequent high degree of mixing. Horizontal density differences may occur as a result of solar heating in sheltered shallow waters.

Depending on the mouth and river flow characteristics of estuaries, the horizontal and vertical distributions of salinity and temperature contribute to a complex distribution of density and the stratification varies continuously with the tidal flow, river discharge, wind shear and solar radiation. An example of the distribution of salinity and temperature measured in the Breede River Estuary on 23 August 2000 is illustrated in Figure 6.23 (CSIR, 2002).

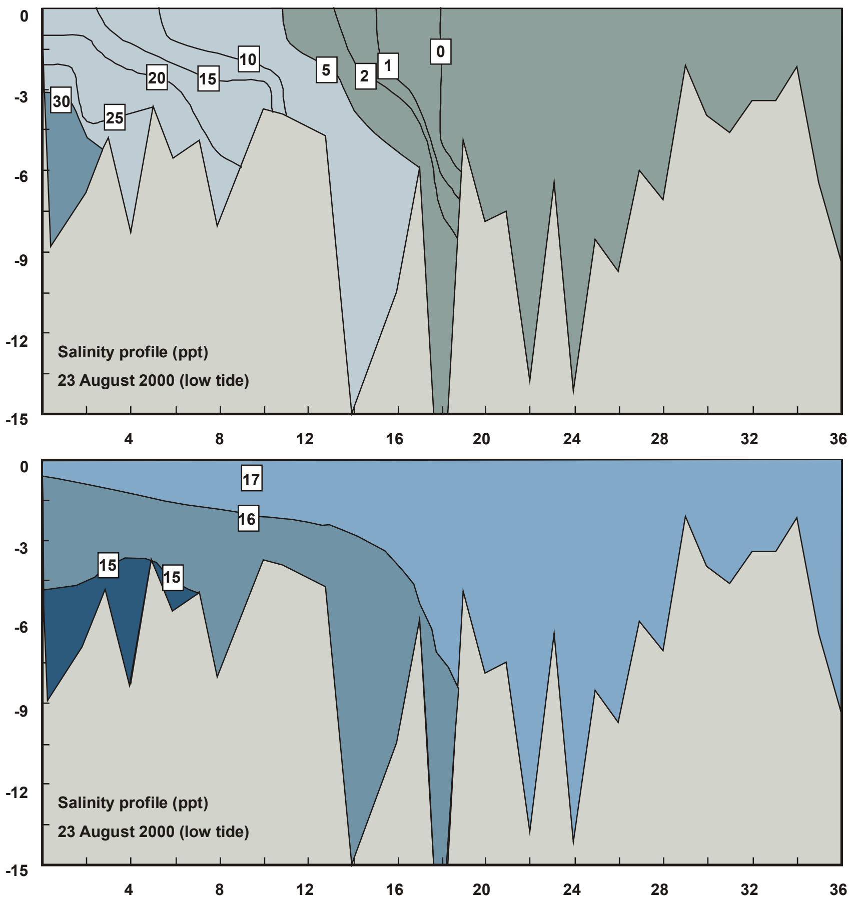


FIGURE 6.23: Salinity and temperature distribution patterns in the Breede River Estuary on 23 August 2000 (CSIR, 2002)

6.1.2 Data requirements for pre-assessment and detailed investigation

i. Pre-assessment

A pre-assessment is usually based on available data and information on the relevant physical processes, as described in Section 6.1.1. In particular, the following important data and information should be obtained:

- Observations of site-specific features, such as coastline configuration and shoreline/beach characteristics, rocky/sandy offshore areas, existing structures/obstructions, navigational routes etc.
- Existing topographical maps (1:50 000), bathymetric charts/surveys, aerial photographs
- Wind data from the nearest weather stations
- Existing wave and tidal data
- Any available data on water circulation and stratification. Where available data are insufficient, some short-term observations, using drogues or dye, can be conducted.
- Identification of potential depositional areas. These typically include areas in which current velocities are low or are protected from wave action. Sediments in these areas usually consist of fine particles.

As part of a pre-assessment, the following items need to be addressed:

- The selection of a feasible outfall site with regard to the proposed location of the head works and a feasible pipeline route (seabed slope, seabed geology, discharge depth and other physical constraints such as existing structure, wrecks, navigational routes, etc.)
- Average, maximum and minimum current velocities at the proposed outfall site for spring, mean and neap tides
- Directional occurrences and average, maximum and minimum current velocities (of particular importance is the onshore directional occurrence and the maximum velocities)
- Diurnal and seasonal variations and the spatial behaviour of the currents (average and maximum current speeds, directional occurrences)
- Wind regime (maximum and average speed, directional occurrences, seasonal and diurnal variations and persistence)
- Wave statistics (wave height and directional occurrences)
- Worst case stratification and the occurrence of density differences through the water column
- Tidal range, mean sea level, tidal currents (in the case of estuaries, the tidal prism for the different tides also needs to be determined)
- Studies involving temporarily open/closed estuaries also require an assessment of the percentage of time when the estuary mouth is likely to close.

A basic overview of statistical techniques that are typically applied in the evaluation of environmental data, where and when appropriate, is provided in Section 7.4.2. It highlights important factors that need to be taken into account when applying statistical analyses to data sets and is by no means exhaustive.

ii. Detailed investigations

A detailed investigation requires intensive field measurement programmes to acquire the data and information on the relevant physical processes, as described in Section 6.1.1. In particular, the following important data and information should be obtained:

- Geophysical data. The following surveys need to be undertaken:

    - Precision bathymetric survey
    - Side scan sonar and seismic profiling
    - Geotechnical investigations (Sea bottom material and exploratory drilling)
    - Surf zone investigation and sediment movement.

- Wind data. Wind recording at the proposed site (one-year deployment of automatic weather station).
  Long-term wind data from nearby weather station need to be correlated with on-site weather station.

- Wave data. Wave recording at the proposed site (one-year deployment of wave buoy or an alternative device). Long-term wave data from nearby recording location to be correlated with on-site wave recordings.

- Current data. The acquisition of quality field data on near-shore currents is extremely costly and time consuming as it must be ensured that the measured data are representative with regard to speed, direction and persistence. It is imperative, therefore, to ensure that all existing data for a specific area have been thoroughly researched, documented and analysed before embarking on any new measurement programme.

  Continuously recording current meters, capable of taking measurements throughout the water column, moored at a number of locations would be the ideal method for describing the current field. However, due to constraints such as the cost of meters, security of meters near the surface, and logistical difficulties in operating several dozen simultaneously recording current meters, compromise is usually necessary. A limited measurement programme, although not ideal, is in most cases sufficient for the design procedures. A limited measurement programme typically consists of:

    - A few moored continuously recording current recorders along and perpendicular to the axis of the proposed diffuser
    - Spatial current profiling from a survey boat at regular intervals (weekly, monthly) at selected locations
    - Regular surface and subsurface current measurements using drogues, dye or drift cards.

  (The output of a calibrated numerical model could be used to supplement the limited current measurements, i.e. provide more extensive spatial information.)

  NOTE:

The measurement programme must also be arranged to reflect seasonal and other cyclical current trends adequately and have a typical duration of 12 or 18 months if previous data are not available.

- Stratification. Spatial profiling (salinity, temperature, depth) should be undertaken at regular intervals to coincide with the current measurements. A thermistor string is to be deployed together with the continuously recording current meters.

In estuaries, longitudinal profiles of salinity and temperature variations at high and low water, both at springtide and at neap tide, are required. Simultaneously gauging of the river flow, and of water level variations near the mouth, need to be undertaken.

The following outputs are required as part of a detailed investigation:

- Geophysical investigation.

  The following are required:

  - Detailed bathymetric charts and contour maps
  - Profile of the seabed along the pipeline route
  - Map of seabed features (sand, rock, etc.)
  - Sub-bottom profile (seismic interpretation supported by diver investigations)
  - Detailed geotechnical reports to support the seismic interpretation (soil classification, cohesive and shear strength of soils, internal angle of friction, soil density characteristics, rock classification and hardness, seismic activities)
  - Sediment transport rates (together with potential scour/accretion probabilities) in the surf zone

- Nearshore circulation, wind, tides and stratification. For a detailed investigation, a 2-D or preferably a 3-D numerical model for the simulation of the composite hydrodynamic processes over the entire project area needs to be applied. This assessment also forms the basis for other process models such as a water quality model for detailed assessments of waste fields for the optimisation of the design of a marine outfall or the impact from an existing outfall(s).

  A state-of-art numerical model will include equations for the simulation of the majority of driving forces:

  - Tidal forcing
  - Surface wind shear stress
  - Seabed shear stress
  - Coriolis force (effect of earth's rotation)
  - Barotropic effects (free surface gradients)
  - Baroclinic effects (horizontal pressure gradients)
  - Water with variable density
  - Turbulence-induced mass and momentum fluxes
  - Thermocline dynamics
  - Insolation and air-sea interactions
  - Drying and flooding in shallow areas.

To assess advection-diffusion, the typical hydrodynamic differential equations for numerical applications (finite difference or finite element methods) are:

For the conservation of momentum (equation of motion) in the x- and y-planes:

$$\partial u/\partial t + u.\ \partial u/\partial x + v.\ \partial u/\partial y + g.\ \partial \eta/\ \partial x - f.v + g.u|U|/c^2 - F_x/(\rho(d+\eta) - \upsilon(\partial^2 u/\partial^2 x + \partial^2 u/\partial^2 y) = 0\ldots\text{.. in x-direction}$$

$$\partial v/\partial t + u.\ \partial v/\partial x + v.\ \partial v/\partial y + g.\ \partial \eta/\ \partial y - f.u + g.v|U|/c^2 - F_y/(\rho(d+\eta) - \upsilon(\partial^2 v/\partial^2 x + \partial^2 v/\partial^2 y) = 0\ldots\ldots\text{ in x-direction}$$

For the conservation of mass (continuity of flow):

$$\partial \eta/\ \partial t + \partial[(d+\eta)u]/\ \partial x + \partial[(d+\eta)v]/\ \partial y = 0$$

The advection-diffusion equation is:

$$\partial C/\partial t - \partial/\partial x[D_x.\ \partial C/\partial x - u.C] - \partial/\partial y[D_y.\ \partial C/\partial y - v.C] - \partial/\partial z[D_z.\ \partial C/\partial z - w.C] = S$$

Where

η	= water level elevation
d	= water depth
u,v,w	= velocity in 3 planes
U	= total current velocity
$F_{x,y}$	= external forces
f	= Coriolis parameter
g	= acceleration due to gravity
ρ	= water density
υ	= eddy viscosity
c	= Chezy coefficient
D_{xyz}	= dispersion coefficient
C	= concentration of constituent
S	= source term

The hydrodynamic model is used to calculate (predict) the water levels and current velocities over the model grid. The model provides the hydrodynamic and dispersion data for further application of water quality models, which simulate the chemical behaviour of ambient as well as introduced (from waste streams) constituents.

The required temporal investigations (the period for which conditions are simulated), the total area to be investigated and the complexity of the bathymetry will determine the dimensions (spatial extent and the grid size) of the model.

The hydrodynamic model should be calibrated with measured Eulerian as well as Lagrangian current measurements and a stratification dataset. For the verification of the model results, a separate dataset should be used. A sensitivity test should be undertaken to determine the sensitivity of the model outputs to uncertainties in input parameters and model assumptions. Examples of spatial outputs of current velocities and temperature distribution from a 3-D model are shown in Figures 6.24a and 6.24b.

The output of the numerical model, as well as the statistical analysis of the data, is used to determine ambient current velocities for the structural design of a marine outfall.

Numerical modelling of the surf zone hydrodynamics is complex and it is not easy to calibrate and verify the model because of the continuous physical changes (beach profiles) and continuously varying shallow water flows, driven mainly by the approaching waves. Surf zone modelling provides results/outputs that tend to be qualitative rather than quantitative.

Conditions in estuaries are complex and are dependent largely on tidal variations, wind shear, and river inflow. Longitudinal and lateral variations in salinity, and hence in water density, can have a significant effect on estuarine dynamics, mixing and subsequent water quality (SEPA, 2002). Selection of an appropriate numerical model with the capability of reproducing these features (if present) is essential.

For a well-mixed ‘narrow’ estuary, the components of acceleration and velocity in the transverse and vertical directions are considered small enough to be neglected and a 1-D model can be used to predict the flows/water exchange in the estuary, assuming average cross-sectional flows. For wider well-mixed estuaries, a 2-D depth-averaged model can be applied. For partially mixed estuaries (vertical salinity variations), a 3-D hydrodynamic model is essential and the water quality model must be capable of simulating the complex chemical processes (Van Ballegooyen *et al.*, in press).

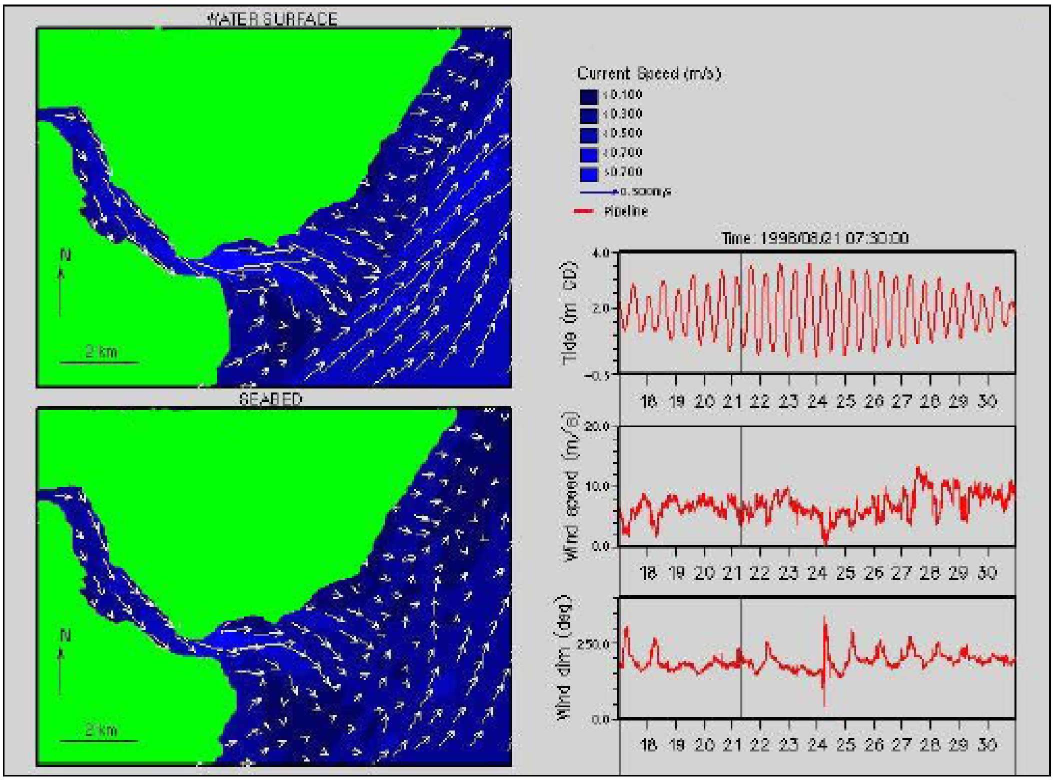


FIGURE 6.24 a: Example: Spatial output from a 3-D numerical model, showing current velocities and direction

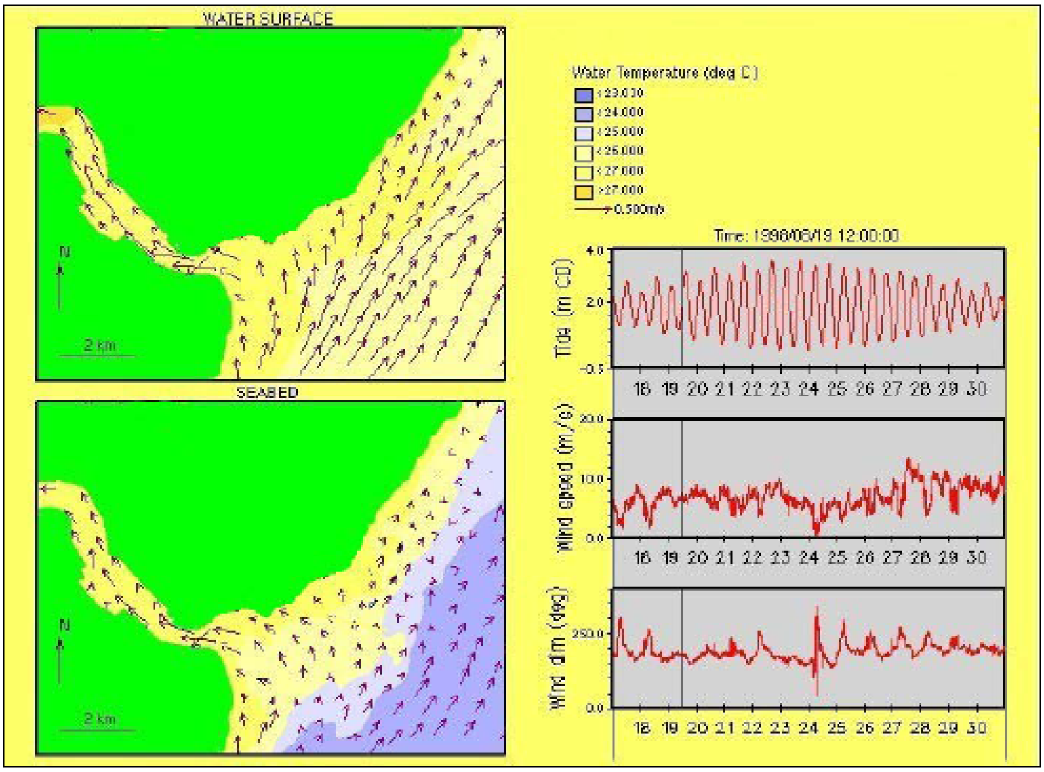


FIGURE 6.24 b: Example: Spatial output from a 3-D numerical model, showing temperature distribution

A theoretical schematisation for a 1-D model for estuaries, with motion in the horizontal plane, can be expressed in the following differential equations:

Along the estuary, choosing the x-axis in the upstream direction, the equation for motion at time t is:

$$\partial h/\partial x = 1/(g.A).\ \partial Q/\partial t - |Q|Q/(C^2.A^2.R) + 2b.Q/(g.A^2).\ \partial h/\partial t + W_x/(\rho.g.R)$$

The equation for continuity of flow is:

$$\partial Q/\partial x = -b.\ \partial h/\partial t$$

Where:

h = water level (m)
x = Distance upstream (m)
Q = Flow (m^3/s)
A =Cross-sectional area (m^2)
b = Stream width (m)
t = Time (s)
C = Chezy coefficient for friction
R = Hydraulic radius (m)
W_x =Wind factor = τ_W Cos θ
τ_W = Wind shear stress = $\rho_{air}.\ C_D.\ V_{10}^2$
C_D = Drag coefficient = $0.5.V_{10}^{1/2}.10^{-3}$
V_{10} = Wind velocity, 10 m above water surface (m/s)
θ = Angle between the wind and the channel direction
ρ = Water density (kg/m^3)

All the differential quotients (example $\partial h/\partial x$) can be replaced with finite difference quotients for example:

$$\partial h/\partial x = (h(x + \Delta x,t) - h(x - \Delta x,t))/2\Delta x$$ (a central difference approximation)

The two equations can be solved using explicit numerical methods (unknown values of h and Q at a certain time are expressed directly in terms of the known values at previous time steps) or implicitly (solving of the unknown values of h and Q over the entire model area).

For the computation of the concentration of water quality constituents (e.g. nutrients or trace metals), the change in the load (volume *x* concentration) with time can be expressed as the diffusive and advective transport in the equation below:

$$\partial(V.C_C)/\partial t = \partial(A.k.\ \partial C_C/\partial x)/\partial t.dx - \partial(A.u.\ C_C/\partial x)/\partial\ x.dx$$

Where:

V = Volume (m^3)
C_C = Concentration (kg/m^3)
k = Diffusion coefficient (m^2s)
u = mean velocity (m/s)

Terms to represent microbiological decay or point source loads can be added to the model as required.

A 1-D numerical model is a fairly simple technique, easy to apply, and if the estuary can be classified as 1-dimensional, provides valuable information with regard to the hydrodynamics and the subsequent mixing and transport of a point source. An example of the outputs (water levels, flows and velocities) of a calibrated 1-D model at three locations for the Swartkops River Estuary (Figure 6.25) is provided in Figure 6.26. The differences in flow and stream velocities at the three locations clearly indicate the importance of the spatial selection of an outfall location with regard to the mixing and transport of a wastewater plume.

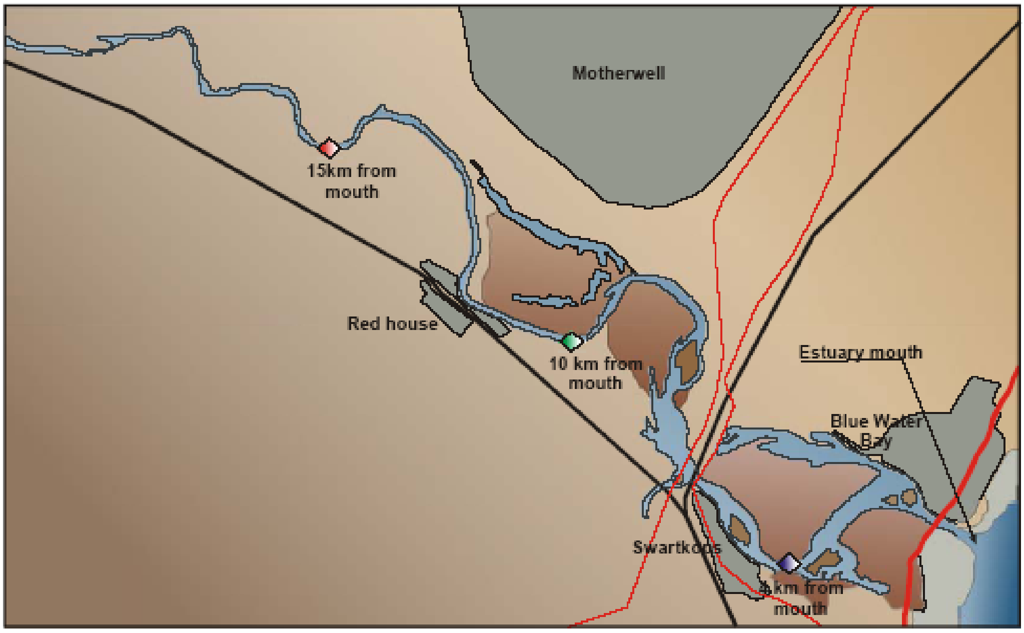


FIGURE 6.25: A map of the Swartkops Estuary, Port Elizabeth

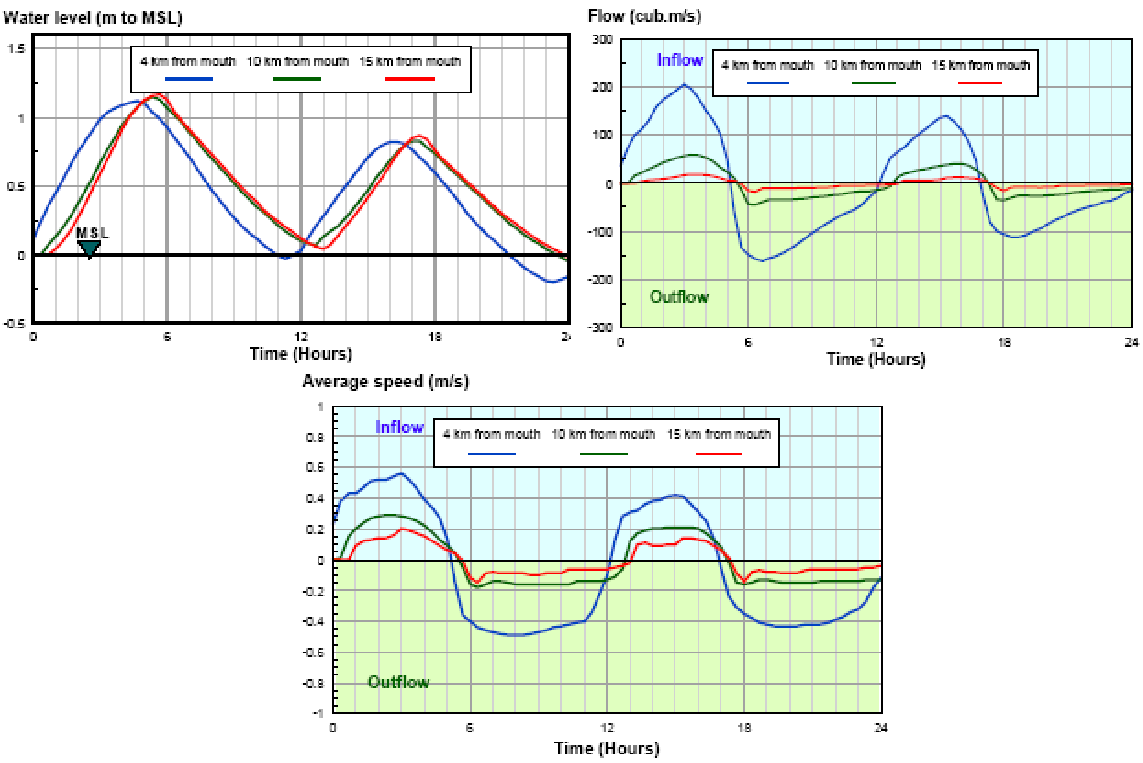


FIGURE 6.26: Water level simulations, flow rates and average stream velocities simulated at different locations in the Swartkops River Estuary under zero river inflow

Where a 2-D numerical model is not available, the 1-D model schematisation approach can be expanded to simulate the hydrodynamics of a more complex 2-D case by creating 1-D branches for all the streams, as illustrated for the Knysna Estuary in Figure 6.27.

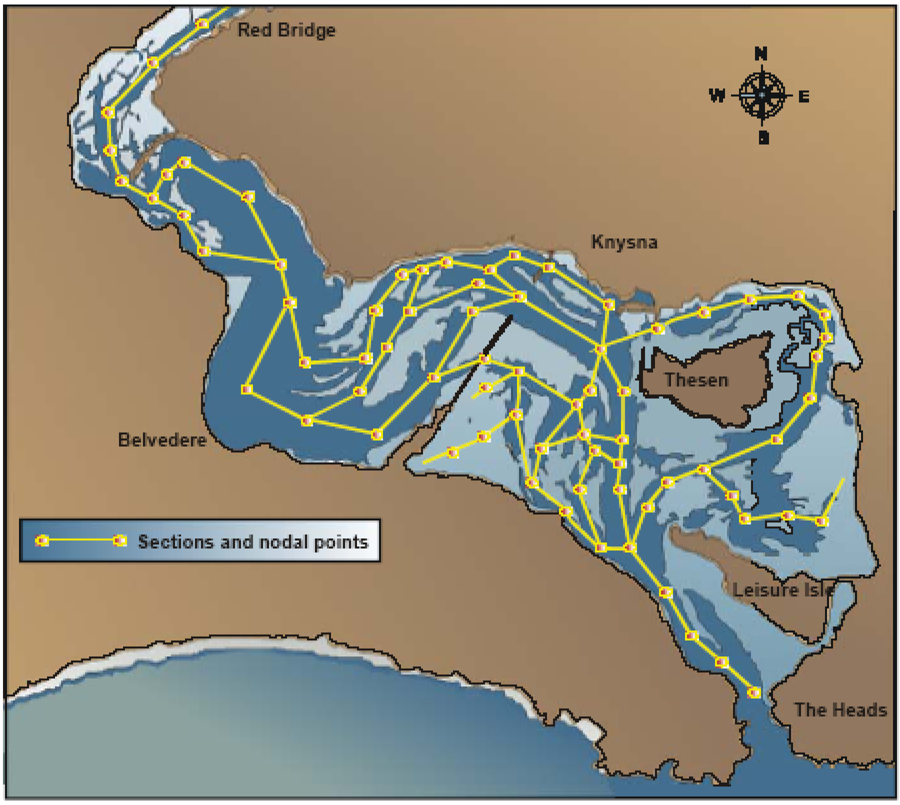


FIGURE 6.27: 1-D schematisation for the Knysna Estuary