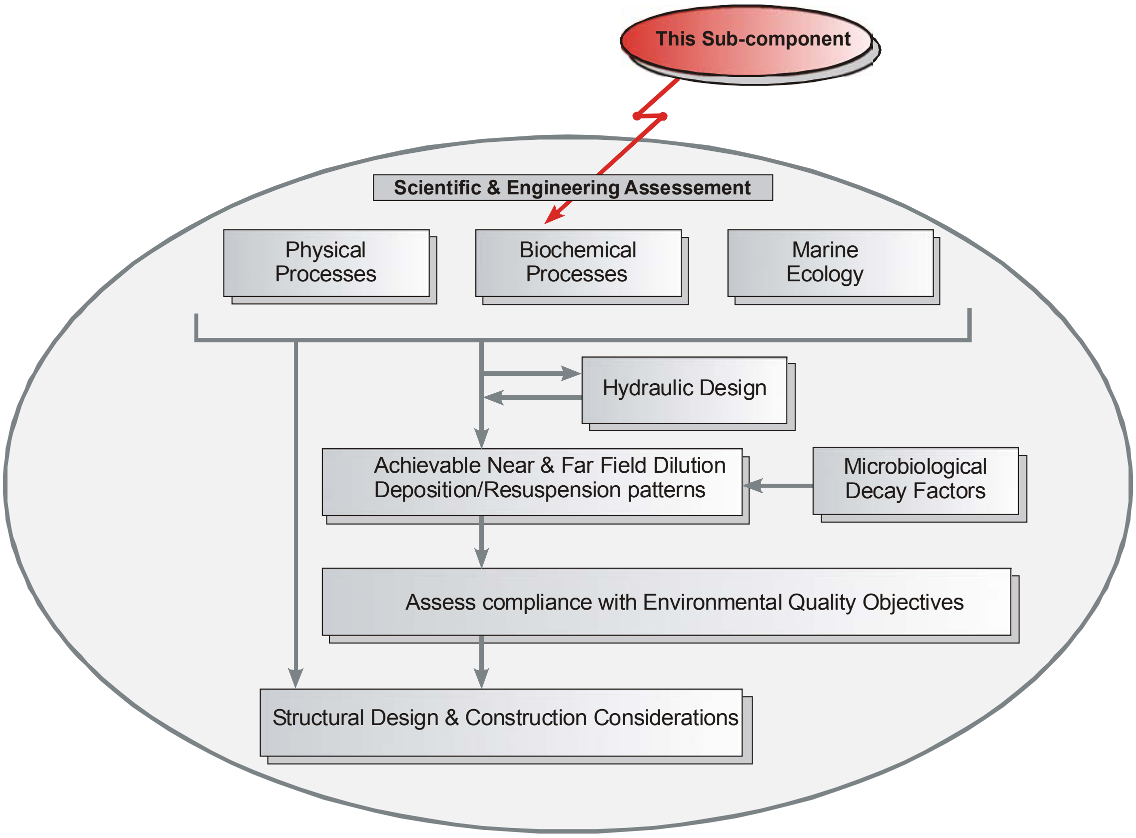
6.2 BIOGEOCHEMICAL PROCESSES (WATER COLUMN AND SEDIMENT)



PURPOSE:

The purpose of this component is to gain an understanding of those key biogeochemical characteristics and processes in the study area that may influence, or will have an influence on, the transport and fate of the wastewater plume. Any existing human interferences/activities in the study area, e.g. existing waste disposal or coastal structures, should also be taken into account.

Because of the site-specific nature of these types of investigations, this section is not intended to be prescriptive. Rather, it sets out the approach to follow when formulating a biogeochemical measurement programme as part of the scientific and engineering assessment process for marine disposal of land-derived wastewater. In particular, it highlights important factors to be taken into account when designing such measurement programmes, as well as the type of output that is required to provide information with sufficient confidence to allow for sound management decisions.

NOTE:

Methods for the Determination of the preliminary Ecological Reserve for Estuaries *(RSA DWAF, 2004), issued under the National Water Act, through the Directorate: Resource Directed Measures, provide guidance on the design of baseline data collection programmes. To ensure alignment with existing initiatives on estuaries, those methods (or future updates thereof) need to be consulted when designing baseline monitoring programmes for estuaries as part of this operational policy (proposed refinements to the design of baseline data collection programmes for estuaries are also provided in a WRC report entitled:* Resource Monitoring Procedures for Estuaries for Application in the Ecological Reserve Determination and Implementation Process *[Taljaard et al., 2003]).*

6.2.1 Overview

Biogeochemical characterisation of the marine environment requires data on the spatial and temporal variability of biogeochemical parameters, both in the water column and in the sediments, as well as an understanding of the key processes that govern such variability. It is important that data used in the characterisation reflect the present status of the receiving marine environment, i.e. any modifications to the biogeochemical characteristics and processes as a result of existing human activities need to be taken into account. This is particularly relevant when assessing the suitability of historical data sets.

Information from the physical processes study programme can be used to assist in the design of the biogeochemical data collection programme, particularly in terms of setting the critical time and space scales.

In addition to assisting in understanding the biogeochemical processes characteristic of the receiving marine environment, biogeochemical data are also used to calibrate and test the validity of model predictions (where applicable), as well as to provide a benchmark (baseline) for future monitoring programmes. It is important, therefore, that the manner in which biogeochemical data are collected is appropriate, e.g. model calibration and validation of water column parameters usually require time series data collected over a pre-determined time-scale.

i. Receiving marine environment

The selection of measurement parameters to be used in the receiving environment is site-specific. A key determining factor in the selection of such parameters is the composition of the proposed wastewater discharges as well as the anticipated effects on the biogeochemical characteristics of, and processes in the receiving environment. Essential, therefore, to the design of the biogeochemical measurement programme is the preparation of a preliminary conceptual model of the key biogeochemical processes governing the ‘cause-and-effect’ linkages between the wastewater discharge and the receiving environment.

Biogeochemical parameters (e.g. pH, dissolved oxygen, turbidity, particulate organic carbon and nitrogen, dissolved nutrients, toxin concentrations and microbiological parameters) can be measured in the water column and/or the sediments, including interstitial waters.

Depending on the nature of the investigation, sediment data should be collected from sub-tidal and/or inter-tidal sediments. An understanding of the physico-chemical characteristics of inter-tidal sediments is particularly relevant where, for example, a wastewater discharge to the surf zone is under investigation.

Spatial scales at which data need to be collected vary. For example, time series data collected from the water column may require only one or two pre-selected locations, whereas data on spatial distribution patterns require more intensive sampling. A guiding principle is that the initial sampling should cover the near and far field scales (e.g. an entire bay), making no assumptions about the locations of, for example, short- and long-term deposition sites, in the case of sediment sampling. This typically requires a high resolution unbiased grid.

The temporal scale at which biogeochemical data need to be collected, as part of the measurement programme, largely depends on:

- The variability in the load of contaminants from waste inputs
- The variability in processes driving transport and fate of the wastewater plume in the receiving environment
- The temporal sensitivity of the ecosystem to contaminant loading, i.e. exposure time versus negative impact.

The temporal scale of sampling should at least resolve the main source of natural variability of the constituent under investigation. Scales of temporal variability are very different in the water column (minutes – days) compared with sediments (days – seasons – decades). Non-periodic events, such as storms, can also have a dramatic influence that needs to be taken into account where appropriate. Therefore, a sampling frequency that is too low relative to the underlying natural variability, will result in biased data that will make it difficult, for example, to separate an anthropogenic impact from a natural water quality anomaly.

EXAMPLE…

A time series plot, showing the natural variability of dissolved oxygen concentrations (mℓ/ℓ) at a depth of 10 m in Small Bay (Saldanha Bay, South Africa) is provided in Figure 6.28 (Monteiro *et al.*, 1999). It shows regular intrusion of cold, low oxygen (< 2mℓ/ℓ) coastal waters into the bay (mℓ/ℓ multiplied by density of O_2 = mg/ℓ).

Weekly sampling would indicate that there is an apparently random variability of high and low oxygen concentrations. Hourly sampling (automated) shows that this variability is linked to variability in upwelling, and the low oxygen concentrations are brought into the system by those upwelled waters rather than by any localised eutrophication effects. Weekly sampling would result in an apparently random variability of high and low concentrations.

The results of the monitoring show that natural variability needs to be well characterised prior to interpreting the impacts of effluents on oxygen concentrations in the receiving water body.

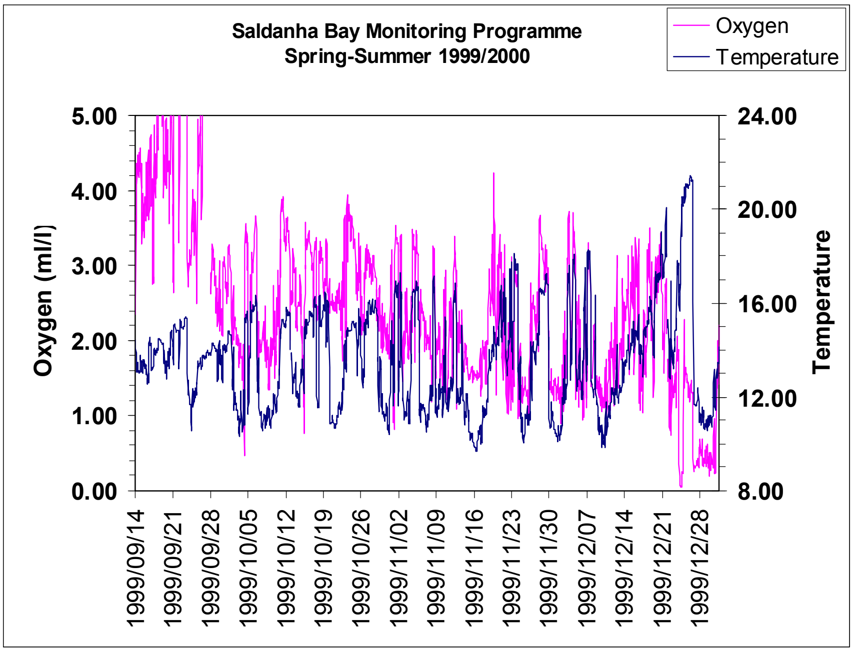


FIGURE 6.28: Dissolved oxygen variability in the bottom water layer in Saldanha Bay, South Africa (from Monteiro et al., 1999)

EXAMPLES…

I. A proposed wastewater discharge containing trace metals is considered for disposal to a marine environment receiving turbid (muddy) river inflow. For such a case, the likely fate of trace metals will be to adsorb onto the fine particles and to be deposited at some location, usually in the far field. The measurement programme, therefore, needs to be designed to enable the characterisation of the variability in river inflow and turbidity, the processes governing such variability, as well as the potential depositional sites in the study area. This will require:

- Time series data on the variability of salinity, temperature and turbidity at pre-selected position/s in the study area (e.g. intensive sampling over a period of two weeks to a month, during periods of high river inflow)
- A spatial survey of the particle size distribution, particulate organic carbon and nitrogen, and trace metal distribution patterns in sediments within the study area.

II. A proposed wastewater discharge contains relatively high dissolved inorganic nitrogen concentrations. In such, a case the processes driving nutrient distribution and primary production and the subsequent degradation of organic matter, need to be characterised. Measurement parameters need to include:

- Time series data on the variability of salinity, temperature, pH, dissolved oxygen, dissolved inorganic nitrogen and phosphate at pre-selected position/s in the study area (e.g. intensive sampling over a period of two weeks to a month, during periods of high river inflow)
- A spatial survey of the particle size distribution, particulate organic carbon and nitrogen distribution patterns in sediments within the study area.

EXAMPLE…

Plots showing the modelled and measured distribution of low turbulence (bed shear stress) zones in Saldanha Bay, South Africa are provided in Figure 6.29 (Monteiro, *et al.*, 1999). These plots show that long-term deposition of contaminant carrying fine particles will only occur at certain locations (blue: model and red in observations). The modelled results show that the wave climate as well as the currents governs the distribution of long-term and short-term depositional zones. The long-term depositional zones are the most vulnerable to contaminant accumulation.

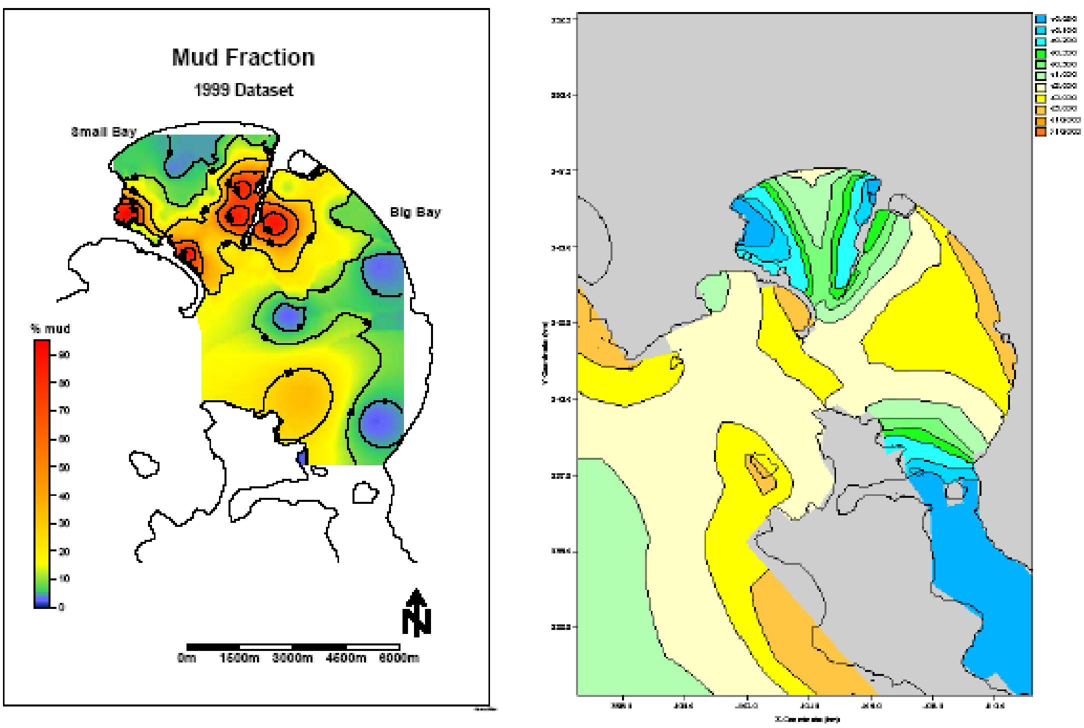


FIGURE 6.29 ***Plots showing the measured particle size distribution in Saldanha Bay, as well as the modelled distribution of low turbulence (bed shear stress) zones in Saldanha Bay, South Africa (Monteiro et al., 1999).***

ii. Behaviour of constituents

Immediately after entering the marine environment, constituents present in a wastewater discharge can either (WHO, 1982):

- Remain in solution (i.e. remain in the 'dissolved phase')
- Adsorb onto solid phase particles
- Precipitate from the water column.

Another type of transformation is that of certain poly-aromatic hydrocarbons, in particular volatile organics (e.g. benzene, toluene, naphthlalene and xylene). On entering marine waters, such compounds do not follow the conventional 'dilution' behaviour. It is thought that these substances are actually extracted out of the aqueous phase and into the buoyant hydrophobic fraction that results in concentration as a film at the water's surface (referred to as the surface micro-layer), which subsequently evaporates to the atmosphere, rather than diluting. It will be extremely difficult to predict the transport and fate of such volatile substances in the receiving environment. Removing such compounds from the wastewater before discharging to sea best mitigates their potential risk to the marine ecosystem and other beneficial uses.

It is important, therefore, as part of the biogeochemical assessment process, to assess possible biogeochemical transformations of the wastewater (i.e. immediately after it enters the marine environment) that could have a major influence on the predicted transport and fate of the specific constituents in the wastewater plume.

Dissolved phase. Constituents associated with the 'dissolved' phase can either behave conservatively (i.e. their behaviour reflects only the advective and dispersive characteristics of the water body) or non-conservatively (i.e. they are rapidly transformed on entering the marine environment as a result of system variables such, as pH, salinity and temperature, being different from that in the wastewater).

Although changes in concentration of constituents behaving non-conservatively are difficult to quantify without sophisticated tools such as numerical models, the concentration after a given dilution of a constituent behaving conservatively can be calculated as follows:

$C_{AE} \,.\, (Q_A + Q_E) = C_E.Q_E + C_A.Q_A$

Where
Q_A = Receiving water flow rate
Q_E = Effluent flow rate
C_E = Effluent concentration
C_A = Ambient concentration in the receiving water
C_{AE} = Concentration after mixing

The physical dilution (S) of the effluent can be expressed as the following dimensionless parameter:

$S = (Q_E + Q_A)/Q_E$ or $Q_A = Q_E(S - 1)$

Substituting Q_A in the mass balance equation, the concentration after mixing is:

$C_{AE} = (C_E + S.C_A - C_A)/ S$

Adsorption. On entering the marine environment, toxic compounds such as trace metals and poly-aromatic hydrocarbons, poly-nuclear aromatics and pesticides, tend to adsorb onto 'solid' phase particles present either in the wastewater or in the receiving environment. 'Solid' phase particles comprise cohesive (non-biological) particles and organic particles.

Cohesive (non-biological) particles represent very fine sediment particles (< 60 μm) on which adsorption phases such as aluminium hydroxides, manganese hydroxides and iron hydroxides are common. The origin of the organic particles can be natural (e.g. phytoplankton) or introduced through anthropogenic activities (e.g. sewage disposal).

Adsorption to ‘solid’ phase particles is typically described by means of equilibrium partitioning, on the basis of partition coefficients, which are different for each ‘solid’ phase particle. Partition coefficients, in this context, are defined as (US-EPA, 1999):

For a given pH and assuming that concentration of the ‘solid’ phase particles is in excess with respect to C_d:

$K_d \sim C_p/C_d$

where

K_d = Partition coefficient (in ml/g)
C_p = Concentration of trace metal adsorbed onto the ‘solid’ phase particle at equilibrium (in μg/g)
C_d = Concentration of trace metal remaining in solution at equilibrium (in μg/mℓ)

The transport and fate of chemical constituents associated with the ‘solid’ phase is largely determined by the flux and sedimentation/re-suspension behaviour of solid phase particles. The sedimentation/re-suspension behaviour of solid phase particles is a sensitive indicator of the potential fate of toxic compounds in the receiving marine environment (Luger *et al.,* 1999; Monteiro, 1999).

Precipitation**.** A rise in pH and oxygen content promotes the formation of metal hydroxides, carbonates and other metal precipitates. Under such conditions, if the concentration of a trace metal is higher than the solubility of the least soluble compounds that can be formed between the metal and available anions in the receiving water, precipitation will occur.

Where appropriate, solubility products and stability constants, which describe precipitation processes and which are specific to the metal/anion complex, need to be sourced from the literature in order to quantify such transformations (Stumm & Morgan, 1970; Faust & Aly, 1984). However, most metals, with the exception of iron (Fe) and manganese (Mn) that readily precipitate their hydroxides, will usually remain in solution in seawater at concentrations, which are much higher than those occurring naturally (Solomons & Förstner, 1984; WHO, 1982).

EXAMPLE…

An iron (Fe)-rich, strongly acid effluent (Fe will be in the dissolved phase) will be neutralised on contact with seawater (releasing CO_2). The change in pH will result in the precipitation of the Fe (i.e. Fe will be in the solid phase). This modification in constituent characteristics needs to be taken into account when quantifying the transport and fate of the wastewater plume in the far field.

6.2.2 Data requirements for pre-assessment and detailed investigation

i. Pre-assessment

A pre-assessment is usually based on published or archived information and data, either from the study area or comparable sites. As much data and information as possible, as described in Section 6.2.1, need to be collated. For the pre-assessment, conceptual and analytical assessment techniques (rather than far field numerical modelling), are used to produce:

- An initial quantitative description of the biogeochemical characteristics of and processes in the study area
- An estimate of the ambient concentrations of relevant biogeochemical parameters
- An identification of the potential depositional areas and estimate of the extent of contamination as a result of existing waste inputs (where data are available, prepare a contour map showing the distribution of toxic compounds). The sediment grain size and particulate organic matter distribution patterns are crucial for the interpretation of results.
- A quantitative assessment of the chemical behaviour of constituents in the wastewater immediately after being discharged to the marine environment.

As part of the pre-assessment, it is also necessary to estimate required dilutions since such information is used as an input parameter in the hydraulic design of offshore marine outfalls, i.e. to provide a first indication of the <u>initial</u> dilution that needs to be achieved in the design of the outfall.

Required dilutions are defined as the dilution necessary to ensure compliance with the environmental quality objective recommended for a particular constituent, taking into account the present concentration in the receiving marine environment as well as the proposed concentration in the wastewater. The required dilution is calculated as follows:

Referring to the mass-balance equation…

$$S = (C_E - C_A) / (C_G - C_A)$$

Where
C_E = Effluent concentration
C_A = Ambient concentration in the receiving water
C_G = Environmental quality objective (target value)
S = Required dilution

EXAMPLE…

The dissolved ammonia concentration is about 30 mg/ℓ after preliminary treatment of sewage:

Concentration of the effluent (C_E):	30 mg/ℓ
Ambient concentration in the sea (C_A):	Low, assume 0.001 mg/ℓ
Guideline (C_G):	0.600 mg/ℓ

The required dilution (S) is:

$$S = (30 – 0.001)/(0.600 – 0.001) = 50$$

ii. Detailed investigation

A detailed investigation requires an intensive data collection programme to acquire the data and information on the relevant physical processes, as described in Section 6.2.1

In a detailed assessment of the biogeochemical characteristics and processes, numerical modelling tools such as water quality models in association with hydrodynamic models need to be applied. These models are particularly useful in the interpretation of existing knowledge of the key processes and thus help to define the temporal and spatial variability of the biogeochemical characteristics of the receiving marine environment.

Outputs required for the characterisation of biogeochemical processes, as part of a detailed investigation, include:

- A contour map showing the distribution of relevant chemical constituents in the marine sediments of the study area, including details on sediment particle size distribution and particulate organic carbon and nitrogen. Expected variability, both temporally and spatially, need to be addressed.

  NOTE:

  Geochemical ratios of trace metals can be used to determine whether the trace metals are of natural or anthropogenic origin. It is possible for conditions to arise in which the total trace metal concentration in the sediment is high (particularly in depositional areas) but completely linked to the natural structure of clay minerals, in which case the trace metals will not be bio-available. This condition would be characterised by geochemical ratios very similar to those of unpolluted sediments typical of the area. The geochemical ratio of each trace metal relative to aluminium (TM [µg/g]: Al [%]) is used, usually allowing a conservative 2-fold natural variation in the geochemical ratios. Natural geochemcial ratios are site specific for different geographical regions and need to be sourced from the literature (Monteiro & Scott, 2000).

- Graphs showing the temporal (and, where applicable, spatial) variability of system variables (temperature, salinity, dissolved oxygen and suspended solids/turbidity), inorganic nutrients (nitrate, ammonia, reactive phosphate and reactive silicate), and organic nutrients (dissolved organic carbon, particulate organic carbon and particulate organic nitrogen) in the water column.

- Description of the expected interaction of the constituents of waste inputs with biogeochemical processes in the receiving marine environment, e.g. whether the constituents are in the 'dissolved' phase (i.e. remain in solution), will precipitate from the water column, or whether they are in the 'solid' phase (e.g. adsorbed to solid phase particles).

As part of a detailed investigation, numerical modelling should be used to refine the required dilutions that were estimated during the pre-assessment stage (refer to Section 6.2.2).

Numerical modelling techniques have proven to be powerful tools in that:

- Models provide a workable platform for incorporating the complexity of spatial and temporal variability in the marine environment

- Model assumptions and inputs provide a means of synthesising an existing understanding of the key processes

- Modelling assists in defining the most critical spatial and time scales of potential negative impacts in the receiving system

- Model outputs provide quantitative results which can be used, together with field data, to check the quality of assumptions and insights.

However, in the application of numerical modelling techniques, the following must be complied with:

- The model chosen must be appropriate to the situation in which it is utilised

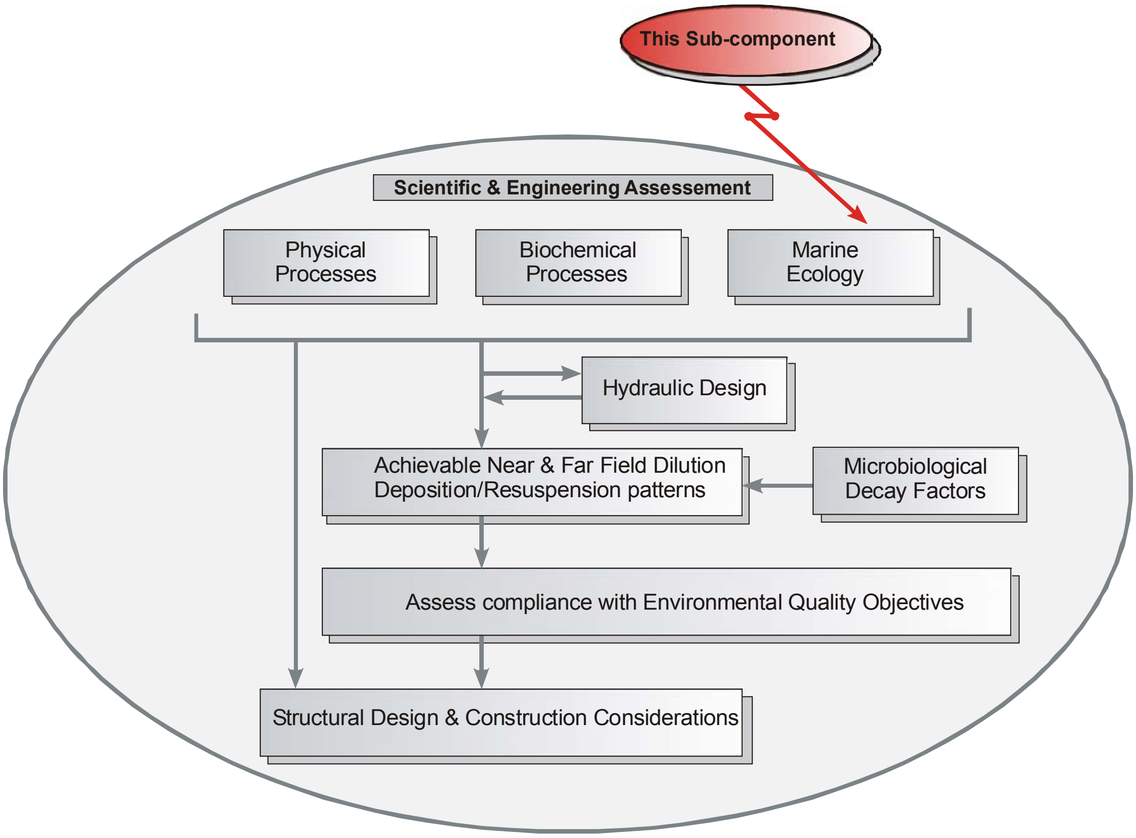
- The model must be calibrated and validated against a full field data set adequately describing the site-specific physical and biogeochemical oceanographic conditions ('ground truthing')

- A sensitivity analysis must be conducted to demonstrate the effect of key parameters, based on the variation in input data and controlling assumptions

- The reporting of model outputs must include a clear description of assumptions, a summary of numerical outputs, and confidence limits and sensitivity analyses.

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.

6.3 MARINE ECOLOGY



PURPOSE:

The purpose of the ecological component, as part of the scientific and engineering assessment, is to:

- ***Establish the biological resources within the study area***
- ***Identify biological resources that are of high conservation value***
- ***Establish which biological resources have already been lost or are stressed by anthropogenic influences, including existing waste inputs***
- ***Identify biological resources that are particularly sensitive to anthropogenic influences in the area (both existing and proposed)***
- ***Refine the ecological objectives for the study area (e.g. the description of the balanced indigenous population [US-EPA, 1994]) and related objectives pertaining to water quality***
- ***Assist in determining a suitable pipeline route so as to minimise damage to the marine ecology***
- ***Provide ecological baseline data for future monitoring programmes.***

6.3.1 Overview

To characterise the ecology of a particular marine environment, data on the following are required:

- Identification of habitat types, e.g. reefs, kelp beds, sandy and rocky bottoms
- Community structure within each of the habitat types
- Community composition and list of species (and abundance) associated with the different habitat types, focusing on dominant species, species of particular conservation importance and species targeted for exploitation.

The high mobility of pelagic and planktonic organisms in the water column makes representative sampling nearly impossible and particular care should be taken when interpreting data on such organisms. In addition, the distribution and abundance of marine organisms often show strong diurnal and/or seasonal variability, depending on numerous climatic, physical and biogeochemical factors. It is important, therefore, to ensure such information is collected simultaneously and is taken into account when interpreting the ecological data.

Ecological data should be adequate to perform valid statistical and community analyses as proposed below.

NOTE:

For estuaries, guidelines on baseline data requirements are provided in the* Methodology for the Determination of the Preliminary Ecological Reserve for Estuaries *(RSA DWAF, 2004) issued under the National Water Act. Proposed refinements to these methods are provided in a WRC report entitled:* 'Resource Monitoring Procedures for Estuaries for Application in the Ecological Reserve Determination and Implementation Process' *(Taljaard et al., 2003).

6.3.2 Data requirements for pre-assessment and detailed investigation

i. Pre-assessment

A pre-assessment is based on published or archived information and data from the study area or comparable sites. As much data and information as possible, as described in Section 6.3.1, need to be collated.

As part of a pre-assessment it is important to provide the following:

- A map showing, at least conceptually, the distribution of the various habitat types and the associated biological resources (i.e. to refine the beneficial use map in terms of the distribution of marine ecosystems), and highlighting areas with:

  - Biological resources of conservation importance
  - Biological resources targeted for exploitation
  - Biological resources that have been lost, or are stressed, as a result of anthropogenic influence.

  (Site photography and video recordings have been used effectively to assist in providing information on the above.)

- Identification of the dominant species, species of particular conservation importance and species targeted for exploitation, providing best estimates of spatial and temporal variability.

- Identification of biological resources that are potentially sensitive to anthropogenic influences already present in the area and/or that may be sensitive to constituents present in the proposed wastewater discharge, and quantification of cause-and-effect relationships as best as possible (i.e. to refine the ecological quality objectives).

ii. Detailed investigation

A detailed investigation requires an intensive data collection programme to acquire the data and information on the relevant ecological processes, as described in Section 6.3.1. In a detailed assessment of the ecological characteristics and processes, ecological modelling tools can be applied. These models are particularly useful in interpreting existing understanding of the key processes in order to improve quantitative predictions with respect to cause-and-effect relationships.

For a detailed investigation, the ecological component should include:

- A geo-referenced map showing the distribution of the various habitat types and their associated biological resources (i.e. to refine the beneficial use map in terms of the distribution of marine ecosystems), highlighting areas with:

  - Biological resources of conservation importance
  - Biological resources targeted for exploitation
  - Biological resources that have been lost, or are stressed, as a result of anthropogenic influence.

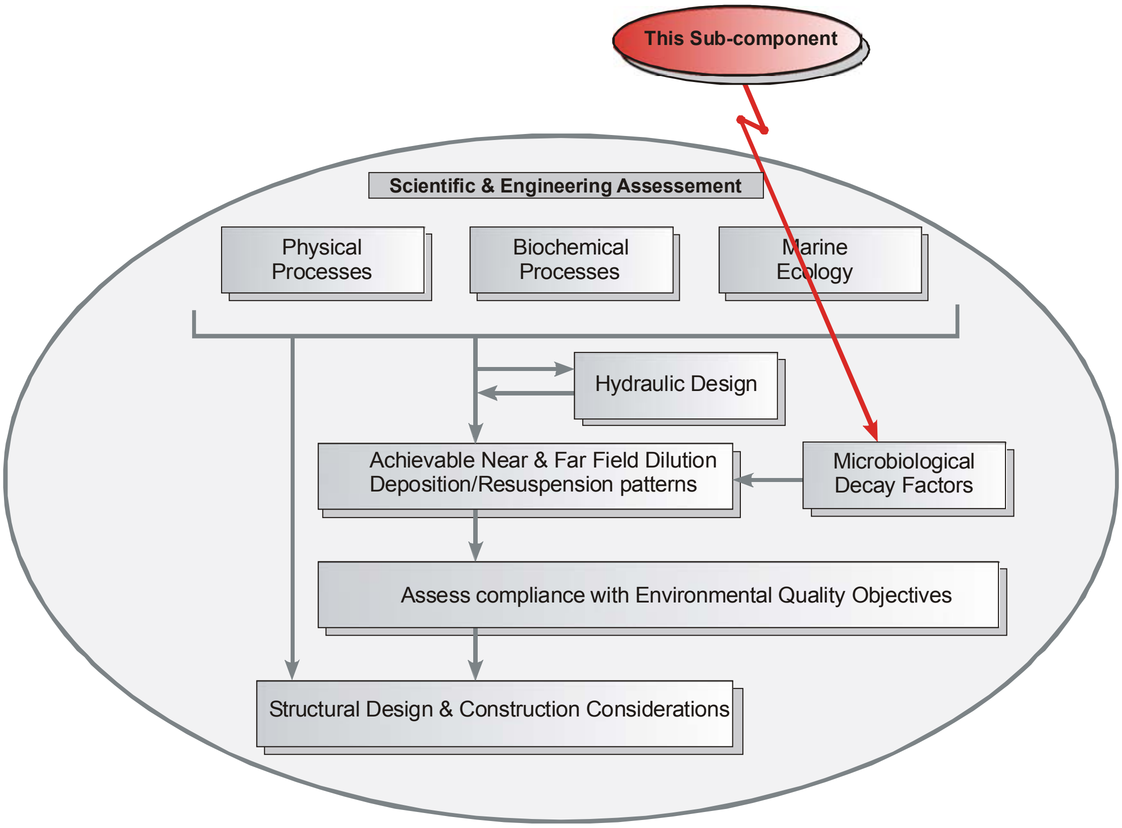
- For each of the habitat types, a listing of the key species and their abundance and community composition, as well as expected temporal and spatial variability (this may be expensive to obtain and it may therefore be more realistic to focus on selected indicator species and community structure)

- Confirmation of the presence of biological resources that are potentially sensitive to anthropogenic influences already present in the area and/or that may be sensitive to constituents present in the proposed wastewater discharge, and also provision of a quantitative assessment of cause-and-effect relationships (i.e. to refine the ecological quality objectives)

- Refinement of the ecological objectives (e.g. described in terms of a *balanced indigenous population*) for the study area (refer to Section 4.2.1 for more details) that can be used as the baseline or reference for future monitoring.

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.

6.4 MICROBIOLOGICAL FACTORS



PURPOSE:

The purpose of this component is to determine the relevant microbiological indicator and associated decay coefficients to use in predicting microbiological die-off in the far field for a specific study area. These decay coefficients for the selected microbiological indicator, for example, depend on exposure to solar radiation (i.e. whether its day or night time) and water salinity of receiving environment.

6.4.1 Overview

The types and numbers of various pathogens in sewage depend on the incidence of disease in the population of an area and the seasonal variation of infections (WHO, 1999). Numbers and types, therefore, will vary throughout the world and between seasons. A general indication of pathogenic numbers in sewage is provided in Table 6.6 (WHO, 1999).

TABLE 6.6: A general indication of pathogens found in sewage, the associated diseases and typical counts (WHO 1999)

PATHOGEN/INDICATOR	***DISEASE/ROLE***	***COUNTS PER LITRE***
Bacteria		
Campylobacter spp.	*Gastro-enteritus*	*37 000*
Clostridium perfringens	*Indicator*	$6 \times 10^5 – 8 \times 10^5$
E.coli	*Indicator*	$10^7 – 10^8$
Salmonella spp.	*Gastro-enteritus*	*20 – 80 000*
Shigella	*Bacillary dysentery*	*10 – 10 000*
Viruses		
Polioviruses	*Indicator*	*1 800 – 5 000 000*
Rotaviruses	*Diarrhoea, vomiting*	*4 000 – 850 000*
Parasitic protozoa		
Cryptosporidium parvum oocysts	*Diarrhoea*	*1 – 390*
Entamoeba histolytica	*Amoebic dysentery*	*4*
Giardia lamblia cysts	*Diarrhoea*	*125 – 200 000*
Helminths		
Ascaris spp.	*Ascariasis*	*5 – 110*
Ancylostoma spp.	*Anaemia*	*6 - 190*
Trichuris spp.	*Diarrhoea*	*10 - 40*

Methods to detect and identify infectious viruses and parasites are very expensive and do not exist for some. The use of indicator organisms to indicate the potential presence of harmful organisms has been used for a long time and the faecal indicator bacteria most commonly used today are thermotolerant coliforms, *E.coli* and Enterococci or faecal streptococci. The advantages and disadvantages of these bacteria as indicators are listed in Table 6.7 (WHO, 1999).

TABLE 6.7: Advantages and disadvantages of different microbiological indicators

INDICATOR	*ADVANTAGES*	*DISADVANTAGES*
Faecal streptococci/ enterococci	*Marine and potentially freshwater human health indicator.* *More persistent in water and sediments than coliforms.*	*May not be valid for tropical waters due to growth in soils.*
Thermotolerant coliforms	*Indicator of recent faecal contamination.*	*Possibly not suitable for tropical waters due to growth in soils and water.* *Confounded by non-sewage sources (eg. Klebsiella spp. in pulp and paper wastewater)*
E. coli	*Potentially a freshwater human health indicator.* *Indicator of recent faecal contamination.* *Rapid identification possible if defined as b-glucuronidase producing bacteria.*	*Possibly not suitable for tropical waters due to growth in soils and water.*

The effect of conventional sewage treatment on the removal of the major pathogen groups is illustrated in Table 6.8.

TABLE 6.8: Effect of conventional sewage treatment on the removal of the major pathogen groups (adapted from WHO, 1999)

TREATMENT	Enteric viruses	Salmonella	C. perfringens	Giardia
Raw sewage	*100 000 – 1 000 000*	*5 000 – 80 000*	*100 000*	*9 000 - 200 000*
Primary treatment				
% removal	*50 - 98,3*	*99,5 – 99,8*	*30*	*27 – 64*
Counts remaining	*1 700 – 500 000*	*160 – 3 360*	*70 000*	*7 200 – 146 000*
Secondary treatment				
% removal	*53 – 99,92*	*98,65 – 99,996*	*98*	
Counts remaining	*80 – 470 000*	*3 – 1 075*	*2 000*	
Tertiary treatment				
% removal	*99,983 – 99,999998*	*99,99 – 99,9999995*	*99,9*	*98,5 – 99,99995*
Countsremaining	*0 - 170*	*0 - 7*	*100*	*0 – 2 951*

Potential risks associated with different levels of treatment and disposal location in the marine environment is indicated in Table 6.9 (WHO, 1999).

TABLE 6.9: Potential risks associated with different levels of treatment and disposal location in the marine environment

TREATMENT	DISCHARGE TYPE		
	Surf zone or estuarine discharge	Marine outfall (less than 10 m water depth)	Marine outfall* (greater than 10 m water depth)
None	*Very high*	*High*	*NA*
Preliminary	*Very high*	*High*	*Low*
Primary	*Very high*	*High*	*Low*
Secondary	*High*	*High*	*Low*
Secondary and disinfection	*Medium*	*Medium*	*Very low*
Tertiary	*Medium*	*Medium*	*Very low*
Tertiary and disinfection	*Very low*	*Very low*	*Very low*

* *Assuming that the design capacity is not exceeded and that extreme climatic and oceanic conditions were considered in the design (i.e. the wastewater plume will not reach the beach).*

In 1999, the WHO (1999) concluded that the data available on T_{90} values were inadequate for use in model predictions, especially in the near-shore zone. At that stage, the WHO referred to Chamberlain and Mitchell (1978), who gave a mean T_{90} value of 2.2 hours for marine waters and a T_{90} value of 58 hours for freshwaters. These numbers were obtained from *in situ* tests at wastewater outfalls. From these data numbers it can be assumed that the mean daytime T_{90} value will be less than 2.2 hours. A summary of T_{90} values provided by Gunnerson (1988) for a number of coastal areas is listed in Table 6.10

TABLE 6.10: Summary of T_{90} values for a number of coastal areas (Gunnerson, 1988)

LOCATION	*DATE*	*T_{90} (hours)*
Raw sewage		
Honolulu	*1970*	*$\leq$ 0.75*
Titahi Bay, New Zealand	*1959 – 1960*	*0.65*
Rio de Janeiro	*1963*	*1.0 – 1.2*
Israel	-	*< 1.0*
Istanbul	*1968*	*0.8 – 1.7*
Genofte, Denmark	-	*1.2*
Tema, Ghana	*1964*	*1.3*
Nice, France	-	*1.1*
England	*1965*	*0.78 – 3.5*
Manila, Philippines	*1968 – 1969*	*1.8 – 3.4*
England	*1969 – 1973*	*1.4 – 5.3*
Mayaquez Bay, Puerto Rico	-	*0.7*
Montevideo, Uruguay	-	*1.5*
Santos, Brazil	-	*0.8 – 1.7*
Porlaleza, Brazil	-	*1.1 – 1.5*
Maceio, Brazil	-	*1.2 – 1.5*
Primary Treated Wastewater		
Ventura, California	*1966*	*1.7*
Seaside, New Jersey	*1966*	*1.8*
Orange County, California	*1954 – 1956*	*1.8 – 2.1*
Santa Barbara, California	*1967*	*2.4*
Los Angeles, California	*1954 - 1956*	*4.1*

Typically, pathogenic organisms are modelled using faecal coliforms as the proxy with appropriate die-off responses to changes in ultraviolet light intensity linked to time of day and penetration of the water column. Night-time values for T_{90} will be higher.

The variability of the T_{90} value, as part of detailed investigations, is normally simulated using numerical models. For a pre-assessment, a value of 10 hours can be used.

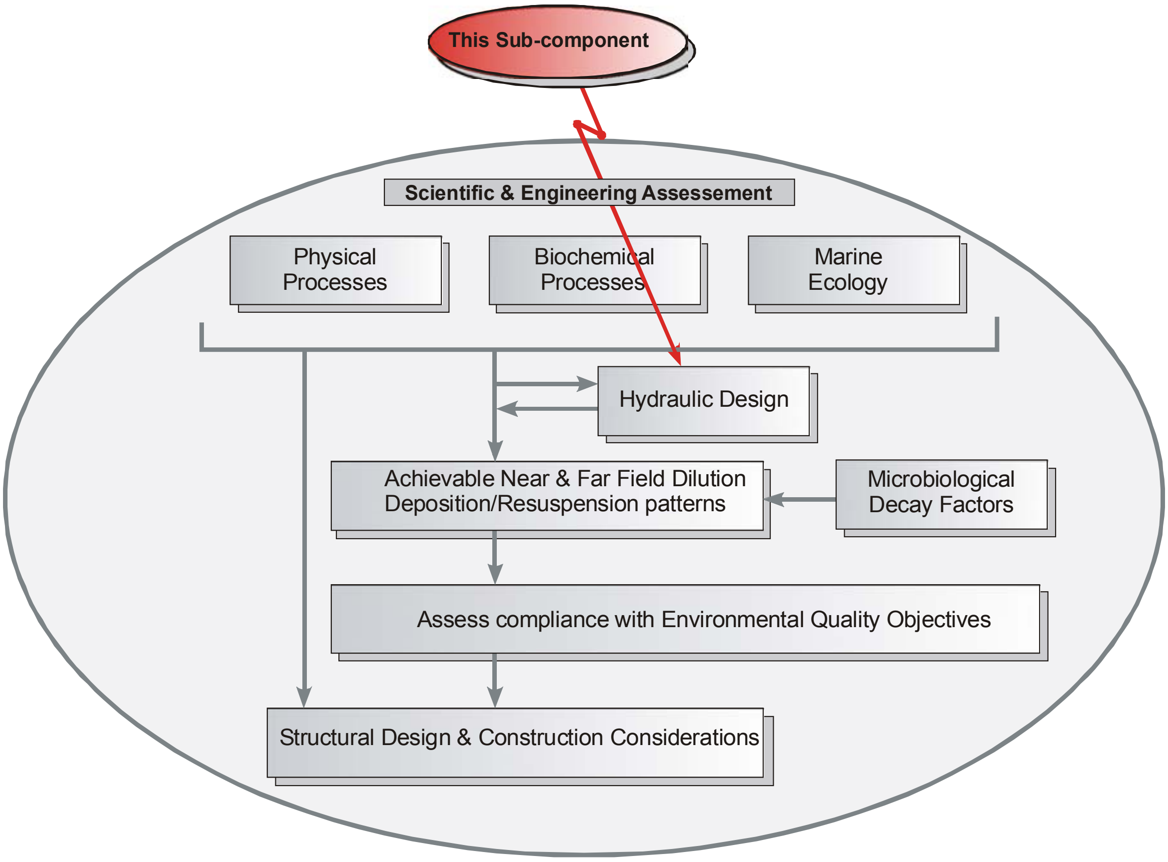
6.4.2 Data requirements for pre-assessment and detailed investigation

For a pre-assessment conservative die-off coefficient, for both daytime and night-time, considered to be representative of conditions at the study area, can be applied.

For a detailed investigation, the above needs to be refined, by using diurnal variations of daytime and night-time die-off coefficients in conjunction with variation in wastewater flow patterns. For large projects it may be required to measure actual die-off coefficients in the study area.

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.

6.5 HYDRAULIC DESIGN



PURPOSE:

A sound hydraulic design for a wastewater discharge system includes the following main functional components:

- ***The head works, to discharge the wastewater***
- ***The main outfall pipe, to convey the wastewater to the discharge location***
- ***The diffuser, to release the wastewater into the receiving environment.***

6.5.1 Outfall site selection

Prior to commencing with the scientific and engineering assessment process, it is important to conduct a preliminary on-site assessment of the possible location of a wastewater discharge system.

A well-designed wastewater discharge system consists of the following main components:

- Head works to discharge the wastewater
- Main outfall pipe to convey the wastewater to the discharge location
- Diffuser to release the wastewater into the receiving environment.

An illustration of the different components is provided Figure 6.30. The 'diffuser' component is specific to marine outfalls (i.e. wastewater discharges to the offshore marine environment).

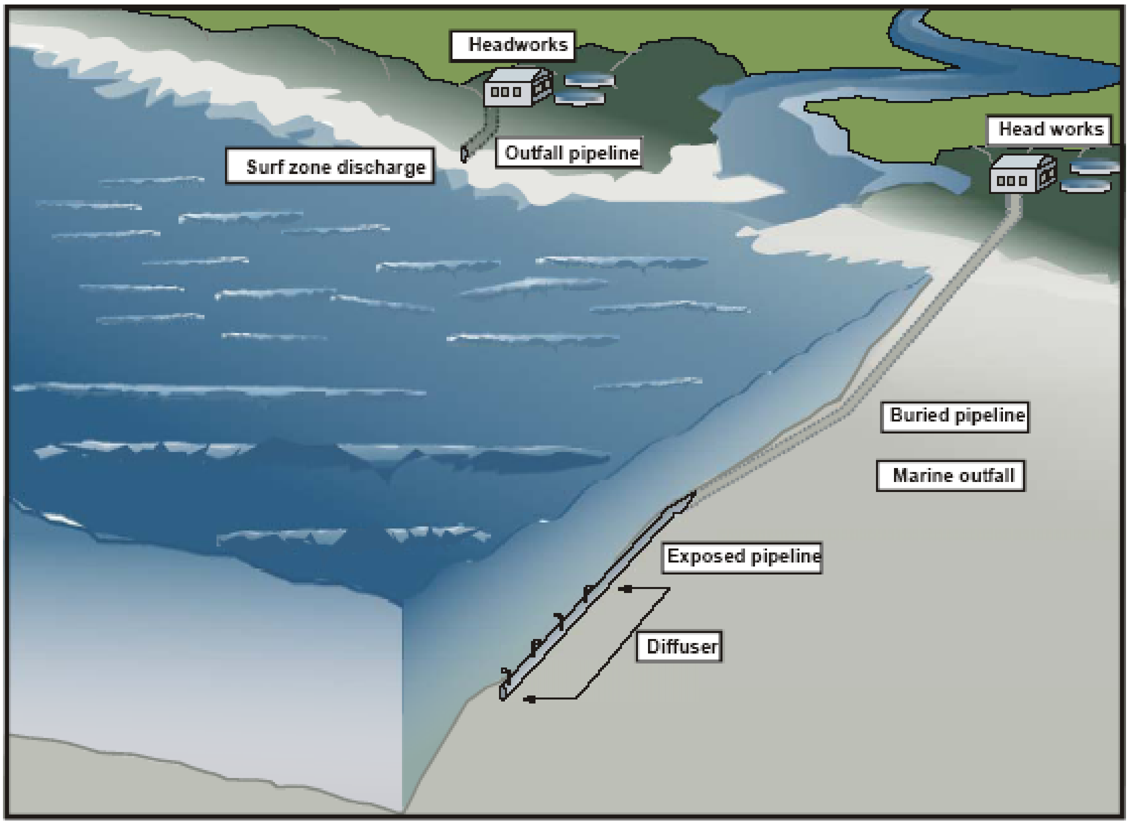


FIGURE 6.30: An illustration of the components of a well-designed wastewater discharge system

The location of the head works is the onshore end of the wastewater discharge system and will control the route of the outfall. Typically, the head works will be on the site where the wastewater is generated (e.g. the WWTW). For a new development, the following aspects have to be taken into account during the selection of the optimum site for the head works:

- The natural drainage of the area
- The existing or future planned reticulation system
- A suitable location for the land-based section of the system with regard to the area available, considering possible future extensions of the treatment processes as well as the existing or future development plans for the area.

In the selection of the discharge/diffuser location, the following needs to be taken into account:

- Delineated beneficial use areas along the coastline
- The bathymetry of the marine environment, keeping in mind the quality of the wastewater and the maximum required initial dilutions
- The coastline configuration and bathymetry, considering the route for the pipeline
- The typical physical processes that can be expected.

Link the onshore end (head works) to the offshore end (diffuser) via the shortest possible route for pipeline (length), considering the following basic requirements and restrictions:

- A shore crossing which will create the minimum interference to the physical characteristics of the coastline, ecology and the existing infrastructure, taking into account the most likely method of construction
- An onshore route (head works to shoreline) with regard to construction impacts on the existing and planned onshore infrastructure
- A gradually sloping seabed without, or with the minimum of, natural or manmade obstacles such as rock outcrops, underwater cables or shipwrecks.

6.5.2 Discharging of wastewater

Wastewater can be discharged using a gravity (potential) head, if available, or by using a pressure head provided by pumps. Where gravity flows are used, these will vary according to the diurnal flow patterns. Where pumps provide the pressure head, wastewater can be discharged intermittently at a specific flow rate from a storage tank.

NOTE:

Energy (potential or gravity, kinetic and pressure) or energy losses (e.g. friction loss) per unit weight is expressed as 'head' (in meters water of specific gravity).

There are a number of factors that need to be taken into account when planning the discharge of wastewater:

- ***Surge effects***. The most common pressure transient (or momentary) effect affecting a pumping system is the switching off of pumps or the uncontrolled loss of the power supply. Operation of valves can also cause large transient effects and, subsequently, pressure surges. Variations in discharge rates normally do not result in significant transient effects. Pressure surge analyses should be conducted for all marine outfalls that use pumps. This is to ensure that no structural damage occurs to any component of the outfall during any flow scenario as a result of possible transient effects that may occur during operations. Gravity surge, related to sudden pressure changes and subsequent rapid flow changes in a marine outfall, should also be carefully examined for both pumped systems and those using gravity flow.

- ***Air entrainment***. Air entrainment may occur during high flows in the drop shaft of an outfall, resulting in flow reduction and an increase in pressure.

- ***Saline intrusion***. Seawater intrusion into outfall diffusers can cause higher pumping heads, reduce the initial dilutions and result in sedimentation (Charlton *et al* 1987). As it is not practical to prevent saline intrusion completely without the use of non-return valves, the hydraulic design must be such that salt water can be purged from the pipeline and diffusers.

6.5.3 Main pipe diameter

The optimisation of the main pipe diameter, a key component in determining the cost and hydraulic performance of a marine outfall, depends on:

- Flow scenarios (present flow as well as the ultimate flow conditions)
- Available or practical head to discharge the wastewater (gravity or pumps)

In the case of small diameter outfall, scouring velocities can be maintained more easily and the capital investment will be lower. However headlosses resulting from friction will require higher pressure/gravity heads and subsequent higher running costs if a gravity head is not available. The design criteria for a first assessment are:

- Maintain a main pipe velocity of greater or equal to 0,7 m/s during low flows to prevent deposition of solids.
- Discharge maximum flows with available gravity head or by cost-effective pumping, taking into account the increase in roughness during the lifetime of the outfall as well as all losses at fittings (entrances, exits, bends, contractions, expansions, valves) in the main pipe and the diffuser.

Headloss (h_f) resulting from friction can be calculated using the Darcy-Weisbach equation (Shand, 1993):

$$h_f = \lambda LV^2/(2gD)$$

Where

λ = friction factor
L = length of the pipe (m)
D = pipe diameter (m)
V = velocity in the main pipe (m/s)

The Colebrook-White formula can be applied to determine the friction coefficient (λ), as it correctly models the laws for smooth and rough pipes as well as for the transition zones (Shand, 1993). The Moody diagram for pipe friction (Shand, 1993) is given in Figure 6.31.

$$\lambda = 0.25[\log_{10}\{k_s/3.7D + 2.51/(R_e\lambda^{1/2})\}]^{-2}$$

Where

k_s = roughness height (mm)
R_e = Reynolds number

Typical roughness heights (i.e. the characteristic size of surface roughness) for pipe materials are (Shand, 1993):

PIPE MATERIAL	***SMOOTH***	***AVERAGE***	***ROUGH***
Plastic (PVC)	*0.015*	*0.03*	*0.06*
Coated steel	*0.03*	*0.06*	*0.15*
Cast iron or cement mortar lined	*0.15*	*0.3*	*0.6*
Spun concrete	*0.3*	*0.6*	*1.5*
Rough concrete or riveted steel	*1.5*	*3*	*6*

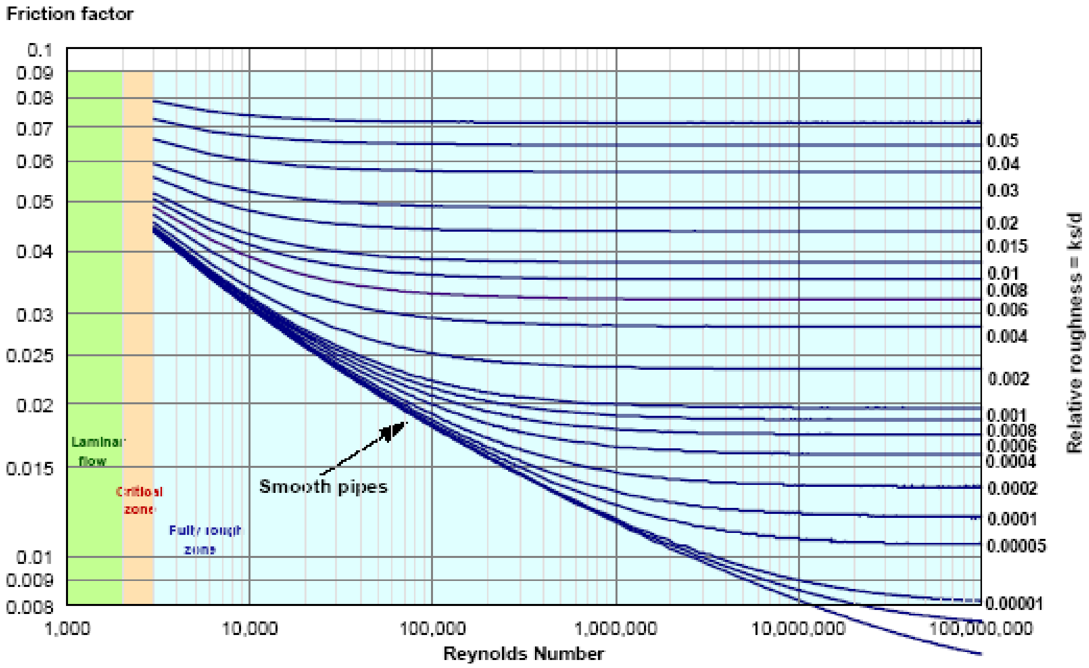


FIGURE 6.31: Moody diagram for pipe friction (Shand, 1993)

It is important to investigate the maximum friction losses that may occur during the lifetime of an outfall. These losses need to be determined for the maximum possible flows and for an expected pipe roughness after 20 to 30 years in operation.

Entrance, exit, bend and contraction losses (h_e) are defined as:

$h_{e,b,c} = K_{e,b,c}V^2/2g$

where
$K_{e,b,c}$ = Loss coefficient for entrance, exit, bend and contraction losses.

Shand (1993) summarised typical fitting loss coefficients as follows:

<table>
<tr><th>PIPE DIMENSION</th><th>TYPE</th><th colspan="2">K_e</th></tr>
<tr><td rowspan="4">Pipe entrance</td><td>Projecting</td><td colspan="2">0.80</td></tr>
<tr><td>Sharp cornered</td><td colspan="2">0.50</td></tr>
<tr><td>Slightly rounded</td><td colspan="2">0.25</td></tr>
<tr><td>Bellmouth</td><td colspan="2">0.05</td></tr>
<tr><td rowspan="4">Pipe exit</td><td>Projecting</td><td colspan="2">1.0</td></tr>
<tr><td>Sharp cornered</td><td colspan="2">1.0</td></tr>
<tr><td>Slightly rounded</td><td colspan="2">0.5</td></tr>
<tr><td>Bellmouth</td><td colspan="2">0.2</td></tr>
<tr><td rowspan="8">Pipe bends</td><td>R_b/D</td><td>K_b for 45°</td><td>K_b for 90°</td></tr>
<tr><td>1</td><td>0.15</td><td>0.20</td></tr>
<tr><td>2</td><td>0.09</td><td>0.13</td></tr>
<tr><td>3</td><td>0.07</td><td>0.10</td></tr>
<tr><td>4</td><td>0.06</td><td>0.08</td></tr>
<tr><td>6</td><td>0.05</td><td>0.07</td></tr>
<tr><td>8</td><td>0.05</td><td>0.07</td></tr>
<tr><td colspan="3">Where R_b = bend radius</td></tr>
<tr><td rowspan="11">Contractions</td><td>D_1/D_2</td><td colspan="2">K_c</td></tr>
<tr><td>1.1</td><td colspan="2">0.05</td></tr>
<tr><td>1.2</td><td colspan="2">0.11</td></tr>
<tr><td>1.4</td><td colspan="2">0.20</td></tr>
<tr><td>1.6</td><td colspan="2">0.26</td></tr>
<tr><td>1.8</td><td colspan="2">0.34</td></tr>
<tr><td>2.0</td><td colspan="2">0.38</td></tr>
<tr><td>2.5</td><td colspan="2">0.42</td></tr>
<tr><td>3.0</td><td colspan="2">0.44</td></tr>
<tr><td>4.0</td><td colspan="2">0.47</td></tr>
<tr><td colspan="3">D_1: Upstream diameter, D_2: downstream diameter</td></tr>
</table>

6.5.4 Diffuser design

For the optimisation of the diffuser, the following criteria must be met:

- Design flows must be discharged satisfactorily through the ports. A rule of thumb for the continuity of flow is that the total cross-sectional areas of the ports should not be less than 0.7 times the cross-sectional area of the main pipe at any point in the diffuser. A port diameter of less than 75 mm is not recommended because it will be more susceptible to blockage (from particulates in the wastewater as well as from outside).

- Maintain sufficient flow in each port to prevent the intrusion of seawater. This flow can be achieved by the gradual increasing of the sizes of the ports towards the end of the pipe. To prevent the intrusion of seawater, the port exit velocities must be such that the densimetric Froude Number for each port is greater than unity (i.e. 1).

  The densimetric Froude Number of the jet at exit is expressed as follows:

$$F_r = v_p/[g.d_p(\Delta\rho/\rho_s)]^{1/2}$$

Where

v_p	=	port velocity (m/s)
$\Delta\rho$	=	$\rho_s - \rho_e$
ρ_s	=	seawater density (kg/m^3)
ρ_e	=	density of wastewater (kg/m^3)
d_p	=	port diameter (m)

- Ensure an even distribution of flows, through all the diffuser ports, because the flow is directly related to the achievable initial dilution, and the worst performing port (highest flow and lowest dilution) will be considered as representative of the performance of the diffuser. Even distribution can be achieved by the gradual increase of the port sizes.

- Maintain scouring flows within the diffuser section: this can be achieved by introducing tapers in the diffuser section together with increasing port sizes towards the seaward end of the diffuser.

- Optimum dilution will be obtained with diffusers discharging horizontally and with alternate ports directed in opposite directions.

- The distance between any two ports must be such that the plumes do not merge during the rise of the buoyant plumes. This can be achieved by ensuring that the distance between any two adjacent ports is greater than one third of the water depth.

EXAMPLE…

As a first assessment, outfall configuration can be obtained as follows:

For a population of 100 000 and an average flow of 250 ℓ/day per person, the total daily flow is:

Q_d = 100 000 x 0.25 m^3/day = 25 Mℓ/day or 25 million ℓ/day

resulting in an average discharge rate of:

Q_{ave} = 25 000/(3600 x 24) m^3/s = 0.289 m^3/s

Referring to Chapter 2 of this Section, this discharge rate will result in a peak diurnal flow of approximately:

Q_{peak} = 0.289 x 2 = 0.578 m^3/s

In order to maintain velocities (V) in the main pipe and to prevent deposition of solids in the main pipeline during average flow conditions, the diameter of the main pipe is:

$V > 0.7$ m/s as $V = Q/A$

$\therefore \quad A = Q/V$ or $\pi D^2/4 = Q/V$

$\therefore \quad D = [4QV/\pi]^{1/2}$

$\therefore \quad D \geq [(4 \times 0.289) / (0.7 \times \pi)]^{1/2} \geq 0.72$ m

where

A = cross-sectional area of the main pipe = $\pi D^2/4$

Therefore, a main pipe diameter of 0,72 m will be required. For the estimation of the number (n) of ports required, apply the rule for continuity of flow:

Σ (port cross-sectional areas) < 0.7 x cross-sectional area of the main pipe (A)

Using a port diameter (d_p) of 100 mm:

$n.[\pi d_p^2/4] < 0.7 \times \pi D^2/4$

$n \times d_p^2 < 0.7 \times D^2$

$n < 0.7 \times 0.72^2/0,1^2$

n (number of ports) < 36

Thus for a water depth of 20 m a main outfall pipe with an inside diameter of 0.72 m and a diffuser with 35 ports with a diameter of 0.1 m, spaced at 7 m intervals, will be a first estimate. The average discharge (q_p) per port (port flow rate) is:

q_p = 289/35 = 8.25 ℓ/s and for a peak diurnal flow rate q_p = 16.5 ℓ/s

The port exit velocity (vp) for average flows is:

$v_p = q_p/a_p = 0.00825/[\pi d_p^2/4] = 1.08$ m/s

Check if the Froude No > 1 for a seawater density (ρ_s) of 1026 kg/m^3 and an effluent density (ρ_e) of 1000 kg/m^3

$F_r = v_p/[g.d_p((\rho_s-\rho_e)/\rho_s)]^{1/2} = 1.08/[9.81x.1((1026-1000)/1026)]^{1/2} = 6.85 > 1$

A detailed hydraulic analysis will have to be conducted to optimise the diffuser in order to maintain the main pipe velocity throughout the diffuser (introduce tapers) and the port diameters will have to be increased to ensure that the discharge is uniform along the diffuser.

6.5.5 Hydraulic analysis

The hydraulic analysis is based on the hydraulic energy balance for the complete system by comparing the specific energy between any two points in the system, taking into account all friction and fitting losses between two adjacent points. This balance ensures continuity of flow.

The flow (discharge) from a single port is given in Figure 6.32 (Rawn *et al*, 1960):

$q = C_D.a(2g.E)^{1/2}$ where $q = v_p.a$

thus

$v_p = C_D(2g.E)^{1/2}$

$E = V^2/2g + P/\rho_e - H.\ \rho_s/\rho_e$

Where

q	=	port discharge (m^3/s)
C_D	=	port discharge coefficient which is a function of the main pipe velocity and the entrance configuration (smooth, rounded edges, elbow-port, etc.). For an elbow port a value of 0.75 can be assumed for a first assessment.
a	=	port cross-sectional area (m^2)
E	=	Total energy head in the outfall line (m)
v_p	=	port velocity (m/s)
ρ_s	=	seawater density (kg/m^3)
ρ_e	=	effluent density (kg/m^3)
V	=	main pipe velocity (m/s)
H	=	water depth (m)
P	=	pressure in the pipe (kg/m^2)

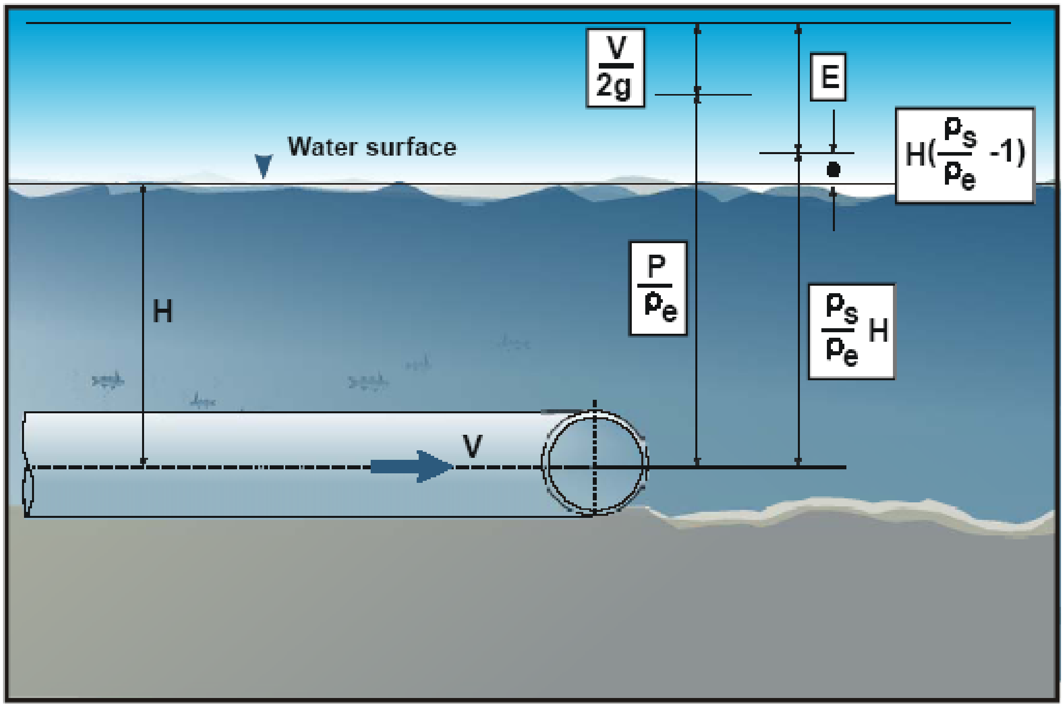


FIGURE 6.32: Energy balance for flow from a single port

As the flow from each port is a function of the total energy head (E), the energy increases from the offshore port inshore. This is a result of the friction loss between adjacent ports and the increase in head resulting from the increase in the slope of the seabed (Refer to the definition sketch for head losses in the main pipe in Figure 6.33 taken from Williams [1985]):

$$E = E_1 + \sum_{j=1 \text{ to } n}[(f.s/2g.D)V_j^2] + \sum_{j=1 \text{ to } n}[\beta(H_1-H_j)]$$

and for continuity of flow at each port

$$Q_j = Q_{j-1} + q_j$$

Where

f	=	friction factor
s	=	distance between ports (m)
V_j	=	Velocity in the diffuser pipe between ports j and (j+1) (m/s)
Q	=	Flow in the diffuser pipe (m^3/s)
q	=	Port flow (m^3/s)
β	=	$\rho_s/\rho_e - 1$

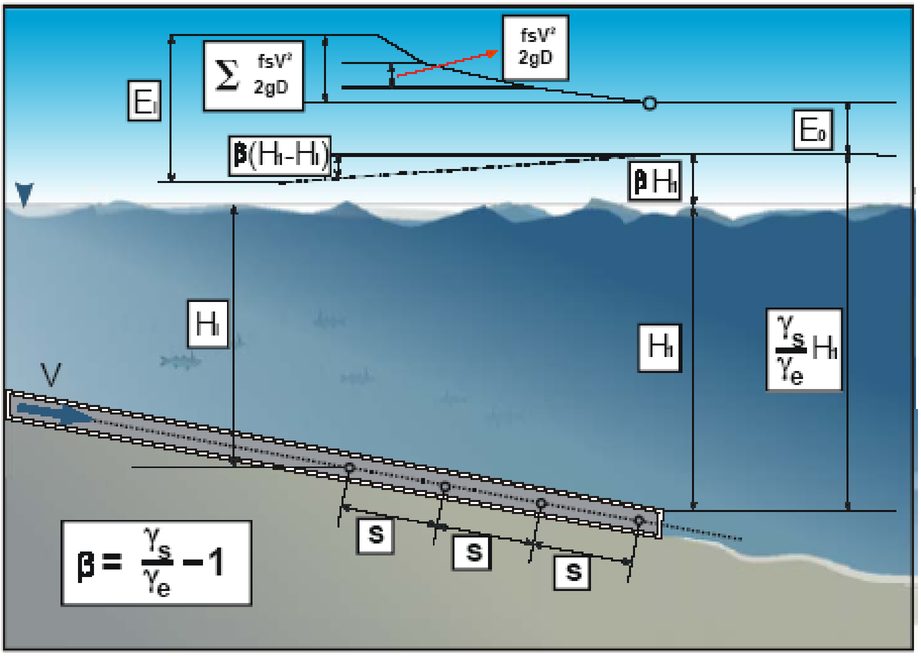


FIGURE 6.33: Head losses in a multi-port diffuser (Williams, 1985)

The equations presented above can be solved manually. However because hydraulic analysis is an iterative procedure, hydraulic engineers should use an existing computer programme, or write their own, to optimise a multi-port diffuser, because numerous runs may be required to comply with the requirements (ensure even port flow distribution along the diffuser, maintain main pipe velocities to prevent deposition, ensure that Froude numbers for all ports are greater than one, achieve the required initial dilutions). Typical outputs required to evaluate the functionality of a diffuser configuration are:

- Total headloss (friction and fitting losses in the main pipe as well as the diffuser)
- Minimum velocity in the main pipe at any point in the diffuser
- Minimum Froude Number.

A typical diffuser layout is shown in Figure 6.34 and the graphical outputs required to evaluate the hydraulic functionality of the outfall system in Figures 6.35a and 6.35b.

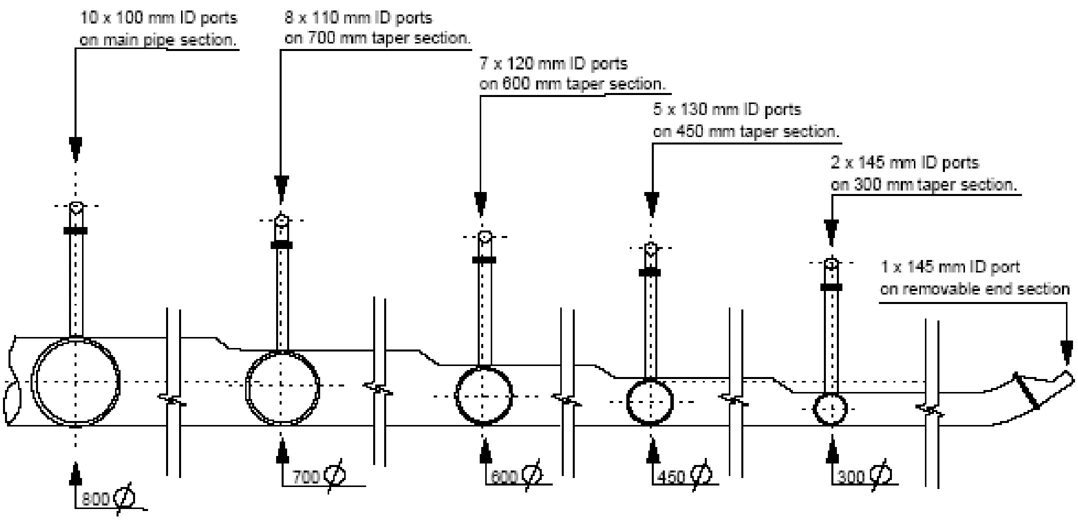


FIGURE 6.34: Typical diffuser layout

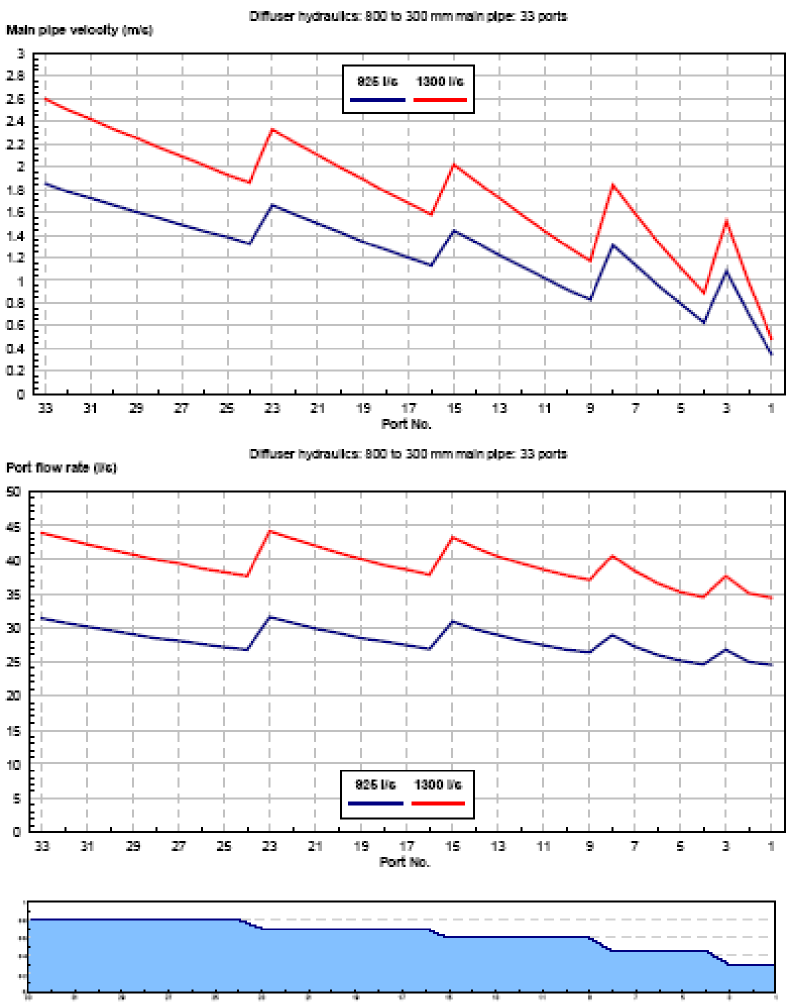


FIGURE 6.35 a: Example of graphical output required to evaluate hydraulic functionality: Main pipe velocities in the diffuser section (top) and port flow rates (bottom)

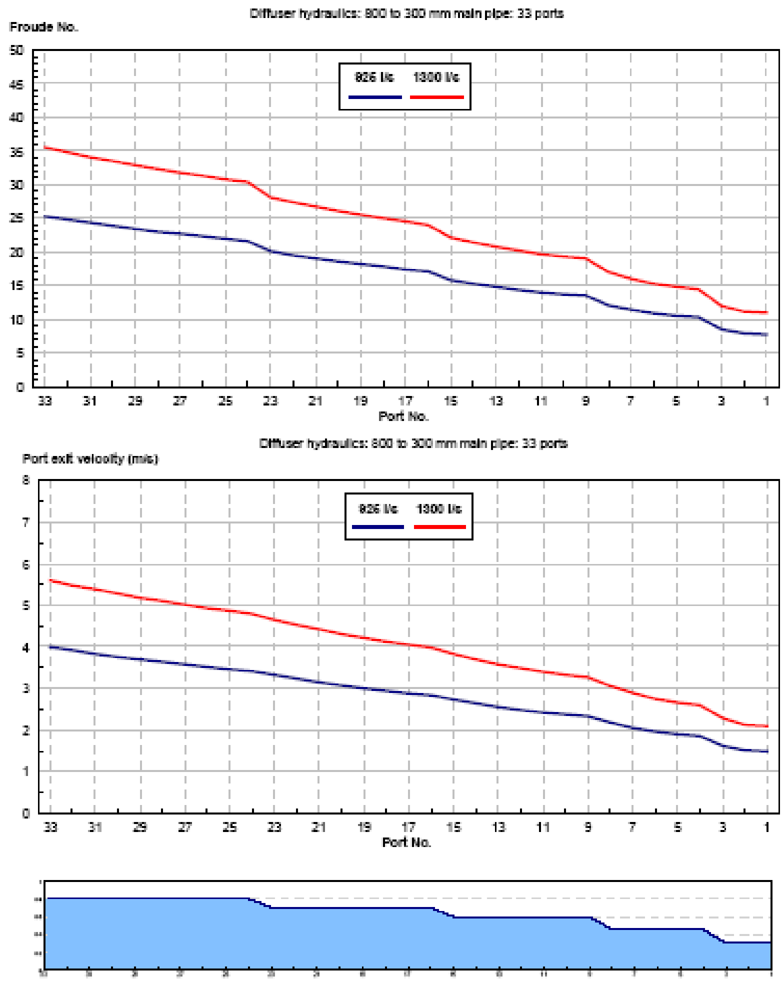


FIGURE 6.35 b: Example of graphical output required to evaluate hydraulic functionality: Port Froude Numbers (top) and port exit velocities (bottom)

6.5.6 Data requirements for pre-assessment and detailed investigation

The procedures described in Section 6.5.1 to 6.5.5 need to followed, in both the pre-assessment and detailed investigation stages, albeit to different levels of detail.

For the pre-assessment, the level of detail that would typically be required includes:

- A range of friction factors (e.g. average to maximum) for possible pipe material types
- Main friction components, e.g. taking into account only the friction in the main pipeline and the diffuser section (excluding detailed components such as bends, contractions and valves)
- Single (rather than detailed dynamic) hydraulic calculations to assess typical discharge patterns for the average to worst case wastewater flow scenarios
- Available geophysical data and information to estimate the pipeline profile and physical conditions at the discharge location.

For a detailed investigation, a much higher confidence is required and typical requirements include:

- Refinement of friction factors according to the manufacturer's specification for the selected pipe material, also taking into account detailed components such as bends, contractions and valves
- Detailed transient pressure calculations of the entire outfall system
- Detailed modelling of dynamic hydraulic processes, taking into account realistic wastewater discharge patterns
- Determining the actual pipeline profile and physical conditions at the discharge location, using detailed geophysical measurements.