UNEP- GEF WIO-LaB Project
Addressing Land Based Activities in the Western Indian Ocean

TOWARDS A PROTOCOL FOR LONG-TERM MONITORING OF MARINE ENVIRONMENTAL QUALITY IN THE WESTERN INDIAN OCEAN

UNEP

GEF

CSIR
our future through science

December 2009

[Type text]

Towards a Protocol for Long-term Monitoring of Marine Environmental Quality in the Western Indian Ocean

CSIR
Natural Resources and the Environment
Coasts and Oceans

KwaZulu-Natal (Durban)
P O Box 17001
4013 Congella
South Africa

Western Cape (Stellenbosch)
P O Box 320
7599 Stellenbosch
South Africa

This report was compiled by:

S.P. Weerts (CSIR, Durban, Email: sweerts@csir.co.za)
S. Taljaard (CSIR, Stellenbosch)
B.K. Newman (CSIR, Durban)

CSIR REPORT No: CSIR/NRE/CO/ER/2009/0139/C

TABLE OF CONTENTS

1. INTRODUCTION 1

2. CONTEXT OF MONITORING WITHIN AN ECOSYSTEM-BASED MANAGEMENT FRAMEWORK 1

3. BASELINE MEASUREMENT PROGRAMMES 7
   3.1 Physical data 8
   3.2 Biogeochemical data 13
   3.3 Biological data 15

4. LONG-TERM MONITORING PROGRAMMES 16
   4.1 Source monitoring 16
   4.2 Environmental monitoring 17

5. PRIORITY CATEGORIES OF PARAMETERS RELEVANT TO THE WEST INDIAN OCEAN REGION 33

6. REFERENCES 39

1. INTRODUCTION

A rapidly increasing coastal population combined with a lack of effective resource management strategies is placing pressure on the marine and coastal environment in countries of the Western Indian Ocean (WIO) region. The African Process, the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) and the World Summit on Sustainable Development all recognise the need to address the issue of land-based sources of pollution.

To this end the United Nations Environmental Programme (UNEP) - Global Environment Facility (GEF) project titled Addressing Land-based Sources of Pollution in the Western Indian Ocean (WIO-LaB) was launched in Madagascar in July 2004. The project represents a partnership among the eight participating countries, Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa, Tanzania and UNEP, GEF and the Norwegian Government. The projects objectives are threefold:

- Improve the knowledge base and establish regional guidelines for the reduction of stress to the marine and coastal ecosystem by improving water and sediment quality
- Strengthen the regional legal basis for preventing land-based sources of pollution
- Develop regional capacity and strengthen institutions for sustainable, less polluting development.

The development and implementation of a water, sediment and biota quality monitoring programme for the WIO region was one of the initiatives undertaken to address these objectives. To this end a pilot monitoring plan for the Western Indian Ocean was proposed, accepted and implemented by participating countries. This gave a regionally comparable first estimate of pollution in perceived hotspots of pollution in the region. One of the required outcomes of WIO-LaB is the establishment of a long-term monitoring programme for marine environmental quality in the region. This document presents a protocol for establishing such a programme.

The document is structured to provide a context for monitoring within a broader, ecosystem-based framework (Section 2). Sections 3 and 4 deal with theoretical aspects of baseline measurement programmes and long-term monitoring programmes respectively. Specific focus is placed on long-term monitoring programmes as the main focus of this work. Section 5 outlines the process by which categories of monitoring parameters relevant to the WIO-LaB were prioritised, and proposes a core set of parameters to be monitored in the different WIO-Lab countries as part of the establishment of a basic level monitoring programme in the WIO region.

2. CONTEXT OF MONITORING WITHIN AN ECOSYSTEM-BASED MANAGEMENT FRAMEWORK

Traditionally, management of natural resources and the environment, including the coastal zone, has been organised around specific uses or sectors, such as fisheries, agriculture, water supply and demand, wastewater treatment and discharge, and housing development, each with their own governing structures (UNEP/GPA 2006a).

NOTE:

Governance concerns the values, policies, laws and institutions by which issues are addressed and it defines the fundamental goals, the institutional processes and the structures that are the basis for planning and decision-making (Olsen and Nickerson 2003, Olsen 2003). *Management,* in contrast, is the process by which human and material resources are harnessed to achieve a known goal within a known institutional structure. Thus, governance sets the stage within which management occurs (UNEP/GPA 2006b).

This sectoral approach has not only resulted in conflict among different uses, but also in ineffective and inappropriate utilisation of valuable, and often limited, human and financial resources. This led to the realisation that natural resources and the environment can be managed much more effectively, if the 'ecosystem' becomes central and management occurs through cooperative governance between different sectors. This is referred to as ecosystem-based management.

In essence, ecosystem-based management recognises that plant, animal and human communities are interdependent and interact with their physical environment to form distinct ecological units called ecosystems (UNEP 2006b). At the largest scale is the Earth ecosystem, and although it is important that governance and management strategies be formulated at this large (international) scale, decentralization to regional, national and local levels is logical since in many instances implementation occurs at the 'distinct ecological unit' (local or regional) level.

The challenge in ecosystem-based management is to ensure sustainable development, which can be defined as: "… *development which fulfils the needs of the present generation without jeopardizing the possibilities of future generations to fulfil their needs*" (WCED 1987).

In this context, the ultimate goal in coastal ecosystem-based management is to ensure that resources are maintained in suitable states for all designated uses, both existing and future (this includes the 'use' of designated areas for biodiversity protection and ecosystem functioning). To achieve this goal it is important to protect the biodiversity and functioning of coastal aquatic ecosystems (i.e. ecology) to support important (beneficial) uses of the marine environment (i.e. social and economic values).

An ecosystem-based management framework for marine water quality has been proposed for the WIO region (Taljaard *et al*. 2006; UNEP/CSIR 2009) with long-term monitoring programmes as a key component (Figure 1).

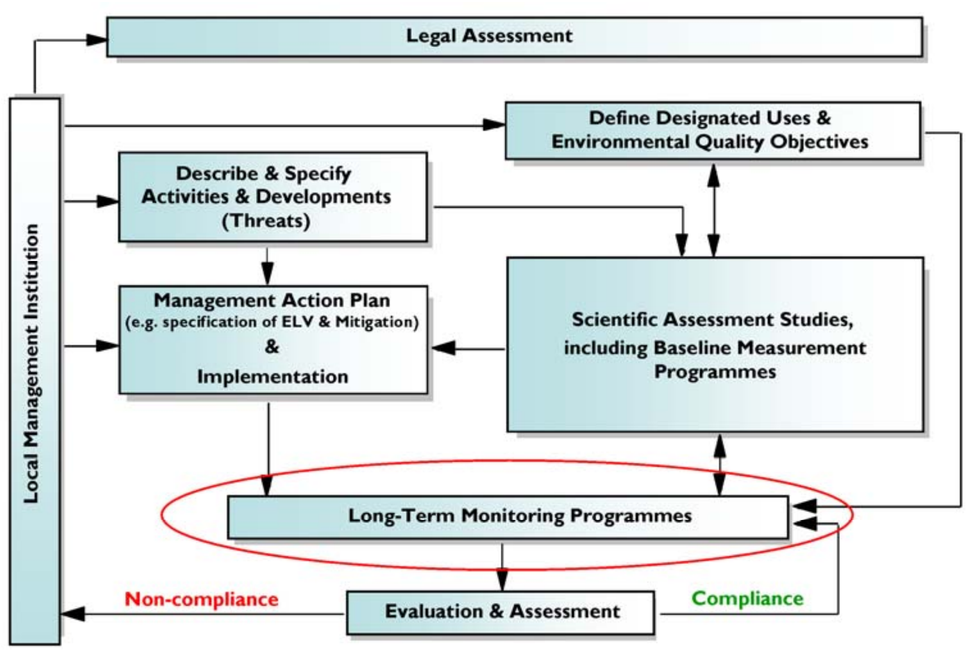


Figure 1: Eco-system-based management framework for marine water quality proposed for the WIO region (after UNEP/CSIR 2009)

Local Management Institution

A key factor in the implementation of an effective coastal management programme is the establishment of appropriate cross-sectoral management institutions and the identification of the roles and responsibilities of the different parties. The responsibility for coastal management in most countries is vested in the state. However, the value of involving other interested and affected parties through stakeholder forums or local management institutions has proved to add significant value to the overall management process (e.g. Taljaard and Monteiro 2002). Not only do these local management institutions provide an ideal platform to consult stakeholders on various issues, such as designated uses and Environmental Quality Objectives for a particular area, but they also fulfil the important role of 'local watchdogs' or 'custodians'. Although such institutions usually do not have executive powers, they can be very successful mechanisms to empower (and pressurise) responsible authorities to execute their legal responsibilities. Local management institutions should include all relevant stakeholders, in order to facilitate a participatory approach to decision-making. The inclusion of responsible local, provincial and national authorities is important, as these are usually the routes through which the institutions gain executive powers. Local management institutions should, therefore, include representatives from:

- National and provincial government departments
- Nature conservation authorities
- Local authorities
- Industries
- Tourism boards and recreation clubs
- Local residents, e.g. through ratepayers' association
- Non-government organizations.

The key to the success of local management institutions is a sound scientific information base, containing explicit scientific assumptions and outcomes, by which authorities, and also local stakeholders, are empowered to partake in the decision- making process. The institutional and societal conditions necessary for an ecosystem-based (coastal) management framework to be successful are (UNEP 2006b):

- Unambiguous goals (objectives) against which to measure the effectiveness of a programme (see Environmental Quality Objectives)
- Active support from a core of well-informed and supportive constituencies composed of stakeholders in both the private sector and government agencies
- Governmental commitment to the policies of a programme and allocation of financial resources required for long-term implementation
- Sufficient initial capacity within the institutions responsible for the programme to implement its policies and plan of action.

A management institution, being actively involved in coastal management at the local level, is also ideally positioned to test the effectiveness and applicability of legislation and policies, which are normally developed at national or regional levels. It is therefore also important that these institutions be utilised by higher tiers of government as a mechanism for improving legislative frameworks related to coastal management, supporting the principle of adaptive management.

Legal assessment

A coastal management programme needs to be designed and implemented within the statutory framework governing coastal related issues in a particular country, taking into account international treaties and obligations. Statutory frameworks are likely to differ from one country to another, and the purpose of this legal assessment is to establish existing policies and management strategies that need to be considered. Often the legal frameworks within countries are still very much sectorally-based and this assessment, therefore, also aims at extracting and consolidating that that which is relevant to the coastal zone.

Environmental Quality Objectives

Environmental Quality Objectives must be set as part of the management framework to provide a basis from which to assess and evaluate management strategies and actions, supporting the Management by Objectives (MBO) approach (Edvardsson 2004, Wibeck *et al*. 2006). This may be achieved through a four-step approach:

- Define the geographical boundaries of the study area
- Define important and sensitive coastal aquatic ecosystems and designated uses within the area
- Define site-specific EQOs for important and sensitive coastal aquatic ecosystems and each of the designated uses
- Determine site-specific environmental quality target values.

NOTE:

The approach for setting Environmental Quality Objectives and target values, as proposed above, is in line with the concept of *ocean zoning*. Ocean zoning is a planning tool that comes straight out of the land use planning methodologies that are used at the municipal, county, state, regional, and national levels. As on land, it allows a strategic allocation of uses based on a determination of an area's suitability for those uses, and reduction of user conflicts by separating incompatible activities. There are generally two components to an ocean zoning plan: 1) a map that depicts the zones and 2) a set of regulations or standards applicable to each type of zone created. More on ocean zoning can be obtained from Agardy (2007).

Definition of the geographical boundary of the management area is an important step. It needs to consider interdependencies between the coastal fauna and flora and human communities, as well as their interaction with the physical coastal environment. Aspects that need to be considered include:

- Anticipated spatial influence of human activities and developments, both in the near- and far-field, including land-derived wastewater discharges
- Proximity of depositional areas where pollutants can accumulate – these can be at distant locations for specific sources, particularly where the source discharges into a very dynamic environment but subsequently is transported to an area of lower turbulence
- Possible synergistic effects in which the negative impacts resulting from a particular activity could be aggravated through another activities or even through interaction with natural processes.

Once the geographical boundaries of the management area have been defined, designated uses for specific areas within this boundary need to be defined. The designated uses should be decided and agreed upon through consultation with local interested and affected parties (or stakeholders). Management goals then need to be defined for each of these uses. Once agreement has been obtained on important aquatic ecosystems and designated uses, their location, as well as the management goals for each particular area, site-specific Environmental Quality Objectives pertaining to sediment and water quality requirements need to be derived. The rationale here is that, although management goals are the real management end-points, the goals will only be achieved if certain sediment and water quality targets are maintained, as the proximal causes in the cause-effect relationship (Ward and Jacoby 1992). Guidelines have been developed for the establishment of Environmental Quality Objectives and Environmental Quality Targets in the coastal zone of the WIO region (UNEP/CSIR 2009), and these can be used as a basis for formulating management goals.

Activities and developments (Threats)

Effective coastal management requires, amongst other things, quantitative data on activities or developments that directly (or indirectly) affect water and sediment quality (e.g. land-derived wastewater discharges). Although human perturbations of coastal water and sediment quality are usually perceived to be the result of land-based sources of pollution, it is important to realise that developments that modify circulation dynamics in the coastal areas, such as port and marina structures, can also modify quality characteristics (e.g. by creating depositional or stagnant areas).

NOTE:

Recognising that many of the challenges posed by intensifying human activity and ecosystem change cannot necessarily be solved by managing river basins (or catchments), coast zones and larger marine ecosystems (LMEs) in isolation (UNEP 2006a), it may be necessary from a practical perspective to limit the size of the 'local management unit'. Coastal waters adjacent to large urban areas or that received runoff from large catchments are usually most impacted by land-based activities. It is therefore considered appropriated to use these 'hotspots' as departure point for defining the geographical boundaries of local coastal ecosystem, insofar as it pertains to management of land-based activities, but still recognising interaction with adjacent environments (e.g. river basins and the LME). In this context, the local coastal management unit can be seen as a sub-section of the larger integrated river basin and/or LME management unit.

Scientific assessment studies

Scientific assessment studies are required to assess whether the coastal system is able to support important ecosystems and designated beneficial uses (as defined in terms of the EQOs) in a sustainable manner, in addition to being subject to modifications associated with human activities and developments in the area. These assessments must take into account complex environmental processes and natural variability. This requires data, information and understanding of physical, biogeochemical and biological characteristics and process scales. Depending on the availability of scientific data and information on the area, scientific assessments may also include baseline field measurement programmes (see Section 3). The level of detail required for scientific assessment studies largely depends on the type of investigation and the purpose for which it is intended.

Numerical (predictive) modelling techniques have proven to be powerful tools in the management of marine water and sediment quality (provided that these are properly calibrated and validated) 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 synthesizing existing understanding of the key processes and, in doing so, provide a means of stimulating stakeholder discussion on their relevance to achieving environmental quality objectives
- Modelling assists in defining the most critical spatial and temporal scales of potential negative impacts on the receiving system
- Model outputs provide quantitative results which can be used, together with field data, to check the quality of assumptions and insights.

Management actions

The outcomes of the scientific assessment studies, amongst others, are typically presented to the responsible management authorities and institutions for final decision making to provide management actions regarding, for example:

- Critical limits for developments and activities (e.g. setting wastewater emission targets)
- Modifications to the structural design of the development where relevant
- Mitigating actions to be implemented during the construction and/or operation of coastal developments and activities.

Based on the outcome of the scientific assessment studies it may be necessary to negotiate 'trade-offs' in terms of recommended environmental quality targets versus allowing activities and developments with large socio-economic benefits to proceed, provided that all reasonable attempts have been taken to mitigate or minimise environmental impacts. In order to facilitate a participatory approach in decision-making, governing authorities need to take decisions on such matters in consultation with local stakeholders, e.g. through local management institutions.

Long-term monitoring

Long-term monitoring programmes (see Section 4) form an integral part of a coastal management programme and are designed to evaluate:

- Effectiveness of management actions in achieving compliance with Environmental Quality Objectives, critical limits (e.g. wastewater emission targets) and the implementation of mitigating actions
- Status and trends in the environment in terms of the health of important ecosystem components and designated beneficial uses in order to respond, where appropriate, in good time to potentially negative impacts, including cumulative effects
- Whether the predicted environmental responses, identified during the scientific assessment process, match the actual responses
- Whether the initial assumptions remain valid, such as, for example, the geographical boundary conditions.

Long-term monitoring programmes should be dynamic, iterative processes and need to be adjusted continuously to incorporate new knowledge, thereby supporting the principle of adaptive management.

NOTE:

It is important to note the differences between *baseline measurement programmes* (usually part of scientific assessment studies) and *monitoring programmes* (implemented as part of long-term monitoring programmes):

- Baseline measurement programmes (or surveys) usually refer to short-term, intensive investigations on a wide range of parameters to obtain a better understanding of ecosystem functioning
- Long-term monitoring programmes refer to ongoing data collection programmes that are preformed (using selected indicators) to evaluate continuously the effectiveness of management strategies and actions designed to maintain a desired environmental state so that responses to potentially negative impacts, including cumulative effects, can be implemented in good time.

Proposed protocols (or guidance) for the design of baseline measurement and long-term monitoring programmes related to the management of marine pollution are provided in Sections 3 and 4 of this report respectively.

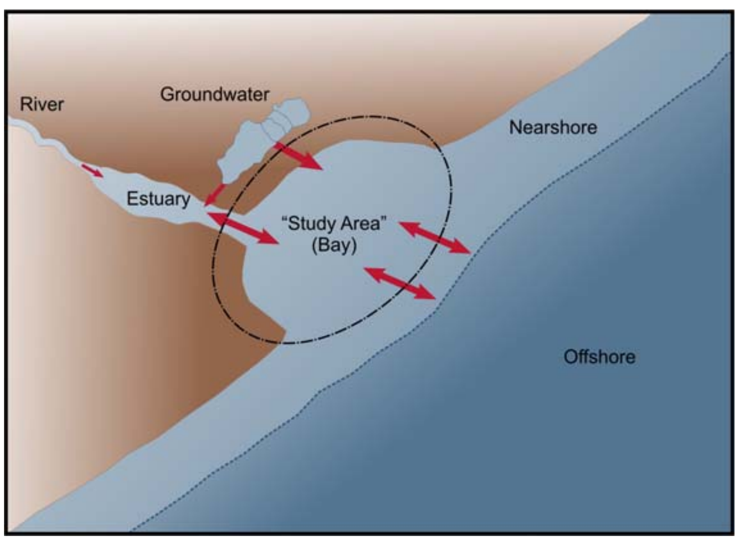
Evaluation and assessment

This component within a coastal management programme provides an explicit mechanism whereby the outcomes of the programme are assessed and evaluated to guide an appropriate management response. Evaluation and assessment can take on different formats and can occur on different time scales, for example:

- Monthly to quarterly meetings of the local management institution to evaluate short-term progress and highlight concerns
- Annual progress reports and public meetings to communicate outcomes of the management programme to the wider community
- Five-yearly State of the Coast Reports using, for example a Driver-Pressure-State-Impact-Response (DPSIR) method.

3. BASELINE MEASUREMENT PROGRAMMES

The main purpose of baseline measurement programmes is to develop an understanding on the physical, biogeochemical and biological processes and the interrelationships between these processes in a particular area, in order to understand ecosystem functioning (Taljaard 2006). It is important to understand and, where applicable, to measure processes in adjacent aquatic domains that influence ecosystem functioning in the study area, as illustrated below.



Together with the data and information on marine pollution sources baseline measurement programmes are crucial for quantitatively assessing or predicting the impact of human activities within a particular study area, and subsequently, for deciding on appropriate management actions that will ensure sustainable utilization of the resource.

3.1 Physical data

Data on physical parameters are required to quantify hydrodynamic (or water circulation) processes and sediment dynamics (i.e. the transport, deposition and re-suspension of sediment particles). This should include data on:

- Bathymetry
- Winds
- Currents
- Tides
- Waves
- Water column stratification
- Geomorphology.

Hydro- and sediment dynamics are key determinants of the transport and fate of pollutants in the marine environment. Information on these processes is also important for engineering studies, e.g. the structural design of offshore marine wastewater disposal schemes.

Bathymetry

The bottom topography or bathymetry of a particular area strongly influences its hydrodynamic and sediment dynamic processes (Figure 2). During a bathymetric survey, depths at a large number of sites are determined using an echo-sounder operated from a survey boat. Integrative survey software packages are available that provide accurate position fixing, capturing of bathymetric data and corrections for tides and swells (RSA DWAF 2004). Bathymetric surveys are usually once-off unless there is evidence that the bathymetry of an area has been markedly modified, e.g. large floods are known to have a major influence on the bathymetry of estuaries.

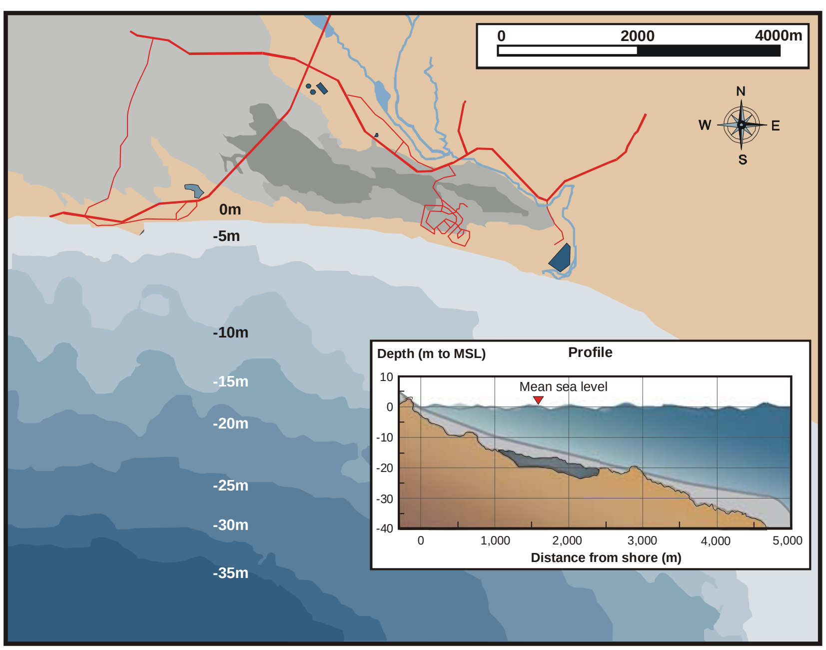


Figure 2: Example of bathymetric contour map and typical profile (taken form RSA DWAF 2004)

Wind

Wind can play an important role in the behaviour of surface currents, and consequently influence the transport and fate of pollutants. In the absence of strong ocean currents, wind-driven currents usually dominate.

To obtain representative wind data, wind recordings are typically collected from a particular study area for a limited period (e.g. one year) using an automatic weather station. The limited data set is then correlated with long-term wind data from a nearby weather station to predict long-term wind patterns for the study area. Wind data records need to reflect natural variability. Usually wind patterns show strong seasonal variability, influenced by remote climatological conditions. However, a local phenomenon can also affect wind patterns. For example, near the coast changes in the temperature differences between land and sea can change the direction of winds, resulting in a strong diurnal signal (Figure 3) (RSA DWAF 2004).

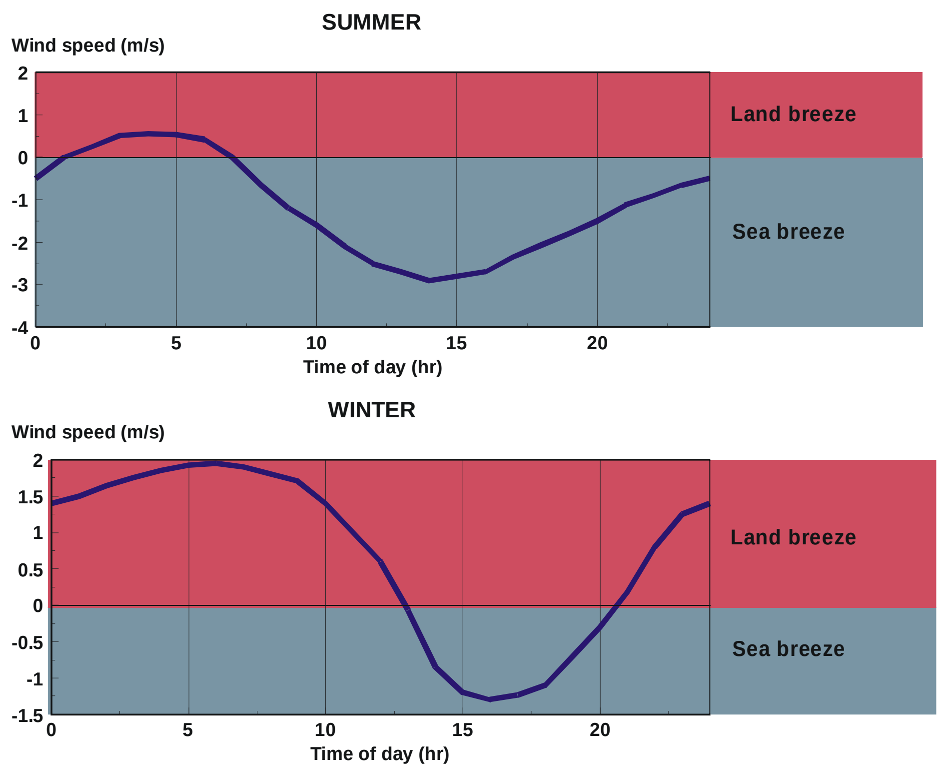


Figure 3: **Typical diurnal land- sea breeze variations (taken from RSA DWAF 2004)**

Waves

Wave data are particularly important for understanding or predicting the deposition and redistribution of sediment or other solid phase particles. Also, waves are an important factor in determining the sediment dynamics in shallower water and in the shoreline geomorphology. In the surf zone, the mixing, transport and dispersion of pollutants in the water column are controlled by the breaking waves and the currents generated by waves approaching the shoreline (RSA DWAF 2004).

To obtain representative wave data, wave recordings are usually collected at a particular study area for a limited period (e.g. one year) using, for example, a wave buoy. The limited data set is then correlated with a nearby long-term wave data recording location to predict long-term wave patterns for the study area. Wave data typically need to include time-series plots of wave height and period, occurrences and exceedances for wave height and period and persistence of calms and storms.

Currents

The speed and direction of currents are the main oceanographic processes that influence the transport and fate of pollutants in the marine environment.

In the offshore zone, the net current is the result of a complex of numerous driving forces: the local wind forcing, ambient continental currents (for example the Augulhas current), surf zone long-shore and rip currents generated by waves, tidal currents and density differences. In the near-shore zone, the circulation is strongly influenced by the seabed topography and the configuration of the coastline. Currents in the surf zone are usually wave-dominated. 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. In open estuaries, currents are primarily influenced by the state of the tide, the size (cross-sectional area) of the estuary mouth and the volume and timing of river inflow (RSA DWAF 2004).

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. Lagrangian measurements include spatial studies with drogues, drifters, or dye, in which the path and velocity of a particle are determined.

Continuous current measurements, preferably taken throughout the water column (i.e. current profiles) are ideally required, using, for example, an Acoustic Doppler Current Profiler. A baseline measurement programme must be arranged to reflect adequately seasonal and other cyclical current trends and should have a typical duration of between 12 and 18 months if previous data are not available (Figure 4). The output of a calibrated numerical model could be used to supplement limited current measurements, i.e. provide more extensive spatial information.

Stratification

In the marine environment, vertical density gradients develop as a result of differences in water temperature and salinities through the water column. Density stratification is a major factor determining whether a buoyant effluent discharge from an ocean outfall remains beneath the surface as a submerged field or continues to rise and become a surface field. Density stratification therefore affects the transport and fate of pollutants in marine waters.

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 these properties. Measurements should be taken on a similar scale as that used for the current measurements. For example, temperature and salinity probes could be attached to current profilers so as to maximise the information obtained from each measured profile. Conductivity-Temperature-Depth (CTD) profilers can also be used for measurements from a survey boat.

Geomorphological data

The purpose of geomorphological measurement programmes is to obtain data on the sediment characteristics of the study area. These data, together with information on the hydrodynamic processes, are used to assess and predict sediment processes (i.e. transport deposition and re-suspension).

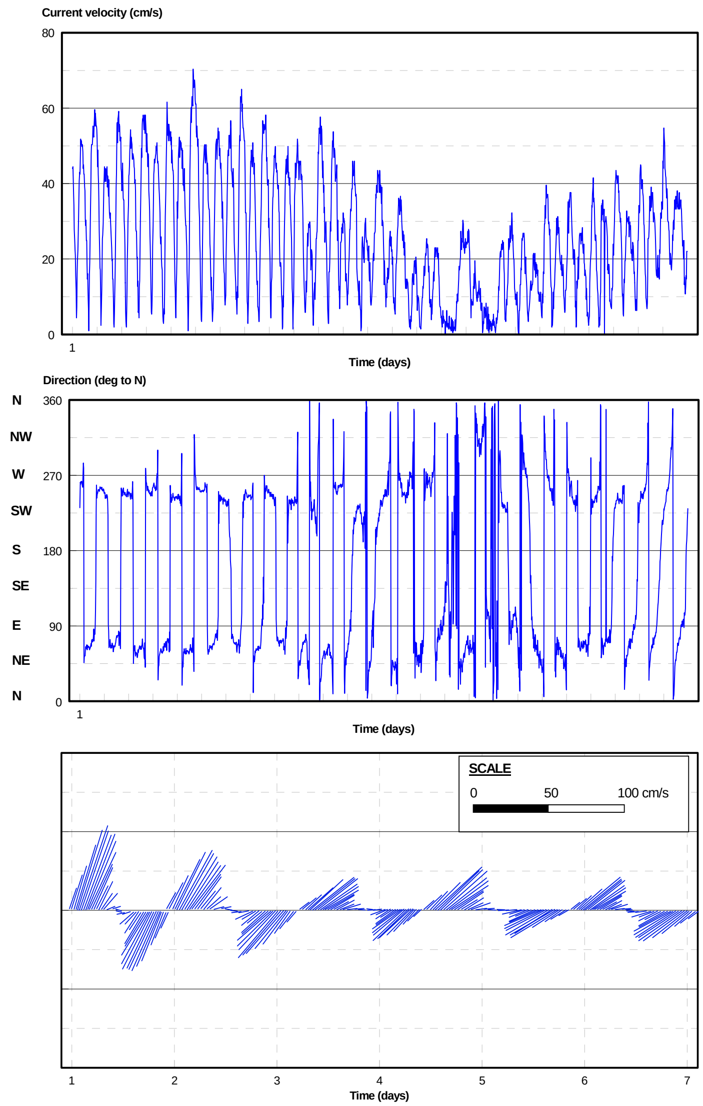


Figure 4: Time series data showing current velocities, directions and vectors (taken from RSA DWAF 2004)

Important aspects that need to be measured as part of geomorphological surveys are particle size distribution and organic content (deposited particles in the marine environment are not only of lithogenous origin but can also be of an organic nature - breakdown of marine fauna and flora or introduced from land sources such as rivers, stormwater and wastewater streams) (Figure 5). Samples can either be collected as grab samples (which essentially provide data on surface sediments) or sediment cores (which provide a 'history' of the geomorphology of the sediments). Traditionally, samples were collected along uniform sampling grids across the study area, but it has been shown that an understanding of the hydrodynamic processes (e.g. using numerical modelling) greatly assists in optimizing these spatial grids (RSA DWAF 2004).

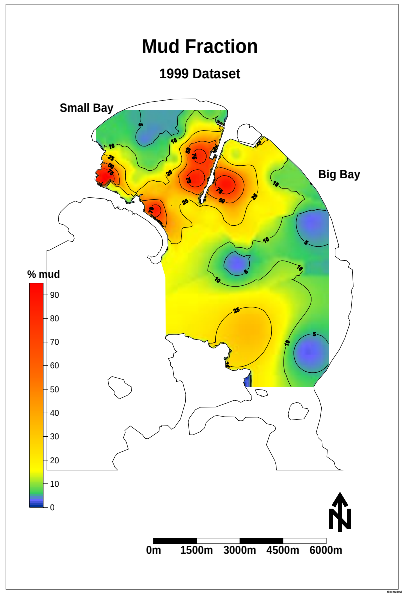


Figure 5: **Example of the spatial plot of the distribution of particle in a coastal area (Monteiro *et al.* 1999)**

In terms of engineering studies the design of structures, such as offshore marine outfalls, usually requires more detailed, site-specific geomorphological studies, including:

- Seismic surveys, which 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 (Figure 6)
- 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).

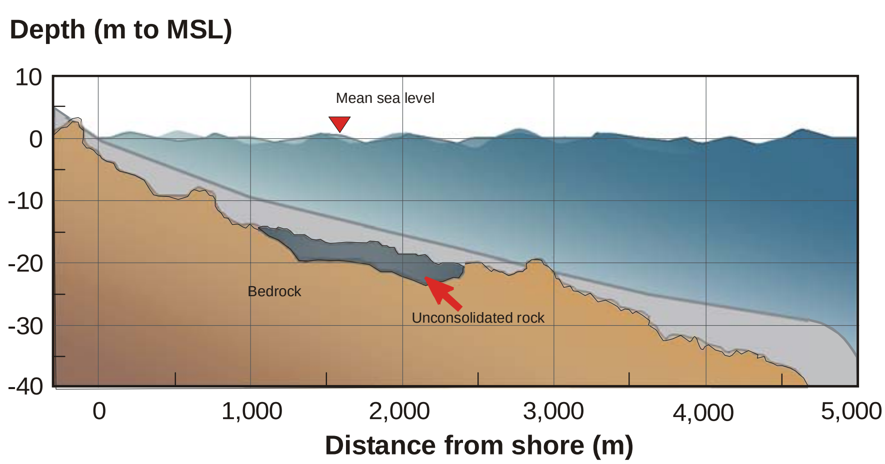


Figure 6: **Sub-bottom profile derived from a seismic trace (taken form RSA DWAF 2004)**

3.2 Biogeochemical data

Biogeochemical characterisation of the marine environment requires data on the spatial and temporal variability of biogeochemical parameters 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 process 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 gaining knowledge on biogeochemical processes in the study area, biogeochemical data are also required for the calibration and validation of numerical modelling platforms (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 for different purposes. For example, numerical model calibration and validation usually require time-series data.

Receiving marine environment

The parameters to be monitored in the receiving environment are site-specific. A key determining factor in the selection of such parameters is the composition of pollution sources as well as the anticipated effects on the biogeochemical characteristics of, and processes in, the receiving environment. Therefore, 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 is essential to the design of biogeochemical measurement programmes.

Biogeochemical parameters (e.g. pH, dissolved oxygen, turbidity, particulate organic carbon and nitrogen, dissolved nutrients, trace metal and organic contaminant concentrations, and microbiological parameters) can be measured in the water column and/or the sediments and their 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 the inter-tidal area is particularly relevant where a wastewater discharge to the surf zone is under investigation.

The 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 on the locations of, for example, depositional areas. 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 to separate anthropogenic impact from natural water quality anomalies. This is illustrated in dissolved oxygen concentrations measured in a coastal area (Figure 7). With an hourly data record (automated) it was possible to show that variability in oxygen concentrations was linked to upwelling, and that the low oxygen concentrations were brought into the system by upwelled waters rather than by any localised anthropogenic effects. Weekly sampling, for example, would have resulted in an apparently random variability of high and low concentrations. This illustrates the importance of characterising natural variability prior to interpreting the impacts of pollutant sources on the biogeochemistry of a receiving water body.

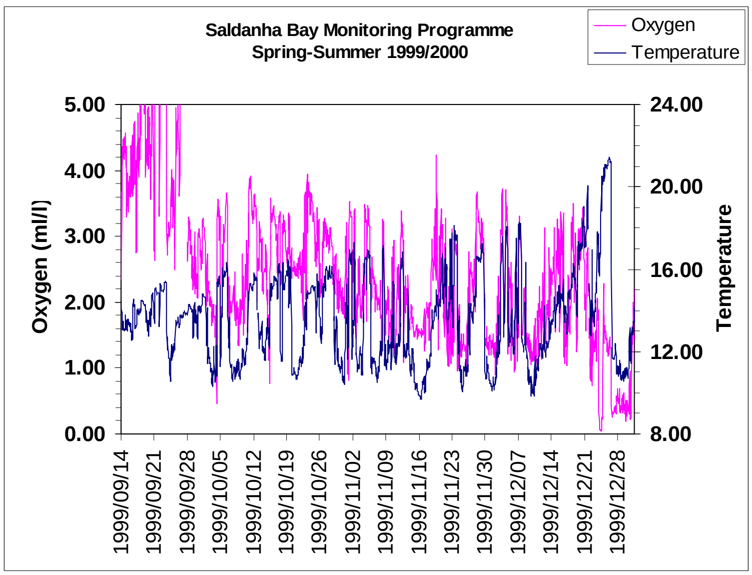


Figure 7: Dissolved oxygen variability (ml/l) in the bottom water layer in a coastal area (from Monteiro 1999)

Behaviour of pollutants

To interpret biogeochemical data, an understanding of the behaviour of contaminants immediately after entering the marine environment is required. A description of the expected interaction of contaminants with biogeochemical processes in the receiving marine environment is therefore important. On entering the marine environment, contaminants can either (WHO 1982):

- Remain in solution (i.e. remain in the 'free' or dissolved phase). Contaminants in 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 those in a wastewater).
- Adsorb onto solid phase particles. On entering the marine environment many contaminants, such as trace metals, poly-aromatic hydrocarbons and pesticides, adsorb onto particulate matter. 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, that are different for each solid phase particle. 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 (Monteiro 1999).
- Precipitate from the water column. A rise in pH and oxygen concentration of water 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 and Morgan 1970; Faust and Aly 1981). 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 that are much higher than those occurring naturally (Solomons and Förstner 1984; WHO 1982).

Another form of transformation is that for certain poly-aromatic hydrocarbons, in particular volatile organics (e.g. benzene, toluene and xylene). On entering marine waters, these compounds do not follow the conventional 'dilution' behaviour. It is thought that these compounds are actually extracted out of the aqueous phase and into the buoyant hydrophobic fraction that results in their concentration in a film at the water's surface (referred to as the surface micro-layer), which subsequently evaporates to the atmosphere, rather than diluting. It is extremely difficult to predict the transport and fate of such volatile compounds in the receiving environment.

3.3 Biological data

To characterise the biology of a particular marine environment requires data on the following:

- 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.

In summary, data required to characterise biological processes 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)
- Data on biological resources that are potentially sensitive to anthropogenic influences (existing or proposed) and information on cause-and-effect relationships.

4. LONG-TERM MONITORING PROGRAMMES

Long-term monitoring programmes refer to ongoing data collection programmes that are usually less intensive than baseline measurement programmes. Long-term monitoring programmes pertinent to the management of marine pollution comprise two main categories, namely:

- Source monitoring, to determine the effectiveness with which facilities, aimed at managing and controlling marine pollution, are operated, as well as to determine the effectiveness of management strategies and actions to meet wastewater emission targets or standards (i.e. the critical limits that were defined for a specific marine pollution source),
- Environmental monitoring, to determine the status and trends in the receiving marine environment, in terms of the health of important ecosystems and designated beneficial uses. Also, to evaluate whether the actual environmental responses match those predicted during the assessment process. This evaluation is necessary in order to respond, where appropriate, in good time to potentially negative impacts, including cumulative effects.

4.1 Source monitoring

Source monitoring programmes are primarily focused on determining whether potential sources of marine pollution are compliant with emission targets (or critical limits). For point source discharges (e.g. municipal wastewater or industrial effluents) the implementation of source monitoring programmes is often a legal requirement, as part of their licence agreements. Parameters to be monitored include:

- Volume of the discharge: *The volume of the discharge at daily, or at least weekly intervals, must be established since this permits determination of the load of wastewater constituents discharged to the receiving water.*
- Physico-chemical composition of the discharge: *The list of physico-chemical parameters monitored depends to some extent on the composition of the wastewater. The physico-chemical parameters that require monitoring are usually stipulated in licenses providing authority for the discharge, but where no license conditions are set then water and sediment quality guidelines can be used as a basis for identifying parameters that should be monitored.*

Municipal wastewater discharges that are comprised predominantly of domestic sewage have a characteristic physico-chemical composition. Important constituents that need to be monitored in domestic sewage discharges to the marine environment include:

- Biochemical oxygen demand/Chemical oxygen demand
- Total suspended solids
- Particulate organic carbon and nitrogen
- Inorganic nitrogen and phosphate
- Microbiological indicators.

In the case of industrial wastewater discharges, or where industrial wastewater discharges enter a municipal wastewater treatment works, the constituents included in the monitoring programme will depend on the constituents present in the wastewater and their potential to impact negatively on the receiving marine environment and its designated beneficial uses.

Systems performance monitoring (also a form of source monitoring) refers to performance monitoring of effluent disposal schemes (e.g. offshore marine outfalls). However, similar monitoring programmes can also be designed for other facilities aimed at preventing marine pollution, such as artificial wetlands constructed to improve the quality of urban stormwater runoff, or for monitoring the effectiveness of certain agricultural practices so as to the prevent contamination of river runoff.

In the case of effluent disposal schemes, system performance monitoring programmes typically include:

- Regular physical inspections of the system to identify malfunctioning or system failures
- Hydraulic performance (e.g. offshore marine outfalls) inspections, which should be conducted at any stage during the lifetime of the outfall when physical changes or alterations which may have an effect on the hydraulic characteristics are introduced, or when there is a substantial change to the wastewater quantity or composition.

4.2 Environmental monitoring

Long-term environmental monitoring programmes involve data collection over an extended period. These programmes are usually designed to evaluate environmental status and trends. This information can be used to identify emerging problems or problem areas, providing the opportunity to respond in good time to potentially adverse impacts (including cumulative effects). Environmental monitoring typically occurs at two levels, namely:

- Strategic monitoring: conducted at a strategic (national or regional) level to establish long-term natural (and possibly large-scale anthropogenically-induced) variability and trends in the marine environment
- Compliance monitoring: more site-specific and primarily aimed at establishing whether operations and activities within a particular coastal area (coastal management unit) complies with pre-determined environmental quality objectives and targets for the receiving marine environment and its uses.

Design of long-term environmental monitoring programmes

Environmental monitoring programmes should be dynamic, iterative processes that can be adjusted continuously to incorporate new knowledge, thereby supporting the principle of adaptive management. They comprise a number of key elements (ANZECC 2000b; USEPA 2003). At the broadest level there are three phases in the life cycle of a monitoring programme; an objective setting phase, a design phase and an implementation phase (Figure 8). Steps within these phases are:

- Define monitoring programme objectives
- Review available data and literature
- Develop conceptual model
- Identify measurement parameters (indicators) and sampling media
- Define sampling design
- Implement monitoring programme
- Reporting and communication.

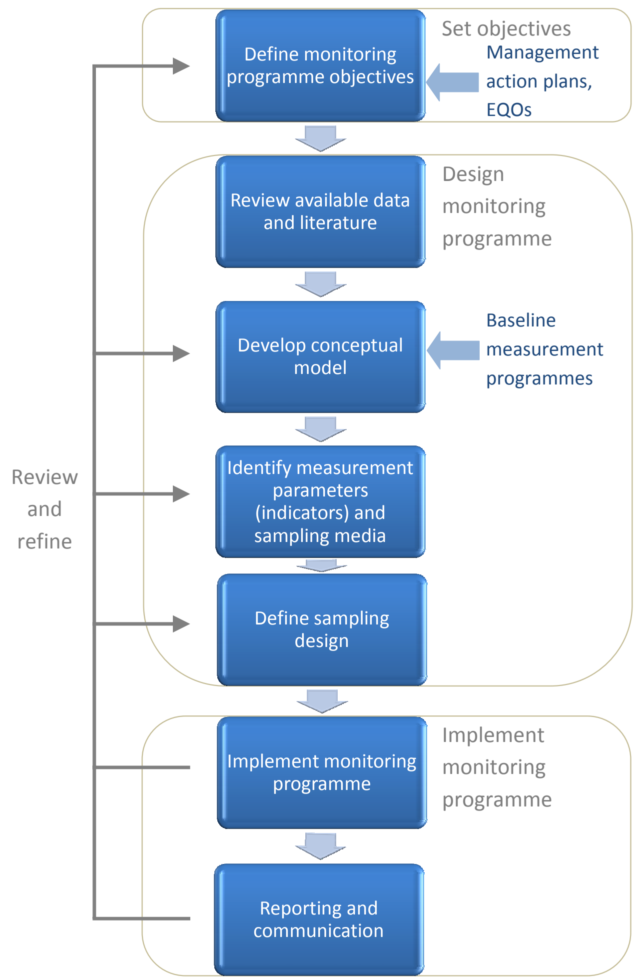


Figure 8: Key components of a long-term monitoring programme

Elements characteristic of monitoring programmes are expanded upon below to provide guidance in the design of long-term monitoring programmes in the WIO region. The discussion is by no means exhaustive and the reader is referred to additional reading for further details.

General issues for consideration

Prior to discussing specific steps in the design of monitoring programmes it is necessary to describe some general considerations:

- Document the monitoring programme design: *All aspects pertinent to the design of a monitoring programme should be comprehensively documented. This process will ensure that the design team directs attention to all of the components required for successful implementation and completion of the programme. The documentation also provides stakeholders an opportunity to understand the rationale for the monitoring programme design and provides a record for other scientists to return to in future.*
- Continuously interact with stakeholders: *The design team should continuously interact with stakeholders at all stages of the monitoring programme design process. Stakeholders may include local management institutions, the*

commissioning organisation, regulatory authorities, industry, non-governmental organisations and the general public. The value of this interaction is that it provides continual assurance that the monitoring programme design is aligned with the needs and concerns of the stakeholders, and provides continuous affirmation for the design team that the programme design is acceptable. Given the opportunity, scientists may design a monitoring programme that is strongly aligned with their research expertise and interests. This should be avoided, by continually ensuring that the monitoring programme is aligned with the needs and concerns of the stakeholders. Stakeholders and end-users should either collaborate on or provide input to the monitoring programme design.

- Budget considerations: *Environmental monitoring can be expensive, especially for programmes that cover large spatial and temporal scales. There are very few occasions when the budget is tailored to fit a water quality monitoring programme. Rather, water quality monitoring programmes are usually tailored to fit budgets. If at all possible, the budget should be identified upfront, to limit the wastage of resources designing a monitoring programme of a scope that is unlikely to be funded. If the allocated budget is insufficient to meet the programme objectives definitively, then either the objective has to be revised and simplified or additional funds sourced. Reducing the scope of a monitoring programme to suit a budget necessitates an assessment of whether the statistical validity of the programme can be maintained with the reduced budget. This input will provide clarity on where the reduced monitoring effort should best be concentrated (hence defining the allocation of funds).*
- Identify a programme design team: *A range of skills and competencies are required to successfully develop and implement a water quality monitoring programme. It is necessary from the outset to identify a monitoring programme design team. The design team will usually comprise a programme manager and a group of scientists with experience and expertise in the various fields of the programme that need to be addressed (as are identifiable at this early stage). The core skills and competencies required for designing most water quality monitoring programmes are statistical, chemical and biological. Of these, perhaps the most important team member is the statistician. While most environmental scientists have a basic grounding in statistical principles, most do not have a sufficiently strong grounding for the design of statistically defensible programmes. Involving a statistician in the design process from the outset can avoid numerous problems.*

Define monitoring objectives

A key objective of long-term monitoring programmes is to evaluate the effectiveness of management strategies and actions designed to maintain a desired environmental state. It is, therefore, critical that long-term monitoring programmes consider the outcomes of other components within the Management Framework (Figure 1), in particular Environmental Quality Objectives and Management Action Plans. Without taking these aspects into consideration the danger exists that a long-term monitoring programme will become monitoring-for-the-sake-of-monitoring, rather than fulfilling the crucial role of informing and subsequently providing a means of adapting and improving management programmes. Well defined objectives are needed to determine what data must be gathered and what it will be used for. They are thus the focal point for consideration in all subsequent components of the monitoring programme design process. It is important that the monitoring objectives are explicitly and concisely defined, since well defined objectives make it possible to design a focused and cost-effective monitoring programme. The objectives can be translated into testable hypotheses. Testable hypotheses are in fact especially useful since they guide the development of statistical strategies for determining sample locations and times as well as the selection of statistical tests that will be used to analyze the resulting data. Should monitoring objectives not be adequately understood and defined, monitoring programmes developed and implemented risk being unable to address the intended objectives, with a resultant waste of resources and the irretrievable loss of opportunity to collect data.

Usually, monitoring objectives are distilled from the Environmental Quality Objectives, which, in turn, are based on site-specific management goals for the protection of marine ecosystems and designated uses in a particular area. In many instances these objectives will have been derived using national (or regional) water and sediment quality guidelines.

To assist the definition of monitoring programme objectives, the following questions might be addressed (Bartram and Balance 1996):

- Why is monitoring going to be performed? Is it for basic information, planning and policy information, management and operational information, regulation and compliance, resource assessment, or other purposes?
- What information is required on water quality for various uses? Which variables should be measured, at what frequency and in response to which natural or man-made events?
- What is practical in terms of the human and financial resources available for monitoring?
- Who is responsible for the different elements of monitoring?
- Who is going to use the monitoring data and what are they intending to do with the information? Will it support management decisions, ensure compliance with standards, identify priorities for action, provide early warning of future problems or detect gaps in current knowledge?

In recent years a *results-based approach* to monitoring has been increasingly applied throughout the world instead of only applying the more traditional *implementation-based approach* adopted by many governments. A major difference between these two approaches is that the objectives of the *implementation approach* largely focuses on outputs (e.g. were the environmental quality objectives/targets met?), while the objectives in the *results-based approach* also include outcomes (e.g. how did the achievement of these targets improve social or economic well-being?) (Kusek and Risk 2004).

Review available data and literature

The next phase in the design process is to collect and review available information and data that relates to the issue at hand and to the study area. Depending on the issue at hand, this step could entail a comprehensive literature review of international understanding or a review of relevant monitoring information collected either for the area of concern or for other locations. Important reasons for collecting information relating to the study area are to:

- Permit a general description of the area
- Identify various issues of concern, including sources of water quality impairment if appropriate
- Identify whether data generated through other monitoring programmes provides insight on assumptions that may have been made in the design process or which will feed into the conceptual model (see below)
- Provide direction on the type of scientific assessments that might be necessary
- Avoid the duplication of effort by repeating monitoring that may have been performed previously.

A review of comparable monitoring programmes performed in other locations provides an opportunity to identify issues that the design team might not have considered, or to identify limitations in these studies that should be avoided during the design of a monitoring programme.

Develop a conceptual model

The next phase of the design process is to develop a conceptual model of the ecosystem and situation at hand. (In some situations it may be necessary to develop the conceptual model before defining the objectives, since the objectives will be identified based on the conceptual model.) A conceptual model describes key relationships between natural processes (including natural stressors), human activities (including anthropogenic stressors), and plants and animals that utilise habitats within an aquatic ecosystem (i.e. human and ecological receptors; MacDonald *et al*. 2009). Conceptual models typically take the form of flow diagrams (usually of the box and arrow type) and accompanying narratives. However, a conceptual model can also be presented on a map, or even a table.

Conceptual models are important because the learning that accompanies the design, construction, and revision of the models contributes to the design team's understanding of the ecosystems dynamics and appreciation of the diversity of information that is needed to identify an appropriate suite of ecosystem indicators. Conceptual models thus assist in providing focus. Well designed conceptual models (USEPA 1998):

- Articulate important processes and variables,
- Identify key linkages between drivers, stressors and responses
- Facilitate the selection and justification of monitoring variables
- Facilitate the evaluation of data from the monitoring programme
- Clearly communicate dynamic processes to technical and non-technical audiences.

In the context of water quality monitoring programmes, conceptual models usually describe relationships between contaminant sources, transport and fate processes, and exposure pathways for ecological and human receptors. The steps involved in developing a conceptual model include (USEPA 1998):

- Refinement of the list of stressors
- Evaluation of the potential effects of each stressor on human health and the environment
- Identification of contaminant transport and fate processes, ecosystems potentially at risk, and complete exposure pathways
- Development of conceptual model diagrams
- Selection of assessment endpoints.

Important processes that may need to be incorporated into conceptual model for coastal pollution monitoring are broadly classified as hydrodynamic, physical, chemical and biological, and include (Bartram and Balance 1996):

- Transport, flow, turbulence, flushing, mixing and stratification
- Precipitation, evaporation, wet and dry deposition
- Contaminant transport, sedimentation, burial, resuspension and diffusion
- Contaminant transformation, degradation, adsorption, desorption, precipitation, dissolution
- Sulphate reduction, methanogenesis, organic diagenesis
- Bioturbation, bioirrigation
- Organism growth, primary productivity, grazing, succession
- Nutrient recycling, loss, transformation, recycling, ammonification, nitrification, denitrification.

From the above it is clear why the review of site specific data and the literature review are important, as the information generated through this step of the design process will feed into the conceptual model. The underlying aim is to develop a good understanding of key processes. Results from specific assessment studies and baseline measurement programmes (see Section 3) could be critical for the development of suitably accurate conceptual model. In the context of pollution monitoring programmes, it is important that the design team have a strong understanding of the behaviour, fate, and possible ecotoxicologial effects of potential pollutants. Although a suite of contaminants may be introduced into a receiving water body through effluent discharge, their behaviour and ecological effects in the environment may be very different. Some of the contaminants might, for example, remain predominantly in solution while others may adsorb onto suspended matter and in this manner be scavenged from the water column to bottom sediment. A failure to understand these different behaviours might result in the design team focussing on the wrong medium (i.e. water rather than sediment, or vice versa) (see Section 3). As a further example, many contaminants do not bioaccumulate. There is little reason, therefore, to focus on those contaminants that do not bioaccumulate during fish and shellfish contaminant burden studies since these will not reveal trends of significance. The conceptual model, by illustrating and documenting linkages and fates, helps focus attention on these types of issues and ensures that they are considered in subsequent steps of the design process.

SUGGESTED READING:

Guidance for developing conceptual models can be found in:

- USEPA (1998). *Guidelines for ecological risk assessment.* http://cfpub.epa.gov/ncea/CFM/recordisplay.cfm?deid=12460
- USEPA (2000) Stressor Identification Guidance. http://www.epa.gov/waterscience/biocriteria/stressors/stressorid.pdf
- Henderson JE and O'Neil LJ (2004) Conceptual models to support environmental planning and operations. http://el.erdc.usace.army.mil/elpubs/pdf/smart04-9.pdf
- University of Maryland Center for Environmental Studies, Integration and Application Network. http://ian.umces.edu/

Identify measurement parameters (indicators) and sampling media

The selection of parameters to be measured is based on the objectives of the monitoring programme and local site considerations. Measurement parameters have to be able to quantify whether defined monitoring objectives are being met. Key determining factors in the selection of monitoring parameters are:

- Characteristics of marine pollution sources
- Anticipated impacts on water and sediment quality, and subsequently on the health of aquatic ecosystems and other beneficial uses
- Collection, measurement and analysis costs involved
- The range of natural variability for the indicator since this will influence its ability to detect change. (Very often, however, this natural variability will be unknown until the monitoring programme has generated data.)

The following criteria can be used to guide identification of an indicator's suitability (ANZECC 2000b):

- Relevance: *Does the measurement parameter reflect directly on the issue of concern?*
- Validity: *Does the measurement parameter respond to changes in the environment and have some explanatory power?*
- Diagnostic value: *The measurement parameter must be able to detect changes and trends in conditions for the specified period. Can the amount of change be assessed quantitatively or qualitatively? Do changes in the variable explain measured changes in the environment?*
- Responsiveness: *Does the measurement parameter detect changes early enough to permit a management response, and will it reflect changes due to the manipulation by management?*
- Reliability: *The measurement parameter should be measurable in a reliable, reproducible and cost-effective way. Can the variable be measured reliably, repeatedly and consistently?*
- Appropriateness: *Is the measurement parameter appropriate for the time and spatial scales that need to be resolved? Is the variable appropriate given the time frame or scope of the study?*

Three media can be used for aquatic monitoring, namely water, sediment and living organisms. The quality of water and sediment is estimated through physical, chemical and microbiological analyses. Biological quality can be determined through specific ecological surveys (e.g. benthic invertebrate community surveys), toxicity tests, histological and enzymatic studies, and the chemical analysis of body tissues. Depending on the objectives of the monitoring programme any one or combination of the media can be used.

A major consideration in the choice of media is the environmental time spans that they reflect (Chapman 1996). The water column is typically a highly variable environment, due to factors such as turbulence, tidal action, and often strong diurnal differences. The analysis of a water sample thus provides only a snapshot of conditions at the time of sampling, or at most about an hour prior to sampling. For this reason the collection of numerous samples is usually required to characterise adequately conditions in the water column. This has obvious cost implications. It is, therefore, usually more appropriate (and cost effective) to focus on those environmental components that tend to integrate impacts or change over time, such as sediments and organisms. Sediment integrates environmental conditions for at least several weeks, but it can take months or even a year to observe changes in the quality of deposited sediments. Thus, fewer samples are required to characterise the quality of sediment compared to the water column.

An increasingly widely used method of providing a long-term integration of environmental conditions, particularly the presence of contaminants, and for assessing the potential health risks posed to human consumers is the chemical analysis of biological tissue. Filter feeding bivalves (such as mussels and oysters) are internationally recognised as suitable indicators for bioccumulation studies in the marine environment (Cantillo 1998). The basis for biomonitoring with bivalves is their ability to bioaccumulate contaminants to a degree that is proportional to the contaminants bioavailability. There are several additional reasons why bivalves are beneficial for evaluating water quality status and trends. Bivalves bioaccumulate contaminants in their tissues to far higher concentrations than those present in the water column. This makes detection and measurement easier. Since most bivalves are sessile they provide a temporally integrated indicator of site specific water quality, and when collected from a wide area and at defined intervals can also be used to assess spatially and temporally explicit water quality status and trends. It is important to note that bivalves (and other organisms) only bioaccumulate contaminants that are in a bioavailable form. As a last benefit for monitoring contaminant burdens in bivalve tissue, many bivalves are consumed by humans (and indeed other organisms) and thus provide a measure of potential health and ecological implications associated with consumption. Analysis of the tissue of higher order taxa (especially fish and mammals) allows time scales of years to be considered. (Caution needs to be exercised in taking age, development stage and/or size class into account when using biological tissues analysis in pollution assessment.)

The representative time span of other types of biological methods is often unclear to non-biologists, although it is implied by their principal suitability for indicating changes over long time periods. Species diversity, relative abundance, and community structure and composition of the biological communities in a study area can be monitored. Since it is expensive to perform detailed biological monitoring programmes that measure entire biotic communities, indicator species are often identified as proxies for evaluating ecosystem health. In studies throughout the world, macroinvertebrate communities have been used successfully for assessing ecosystem health (ANZECC 2000b). Meiofauna distribution patterns, in conjunction with related biogeochemical parameters, have also been used successfully in this regard (e.g. in intertidal areas along sandy beaches (Skibbe 1991; Skibbe 1992)). Macrophytes have also been used as long-term indicators of ecosystem health in estuaries (CSIR 2003). Fish have also been successfully used (ANZECC 2000b), particularly in areas that support resident populations, such as estuaries, shoals, reefs and settlements on moored substrates. Biotic indices based on biological communities usually integrate conditions over the time required for the organisms' life cycles or development. This can range from a few weeks to several months (meiofuana, macroinvertebrates), years (fish, macrophytes), and to decades and longer (coral reefs).

Where the boundaries of the study area include areas that support biotic species of economic importance (e.g. the prawn populations on the Thukela banks off the KwaZulu-Natal coast, South Africa), the distribution and abundance of these species are also effective monitoring parameters as part of ongoing long-term monitoring programmes. It is, however, important that scientifically sound reasons are provided for the selection of specific biotic indicator species in a particular study area.

In some cases the choice of indicator, or need for real time data, dictates the choice of sampling media. Sampling of the water column is essential in the case of monitoring of microbiological indicators (e.g. Enterococci or *E. coli*) at recreational or marine aquaculture areas. Management of such areas requires near real time data to ensure that potential risks to human health are mitigated timeously. As a result, data need to be collected at weekly or two-weekly intervals (and even daily during high usage periods, such as vacations).

Other pragmatic considerations play a role in deciding which medium should be the focus of attention. For example, concentrations of most contaminants in the water column are far lower compared to concentrations in sediment. The higher contaminant concentrations in sediment makes detection and measurement in the laboratory far easier compared to the analysis of water samples. This, together with the variability in concentrations mentioned above, is the reason why the measurement of some contaminants (e.g. organic contaminants) in water is not commonly included in monitoring programmes. Other important considerations include whether the expertise and facilities to measure a parameter are available and logistical challenges in transferring samples from the field to the laboratory within specified holding times and conditions for analysis. Although samples of most media can be preserved in the field and frozen in the laboratory until analysis, the analysis of many water column parameters must proceed within relatively short timeframes after sample collection (e.g. a few hours for bacteria).

Because of the limitations and advantages that each medium poses in the development a holistic understanding of environmental quality, some monitoring programmes focus on two or more of the media and use a weight-of-evidence approach to reach conclusions on environmental impacts or quality (e.g. Chapman *et al*. 2002). These are so-called comprehensive monitoring programmes. This approach requires a significantly higher investment of resources compared to focussing on a single medium. In many cases, therefore, monitoring programmes are developed along a tiered framework. In this framework, different tiers (or assessment levels) are identified, each tier usually leading to an increased understanding of the issue at hand. For example, in a sediment quality monitoring programme the first tier may focus only on the measurement of contaminant concentrations in sediment, the second tier on sediment toxicity testing, and the third tier on analysis of benthic invertebrate community composition and structure. The logic behind this framework is that it is pointless to proceed to the next tier if the results obtained from the first tier do not point to a significant problem. However, if it is demonstrated through the monitoring that contaminant concentrations in the sediment are high and there is thus a high probability for adverse biological effects, then the next tier can be invoked to confirm this and so on.

SUGGESTED READING:

Guidance on the utility of indicators for water quality monitoring can be found in:

- Scheltinga DM, Counihan R, Moss A, Cox M and Bennett J (2004) Users' guide for Estuarine, Coastal and Marine indicators for regional NRM monitoring. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management.
  http://nlwra.gov.au/files/products/national-land-and-water-resources-audit/pn21280/pn21280.pdf
- USEPA. Estuarine and coastal marine waters: Bioassessment and biocriteria technical guidance.
  http://www.epa.gov/ost/biocriteria/States/estuaries/estuaries.pdf.
- USEPA. Evaluation guidelines for ecological indicators.
  http://www.epa.gov/emap/html/pubs/docs/resdocs/ecol_ind.pdf.
- Environmental Protection Agency (Ireland) (2001) Parameters of water quality: Interpretation and standards.
  http://www.epa.ie/rivermap/docs/Parameters.pdf
- California Environmental Protection Agency and California Resources Agency. Environmental protection indicators for California.
  http://www.oehha.ca.gov/multimedia/epic/Epicreport.html#bigfile.

Define the sampling design

The next step in the monitoring programme design process is to define the sampling design. The sampling design incorporates such aspects of the monitoring programme as:

- Boundaries of the monitoring site and location of sampling stations
- Frequency and timing of sampling
- Number of samples to collect
- Sample collection and analysis methods
- Methods for data analysis
- Resource requirements.

Developing an adequate sampling design requires careful and methodical planning to ensure that the study objectives will be accomplished. Many studies fail because insufficient detail has been afforded to this important component of the monitoring process. Before dealing with practical issues of the aspects listed above, it is worth dealing with important statistical considerations of different sampling strategies [see USEPA (2002) for information on the following and other sampling strategies].

Sampling strategy

There are two main categories of sampling strategy: probability-based and authoritative. Probability-based sampling strategies apply sampling theory and involve the random selection of sampling units. An essential feature of a probability-based sample is that each member of the population from which the sample was selected has a known probability of inclusion. When a probability-based design is used, statistical inferences may be made about the sampled population from the data obtained from the sampling units. Authoritative sampling strategies involve the selection of sampling units on the basis of expert knowledge or professional judgment. Authoritative sampling is not equi-probable, meaning that each member of the population from which the sample was selected does not have an equal or known probability of inclusion. Therefore, it is not possible to draw inferences about the sampled population because an authoritative bias is introduced. Thus, the validity of the data gathered is dependent on the knowledge of the sampler, and if new knowledge comes to light or previous knowledge is discredited then the validity of the data is called into question.

Authoritative sampling

- Haphazard sampling: *Samples are taken in a haphazard (not random) manner, usually at the convenience of the sampler when time permits. This is only possible with a very homogeneous condition over time and space; otherwise biases are introduced in the measured population parameters. It is not recommended because of the difficulty in verifying the homogeneous assumption.*
- Judgmental sampling: *In this sampling, the selection of sampling units (i.e. the number and location and/or timing of collecting samples) is based on the investigators knowledge of the system or condition under investigation and on professional judgment. Judgmental sampling is distinguished from probability-based sampling in that inferences are based on professional judgment, not statistical theory. Therefore, conclusions about the target population are limited and depend entirely on the validity and accuracy of professional judgment. Probabilistic statements about parameters are not possible. This type of sampling is commonly used in screening surveys, to document whether there is, or is not a problem with regard to a specific issue. For example, investigators may have a good understanding of the most probable sources of a contaminant in a specific area and, based on this knowledge, may focus attention on these sources only.*

Probability based sampling

- Simple random sampling: *In simple random sampling, particular sampling units (e.g. locations and/or times) are selected using random numbers. As a result, all possible selections of a given number of units are equally likely. There should be no conscious or unconscious selection of units to be included in the sample. A computer-generated set of random numbers can be used, but this requires that a grid or co-ordinate system be established in the study site so that each potential sample member can be identified. Simple random sampling is most useful when the population of interest is relatively homogeneous (i.e. no major patterns of contamination or hotspots are expected). The main advantages of this design are that it provides a statistically unbiased estimate of the mean, proportions, and variability, it is easy to understand and easy to implement, and sample size calculations and data analysis are straightforward. Despite its simplicity, simple random sampling is rarely used in environmental monitoring programmes, especially in aquatic ecosystems. The main reason is that aquatic ecosystems are rarely homogenous, either spatially or temporally. Because every portion of the site has an equal opportunity of being selected, if contaminant hotspots constitute only a small portion of the total study area then it is likely that random sampling will fail to detect them. Under these circumstances, random sampling will give undue weight to the less contaminated portions of the site. Random sampling may also be less efficient and, as a result, more expensive than other sampling strategies because it requires more samples to obtain the same result. It is most viable when the target population or study area is small.*
- Stratified random sampling*: In stratified random sampling, the target population is separated into non-overlapping strata or subpopulations that are known (or thought to be) more homogeneous (relative to the environmental medium or the contaminant). Thus there tends to be less variation among sampling units in the same stratum than among sampling units in different strata. Strata may be chosen on the basis of spatial or temporal proximity of the units, or on the basis of pre-existing information or professional judgment about the site or process. An estuary, for example, can be stratified on the basis of a salinity gradient. Once the strata are defined, each stratum is randomly sampled. This approach allows the project team to focus on areas of greatest concern while retaining the benefits of a random sampling plan. One of the principal reasons for using a stratified design is to ensure a more representative sample by distributing the sample throughout the spatial and/or temporal dimensions of the population. Advantages of this sampling design are that it has potential for achieving greater precision in estimates of the mean and variance, and that it allows computation of reliable estimates for population subgroups of special interest. The main disadvantage of this design is that the design team needs to have prior knowledge of the population in order to effectively define the strata and allocate the sample sizes. This type of knowledge is often not available in aquatic ecosystems.*
- Systematic sampling: *In systematic sampling, samples are collected at regular intervals over space or time. An initial location or time is chosen at random, and then the remaining sampling locations are defined so that all locations are at regular intervals over an area (grid) or time (systematic). For example, samples might be collected from a square grid over a set geographical area or at equal intervals over time. Systematic designs are good for uniform coverage, ease of use, and the intuitive notion that important features of the population being sampled will not be missed. Also, samples taken at regular intervals, such as at every node of an area defined by a grid, are useful when the goal is to estimate spatial or temporal correlations or to identify a pattern. Examples of systematic grids include square, rectangular, triangular, or radial grids. In random systematic sampling, an initial sampling location (or time) is chosen at random and the remaining sampling sites are specified so that they are located according to a regular pattern. Systematic and grid sampling is used to search for hot spots and to infer means, percentiles, or other parameters and is also useful for estimating spatial patterns or trends over time. This design provides a practical and easy method for designating sample locations and ensures uniform coverage of a site, unit, or process.*
- Composite sampling: *Composite sampling involves physically combining and homogenizing environmental samples or subsamples to form a new sample (i.e. a composite sample). The chemical or biological analyses of interest are then performed on (aliquots of) the composite sample. Because compositing physically averages the individual samples, averaging the analytical results of a few composites can produce an estimated mean that is as precise as one based on many more individual sample results. Compositing can be very cost effective because it reduces the*

number of chemical analyses needed. It is most cost effective when analysis costs are large relative to sampling costs. It demands, however, that there are no safety hazards or potential biases (for example, loss of volatile organic components) associated with the compositing process. Compositing is often used in conjunction with other sampling designs when the goal is to estimate the population mean and when information on spatial or temporal variability is not needed. Perhaps the most well known form of composite sampling in the marine environment is that used for Mussel Watch programmes. In these programmes, numerous mussels are collected from a sampling site, and the tissue is then composited and homogenised before laboratory analysis for targeted chemicals.

- Cluster sampling: *In cluster sampling, pre-defined sites are identified and several replicate samples are collected within the site. This type of sampling is commonly used for impact monitoring programmes, and especially for the analysis of benthic invertebrate communities since these often display considerable small-scale spatial variability. The collection of a single sample is therefore considered insufficient to provide an adequate understanding of the community composition and structure. Furthermore, the collection of replicate samples at each site permits the statistical comparison of data through such procedures as Analysis of Variance.*

SUGGESTED READING:

Guidance on sampling strategies can be found in:

- Keough MJ and Mapstone BD (1995) Protocols for designing marine ecological monitoring programs associated with BEK Mills. National Pulp Mills Research Program, Technical Report No. 11, CSIRO, Canberra. http://www.library.for.gov.bc.ca/
- Underwood AJ (1997) On beyond BACI: sampling designs that might reliably detect environmental disturbances, *Ecological Application* 4: 3-15.
- Underwood AJ (2000) Importance of experimental design in detecting and measuring stresses in marine populations. *Journal of Aquatic Ecosystem Stress and Recovery* 7: 3-24.
- USEPA (2002). Guidance on choosing a sampling design for environmental data collection. EPA/240/R-02/005. http://www.epa.gov/QUALITY/qs-docs/g5s-final.pdf

Boundaries of the monitoring site and location of sampling stations

The objectives of the monitoring programme and the sampling strategy (see above) determine the geographical boundaries of the monitoring site and the location of sampling stations. Setting spatial boundaries for a monitoring programme is important because inappropriate boundaries might focus efforts away from driving or consequential factors (ANZECC 2000b). The anticipated influence of marine pollution sources therefore needs to be taken into account. This, in turn, depends on the transport and fate of pollutants, in both the near- and far-fields, as well as potential synergistic effects associated with other anthropogenic activities that may affect water and sediment quality in the study area. Consideration must therefore be given to the physical, chemical and biological processes that affect water quality in the monitoring area when defining the boundaries of the monitoring site and the location of sampling stations. For example, current regimes may disperse effluent discharged from an outfall predominantly in one direction, and this will need to be considered. (This provides another reason for why the development of a conceptual model is so important.)

Impact monitoring is probably the most challenging in terms of locating sampling stations. In this type of monitoring, stations are located relative to the disturbance under consideration. Some stations (the so-called impact stations) must be situated in the immediate vicinity of the disturbance, while other stations (the reference or control stations) must be situated in areas that are beyond the influence of the disturbance. Identifying suitable locations for the reference or control stations is often difficult. Ideally the physical and chemical conditions at these stations should be identical in all ways to the impact stations with the exception of the influence of the disturbance. Finding comparable conditions is extremely challenging in the aquatic environment, especially if there is no data on which to base these decisions. It may be necessary, therefore, to perform a pilot survey that is limited to a few key indicators, in order to identify suitable sampling areas.

There are situations when locating sampling stations is much easier as they are fixed by the presence of the disturbance being monitoring and/or the location of designated beneficial use areas. For example, marine aquaculture facilities are logical sampling locations if located in areas where marine pollution sources pose potential risks to human health or the quality of farmed finfish and shellfish.

Lastly, practical considerations, such as accessibility and safety concerns, will also play a role in the locations of sampling stations. It is pointless identifying a sampling station location that cannot be accessed under normal conditions.

Preliminarily identified locations for sampling stations should be marked on a map or an aerial photograph, but the final locations should be decided upon only after a field reconnaissance. This reconnaissance may reveal important issues that the design team was not aware of from the map or photograph, such as the inability to gain access to a station or safety concerns posed through sampling at the station. Should such issues arise, then the stations should be re-located. Google Earth™ (http://earth.google.com/) is a particularly useful tool for the preliminarily identifying the locations of sampling stations.

Frequency and timing of sampling

The objectives of the monitoring program dictate the basis for determining sampling frequency and usually the timing of sampling. Sampling frequency (number of samples collected over a set period) largely depends on the:

- Variability in the load of contaminants from marine pollution sources
- Variability in processes driving transport and fate in the receiving environment
- Temporal sensitivity of the ecosystem to pollutant loading, i.e. exposure time versus negative impact.

Thus, in order to define adequately the sampling frequency, the design team must understand how the system operates and the issue that is being investigated. (Scientific assessment studies, baseline monitoring programmes and conceptual models previously mentioned become important once again.) The expected statistical analyses also influence the frequency of sample collection. For example, the objective for the monitoring programme may be to determine the frequency that a parameter exceeds a water quality guideline at a certain level of confidence. In this case the number of sampling periods can be determined using appropriate statistics.

The sampling frequency should at least resolve the main source of natural variability of the constituent under investigation. Scales of change over time differ widely in the water column (minutes - days) compared with sediments (days - seasons - decades), as previously discussed. Non-periodic events, such as storms, can also have a dramatic influence that needs to be taken into account where appropriate.

In the water column, high frequency physical processes, such as tides, currents, wind and waves, mainly control variability. A sampling frequency that is too low relative to the underlying natural variability will, therefore, result in biased data that will make it difficult to separate a human-derived impact from a natural anomaly. In the same way, sampling at a frequency that is too low relative to the variability in waste inputs may result in marked negative impacts being missed. In order to resolve the problem of the variability in the water column, sampling frequencies generally have to be high (e.g. hourly-daily-weekly). As a result, the use of water column measurement parameters as part of monitoring programmes is usually not cost-effective.

Sediment sampling frequency is strongly linked to the time-scale within which the sediments act as 'particle traps'. As with sampling of the water column, sediment sampling at a frequency that is lower than the periodic re-suspension events will make trends difficult to interpret and could lead to spurious conclusions. Therefore, where cost constraints necessitate limitations on sampling frequencies, it will be inappropriate to select sampling locations that are situated in areas reflecting short-term variability. In such instances, longer-term depositional areas should rather be targeted. For example, because sediment processes often show strong seasonal trends, sampling is often confined to a particular season. Depositional sites can be designated as short- or long-term. A location on an open coast may be a depositional site for a period of days to weeks whereas an estuary may be a depositional site for a period of months to years. The ecological impact of both does not have to be linearly related to the persistence. Both provide important insights into the sediment and pollutant dynamics of the coastal and estuarine environments and are key to the design of optimal monitoring programmes, particularly in terms of sampling frequency.

The use of biological media is commonly resorted to as a technique to overcome the problem of high temporal variability, particularly analysis of body tissues of filter feeders (e.g. mussels, oysters). It is, however, important to realise that the body mass of these organisms also has a strong seasonal variability related to spawning cycles. Natural variability therefore needs to be separated from potential long-term signals caused by human interference. To address this issue, the following are required as a minimum:

- Samples need to be taken at six-monthly intervals
- Long-term sampling needs to be performed within a narrow time-window each year to reduce seasonal uncertainty.

Lastly, beneficial uses and patterns of usage of a waterbody may determine sampling frequency. For example, one objective for monitoring bathing waters is to determine potential exposure of humans to sewage derived pathogens. If there is a strong seasonality in bathing, then it makes sense to focus most of the sampling effort during the bathing season. As previously noted, in such cases where there is potential risks to human health, near real time data are needed and peak bathing seasons might require daily sample collection.

The use of numerical modelling

To overcome the inherent uncertainties of the spatial and temporal variability of coastal aquatic systems, long-term monitoring programmes have traditionally involved the frequent monitoring of spatially extensive sampling grids. However, with the use of numerical modelling many of the inherent problems of the traditional approach can be overcome. Numerical modelling has proven to be very useful in enhancing the design of long-term monitoring programmes and improving the interpretation of the results of monitoring. Such numerical models provide the process links that enhance the ability to diagnose problem areas, as well as anticipating problems through their predictive capacity. The benefits of numerical modelling in the design of long-term monitoring programmes include:

- Definition of the most critical spatial and temporal scales of impact in the system. Important insights are provided by combination of the synthesis of the existing understanding of the key processes and the model assumptions and inputs
- Improved interpretation and understanding of the monitoring results in the context of a dynamic environment that determines the transport and fate of pollutants.

The aim, therefore, is to use the capability of numerical models to reduce uncertainties in relation to system variability, key processes, and how these influence the transport and fate of contaminants. Because this increased understanding provides greater confidence in the predicted outcomes, the investment in the monitoring can be limited to only a number of critical parameters measured at critical spatial and temporal scales.

Although long-term monitoring programmes may, initially, still require relatively extensive spatial and intensive temporal scales to address uncertainties in a system's response, over a number of years these can be reduced to only a few selected points through an iterative process, as the predicted responses of the system are verified.

Number of samples to collect

The number of samples required is based on several factors, including the programme objectives, sampling strategy, sampling media, the level of confidence required, and financial constraints. Larger monitoring areas and longer monitoring programmes obviously require a greater number of samples, but the actual number collected at each monitoring interval or station may vary. This is driven by statistical considerations. If there is knowledge of conditions (variability) in the study area, then power analysis is a useful tool for identifying how many samples are required. However, consideration should also be given to such factors as compositing techniques, which can reduce the actual number of samples required yet still improve the representativeness by the physical process of averaging. The design team must also consider that quality assurance and quality control required in the collection and analysis of additional samples. The number of quality assurance and quality control samples required depends on several factors, but a rule of thumb is that 10% of the samples should be for this purpose..

Sample collection and analysis methods

The choice of sampling and analytical techniques to apply in a monitoring programme is dependent on factors such as the sampled media, the analytes targeted for monitoring, the waterbody characteristics, and sampling site accessibility. There is an extremely wide range of field and laboratory methods that can be applied. These are far too numerous to discuss in this document. It is strongly recommended that an accredited analytical laboratory perform chemical analyses of marine biogeochemical parameters.

SUGGESTED READING:

Guidance on sample collection and handling can be found in:

General

- USEPA guidance on field sampling.
  http://www.epa.gov/region4/sesd/fbqstp/

Water

- Davis BE (2005) A guide to the proper selection and use of federally approved sediment and water-quality samplers: Vicksburg, MS, U.S. Geological Survey, Open File Report 2005-1087.
  Available at: http://water.usgs.gov/osw/pubs/OFR_2005_1087/ OFR_2005-1087.pdf
- Washington State Department of Ecology (2006) Standard operating procedure for manually obtaining surface water samples.
  http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_015ManuallyObtainingSurfaceWaterSamples.pdf
- Washington State Department of Ecology (2007) Standard operating procedure for sampling bacteria in water.
  http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP-SOP_012SamplingBacterialnWater.pdf

Sediment

- USEPA (2001)Methods for collection, storage and manipulation of sediments for chemical and toxicological analyses: Technical manual. EPA 823-B-01-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC.
  http://www.epa.gov/waterscience/cs/library/collection.html
- Davis BE (2005) A guide to the proper selection and use of federally approved sediment and water-quality samplers: Vicksburg, MS, U.S. Geological Survey, Open File Report 2005-1087.
  http://water.usgs.gov/osw/pubs/OFR_2005_1087/ OFR_2005-1087.pdf

Biology (including tissue analysis)

- USEPA (2000). Guidance for assessing chemical contaminant data for use in fish advisories. Volume 1: Fish sampling and analysis.
  www.epa.gov/fishadvisories/technical/index.html

- USEPA (2000). Guidance for assessing chemical contaminant data for use in fish advisories. Volume 2: Risk assessment and fish consumption limits
  www.epa.gov/fishadvisories/technical/index.html
- Washington State Department of Ecology (2006) Field collection, processing and preservation of finfish samples at the time of collection in the field.
  http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_009FishFieldCollectionProcessing.pdf
- Washington State Department of Ecology (2006) Standard operating procedures for resecting finfish whole body, body parts or tissue samples.
  http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_007ResectingFinfishWholeBodyPartsTissue Samples.pdf
- Washington State Department of Ecology (2007) Standard operating procedures for macrobenthic sample analysis.
  http://www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_043MarineMacrobenthicSampleAnalysis.pdf

Sample analysis

- USEPA guidance for the analysis of an extremely wide suite of physical and chemical parameters in all types of media can be found at:
  http://www.epa.gov/epawaste/hazard/testmethods/sw846/online/ index.htm

Methods for data analysis

There are three basic approaches for data assessment:

- Assessment over long periods of record for the purpose of determining trends and changes over time (e.g. for trend monitoring)
- Analysing the relationships between measured values for variables in the monitoring program to determine differences and the significance of the differences (e.g. for impact monitoring)
- Assessment of the extent to which measured water quality meets published guidelines, criteria or objectives (e.g. for compliance monitoring).

Although the data analysis step of the monitoring programme design intuitively occurs after implementation of sample collection and availability of results, statistical considerations should inform the entire sampling design process. Therefore, a large proportion of the data analysis procedures will have been defined during the sampling design process. Of course there are instances where this cannot be anticipated. For example, an unknown relationship between two parameters could be found to be strongly correlated, permitting correlation analysis.

SUGGESTED READING:

Guidance on data analysis can be found in:

- Helsel DR and Hirsch RM (1992). Statistical Methods in Water Resources. Studies in Environmental Science 49. Elsevier Publishing, NY.
  http://water.usgs.gov/pubs/twri/twri4a3/pdf/twri4a3.pdf
- USEPA (2006) Data Quality Assessment: Statistical Methods for Practitioners. EPA/240/B-06/003.
  http://www.epa.gov/quality/qs-docs/g9s-final.pdf
- Schwarz CJ (2006) Sampling, regression, experimental design and analysis for environmental scientists, biologists, and resource managers.
  http://www.stat.sfu.ca/~cschwarz/Stat-650/Notes/PDF/ALLchapters.pdf

Resource requirements

Once the above steps of the sampling design have been finalised, the next step is to identity resource requirements. These include human resources as well as the equipment, consumables and funding necessary to perform all aspects pertinent to the collection and analysis of samples.

Implement monitoring programme

The successful execution of the sampling strategy is clearly critical to the success of the monitoring programme. In essence, this requires considerable organisational and logistical skills. The safe and correct deployment and use of sampling equipment, sample collection, handling and storage, field measurement and metadata collection requires experienced multi-disciplinary field teams. Returning samples to laboratories within prescribed time periods, their analysis and quality control similarly involves a high level of planning and co-ordination. A project leader with suitable project management skills is therefore required.

Data management is an especially important consideration. Environmental quality monitoring programmes lead to the generation of large amounts of data. These data are expensive to collect and require substantial investments of both human and financial resources. A data management system must be developed to store these data for both immediate and future use. The data management system must include a detailed description of data identifiers. Data should be stored in a manner that facilitates its usage for purposes other than simple archiving, including for statistical analysis or importation into Geographical Information System software. Software packages have specific data format requirements and it is imperative that these requirements are understood prior to designing the data management system. This will avoid unnecessary and time consuming data conversion. A good data management system should have (ANZECC 2000b):

- Reliable procedures for the recording of analytical and field observations
- Procedures for systematic screening and validation of data (quality control)
- Secure storage of information
- Simple retrieval system
- Simple means of analysing data
- Flexibility to accommodate additional information.

Reporting and communication

There is little logic in performing an environmental monitoring programme if the information is not disseminated. The findings of monitoring programmes are usually of interest to a wide range of stakeholders, including the scientific community, policymakers, non-governmental organisations, and the general public. Given the usually strong differences in the level of understanding of technical details by these audiences, an information dissemination strategy to account for different needs must be developed as the monitoring programme matures.

The most common form of information dissemination is through the preparation of technical reports. Further information dissemination occurs through the publication of findings in peer reviewed scientific journals, although this is targeted at the scientific community. The vast majority of stakeholders interested in monitoring programme findings do not have a scientific background. Technical reports are usually difficult for these stakeholders to understand. It is important, therefore, that the needs of these stakeholders be considered, through the preparation of a non-technical (summary) report. Another useful way of communicating with a non-technical audience is by summarising data in graphical plots and the presentation of data summaries in maps wherever possible. All of these tools can also be used in public presentations, which are useful for disseminating programme findings. While printed reports were historically the dominant form of disseminating data, the internet is increasingly being used for this purpose. Various other communication routes can be utilised to communicate findings to wider stakeholder groups, such as pamphlets and media reporting.

The frequency of reporting is important. Source monitoring (referring to monitoring of composition and volumes of marine pollution sources) requires near real-time reporting (i.e. as close as possible to the time of sampling) to ensure that mitigating measures are implemented timeously. Environmental monitoring programmes require less frequent reporting, e.g. usually six-monthly or annually. In general monitoring reports should include

- A list of monitoring objectives (or hypotheses) and how these relate to the overall Environmental Quality Objectives specified for the study area
- Details of the design and implementation of the monitoring programme (also indicating the relationship between selected measurement parameters and monitoring objectives)
- An evaluation of the monitoring data in relation to the monitoring objectives (or hypotheses). This evaluation should make use of data summaries and graphical presentations in order to enhance readability
- A statement on whether the monitoring objectives have been met
- In the event of non-compliance, possible reasons for the non-compliance
- Management strategies and actions required to address non-compliance
- Recommendations on refinements to the monitoring programme
- Appendices containing cruise and laboratory reports, raw data tables and other relevant background information.

Evaluation and assessment of the monitoring programme (review and refine)

The objectives of monitoring programmes usually do not remain static. Rather, they evolve as new information from the existing programme or from aligned research comes to the fore and management needs and priorities change. Similarly, methods used in the implementation of monitoring programmes may change, such as when new measurement technologies become available. It is important, therefore, to continually review whether the monitoring programme is addressing the intended objectives and whether there are opportunities for its improvement. It is recommended that the design and findings of monitoring programmes are subjected to peer review by technical experts that have no vested interest in the programme.

5. PRIORITY CATEGORIES OF PARAMETERS RELEVANT TO THE WEST INDIAN OCEAN REGION

One aim of the WIO-LaB project was to establish a basic level monitoring programme in the WIO region. Capacity developed as part of the WIO-LaB project, by means of training and funding of equipment and skills development, could then be put to meaningful use in implementing long-term marine pollution monitoring in the region. A key step towards establishing this basic level monitoring programme was recognised as reaching consensus on what parameters to monitor. As discussed elsewhere in this document, it is clear that the selection of parameters to be measured in monitoring programmes is site- and situation specific. The aim therefore, was to identify parameters to be monitored that were relevant to priority pollution issues common to participating WIO countries, and that were able to be implemented in the short term, recognising limitations imposed by a general lack of resources and by logistical constraints in many of the participating countries.

Priority categories of parameters relevant to the WIO region were identified as part of the process of developing guidelines for the establishment of Environmental Quality Objectives and Targets in the coastal zone of the WIO region (UNEP/CSIR 2009). The Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) recognises nine source categories of threats from land-based activities to both human health and well-being and to the integrity of coastal ecosystems. These formed a starting point in the identification of priority categories of parameters relevant to the WIO region:

- Sewage (introducing nutrients, organic matter, suspended solids and microbiological contaminants)
- Nutrients
- Heavy metals
- Oils (hydrocarbons)
- Marine litter
- Persistent organic pollutants
- Radioactive substances
- Sediment mobilization (introducing turbidity and causing siltation)
- Physical alteration and destruction of habitats.

Although most of these source categories arise from land-based pollution, modification of river flows, over-exploitation of resources and infrastructure development (e.g. clearing of coastal areas for housing and agriculture) also contribute, in particular to physical alteration and destruction of habitats.

The major sources of land-based pollution in the WIO region are anthropogenic activities whose social and economic drivers are not controlled or adequately managed by the responsible authorities (UNEP/GPA 2006a). Important social and economic drivers in the WIO region are documented in the Regional Synthesis Report on the Status of Pollution in the Western Indian Ocean Region (see http://www.wiolab.org/):

- Poverty and inequality
- Population growth
- Urbanisation
- Tourism
- Industrialisation.

Major land-based sources of pollution include:

- Municipal waste (e.g. domestic sewage, contaminated urban storm water and solid waste)
- Tourist developments
- Agricultural activities
- Industrial activities (including harbour and ports)
- Mineral exploitation
- Atmospheric emissions
- Climate change.

The lack of proper sewage and storm water reticulation systems, as well as treatment facilities for municipal liquid and solid waste is identified as a major cause of coastal pollution in urban centres within the WIO region. Population growth and rural-urban migration result in large, rapidly expanding coastal urban populations that generate large quantities of domestic sewage. In addition, changes in lifestyles, characterised by high consumption rates, result in increased generation of solid waste. Many coastal cities still rely on septic tank or pit latrine systems that, when overloaded, cause severe pollution of groundwater resources. Furthermore, impermeable urban surfaces lead to runoff of contaminated stormwater to surface waters. Priority parameter categories associated with municipal waste include:

- Organic matter (or biochemical oxygen demand, BOD)
- Suspended solids
- (Low) salinity (e.g. large quantities of storm water can reduce salinity is coastal waters)
- Nutrients (e.g. nitrogen and phosphorous)
- Microbiological contaminants
- Litter (or objectionable matter).

Within the WIO region tourism forms an integral, if not the most important (e.g. Seychelles), driver of countries' economies. Although the most significant impact of tourism infrastructure and associated activities is usually the physical destruction and alterations of coastal habitats, these developments also pose pollution risks. Similar to municipal areas they generated large quantities of liquid (sewage) and solid waste. Many of these resorts include golf courses that use large quantities of fertilisers which leach into sheltered coastal areas posing eutrophication risks. The discharge of chlorinated swimming pool water into coastal areas is also seen as a growing problem. Although individually small, their cumulative impacts can be considerable (e.g. bleaching of coral and lower salinities). Priority parameter categories associated with tourism development include:

- Organic matter (or BOD)
- Suspended solids
- (Low) salinity
- Nutrients (e.g. nitrogen and phosphorous)
- Microbiological contaminants
- Litter (or objectionable matter)
- Chlorine (discharging of chlorinated swimming pool water).

In many of the WIO region countries agriculture is the most significant economic activity, both as a foreign exchange earner and as the mainstay of rural farmers and inhabitants. Commercial farming is an important activity in the catchments of most rivers, and contributes to land degradation through inappropriate practices result in soil erosion. This erosion leads to increased turbidity and suspended solids loads in both the rivers and coastal waters. Pesticides, herbicides and fertilisers applied to agricultural lands leach into rivers and ultimately reach coastal areas (UNEP/GPA 2006a). Priority parameter categories associated with agricultural activities include:

- Suspended solids and turbidity (associated with soil erosion)
- Nutrients (e.g. nitrogen and phosphorous)
- Persistent organic pollutants.

Industrial activities in the WIO region are concentrated in large urban centres and are dominated by food and beverage processing, textile manufacturing, and to a lesser extent chemical manufacturing, oil refineries and cement factories. Port activities are also major sources of pollution in the region. Priority parameter categories associated with industrial waste and activities are obviously strongly dependent on the type of industry, but generally include:

- Organic matter (e.g. food processing industries)
- Suspended solids and turbidity
- Trace metals (e.g. chemical manufacturing and oil refineries)
- Oils (hydrocarbons, e.g. oil refineries and harbours and ports).

Mineral exploitation in the WIO coastal region includes sand winning (for construction purposes) and precious and semi-precious stones (e.g. Madagascar). Although the impacts of mineral exploration are primarily the physical destruction and alteration of coastal habitat, these activities can introduce contaminants to coastal areas in the form of increased suspended solid loads.

Atmospheric emissions in the WIO region are mainly associated with vehicle traffic, wood fuel burning (for domestic energy needs), and emissions from industries. Priority parameter categories associated with atmospheric emissions are obviously strongly dependent on the source, but parameters that pose risks to coastal pollution generally include:

- Suspended solids
- Nutrients (nitrogen from nitrous oxide)
- Trace metals
- Oils (hydrocarbons).

Climate change, which can be viewed as the cumulative effect of numerous land-based activities (e.g. deforestation, atmospheric emissions, etc), also poses a serious risk to coastal ecosystems in the WIO region, where increases in temperatures are resulting in coral bleaching (UNEP/GPA 2006a).

A summary of the priority parameter categories associated with each of the major sources of land-based pollution in the WIO region, as discussed above, is provided below:

PRIORITY PARAMETER CATEGORIES	MAJOR SOURCES OF LAND-BASED POLLUTION						
	Municipal waste	Tourism development	Agriculture	Industry	Mineral exploration	Atmospheric emissions	Climate change
Organic matter (BOD)	X	X		X			
Suspended solids/turbidity	X	X	X	X	X		
Salinity (reduction)	X	X					
Temperature				X			X
Nutrients	X	X	X			X	
Chlorine		X					
Trace metals				X		X	
Persistent organic pollutants			X				
Oils (hydrocarbons)				X		X	
Litter (objectionable matter)	X	X					
Microbiological contaminants	X	X					

NOTE:

The marine waters off the coast of East Africa are one of the major transportation routes for oil from the Middle East to Europe and the Unites States of America. As a result maritime transportation poses an equally serious threat to the coastal environment of WIO region, if not greater than some of the sources listed above. However these activities are not considered to be land-based and are therefore not discussed further here.

The 4th Regional Meeting of the WIO-LaB Water and Sediment Quality Working Group was held in Dar es Salaam in June 2009. At this meeting the results of water and sediment quality monitoring programmes implemented in participating countries were reviewed, and a regional assessment was made by comparison of data from participating countries against proposed WIO Environmental Quality Targets (UNEP/CSIR 2009). Criteria for the designation of pollution hotspots were developed and applied to categorise coastal WIO areas affected by land-based sources of pollution. A daft long-term monitoring protocol was presented together with a proposed list of priority categories of monitoring parameters relevant to the WIO region. With this information the group discussed and agreed on the outline of a basic level monitoring programme for the WIO region. The intention is that this will form the basis of an initial programme to be further developed and built upon, and participating countries were encouraged to expand the programme to suit their specific national interests. Recognition was given to the fact that not all countries have the resources to implement even a basic programme immediately. Therefore a phased approach was proposed by which inclusion of parameters was considered:

- Important and achievable to occur immediately
- Important, but only achievable in the medium term (5 years)
- Achievable immediately at limited additional cost, and whose inclusion will enhance the diagnostic strength of monitoring (secondary importance)

The basic level monitoring programme agreed upon is as indicated and discussed below.

PRIORITY PARAMETER CATEGORIES	Parameter	Media	Basic programme	Sample sites	Sampling frequency
Microbiological contaminants	Enterococci, *E. coli*, faecal coliforms	Water	Immediate	Recreational, mariculture, shellfish collection areas	2 weeks
	Salinity				
	Temperature (°C)	Water	Secondary		
	Turbidity (NTU)				
Trace metals	Full set of appropriate metals	Biological tissues (bivalves)	Immediate	Hotspots and reference sites	6 months
Trace metals	Full set of appropriate metals, including Al and Fe to act as normalisers	Sediment	Secondary		
Persistent organic pollutants	As appropriate	Biological tissues (bivalves), sediment	Medium-term		
Oils (hydrocarbons)					
Litter (objectionable matter)	Volume of litter collected during clean-up programmes	-	Medium-term	Litter hotspots	1 year, reported every 5 years (e.g. National State of the Environment Reports)

Microbiological contaminants

Microbiological contamination is widespread in many of the WIO countries. It is typically associated with inappropriate disposal of municipal wastewater (including sewage), contaminated surface and sub-surface runoff from urban areas, contaminated runoff from agricultural areas used for livestock rearing and industrial effluents (mainly from food processing industries). Microbial contamination can have severe socio-economic consequences including human health risks associated with contact recreation or ingestion of contaminated seafood and reduced quality of seafood cultured or harvested in a particular area. These consequences affect stakeholders across society, from local communities to international tourists, and industrial and aquaculture operations, all of which utilise the marine environment for recreation and the collection and culture of seafood. Loss, or potential loss, of the recreational value of coastal waters, due to unacceptable levels of faecal bacteria (typically used as indicators of microbial contamination), is evident throughout the coastal zone of the WIO region. This is especially problematic in areas where tourism comprises an important part of local economies.

Given the above, the monitoring of Enterococci, *E. coli* and faecal coliforms, as indicators of microbiological contamination, was considered the priority for immediate inclusion in the basic level monitoring programme. The concurrent measurement of salinity permits some assessment of the source of microbiological contamination, should it be recorded. Additional physico-chemical parameters (temperature and turbidity), although not essential, will enhance the diagnostic strength of microbiological monitoring and should also be considered.

Microbiological contaminants should be monitored in all areas where there is potential microbiological contamination and humans have direct contact with coastal waters (e.g. bathing areas). Mariculture and shellfish collection areas should also be monitored. Sampling should be performed at two weekly or at shorter intervals.

Trace metals

Contamination by heavy metals is a common consequence of pollution arising from many anthropogenic activities. The key sectors contributing to metal contamination of coastal waters in the WIO region include industry (disposal in wastewaters) and transportation (dredging activities in ports and harbours, traffic emissions). Metal contamination poses risks to human health and affects stakeholders across society. Ecosystem health is impaired and commercial and artisanal fisheries, as well as aquaculture and seafood production industries, may be affected.

Recognising the cost implications of monitoring metals in water (given the need for high frequency sampling) and taking other pragmatic considerations into account (see Section 4.2, this report), monitoring trace metals in biological tissues (bivalves) was proposed for the basic level monitoring programme. Monitoring of contaminant concentrations in bivalves not only provides an understanding of whether and where there are pollution problems, but also provides a measure of potential human health risks posed by shellfish consumption. Consideration should also be given to the analysis of metal concentrations in sediment, since this permits an understanding of contamination in areas where bivalves do not grow or cannot be collected. The measurement of iron and aluminium concentrations must be included, to permit the development of baseline metal concentration models or for normalisation to a common (usually non-anthropogenically influenced) factor (see Newman and Watling 2007).

For biological tissue monitoring, trace metal concentrations should be monitored at six month intervals. The actual timing of sample collection should consider such issues as wet and dry seasons, and such aspects of the target species as breeding cycles. Trace metal concentrations in sediment can be measured at yearly intervals, although sediment from baseline or reference areas should be collected as frequently as possible in order to permit the definition of statistically robust baseline metal concentration models.

Organic contaminants (persistent organic pollutants and hydrocarbons)

Sectors that are sources of organic contaminants are mainly agriculture (pesticides and fertilisers), industry (disposal of a suite of organic substances in wastewaters, accidental spills), urbanisation (a suite of organic substances in wastewaters and urban runoff), and transportation (a suite of organic substances from vessel operations and accidental spills in ports, and from vehicle emissions). Despite the prevalence of these sources of organic contaminants in coastal areas of the WIO region, very little monitoring of persistent organic pollutants and hydrocarbons has been performed. Therefore, the extent and magnitude of organic contamination of coastal waters in the WIO region is largely unknown. This, in itself, provides strong motivation for the inclusion of these potential contaminants in monitoring programmes. Organic pollution can pose risks to human and ecosystem health.

There is limited capacity in the WIO region at present for organic analyses. Equipment costs associated with this type of analysis are high. Some capacity has been developed as part of the WIO-LaB programme, and this needs to be grown. This is recognised in the proposed basic level monitoring programme. Participating WIO region countries should aim at introducing persistent organic pollutant and hydrocarbon monitoring in the medium term (5 years). The cost implications of monitoring persistent organic pollutants and hydrocarbons in water (given the need for high frequency sampling) and other pragmatic considerations (see Section 4.2 of this document) render the use of this sampling medium impractical. Rather, organic contaminant concentrations should be measured in integrator media, such as (first priority) biological tissue (bivalves) and sediment.

For biological tissue monitoring, organic contaminant concentrations should be monitored at six month intervals. The actual timing of sample collection should consider such issues as wet and dry seasons, and such aspects of the target species as breeding cycles. Organic contaminant concentrations in sediment can be measured at yearly intervals.

Litter (objectionable matter)

Solid waste (which either floats or sinks) is introduced into coastal waters of the WIO region as a consequence of inadequate waste collection and disposal. This is a serious problem in most coastal urban centres in the WIO region. Major environmental impacts of litter include ingestion by marine organisms, or entanglement, resulting in the loss of biodiversity. Socio-economic consequences include the loss of aesthetic value of coastal areas and risks to human heath through contact with contaminated waste products (e.g. medical waste).

The monitoring of litter loads in coastal areas is frequently omitted from traditional water quality monitoring programmes. However, given the prevalence of litter in coastal urban centres in the WIO region and the potential adverse impacts of litter in coastal waters, and the strong dependency of people in the WIO region on coastal ecosystems, the inclusion of litter monitoring in the basic level monitoring programme is important. Monitoring (trends in) litter loads is relatively easy if clean-up programmes are put in place, by simply recording the volume of litter collected. In some WIO region countries formal clean-up programmes still need to be implemented, with the result that this monitoring cannot be immediately included in the basic level monitoring programme. Countries however, should aim at introducing litter monitoring in the medium term (5 years).

6. REFERENCES

AGARDY T (2007). Ocean zoning is coming. The W2O Observer - Newsletter of the World Ocean Observatory. February 2007 (http://www.thew2o.net/newsletter_arc.html).

AUSTRALIA and NEW ZEALAND ENVIRONMENT and CONSERVATION COUNCIL (ANZECC) (2000a). Australian and New Zealand guidelines for fresh and marine water quality. National Water Quality Management Strategy No 4. Canberra, Australia.

AUSTRALIA and NEW ZEALAND ENVIRONMENT and CONSERVATION COUNCIL (ANZECC) (2000b). Australian guidelines for water quality monitoring and reporting. National Water Quality Management Strategy No 7. Canberra, Australia.

CANTILLO AY (1998). Comparison of results of mussel watch programs of the United States and France with worldwide mussel watch studies. *Marine Pollution Bulletin* 39: 712–717.

CHAPMAN D (1996). Water quality assessments - A guide to use of biota, sediments and water in Environmental Monitoring. Published on behalf of WHO by F & FN Spon.

CHAPMAN PM, McDONALD BG and LAWRENCE GS (2002). Weight-of-evidence issues and frameworks for sediment quality (and other) assessments. *Human and Ecological Risk Assessment* 8: 1489-515.

CLARKE KR and GREEN RH (1988). Statistical design and analysis for a 'biological effects' study. *Marine Ecology Progress Series* 46: 213-226.

CSIR (2003). Great Brak Estuary Management Programme. Review Report - March 2003. CSIR Report No. ENV-S-C 2003-092. CSIR Environmentek, Stellenbosch, South Africa.

DEVORE JL and FARNUM NR (1999). Applied statistics for engineers and scientists. Duxbury Press. ISBN 053435601X.

EDVARDSSON K (2004). Using Goals in Environmental Management: The Swedish System of Environmental Objectives. *Environmental Management* 34(2):170–180.

FAUST SD and ALY AM (1981). Chemistry of natural waters. Ann Arbor Science Publishers Inc, Michigan.

MONTEIRO PMS (1999). A Modelling-driven environmental baseline assessment for the proposed new Hood Point outfall in East London: Sediment biogeochemistry baseline study. CSIR Report ENV-S-C 99109C. CSIR Environmentek, Stellenbosch, South Africa.

NATIONAL RESEARCH COUNCIL (NRC) (1990). Managing troubled waters: The role of environmental monitoring. National Academy of Sciences. Marine Board. Committee on a Systems Assessment of Marine Environmental Monitoring. National Academy Press, Washington DC.

NEW ZEALAND WATER ENVIRONMENT RESEARCH FOUNDATION (NZWERF) (2002). New Zealand Municipal wastewater monitoring guidelines. Ray, D (Ed.) New Zealand Water Environment Foundation, Wellington. ISBN 1-877134-40-6.

NEWMAN BK and WATLING RJ (2007). Definition of baseline metal concentrations for assessing metal enrichment of sediment from the south-eastern Cape coastline of South Africa. *Water SA* 33: 675-692.

OLSEN S (2003). Frameworks and indicators for assessing progress in integrated coastal management initiatives. *Ocean & Coastal Management* 46: 347-361.

OLSEN SB and NICKERSON D (2003). The governance of coastal ecosystems at the regional scale: An analysis of the strategies and outcomes of long-term programmes. Coastal Management Report No. 2243. Coastal Resources Center, University of Rhode Island, Narragansett.

REPUBLIC of SOUTH AFRICA DEPARTMENT of WATER AFFAIRS and FORESTRY (RSA DWAF) (2004). Water Quality Management Series Sub-Series No. MS 13.3. Operational policy for the disposal of land-derived water containing waste to the marine environment of South Africa - Guidance on Implementation. Edition 1. Pretoria.

SKIBBE E (1991). Impact assessment of the sewage effluent at Zeekoevlei, False Bay. *Transactions of the Royal Society of South Africa* 47 (4/5): 717-730.

SKIBBE E (1992). Pollution assessment of several beaches along the South-Western Cape Coast. CSIR Research Report 702. CSIR Environmentek, Stellenbosch, South Africa.

SOLOMONS W and FÖRSTNER U (1984). Metals in the hydrocycle. Springer-Verlag, Berlin.

SPIEGEL MR (1972). Theory and problems of statistics. Schaum's Outline Series. McGraw-Hill Book, New York.

STUMM W and MORGAN JJ (1970). Aquatic chemistry: An introduction emphasising chemical equilibria in natural waters. Wiley-Interscience, New York.

TALJAARD S (2006). Baseline Assessment of Sources and Management of Land-Based Pollution in the BCLME Region (Project BEHP/LBMP/03/01) Report submitted to UNOPS as part of the Benguela Current Large Marine Ecosystem Programme. CSIR Report CSIR/NRE/ECO/ER/2006/0010/C. Stellenbosch, South Africa (www.bclme.org).

TALJAARD S, MONTEIRO PMS and BOTES WAM (2006). A structured ecosystem-scale approach to marine water quality management. *Water SA* 32(4): 535-542.

TALJAARD S and MONTEIRO PMS (2002). Saldanha Bay marine water quality management plan. Phase I: Situation Assessment. Report to the Saldanha Bay Water Quality Forum Trust. CSIR Report ENV-S-C 2002-115/1. CSIR Environmentek, Stellenbosch, South Africa.

UNITED NATIONS EDUCATIONAL, SCIENTIFIC and CULTURAL ORGANIZATION, WORLD HEALTH ORGANISATION and UNITED NATIONS ENVIRONMENTAL PROGRAMME (UNESCO/WHO/UNEP) (1992). Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring. Second Edition.

UNITED NATIONS ENVIRONMENTAL PROGRAMME/GPA (UNEP/GPA) (2006a). The state of the environment - Regional assessments. Report prepared by the UNEP/GPA Coordination Office, The Hague.

UNITED NATIONS ENVIRONMENTAL PROGRAMME and GLOBAL PROGRAMME OF ACTION FOR THE PROTECTION OF THE MARINE ENVIRONMENT FROM LAND-BASED ACIVITIES (UNEP/GPA) (2006b). Ecosystem-based management: Markers for assessing progress. UNEP/GPA, The Hague.

UNITED NATIONS ENVIRONMENT PROGRAMME/NAIROBI CONVENTION SECRETARIAT and CSIR (2009). Guidelines for the Establishment of Environmental Quality Objectives and Targets in the Coastal Zone of the Western Indian Ocean (WIO) Region. WIO-LaB Technical Report Series No. 01/2009, United Nations Environment Programme, Kenya, Nairobi. 146 pp.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA) (1994). Amended Section 301(h) Technical support document. EPA842-B-94-007. Oceans and Coastal Protection Division, Office of Wetlands, Oceans, and Watersheds, United States Environmental Protection Agency, Washington, DC.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA) (1998). Guidelines for ecological risk assessment. Office of Research and Development. Risk Assessment Forum, Washington, D.C. EPA/630/R-95/002F.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA) (2002). Guidance on choosing a sampling design for environmental data collection. Office of Environmental Information, Washington D.C. EPA/240/R-02/005.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA) (2003). Elements of a State water monitoring and assessment program. EPA 841-B-03-003. Assessment and Watershed Protection Division. Office of Wetlands, Oceans and Watershed. United States Environmental Protection Agency, Washington, DC.

WARD T J and JACOBY CA (1992). A strategy for assessment and management of marine ecosystems: Baseline and monitoring studies in Jervis Bay, a temperate Australian embayment. *Marine Pollution Bulletin* 25: 163-171.

WIBECK V, JOHANSSON M, LARSSON A and ÖBERG G (2006). Communicative Aspects of Environmental Management by Objectives: Examples from the Swedish Context. *Environmental Management* 37(4): 461-469.

WORLD HEALTH ORGANISATION (WHO) (1982). Waste discharge into the marine environment: Principles and guidelines for the Mediterranean Action Plan. Published under the joint sponsorship of the World Health Organisation and the United Nations Environment Programme. Pergamon Press, Oxford.

WORLD COMMISSION ON ENVIRONMENT and DEVELOPMENT (WCED) (1987). *Our Common Future*. Oxford University Press: Oxford.