1. INTRODUCTION

Wetlands, as defined by the Ramsar Convention (1971), include areas that are subject to fresh, brackish and/or marine waters. They are very important ecosystems, often with high levels of productivity. Within the coastal zone, tidal flats support a rich benthic community and provide habitat for many organisms that form the basis of the food web, supplying food to many species of shellfish, fish, invertebrates and birds. Many species of birds depend on wetlands for food and shelter, particularly during migrating and breeding seasons. Within subtidal waters, seagrasses are pivotal to coastal ecosystems being necessary for the sustainability of commercial and recreational fisheries due to their provision of food and shelter for a wide variety of aquatic biota (Keough and Jenkins, 1995). Wetlands fulfill many functions including biohabitat, water quality improvement, hydraulic and social (PIANC, 2003), and are very important to the residential community in terms of safety and protection.

Coastal zone development such as land reclamation, the construction of infrastructure, port facilities, navigation and shipping channels, and sand dredging, have resulted in enormous impacts and alterations to wetlands. Thus the commercial requirements of the coastal zone and wetlands often differ greatly from the natural or environmental value. With large infrastructure projects that alter a site, it is essential to understand the current environment, and then to implement suitable management based on the research findings to provide the best attempts for wetland conservation. If losses are unavoidable, wetland restoration must be undertaken through mitigation measures, trying to restore as best possible the lost elements and functions. It should be noted that always wetland conservation should be favoured (and wetland protection strongly encouraged) at all cost over wetland restoration.

The present study conducted integrated environmental research on the coastal wetland of Awase in Okinawa, which is subject to impact from the construction of a large landfill development. The aim was to improve the understanding of the biological, physical and chemical features, processes and interactions that presently occur (pre-development). In coastal wetlands, close relationships exist between the governing hydrodynamics, sediment and bathymetry. These factors together with the chemical regime greatly influence the biological community and influence habitat type. In this study, the elements and relationships between the intertidal macrobenthos and the abiotic components were examined. Physical, biological and water quality data of the wetland were collated and evaluated using a grid system, and inter-disciplinary relationships investigated. The results were utilized to identify suitable environmental indicators and threshold criteria for the wetland. In order for effective environmental management to be applied, the current status of the environment (represented by selected indicators) was then assessed using the Habitat Suitability Index methodology. From this, the environmental impact of the future landfill development project was appraised, and performance standard criteria developed. It is only through an increased understanding of the Awase wetland elements and dynamics that the environment can be effectively managed.

2. SITE CHARACTERISATION

A range of factors control the colonization of wetlands including elevation, exposure, tidal regime, water quality, sediment composition and quality, influencing the floral and faunal communities that are present. Knowledge of the existing condition and an overview of the current state form the basis for understanding the Awase ecosystem. Therefore it is crucial to characterize the site, identifying the key features and processes that exist and affect the wetland, the history of the location, and its current social and economic uses.

2.1 Location

Awase tidal flat is a coastal wetland located in Nakagusuku Bay, Okinawa (**Figure 2.1**). **Figure 2.2** displays Awase wetland in detail. The intertidal zone is approximately 265ha in size, and the designated subtidal study region is approximately 1100ha. The surrounding region of Nakagusuku Bay has a total area of approximately 24,000ha. The existing habitats present in Awase wetland including adjacent coastal waters are diverse including mangrove forest, tidal flat, seagrass meadows and corals.

The surrounding topography of Awase is a small mountain range (up to 160m in elevation), ringing lowland plains at the base. Dominant land usage in the surrounding vicinity of the wetland includes residential, military communications complex and parkland.

2.2 Climate

As an intertidal and shallow coastal system, Awase wetland is highly responsive to meteorological conditions. Okinawa’s climate is subtropical, with an average annual temperature of 22 degrees Celsius. In Okinawa, 45% of total annual rainfall is concentrated between the rainy season of May-June and the typhoon season of July-October, with total annual rainfall in the Awase region in the order of 1800mm/year. Dominant winds in Nakagusuku area are from NNW or NW direction (**Appendix A**).

2.3 Bathymetry

Bathymetry and elevation are important factors to the hydraulics of the system, influencing inundation, drainage and wave exposure. The bathymetry of Awase wetland was surveyed between 1999 and 2003, and the data was combined using Surfer (Kriging interpolation) to produce a topographic and bathymetric map of the intertidal and subtidal region (**Figure 2.3**). Elevation data for the mangrove region was not available. The tidal flat typically ranges between 0-+2m, with the subtidal region generally less than 10m water depth and most depths ranging between 0-5m.

2.4 Hydraulic Regime

Annual mean wave climate in Nakagusuku Bay is dominated by significant wave heights of up to 1.0m, with 60% from SSE direction (wave station located in 45m water depth on the eastern boundary of Nakagusuku Bay; see **Appendix A** for wave summary). Seasonal conditions are dominated in the extreme by the typhoon season, with offshore peak wave heights frequently greater than 6m and wave period longer than 10 seconds. The tides are semi-diurnal and the range is up to approximately 1.8m. With the exception of higher elevations on the south-western boundary of Awase wetland, the entire tidal flat is inundated at the highest tide. From tidal modelling results (Okinawa General Bureau et al., 2002), it appears that most tidal velocities across the intertidal zone and in the adjacent shallow waters range between 4-8cm/s (during both ebb and flood tides, in summer and winter seasons).

Three major sewage/runoff freshwater drainage channels enter the wetland (**Figure 2.4**), two via the mangrove region (A and B) and the third entering at a location on the northern boundary (C). The current quantity of incoming freshwater flows under both dry and wet conditions is unknown. In 1996, a mean total daily discharge into Awase tidal flat from the catchment (i.e. via the three drainage channels) was estimated at 5875 m^3/day (with the proportions of 56%, 28% and 16% through channels A, B and C respectively), however the sewage system catchment size has increased since that date (Okinawa City, Internet Site). No information was available regarding the groundwater system at Awase.

2.5 Sediment Properties

Sediment particle size and sediment quality are important factors influencing the use of an area by biota. In general, Awase wetland has both coarse sand and finer sandy sediments (some with significant muddy content), together with coral rubble. Sediment composition and sediment quality were sampled seasonally at ten sites in the intertidal zone during the Japanese fiscal years of 2000-2004. Comprehensive sediment composition sampling was also undertaken throughout both the intertidal and subtidal regions in September and October 2001. Contoured median sediment grain size (D50) based on the comprehensive data from 2001 are shown in **Figure 2.5**, together with some example percent compositions from both intertidal and subtidal sites. The majority of median grain size across the wetland is coarse sand (classified using the Wentworth Classification as 0.50-1.0mm), however there are some areas in the upper intertidal zone that have a significant silt-clay fraction (~20%). Further analysis was undertaken on the seasonal intertidal sediment composition data during this research, and will be discussed in **Section 4.3.1**.

Sediment quality parameters measured at the ten intertidal sites included pH, Sulfide (Sulf), Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Total Nitrogen (TN), Total Phosphorus (TP) and Chlorophyll-a (Chla). In the lower zones of the tidal flat and subtidal region, sediment quality has not been assessed. The limited sediment quality sampling means that it is difficult to characterize the wetland. Analysis of the seasonal intertidal sediment quality data was undertaken during this research, and will be discussed in **Section 4.3.2**. It is not known if subtidal sediment quality sampling has been undertaken.

2.6 Water Quality

Monthly water quality samples were taken in the fiscal years of 2001 and 2002 at four subtidal sites. Temperature, Suspended Solids (SS), COD, salinity, pH, TN and TP were measured. Little spatial and temporal variation was apparent with SS averaging approximately 1mg/L, COD less than 2mg/L, pH mean of 8.3, TN typically less than 0.3mg/L, and TP less than 0.02mg/L.

Very limited water quality measurements of the freshwater discharge channels have been undertaken. Singular measurements of Biochemical Oxygen Demand (BOD) and Suspended Solids (SS) at the wetland end of the three channels were recorded on 4 February 2004, with BOD ranging between 10.0-40.8mg/L and SS ranging between 3.4-21.0mg/L. However it is difficult to assess this data, since no accompanying flow quantity data is available, nor the time of measurement and thus position of the tide. It is known that conditions were dry on that date. Suspended Solids levels of greater than 150mg/L have been measured during rainfall events in the water column at the upper zone of the tidal flat (22 February 2004; rainfall 50mm/24hours). Monthly measurements of SS and COD at the wetland end of the three channels were also conducted between August 2001 and March 2002. During a rainfall event from this period, SS of 510mg/L was recorded at one of the sites. Under dry conditions, COD ranged from 9.0-41.0mg/L.

Pore water quality has been routinely sampled at the tidal flat sampling sites between the fiscal years 2000-2004, but the methodology and the results appeared to be questionable, and so the available pore water data was not considered in this research.

2.7 Major Biological Elements

Awase wetland is very diverse, containing a wide variety of habitats (**Figure 2.6** displays a map of the major biological elements of the Awase region). As such it is host to an array of many different organisms. Those deemed most important for this study are discussed below.

2.7.1 Seagrasses and Macroalgae

There are eight seagrass species present in the nearshore waters of Awase, with the small seagrass species consisting of Halophila sp., Halodule uninervis, Halodule pinifolia, and Zostera japonica. The larger seagrass species present are *Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata*, and *Syringodium isoetifolium*. Typically in the Ryukyu Islands, *Halodule pinifolia*, *Cymodocea rotundata* and *Thalassia hemprichii* are dominant in the intertidal to upper subtidal zone, whilst *Cymodocea serrulata* are more abundant in the deeper subtidal zone (Green and Short, 2003).

Five in situ seagrass and macroalgae surveys of Awase were conducted between November 2001 and June 2004. **Figure 2.7** indicates spatial coverage for large and small seagrass surveyed (classified as large seagrass if height >30 cm). At the time of the last aquatic vegetation survey (June 2004), approximately 280 hectares of seagrass were present together with 109 hectares of large macroalgae. The majority of seagrasses consist of 10-50% cover. A dramatic decrease in the quantity of dense seagrass (50% or more cover) has been observed throughout the surveys, particularly in the large seagrass with a sharp decline from approximately 57ha in 2001 to 4ha in 2004. However annual and even decadal temporal variability can be expected in seagrass abundance, as seen through historical aerial photographs (also used to estimate spatial seagrass and macroalgae coverage). Most large seagrass occurs in 0-2m water depth (approximately 65%), with the remainder divided between +0.5-0m and 2-4m depth.

Some of the dominant macroalgae species at Awase include Halicoryne wrightii and Hydroclathrus clathratus. **Figure 2.8** shows spatial coverage and quantity for macroalgae surveyed between November 2001 and June 2004. Large fluctuations in total coverage occur from a minimum of 45ha to a maximum of 136ha. Most macroalgae is present in 0-2m water depth (approximately 60%), with up to half typically being 10-50% in coverage. A significant quantity of macroalgae (approximately 25%) is also present in +0.5-0m water depth in the intertidal zone.

2.7.2 Mangroves

The construction of a roadway in 1984 led to the successful planting and subsequent colonization of mangroves in a small area behind the roadway overpass, currently 0.8ha in size (see **Figure 2.2**). The mangrove species present are *Kandelia candel* (Mehirugi), *Bruguiera gymnorrhiza* (Ohirugi), and *Rhizophora stylosa* (Yaeyamahirugi). Through aerial photographs, the movement of mangroves to the southerly end of this region from their initial colonization in the north is evident. This suggests that sedimentation from freshwater loading has led to increased elevation, culminating in a drying out of the northerly mangrove region.

2.7.3 Coral

Small communities of coral exist at Awase in isolated outcrops, in water depths of 0.2-7.0m (see **Figure 2.6**). They occur in the coarser sediments. It has been suggested that the coral reefs in Awase are expanding slowly.

2.7.4 Benthic Fauna and Flora

Many invertebrates live on the surface or within the substrate of tidal flats and are the primary consumers. Benthic biotic data (macrobenthos, meiobenthos and macrobenthos) have been sampled on ten occasions at ten sites located along the Awase tidal flat (**Figure 2.9**). Most of the sampling sites were located in the mid-upper zone of the tidal flat. At each of the ten sites, four independent sediment samples were taken for biotic sampling using a 30cmx30cm quadrat (0.09 m^2) to a depth of 10cm. The collected sediment was washed through sized sieves and the retained material was preserved. The macroinvertebrate organisms were classified and counted.

Awase tidal flat is especially noted for its rich variety of rare shellfish (The Ministry of Environment, Japan: 500 Important Wetlands in Japan; Internet Site). Macrobenthos (size of 1mm or more) species richness and density greatly varied across the sampling stations, with a total number of 278 species identified within the five year sampling period. Molluscs, Annelids and Arthropods were found to dominate the benthic invertebrate community over the entire sampling period across the tidal flat, yet distinct spatial and temporal variation was apparent. **Figure 2.10** displays box and whisker plots of the macrofauna total number of species and total biomass at each site. Sites S4, S5, S6 and S10 typically contained the greatest number of species, dominated by the *Annelida* and *Mollusca phylum* (**Figure 2.11** displays the average % *phylum* composition at all sites). Site S1 averaged the poorest number of species, and displayed a trend of decreasing specie richness over the sampling period. Sites S2 to S6 had the highest biomass of macrofauna, largely comprised of Molluscs, with site S2 containing greatly elevated numbers due to the large gastropod populations of Batillaria zonalis and Cerithideopsilla cingulata. Sites S7, S8 and S9 repeatedly recorded the lowest densities and biomass of macrobenthic organisms consisting of Annelids and Arthropods, with few Molluscs present. Sites S1, S3 and S7 contained the highest numbers of Arthropod individuals. Further analysis of the tidal flat macrobenthic community was undertaken for this research and is discussed in **Section 4.4**.

The dominant meiobenthos (size range between 0.04mm-1.0mm) groups at Awase include *NEMATODA*, *FORAMINIFERIDA*, and nauplius of *COPEPODA*. **Figure 2.12** displays box and whisker plots of the meiofauna total number of species and total density at each of the ten intertidal sampling sites, with sites S6-S10 having the highest median number of species and abundance.

Bishoalgae was measured at the intertidal sampling sites from 5cm surface sediment cores. Dominant species include *Amphora* sp., *Navicula* sp., *Nitzschia* sp. and *Opephora* sp. **Figure 2.13** displays the mean yearly number of species and cell density of bishoalgae recorded between 2000-2004 (fiscal years). A temporal trend of increasing specie number and abundance was generally apparent, with the greatest abundance recorded in July 2004.

Aerobic and anaerobic bacteria counts were measured from the surface sediment samples at the intertidal sampling sites between 2000-2004. **Figure 2.14** shows the temporal mean bacterial concentration averaged over all sites. The aerobic bacteria averaged over all dates showed little variation between sites, ranging from 4.7E+06 to 1.4E+07.

2.7.5 Fish

Many fish species are present in the subtidal waters, with the wetland being an important area particularly for juveniles and linked to the wider environs of Nakagusuku Bay. Further data was not available regarding dominant fish species and behaviour.

2.7.6 Birds

Shorebirds (waders, gulls and terns) use the intertidal zone for feeding, and are the most important vertebrate organism on the tidal flat. Wetlands provide habitat for both indigenous bird species and migrating birds. Many bird species can be observed at Awase tidal flat particularly during the autumn migrating season and the wintering season. Among important waterfowl species include the little tern (*Sterna albifrons*), Pacific golden plover (*Pluvialis fulva*) and the Kentish plover (*Charadrius alexandrinus*). **Figure 2.15** displays the combined areas of main bird activity during low and high tide, recorded across three occasions of August 2000, November 2000 and February 2001. Most shorebirds forage primarily during low tide in the tidal flat and the mangrove region, and roost in the vegetated land adjacent to the northern edge of Awase, and in the higher elevations in the south-western corner.

2.7.7 Hill Hermit Crabs

Hermit crabs are crustaceans that use empty shells. The vegetated foreshores on the southern-western boundary and the mangrove forest of Awase provide good habitat for the land-based hill hermit crabs. The species present in Awase include *Coenobita cavipes* (Okayadokari), *Coenobita purpureus* (Merasakiokayadokari), and *Coenobita rugosus* (Nakiokayadokari).

2.8 Endangered or Threatened Species

2.8.1 Kubiremidoro

Kubiremidoro (*Pseudodichotomosiphon constricta*) is a type of marine algae, classified as endangered or critically endangered. Little is known about how this species reproduces. Awase tidal flat is one of the few locations it is known to be present in Okinawa. Distribution of Kubiremidoro at Awase has greatly fluctuated, with potential habitat (including sparsely populated areas) ranging up to 16,570m^2 during the monitoring interval of January 2000 and March 2003, and it has strong seasonal influences. Transplanting of Psuedodichotomosiphon constricta was undertaken at six sites within Katsuren Ward, Yakena Ward and Yabuchi Island of Okinawa in February 2002. After 13 months, the transplanted algae were only still present at three sites and displayed great variability.

2.8.2 Tokagehaze

The blue mud skipper or Tokagehaze (*Scartelaos histophorus*) is a threatened fish species that inhabits muddy tidal flats. Nakagusuku Bay is the sole habitat in Japan for this species (The Ministry of the Environment, Japan: 500 Important Wetlands in Japan; Internet Site). This species has been monitored at Awase since 1990, and it has shown great variability with abundance fluctuating between 2 to 37 individuals.

2.9 Anthropogenic Impacts

2.9.1 Historical Changes

Prior to the Second World War, people lived on the peninsula located on the northern boundary of Awase tidal flat. However in 1944 this area was annexed by the American military and local people were re-located to the mainland. It has since been used as a U.S. military communications complex.

Much change to the foreshore and tidal flat areas of Nakagusuku Bay has occurred during the latter half of the 20th century. Significant land reclamation has occurred, particularly from 1960 onwards, producing significant change to the foreshore together with loss of tidal flat area. **Figure 2.16** displays a historical aerial photo of the Awase region taken in 1945, together with a more recent aerial photo (1990). Shoreline development includes land reclamation, roadway construction, and seawall construction. Change has also occurred to the coastal bathymetry from the creation of navigation channels, the dredging of coastal sand for development and the construction of breakwaters.

2.9.2 Point Source Discharges

As mentioned previously in **Section 2.4**, there are presently three sewage/runoff point source discharges in the immediate vicinity of Awase wetland. The sewage system catchment area for Awase in 2001 was approximately 2700 hectares. The sewage effluent is currently not treated, and **Section 2.6** discussed the limited available water quality data of the discharge. The construction of a new sewage treatment plant is expected to be completed in the future, with a significant proportion of the effluent to be re-directed to the new facility, but the expected timeframe of construction is uncertain, nor the remaining loads that will still input into Awase.

2.9.3 Landfill Development

The Okinawa City East Beach Development Plan is an offshore land reclamation project by the Central Government and the Okinawa Prefectural Government. The construction of a landfill island to house hotel complexes amongst other urban development is located within the Awase wetland, 200m from the shore (see **Figure 2.2**). Initial construction commenced in 2004 and the project is due for completion in 2014. The development involves land reclamation, beach and marina construction, together with the creation of navigation channels. The size of the island is 187 ha (hectares). The original project design called for landfill contiguous with the shoreline. This was changed to an artificial island as a measure to avoid impacts on species such as shorebirds and shellfish, and also on marine product harvest by local people.

Direct habitat losses due to the landfill project include the destruction of approximately 49 ha of seagrasses (25ha have coverage greater than 50%) and the loss of 49 ha of tidal flat area. Mitigation measures were recommended in the Environmental Impact Assessment (EIA) conducted for the project to compensate for the unavoidable loss of habitat including the transplanting of 25 ha of seagrasses, the creation of small artificial tidal flats (4 ha in size) and possible bird habitat on the island. Transplanting trials of seagrass have been undertaken. An area based assessment of targeted seagrass species shows significant evidence of a gradual succession after a lag-phase of transplant impacts. Nevertheless, a density based assessment shows the marginal succession.

2.10 Social-Economic Use

The local people have historically used Awase tidal flat and subtidal areas for collecting shellfish and fishing, and it remains an important food source and tradition for the people of the area today. It is also an area for recreation, including activities such as bird-watching, recreational fishing and walking. Other economic uses include the local commercial fishing industry of Nakagusuku Bay (for which Awase wetland is of importance for juvenile fish), and there is an expectation to increase tourism to the area by the offshore landfill development.

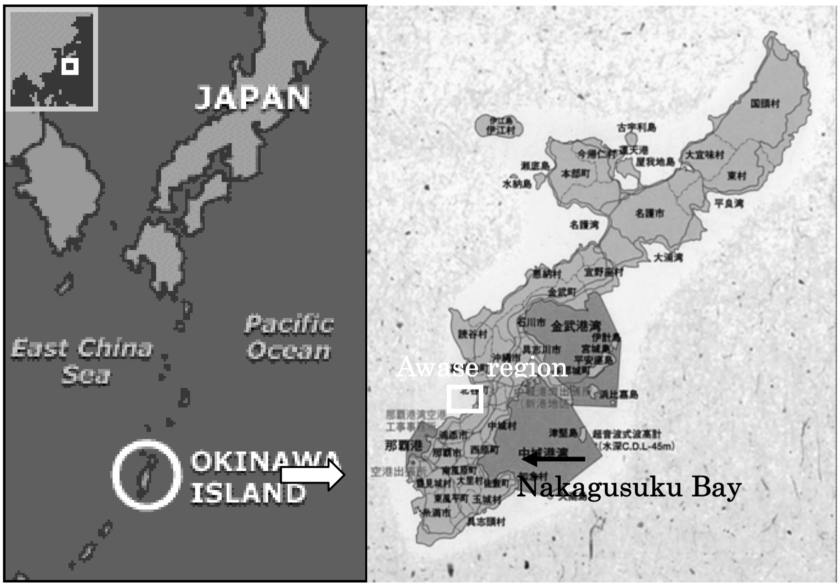

Figure 2.1 Location map of Okinawa Island, Nakagusuku Bay and Awase region.

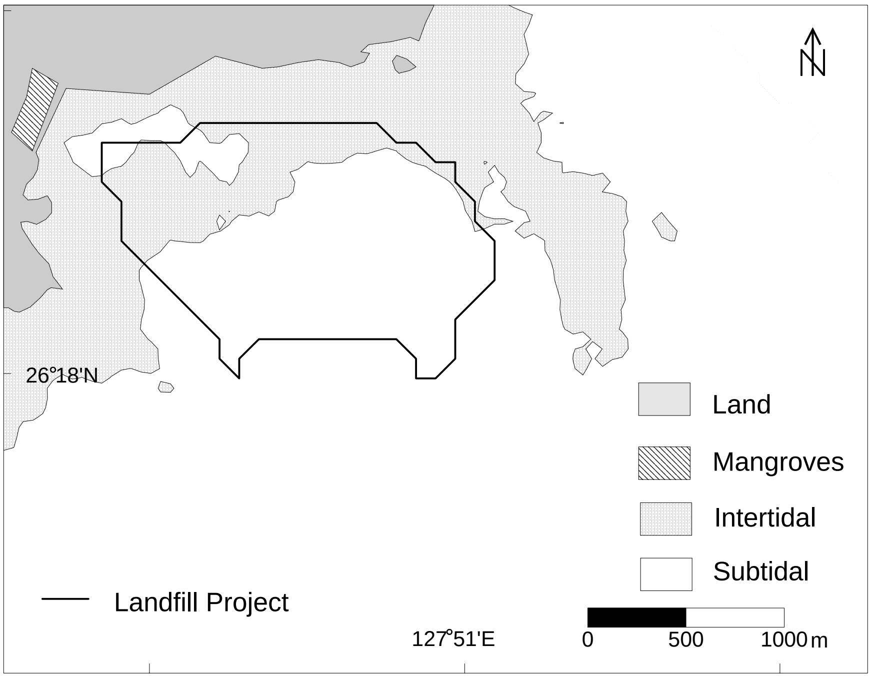

Figure 2.2 Basemap of Awase wetland and future landfill project outline (including marina area).

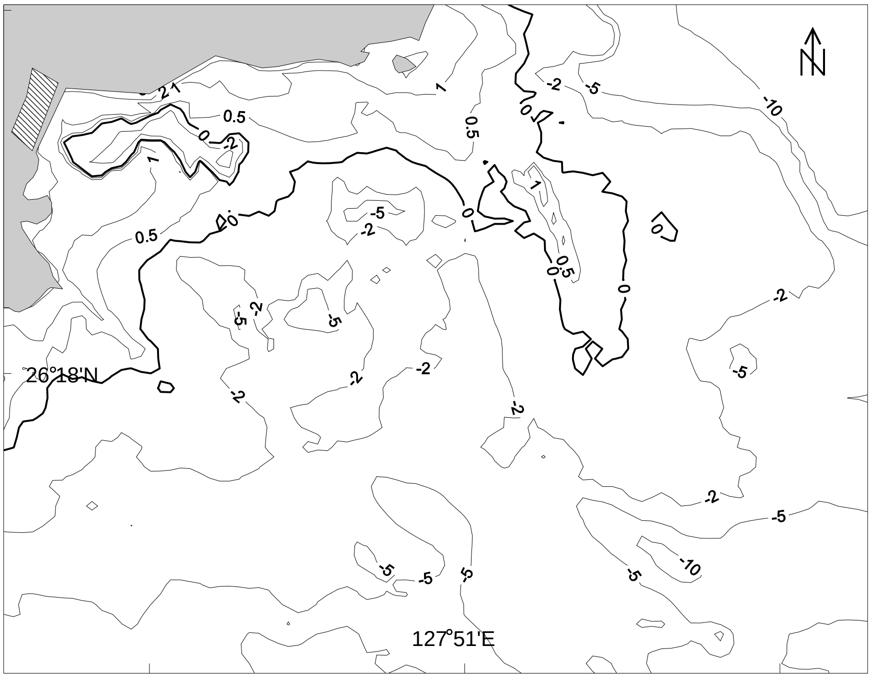

Figure 2.3 Bathymetric and topographic map of Awase region.

Figure 2.4 Freshwater drainage channel paths in Awase.

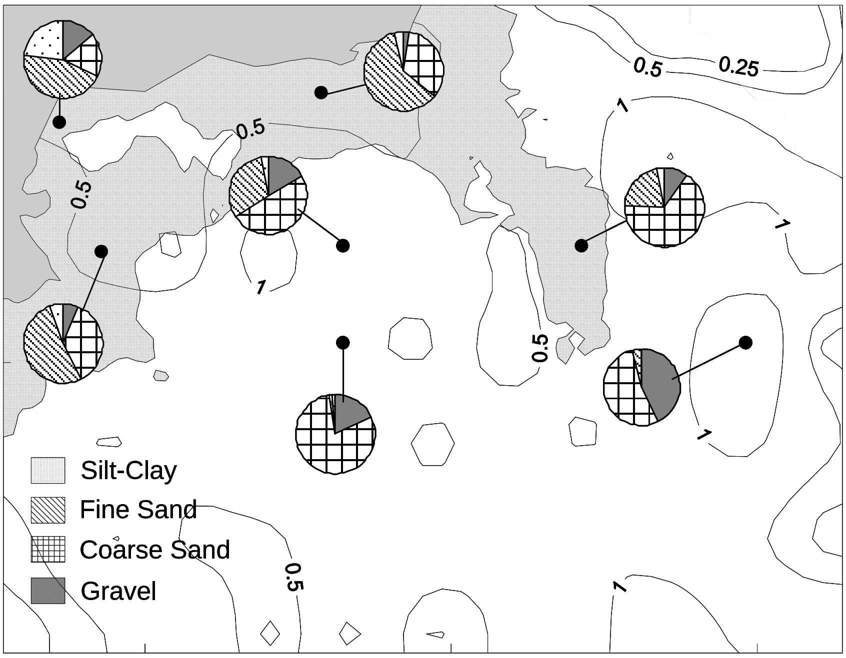

Figure 2.5 Contoured median sediment grain size (D_{50}) based on the comprehensive data from 2001 are shown, together with some example percent compositions from both intertidal and subtidal sites.

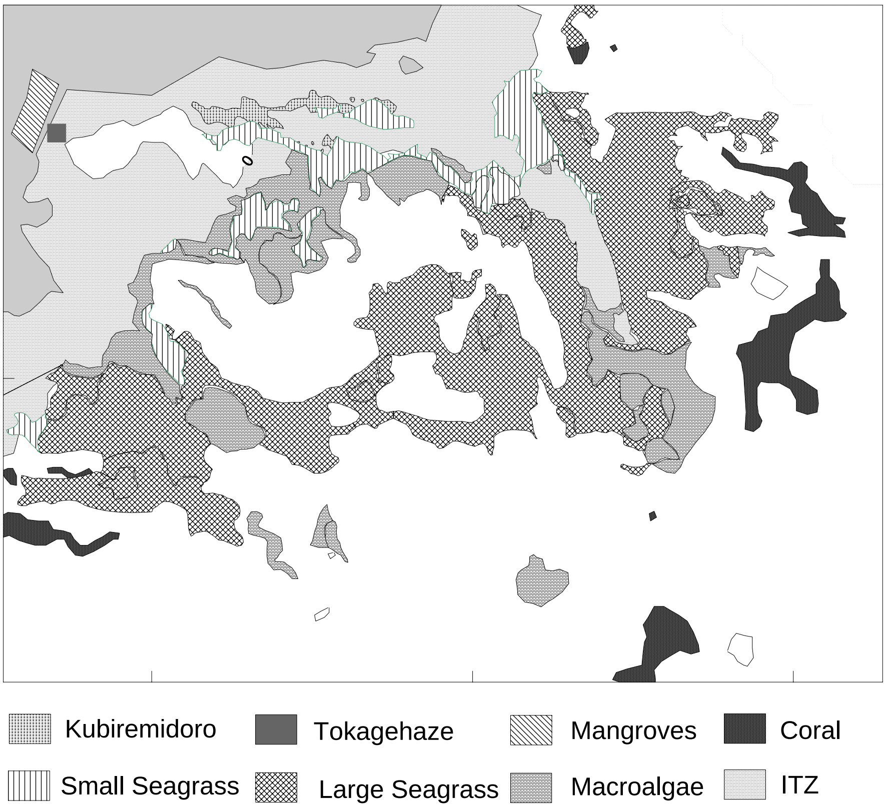

Figure 2.6 Map of major biota and habitat elements of Awase wetland. ITZ refers to intertidal zone.

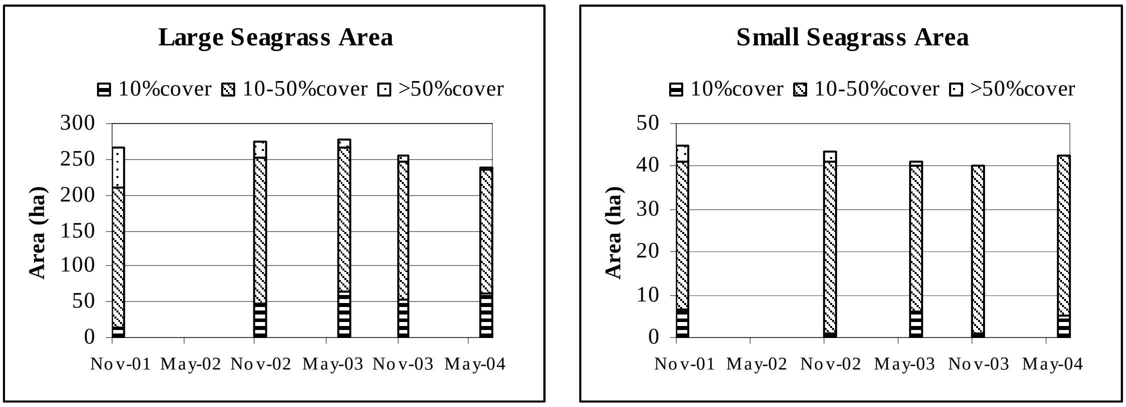

Figure 2.7 Large and small seagrass spatial coverage survey results (2001-2004).

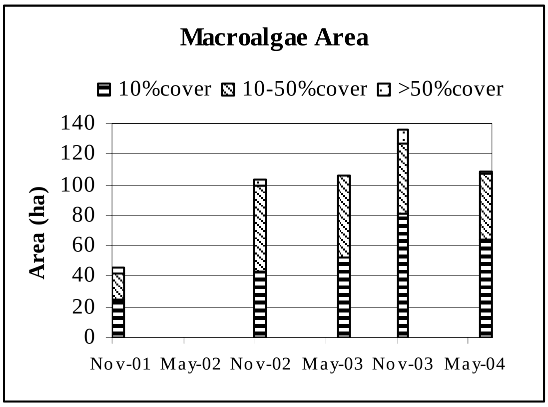

Figure 2.8 Macroalgae spatial coverage survey results (2001-2004).

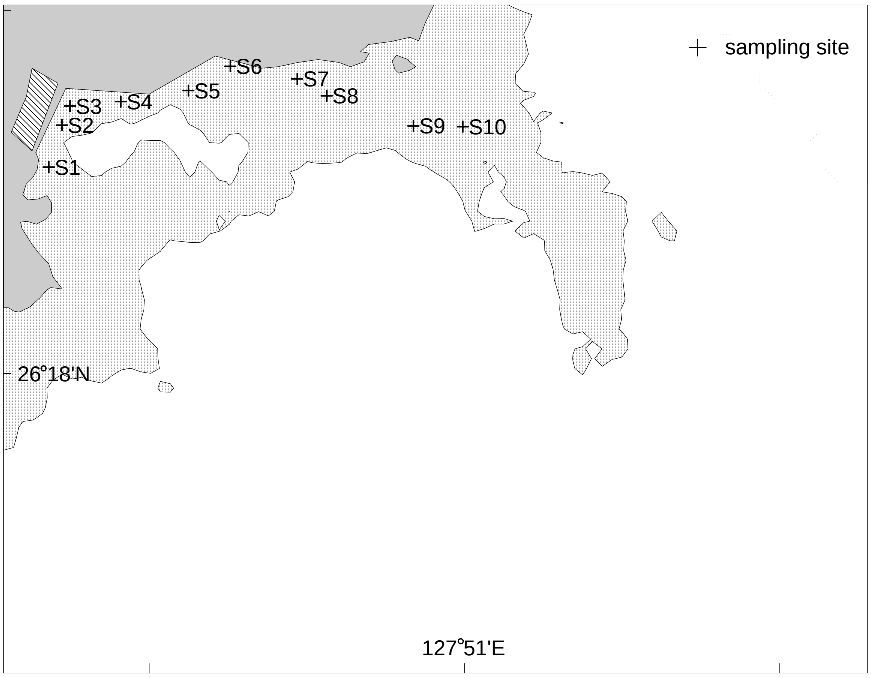

Figure 2.9 Awase tidal flat sediment and biota sampling sites.

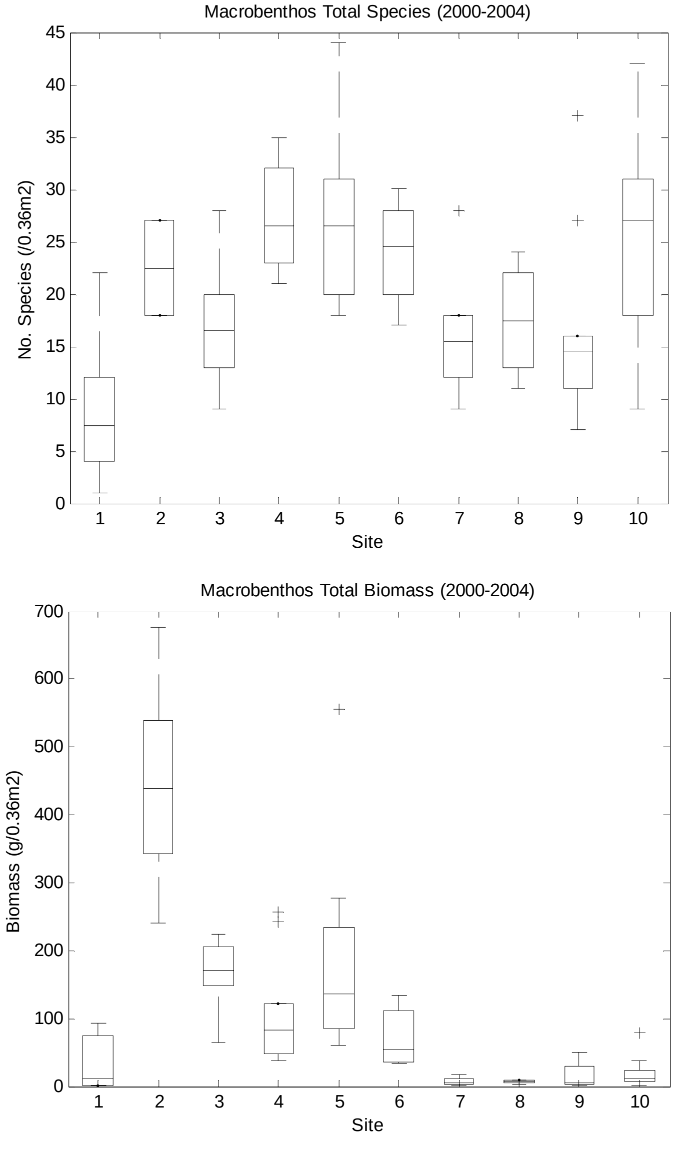

Figure 2.10 Box and whisker plots of macrobenthos total number of species and total biomass respectively, with the lines demarcating the lower quartile, median, and upper quartile values. The whiskers show the extent of the rest of the data and + representing outliers.

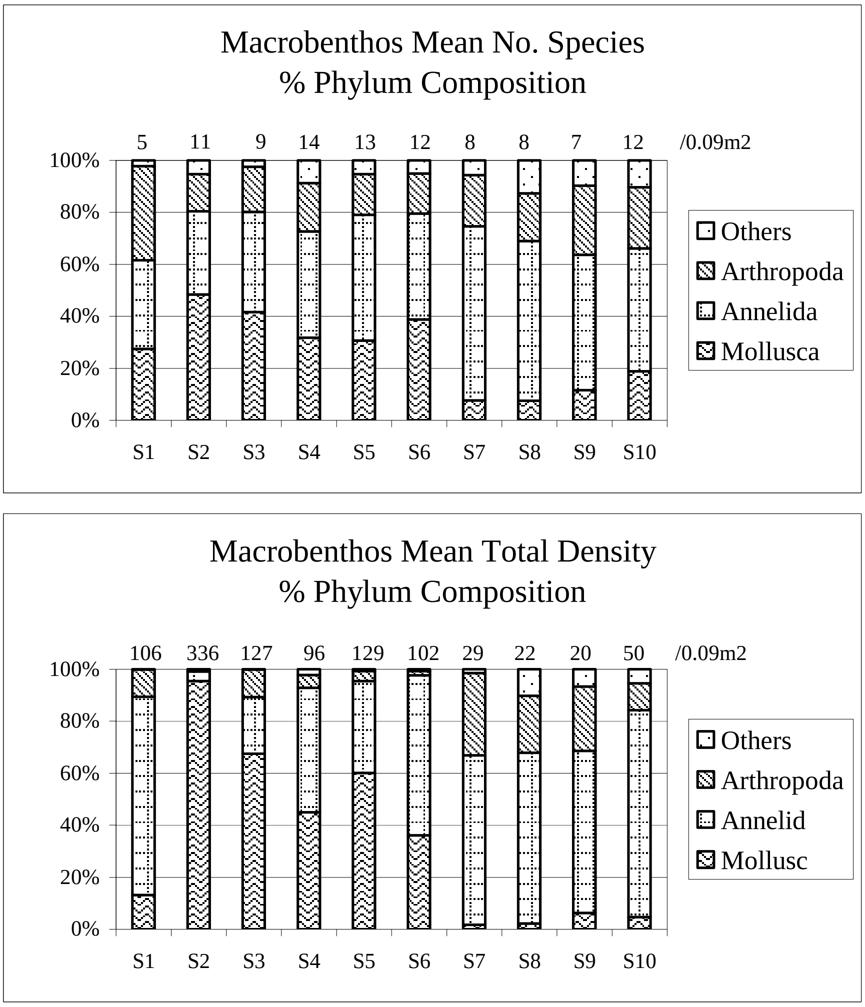

Figure 2.11 Percentage of number of species and abundance of major macrobenthos phylum for sampling sites S1-S10, averaged between fiscal years 2000-2004.

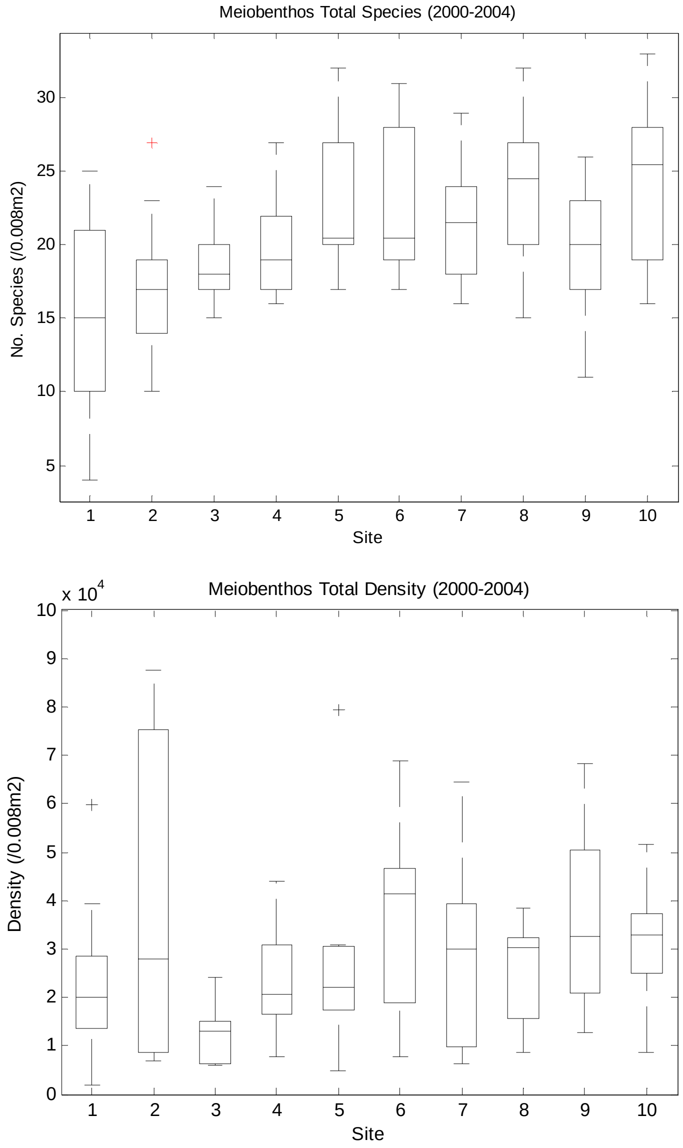

Figure 2.12 Box and whisker plots of meiobenthos total number of species and total biomass respectively, with the lines demarcating the lower quartile, median, and upper quartile values. The whiskers show the extent of the rest of the data and + representing outliers.

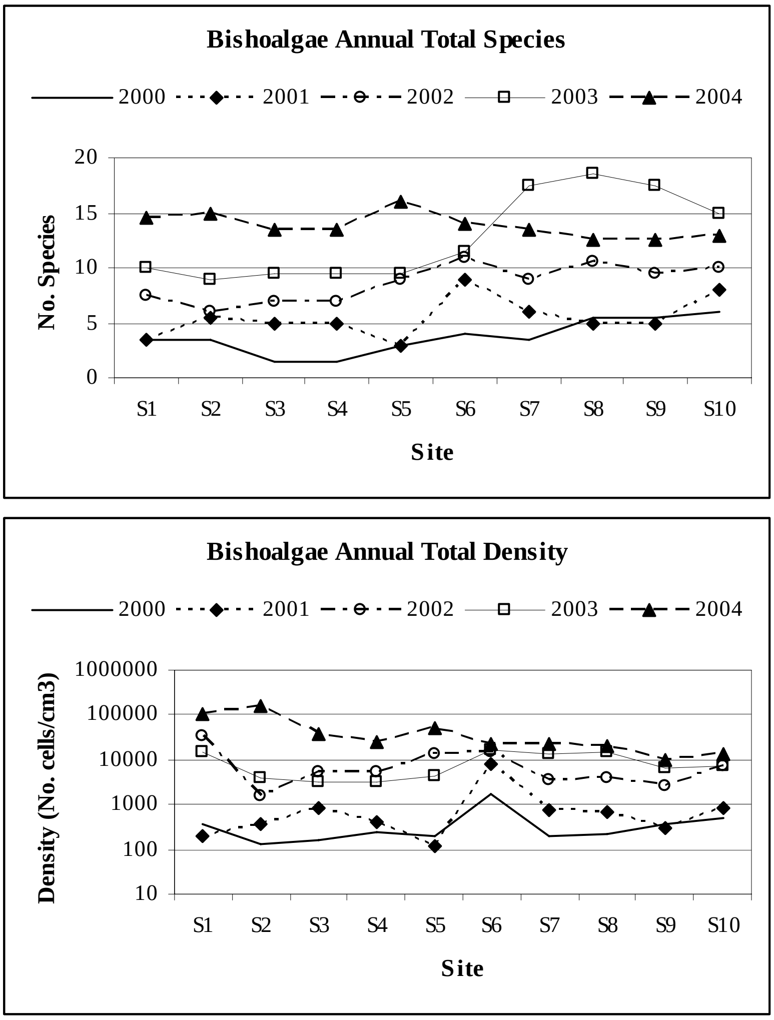

Figure 2.13 Bishoalgae annual total number of species and density for sampling sites S1-S10. Note that dates given refer to the fiscal year.

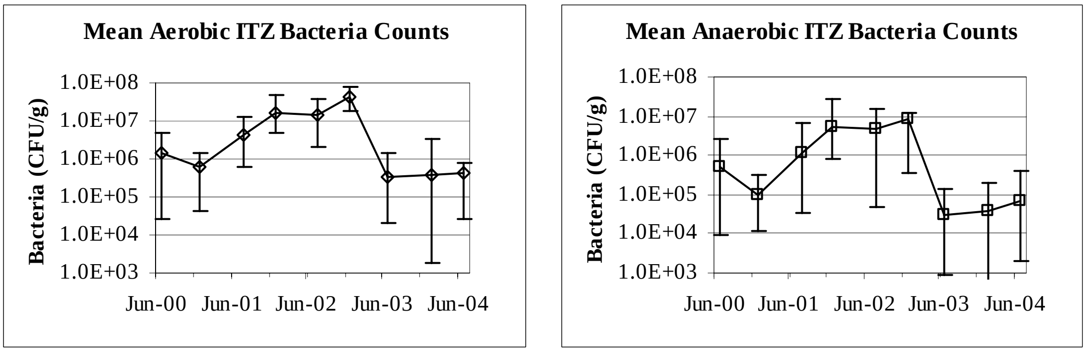

Figure 2.14 Time series of mean aerobic and anaerobic bacteria of sampling sites S1-S10. The bars indicate maximum and minimum values.

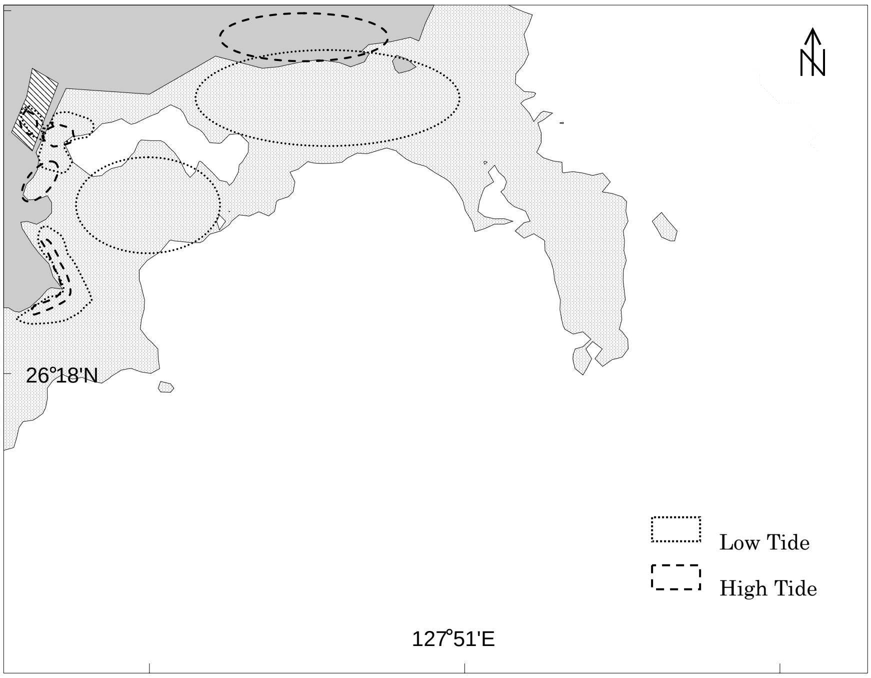

Figure 2.15 Combined bird distribution at Awase at low tide and high tide recorded on August 2000, November 2000 and February 2001.

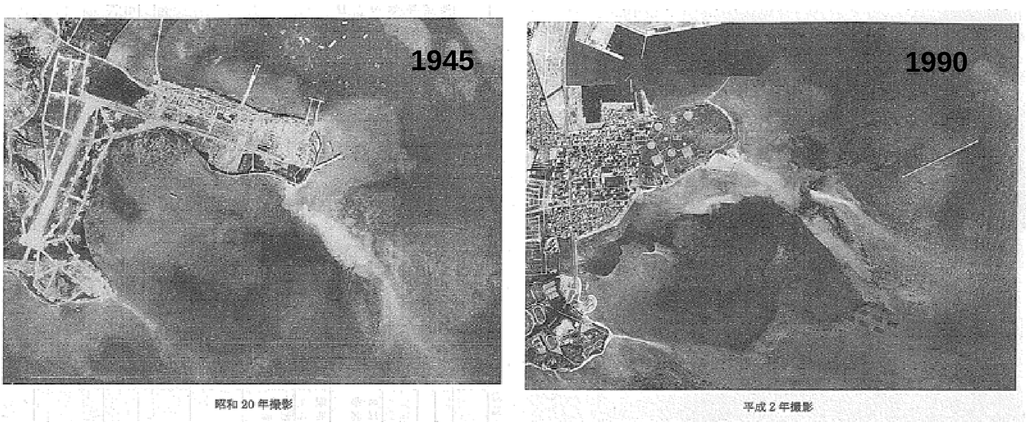

Figure 2.16 Historical aerial photographs of Awase wetland from 1945 and 1990.

3. WETLAND FUNCTIONS

3.1 Functions and Values

In order to determine the wetland condition, the relations and dynamics among the various elements must be understood. Wetlands have many functions over a range of factors and scales. They are very active and dynamic environments with suitable conditions for the growth of organisms that form the basis of the food web and feed many animals such as shellfish. Many species of birds depend on wetlands for food and shelter, particularly during migration and breeding. The biological functions that Awase wetland provides include productivity, diversity and habitat provision. Awase, as a coastal wetland has important hydraulic functions including shoreline protection by attenuating wave energy through frictional effects, providing erosion control, and the trapping of sediment. Awase region also assists in naturally improving the water quality through interception of poor incoming water by the mangrove forest, and by processing and recycling nutrients and elements. In addition, Awase wetland provides socio-economic functions such as food production, recreation, education and research.

3.2 Ecological Functions

The combination of the individual constituents (ecosystem structure) and the relationships between the various elements (function) can be considered in terms of energy input and consumption, and nutrient input and cycling.

3.2.1 Energy Flow

A wetland is a system with many trophic interactions, and a sound understanding of energy flow or food web dynamics and trophic links is essential. **Figure 3.1** displays a representative food web for intertidal flat ecosystems (WAVE, 2001), demonstrating the trophic interactions by which energy or organic matter flows through the system. A simplified summary of the intertidal food web can be described as the primary food supply consisting of organic input (detritus) and primary production (benthic algae), then at the secondary level are macrobenthos as primary consumers, and at the top of the food chain the carnivores, with birds being the largest consumers on the tidal flat (although other organisms such as fish and crabs can also be significant). Intertidal sediments often have high levels of microphytobenthos biomass and productivity (Colijn and de Jonge, 1984). When considering biomass magnitudes, tidal flat systems are often dominated by dense populations of macrobenthos (Kuipers et al., 1981). In Awase wetland, it is important to attempt to identify the biomass, production and consumption at the different trophic levels. Currently the data to do this remains unavailable. However, if the data were available, it is proposed that a simplified energy flow structure like that shown in **Table 3.1** could be applied to Awase tidal flat, with quantities expressed as yearly averages in gC/m^2 where C is carbon. (It should be noted that bacteria, microfauna and meiofauna have complex interactions with the macrobenthos and carnivores within this much simplified larger structure (Kuipers et al., 1981)). The only determinable quantity from the data available at this point in time is the average macrobenthos wet weight biomass estimated from the intertidal sampling sites S2-S10 as $317g/m^2$ (conversion is necessary into carbon).

Local information at Awase of the major species that are consumed (e.g. what benthic fauna are preferred by particular bird species) and identification of what type of feeders the dominant macrobenthos species are, is of importance to better understand the intertidal food web and trophic interactions. Even less knowledge is known at Awase about the subtidal biomass, production and consumption quantities, and of course the food web is completely different with phytoplankton being a dominant primary producer, consumed by zooplankton, then fish and so on. Again further research must be undertaken to gain a more complete understanding of how the wetland functions.

3.2.2 Material Cycling

Tidal flats have a significant role in the degradation and transformation of organic material, either transported in or produced insitu. Material or element cycling describes where and how fast materials move in a system. Ecosystems cycle materials (such as nitrogen, phosphorous and carbon) and important questions include how these materials flow along the pathways in a food chain or the rate at which nutrients are recycled in the system. The cycling of nitrogen and phosphorous is of importance because it is often the limiting element for algal production in the coastal region (particularly nitrogen). There are many biotic and sedimentological interactions that have an effect on tidal flat dynamics, with nutrient cycling being among the most important processes. The major processes of transformation of the nutrient cycle in intertidal flats include mineralization, nitrification, denitrification, nitrate reduction, assimilation and macrofauna excretion, with denitrification being the major process by which nitrogen is lost. Intertidal sediments are important in nutrient cycling, yet the tidal flat is a difficult region to study and define because the intertidal sediment surface changes with the tidal cycle from a sediment-water interface to a sediment-air interface with associated shifts in the biogeochemical processes. Insufficient data exists to begin to assess the nutrient cycles at Awase tidal flat, with available sediment nutrient measurements consisting only of seasonal Total Nitrogen and Total Phosphorous concentrations (i.e. no speciation data), and no associated water column information. The incoming nutrient loading also remains unknown at this point in time. Thus further research must be undertaken to understand these very important processes.

Table 3.1 Simplified tidal flat energy flow identification structure.

Trophic Level	Feature
Primary Food Supply	Detritus input
	Benthic algae production
	Total
Macrobenthos	Consumption
	Biomass
	Production
Carnivores (consumption)	Birds
	Fish
	Invertebrates (e.g. crabs, prawns)
	Total

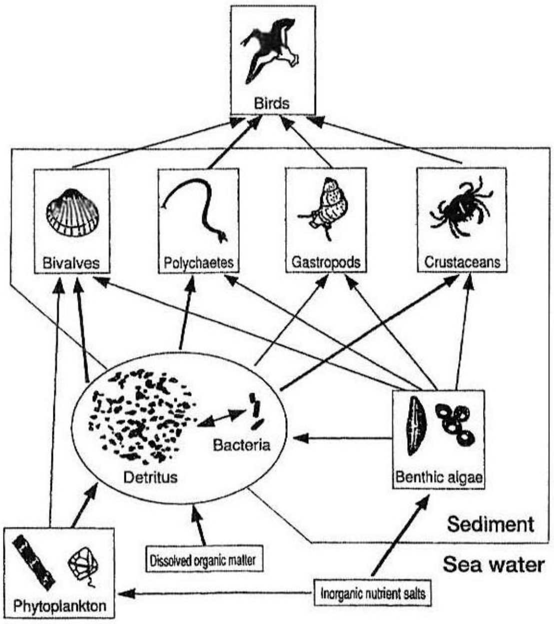

Figure 3.1 Typical food web for intertidal flat ecosystems showing the trophic levels and links (WAVE, 2001).

4. TIDAL FLAT ANALYSIS

The physical and chemical factors that constitute the abiotic environment are crucial to influencing the biological community that is present. The objective at Awase tidal flat was to assess whether macrofauna and environmental conditions varied over the tidal flat, and to identify the environmental properties that most influenced the macrobenthos community.

4.1 Sampling

As mentioned previously, sediment composition, sediment quality and benthic biota were sampled on ten occasions at Awase tidal flat, at the seasonal intervals of summer and winter between July 2000 and February 2005. Ten sites located throughout the intertidal zone were sampled (shown previously in **Figure 2.9**), with station heights ranging in elevation between approximately 0.3-2.0m.

Sediment samples were collected from a 5cm diameter core to a depth of 20cm. Oxidation Reduction Potential (ORP) profiles were measured in the top 20cm of the sediment at depths of 2, 5, 10 and 20cm. Tidal flat surface sediment samples were analysed for sediment composition, pH, Sulfide, COD, TOC, TN, TP and Chlorophyll-a. The benthic sampling details were outlined previously in **Section 2.7.4**.

4.2 Analysis Methodology

Temporal and spatial differences in both the macrobenthos and environmental data were assessed. Prior to analysis, normality and homogeneity of variance was tested using Kolmogorov-Smirnov test and Cochran's test respectively. Transformation of the data was undertaken with the benthic abundance data fourth root transformed, the biomass data log(x+1) transformed, the sediment composition categories were arcsin transformed, and the environmental variables log transformed (i.e. Sulfide, COD, TOC, TN, TP and Chla), with the exception of pH and elevation. When homoscedascity was achieved, two-way ANOVA analysis was applied (station x date), otherwise the non-parametric Kruskal-Wallis test was applied. Significance was applied at the 0.05 level, with post hoc tests using the Bonferroni criteria conducted to further identify differences between sites or dates.

Principal Component Analysis (PCA) was conducted on the sediment composition data to reduce the number of sediment composition categories. Correlations between the first three principal component sediment composition axes (pca1, pca2 and pca3), sediment quality variables and elevation were assessed. Highly correlated parameters ($R^2>0.70$) were reduced.

Both univariate and multivariate statistical methods were used to reveal macrobenthos community patterns. Univariate community measures such as species richness (*S*), Shannon-Wiener Index *H'* (**Eq. 1**), Simpson's Diversity Index *1-D* (**Eq. 2**) and Shannon Evenness *J'* (**Eq. 3**) were determined for the macroinvertebrate specie and abundance quadrat pooled data at each site and sampling date.

Shannon-Wiener Index:

$$H' = \sum_{i=1}^{S} p_i \log p_i \tag{1}$$

Simpson's Diversity Index:

$$1 - D = \sum_{i=1}^{S} \frac{n_i(n_i - 1)}{N(N-1)} \tag{2}$$

Shannon Evenness:

$$J' = \frac{H'}{H'_{\max}} = \frac{H'}{\log S} \tag{3}$$

where *S*=number of species, n_i=number of individuals in the ith species, p_i=proportion of individuals in the ith species, and *N* is the total number of individuals.

Multivariate statistics including cluster analysis and non-metric multi-dimensional scaling (nMDS) were used to evaluate the spatial distribution of the macroinvertebrate community data, with these methods categorizing the sites into groups containing mutually similar benthic community structure. The Bray-Curtis dissimilarity index matrix (**Eq. 4**) was determined from the transformed macroinvertebrate data, ranging from 0 (similar) to 1 (dissimilar).

$$B = \frac{\sum_{i=1}^{S} \left| n_{ij} - n_{ik} \right|}{\sum_{i=1}^{S} \left(n_{ij} + n_{ik} \right)} \qquad (4)$$

where *B* is the measure of dissimilarity, *S* is the number of species in samples, n_{ij}, n_{ik} is the number of individuals in species *i* in each sample *j*, *k*.

Group average linkage was applied and cluster analysis performed, with the results visualized using a dendrogram. ANOSIM (analysis of similarity method) technique was then used to detect statistically significant differences between the groups previously determined from the cluster analysis (Clarke and Green, 1988).

A dissimilarity matrix was calculated based on Euclidean distance measure on the reduced environmental variables. BIOENV analysis, a correlation between the biotic matrix with all possible subsets of the environmental matrix (Clarke and Ainsworth, 1993), was conducted to compare the relationship between abiotic variables with the macrobenthos community structure. Multiple regression of the individual and combined effects of the environmental variables on the major nMDS ordination axes was also undertaken.

Matlab software (Mathworks, 2005) was used for all programming and statistical analysis.

4.3 Sediment Results

Table 4.1 summarises the mean and median characteristic features of the sediment at the sampling sites in the tidal flat. Oxidation Reduction Potential (ORP) results demonstrated that the sediments in sites S6 to S9 inclusive were completely oxidized within the top 20cm sediment depth. Sites S1 to S5 displayed reducing conditions closer to the sediment surface, with site S2 often showing strong reducing conditions at the surface (7 out of 10 sampling dates). Site 10 showed an oxidative condition until a deeper zone, generally greater than 10cm in depth from surface.

4.3.1 Sediment Composition

Mean sediments sizes at the sampling sites were predominantly fine and medium sands (**Figure 4.1**), together with a smaller proportion of gravels (typically between 5-20%). Stations S1, S4 and S10 contained coarser sediments. Site S2 consisted of much finer sediments with the highest silt-clay content across the tidal flat, averaging 20%. There were highly significant statistical differences between the sampling sites for all sediment categories (ANOVA test: $p<0.0001$) with the exception of coarse gravel (not significant). Common features identified through post hoc tests were that S2 was repeatedly different to all other sites for silt-clay, fine and medium sands, and the isolation of S10 due to elevated coarse sand and gravels.

Principal Component Analysis was conducted on the annual sediment composition of sites S2-S10 (site S1 was removed from analysis due to large temporal changes further explained in **Section 4.6**). The first three principal component axes explained 88% of the variance, with Factor 1 positively composed of coarse sand, fine gravel, and medium gravel categories (**Table 4.2**), together with a negative correlation with fine sand. Factor 2 had a strong positive correlation with medium sand and a negative relationship with silt-clay. Factor 3 was dominated by a negative correlation with coarse gravel. **Figure 4.2** displays the scaled sediment category eigenvectors together with the first and second principal component axis co-ordinates for each site. Data partitioning was applied to the three axes in order to ascertain if summer and winter seasonality existed at any of the sites, but no significant seasonality existed in any of the factors at any of the sampling sites. In all further analysis, the three principal component axes were applied for sediment composition unless otherwise stated.

4.3.2 Sediment Quality

Mean sediment quality parameters for sampling sites S1-S10 are shown in **Table 4.3**, together with the standard deviations. Time series sediment quality data for COD, TOC, TN, TP and Chla variables at all sampling sites are shown in **Appendix B**. Sediment pH varied between 7.4 and 9.1 throughout all the sampling sites and dates, with no statistically significant variation between the stations. Mean sediment Sulfide ranged between <0.01 to 0.13 mg/g across all sites, with concentrations frequently being below detection level between sites S6 to S10 (*i.e.* <0.01 mg/g; these results were incorporated in the sediment quality data matrix at half the measurable resolution as 0.005mg/g). Site S2 repeatedly recorded the highest Sulfide levels, averaging 0.10 mg/g. COD concentrations varied from 0.1 to 11.4 mg/g across the sampling sites and dates, with TOC levels between 0.2-8.8 mg/g, TN ranged between 0.005-1.13 mg/g, and TP typically measured between 0.14-0.75 mg/g (see data in **Appendix B**). It is important to note that Total Phosphorous was generally of equivalent magnitude to Total Nitrogen. Sites S1 and S2 averaged the highest mean concentrations of COD, TOC, TN and TP in the sediment, with sites S7, S8 and S9 containing the lowest levels (**Table 4.3**). Sediment Chlorophyll-a ranged between 0.5 to 10.2 μg/g, with site S5 recording the maximum and also the highest mean concentration. Site S2 also contained relatively elevated sediment Chlorophyll-a concentrations.

Sediment quality parameters were statistically different between sites S2-S10 (Kruskal-Wallis test: $p<0.0001$). Post hoc tests demonstrated that for every parameter, site S2 proved to be significantly different to sites S7-S10, and often to site S6 as well, with elevated sediment quality concentrations. Sites S1, S3, S4 and S5 also showed significant differences to sites S6-S9 in various combinations for COD, TOC, TN, TP and Chla, with the former group elevated in relative concentration magnitudes of all these parameters.

Data partitioning was applied to the transformed data and seasonality tested, but no statistically significant differences in seasons existed with the exception of Sulfide at S2 and TN at S9 (Kruskal-Wallis tests: $p<0.05$). Sulfide levels at site S2 were slightly elevated during summer, and total nitrogen had a large increase in July 2004 at site S9.

Substantially increased Sulfide concentrations occurred at site S1 in 2004 and 2005, ranging between 0.32-0.60 mg/g, an increase of an order of magnitude from the levels measured between 2000 to 2003 at this site and statistically different (ANOVA test: $p<0.01$). Other sediment quality concentrations were also elevated at site S1 in 2004 and 2005, with the parameters pH, TOC and TN also proving to be significantly different in these latter years (ANOVA tests: $p<0.01$).

4.3.3 Sediment Properties

Pearson's pairwise linear correlation coefficients were calculated between the sediment composition PCA major axes (pca1, pca2, pca3) and the transformed sediment quality variables for all sampling dates of sites S2-S10. The results are presented in **Table 4.4**. The highest correlation was between TOC and TP ($R^2=0.82$), with strong positive correlations ($R^2\geq0.70$) found between TOC and Sulfide, TOC and TN, COD and Chla, and Sulfide with TP and TN.

The physical and chemical conditions of the sediment of the intertidal sampling sites indicate that the more exposed sites of S6 to S10 contain the lowest silt-clay fractions and sediment organic matter, and consist of sediments that are deeply oxidized. Site S2 represents a region on the tidal flat of high silt-clay particulates with strong sediment reducing conditions and elevated organic carbon and nutrients. Sites S3 to S5 reflect intermediate conditions. Site S1 is highly variable, with large temporal changes during the sampling period in sediment quality.

4.4 Macrobenthos Results

The characterization of the macrobenthos present at Awase tidal flat was discussed previously in **Section 2.7.4**. Macrofauna samples from site S1 displayed large temporal changes with marked difference in community assemblage in latter years, and as such, this site was not incorporated in the multivariate analysis. The method of removing outlier stations is suggested in order that it does not hinder the remaining site groupings (Olsgard, 1993), and thus this site is discussed independently in **Section 4.6**.

4.4.1 Univariate Community Measures

The mean annual univariate community measures of H', $1\text{-}D$ and J' for all stations are presented in **Figure 4.3**. Site S2, and site S1 from August 2002 onwards, frequently displayed the lowest values of diversity in all community measures, and were statistically different from other sites in all three univariate measures (Kruskal-Wallis tests: $p<0.0001$). Relative consistency in macroinvertebrate specie diversity and evenness was apparent between stations S4 to S10.

4.4.2 Seasonality

The number of macrobenthos species, abundance and biomass of the major groups of Mollusca, Annelida and Arthropoda, and the total macrofauna were examined for seasonal summer and winter differences, with the results summarized in **Table 4.5**. Within the major groups, no significant seasonal differences were seen in the Mollusca phylum. The Annelida phylum showed significant seasonality in density at sites S2 and S3 (ANOVA tests: $p<0.05$), and in biomass at sites S2 and S5 (Kruskal-Wallis tests: $p<0.01$), with increased numbers and biomass in the winter season predominantly due to Ceratonereis sp. at sites S2 and S5, and Armandia sp. at site S3. The Arthropoda phylum had slight seasonal variation in the number of species at sites S7 and S10 (ANOVA tests: $p<0.05$), with increased species richness during winter. The total macrofauna showed seasonal difference only in the number of species at site S2 (ANOVA test: $p<0.01$), with increases during winter. Density and biomass of total macrofauna remained indifferent to seasonal variation. Thus it is concluded that since minimal seasonal variation was apparent in the total macrofauna structure data, from this point onward, all multivariate analysis and discussion is related to mean annual data for the macrobenthos specie matrix.

4.4.3 Macrobenthos Assemblage Spatial Distribution

Similarities between the macrobenthos community assemblages from sites S2-S10 were examined. The cluster analysis dendrogram (**Figure 4.4**) identified three groups at the arbitrary 70% dissimilarity level. Group I was composed of sites S2 to S6 inclusive, Group II of sites S7, S8, and S9, and Group III was comprised of site S10 together with sites S8 and S9 2003 results. The cluster groupings were superimposed on the non-metric multi-dimensional scaling ordination plot (**Figure 4.5**) and the pattern distribution shows very good agreement. Analysis of similarity (ANOSIM) between the three groups demonstrated significant differences between all groups (p=0.001), with the global test R statistic being R=0.84 and for all pairwise tests between individual groups R≥0.71. These results indicate a large difference in overall benthic community structure between the three delineated groups (I, II and III), and good intra-group similarity.

4.4.4 Dominant Macrobenthos Species

For the three benthic groups identified from the macrobenthos community assemblages (**Section 4.4.3**) together with anomalous site S1, a comparison of the mean densities and percent occurrence of the five most abundant species are presented in **Table 4.6**. Batillaria zonalis (Group I), Cerithideopsilla cingulata (Group I), Ceratonereis sp. (Group I), Mictyris brevidactylus (Group II) and Syllinae (Group III) were the most numerically dominant macroinvertebrate species in the three benthic groupings. Armandia sp. and Ceratonereis sp. were among the top six species present in all three regions across the intertidal zone. The gastropod Batillaria zonalis was dominant at sites S2 to S6. The gastropod Cerithdeopsilla cingulata was highly represented at site S2, and the polychaetes Ceratonereis sp. at sites S4, S5 and S6, and Armandia sp. at stations S3 and S6 respectively. Further information is required regarding the feeding behaviour of these dominant macrobenthos species.

4.5 Macrobenthos and Environmental Variables

Relationships between the macrobenthos and environmental variables were investigated. Sediment environmental variables that best matched the macrobenthic community assemblage pattern (determined in **Section 4.4.3**) were assessed using non-parametric BIOENV analysis. A reduction in environmental parameters occurred prior to analysis due to inter-correlation between variables, with the remaining parameters of sediment composition PCA factors pca1, pca2, pca3, pH, COD, TOC, and elevation being included in the analysis. From the results of the BIOENV analysis (**Table 4.7**), the combination of variables presenting the largest rank correlation between the biotic and abiotic similarity matrices consisted of pca1, COD, TOC and elevation (ρ=0.59). Chemical Oxygen Demand was the highest correlated single variable (ρ=0.43), followed by total organic carbon (ρ=0.35). **Figure 4.6** displays the data of sediment Factor 1 (pca1), COD and TOC assembled according to the three benthic groups. Typically Group I have higher TOC and COD values, with Groups II and III associated with less finer sediments.

To further examine the effect of all the environmental variables of the macrofauna community distribution, the nMDS ordination of the specie abundance (determined in **Section 4.4.3**) was correlated with all environmental variables, with the results shown in the biplot (**Figure 4.5**). The vectors for each variable are oriented in the direction of maximum correlation, with vector length an indication of the relative contribution of each variable. The sediment organic matter is strongly correlated with the macrofaunal community of Group I (sites S2-S6), driven by the correlations with station S2. The community structure at the more exposed sites of S7-S10 is dominated by sediment grain size and pH. An alternative methodology was applied to assess abiotic variable to biotic matrix correlations by multiple regression of the individual and combined effects of environmental variables on the two nMDS ordination axes (**Table 4.8**). Note that reduced environmental parameters were again employed. COD accounted for 53% (adjusted R2) of the variance of ordination axis 1, with a decreasing gradient from site S2. The combined effect of all variables included in the model accounted for 76% of the variance of axis 1, with the same combined variables as the BIOENV analysis producing the best correlation. The environmental variables had much less influence on the secondary ordination axis, with only the sediment composition factors of pca1, pca2 and COD being significant, with the combined effect accounting for only 31% of the variance. This suggests that perhaps an unknown factor (or factor combination) could be of significance in accounting for the secondary axis variation.

4.6 Site S1

Large temporal changes in the macrofauna have occurred at site S1, with a sharp decline in the total number of species and total biomass in the year of 2002 (**Figure 4.7**). Site S1 showed large temporal variation in univariate community measures (**Figure 4.3**), with a dramatic decrease in the indices of H' and 1-D from August 2002 onwards, and the groups of years 2000-2001 versus years 2002-2004 being very significantly different in all three parameters (Krukal-Wallis tests: p<0.0001). This was confirmed by temporal changes in the macrobenthos community assemblage with **Figure 4.8** showing the nMDS plot, initially demonstrating close community grouping from July 2000 until January 2002. After this point in time, dramatic changes occurred in the community structure, corresponding to the decrease in gastropod dominated population, and later supporting variable populations of fauna such as CHIRONOMIDAE (insect larvae), *CAPITELLIDAE* and *Capitella* sp. (which can be indicative of organic or pollutant loading).

Site S1 has the highest elevation of the intertidal sampling sites (approximately +2.3m). A site visit in October 2005, confirmed that this site is now located in brackish waters. Remnant sediment channel features suggest that marine water influence was present previously. It is believed that in the year of 2002, the tidal influence no longer reached site S1 (for reasons unknown). Thus the biotic community underwent transformations relating to the change in salinity, flow and probably nutrient loads, as it became governed by a brackish water regime.

4.7 Summary

Based on the available data, the macrobenthos community assemblages of the tidal flat sampling sites consist of three distinct benthic groups, with Group I dominated by dense populations of Gastropods, Group II consisting of low densities of Annelids and Arthropods, and Group III colonised by Annelids (with typically greater number of species and biomass than Group II).

The sediment environment was found to greatly influence the spatial distribution of the macrofauna community. A decreasing COD and nutrient gradient along the tidal flat dictates the primary spatial distribution of the benthic community, with the sediment grain size also an influential factor. The biplot indicates that the variables of COD, TOC and sediment Factor 1 (pca1) explain much of the distribution pattern of the benthic community. Thus the results indicate that sediment quality (in particular COD and TOC) and composition greatly influence the present macrofauna community assemblage distribution at Awase tidal flat.

Table 4.1 Tidal flat sampling sites mean (elevation and silt-clay %) and median (D_{50} and reducing zone) characteristics (2000-2004). Reducing zone is the median depth from the sediment surface showing minus potential. The median sediment grain size is represented by D_{50}, and ND refers to reducing zone not detected within the maximum measured depth of 20cm.

Site	Elevation (m)	D_{50} (mm)	Silt-Clay (%)	Reducing zone (cm)
1	2.30	0.63	6.61	-3
2	0.93	0.19	20.49	0
3	1.24	0.38	6.83	-8
4	1.38	0.57	5.56	-5
5	0.70	0.40	5.29	-3
6	1.43	0.49	3.27	ND
7	1.03	0.49	3.12	ND
8	0.81	0.40	3.71	ND
9	0.68	0.42	3.17	ND
10	0.70	0.81	3.24	-11

Table 4.2 Principal Component Analysis results of the annual sediment composition from sites S2-S10, detailing the eigenvectors for the first three major axes.

Sediment Category	Factor 1	Factor 2	Factor 3
Silt-Clay	-0.303	-0.547	0.199
Fine Sand	-0.488	-0.162	-0.108
Medium Sand	-0.030	0.749	0.027
Coarse Sand	0.489	-0.016	0.239
Fine Gravel	0.489	-0.192	0.159
Medium Gravel	0.418	-0.268	-0.164
Coarse Gravel	0.129	-0.067	-0.916

Table 4.3 Mean sediment quality parameters for sampling sites S1-S10 (between fiscal years 2000-2004), with standard deviations shown in brackets.

Variable	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
pH	8.19 (0.45)	8.03 (0.41)	8.17 (0.48)	8.20 (0.52)	8.03 (0.35)	8.25 (0.50)	8.30 (0.47)	8.28 (0.50)	8.29 (0.50)	8.22 (0.53)
Sulfide (mg/g)	0.13 (0.18)	0.10 (0.03)	0.03 (0.02)	0.03 (0.02)	0.04 (0.02)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.02 (0.01)
COD (mg/g)	3.83 (2.68)	3.34 (0.76)	2.03 (0.46)	1.97 (0.45)	1.79 (0.48)	1.16 (0.37)	0.77 (0.33)	0.71 (0.24)	0.64 (0.35)	1.38 (0.56)
TOC (mg/g)	2.72 (1.80)	3.18 (1.00)	2.14 (1.08)	1.77 (1.16)	2.39 (2.17)	1.22 (0.68)	0.96 (0.60)	0.95 (0.72)	0.74 (0.56)	0.98 (0.50)
TN (mg/g)	0.50 (0.26)	0.49 (0.12)	0.36 (0.11)	0.36 (0.06)	0.39 (0.07)	0.32 (0.13)	0.19 (0.07)	0.25 (0.22)	0.26 (0.26)	0.26 (0.06)
TP (mg/g)	0.48 (0.60)	0.36 (0.14)	0.30 (0.10)	0.26 (0.08)	0.30 (0.10)	0.27 (0.08)	0.21 (0.07)	0.21 (0.06)	0.20 (0.06)	0.25 (0.10)
Chla (μg/g)	2.29 (1.96)	4.65 (1.80)	3.18 (0.99)	3.11 (0.75)	4.73 (2.20)	3.10 (0.95)	1.76 (0.47)	1.18 (0.46)	1.71 (0.94)	1.90 (0.78)

Table 4.4 Pearson's pairwise linear correlations between sediment variables using annual transformed data from sampling sites S2-S10.

Variable	pca1	pca2	pca3	pH	Sulf	COD	TOC	TN	TP	Chla
pca1										
pca2	0									
pca3	0	0								
pH	0.15	0.06	-0.32							
Sulf	-0.25	-0.54	-0.37	0.30						
COD	-0.25	-0.69	0.20	-0.43	0.50					
TOC	-0.22	-0.39	-0.47	0.02	0.80	0.52				
TN	-0.15	-0.39	-0.19	0.11	0.70	0.42	0.74			
TP	-0.02	-0.38	-0.51	0.24	0.73	0.39	0.82	0.64		
Chla	-0.30	-0.46	0.02	-0.24	0.55	0.76	0.60	0.51	0.40	
Elev	0.10	-0.33	-0.05	0.12	0.09	0.23	0.24	0.28	0.16	0.23

Table 4.5 Summary of results of statistical tests for significant seasonal differences in macrobenthos major groups and aggregated total. Note that n.s. refers to not significant (i.e. $p>0.05$), $*p<0.05$, $**p<0.01$, $***p<0.001$.

Parameter	No. Species	Density	Biomass
Mollusca	n.s.	n.s.	n.s.
Annelida	n.s.	S2**, S3*	S2*,S5**
Arthropoda	S7*, S10*	n.s.	n.s.
Total Macrofauna	S2**	n.s.	n.s.

Table 4.6 Comparison of the mean densities (number of individuals/0.36m^2) of the five most abundant taxa in each benthic group (where *n*=number of sites in each group), together with site S1. Standard deviations are given in parentheses. The % occurrence was determined over all sites and dates within each group. The phylum levels are M. refers to Mollusca, A. refers to Annelida, and Ar. Refers to Arthropoda. The feeding types (if known) are represented as SF=suspension feeder, DF=deposit feeder and CAR=carnivore.

Group	Dominant Taxa	Phylum Class	Mean (SD) Abundance (Ind./0.36m^2)	% occurrence	Trophic Level
I (*n*=5)	*Batillaria zonalis*	M. Gastropoda	319.0 (384.5)	100	DF, SF
	Cerithdeopsilla cingulata	M. Gastropoda	70.6 (162.1)	56	DF
	Ceratonereis sp.	A. Polychaeta	67.3 (67.3)	100	DF
	Armandia sp.	A. Polychaeta	26.4 (46.6)	92	
	Malacoceros sp.	A. Polychaeta	20.9 (26.0)	100	
II (*n*=3)	*Mictyris brevidactylus*	Ar. Crustacea	17.3 (23.0)	93	
	Malacoceros sp.	A. Polychaeta	9.2 (10.2)	87	
	Phyllochaetopterus sp.	A. Polychaeta	8.7 (15.0)	67	
	Armandia sp.	A. Polychaeta	8.5 (20.2)	80	
	Notomastus sp.	A. Polychaeta	5.6 (17.6)	93	
III (*n*=1)	*Syllinae*	A. Polychaeta	68.5 (128.3)	100	DF
	Armandia sp.	A. Polychaeta	13.2 (23.4)	100	
	Phyllochaetopterus sp.	A. Polychaeta	11.8 (25.5)	60	
	Ceratonereis sp.	A. Polychaeta	10.7 (19.3)	60	DF
	Notomastus sp.	A. Polychaeta	8.3 (9.8)	100	
S1 (*n*=1)	*CAPITELLIDAE*	A. Polychaeta	204.3 (503.1)	40	
	Hediste sp.	A. Polychaeta	47.6 (104.1)	20	
	CHIRONOMIDAE	Ar. Insecta	34.3 (58.6)	60	
	Heteromastus sp.	A. Polychaeta	25.7 (63.0)	60	
	Capitella sp.	A. Polychaeta	24.0 (59.7)	60	DF

Table 4.7 BIOENV results of the combinations of sediment environmental variables best matching the biotic and abiotic similarity matrices calculated from transformed annual data, with associated rank correlation ρ given in brackets. pca1=Sediment Factor 1; pca2=Sediment Factor 2; pca3=Sediment Factor 3; COD=Chemical Oxygen Demand; TOC=Total Organic Carbon; Elev=Elevation.

No. Variables	Highest Variable Combination (ρ)
1	COD (0.43); TOC (0.35); pca2 (0.25)
2	COD TOC (0.51); pca1 COD (0.50)
3	pca1 COD TOC (0.58); pca1 COD Elev (0.50)
4	**pca1 COD TOC Elev (0.59);** pca1 pca2 COD TOC (0.55)
5	pca1 pca2 COD TOC Elev (0.57); pca1 pH COD TOC Elev (0.55)
6	pca1 pca2 pH COD TOC Elev (0.55)
7	pca1 pca2 pca3 pH COD TOC Elev (0.50)

Table 4.8 Multiple regression best model results of effect of environmental variables on macrobenthos ordination axes. COD=Chemical Oxygen Demand; TOC=Total Organic Carbon; pca1=Sediment Factor 1; pca2=Sediment Factor 2; Elev=Elevation.

Dependent Variable = Axis 1				
No. Variables	Independent Variables in Model	Adjusted R^2	F	p
1	COD	0.53	55.12	<0.0001
1	TOC	0.49	44.93	<0.0001
2	COD TOC	0.68	48.28	<0.0001
2	COD pca1	0.59	33.51	<0.0001
3	COD TOC pca1	0.72	39.71	<0.0001
5	COD TOC pca1 Elev	0.76	36.60	<0.0001
Dependent Variable = Axis 2				
1	pca2	0.13	8.5	0.006
2	pca2 pca1	0.24	8.5	0.008
2	pca1 COD	0.31	11.6	<0.0001

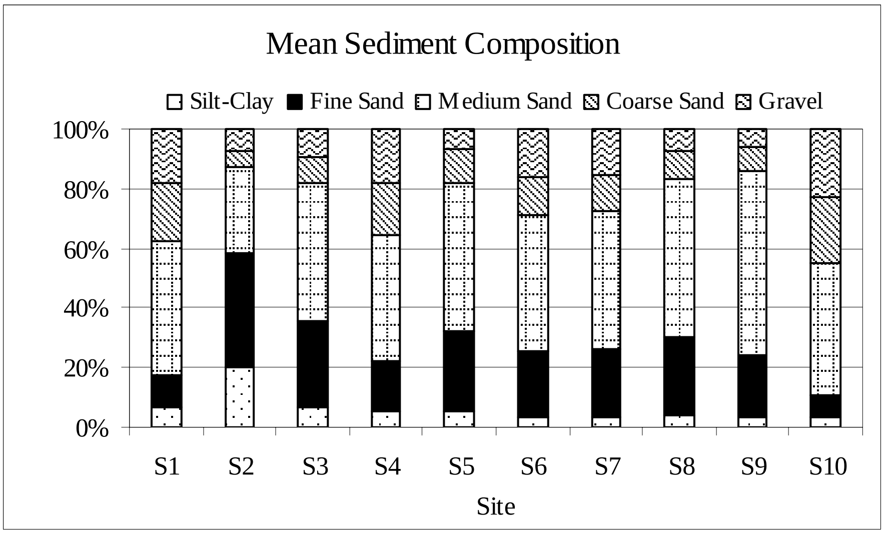

Figure 4.1 Comparison of sediment composition across sampling sites. Percentages correspond to the mean of all sampling dates between the fiscal years 2000-2004.

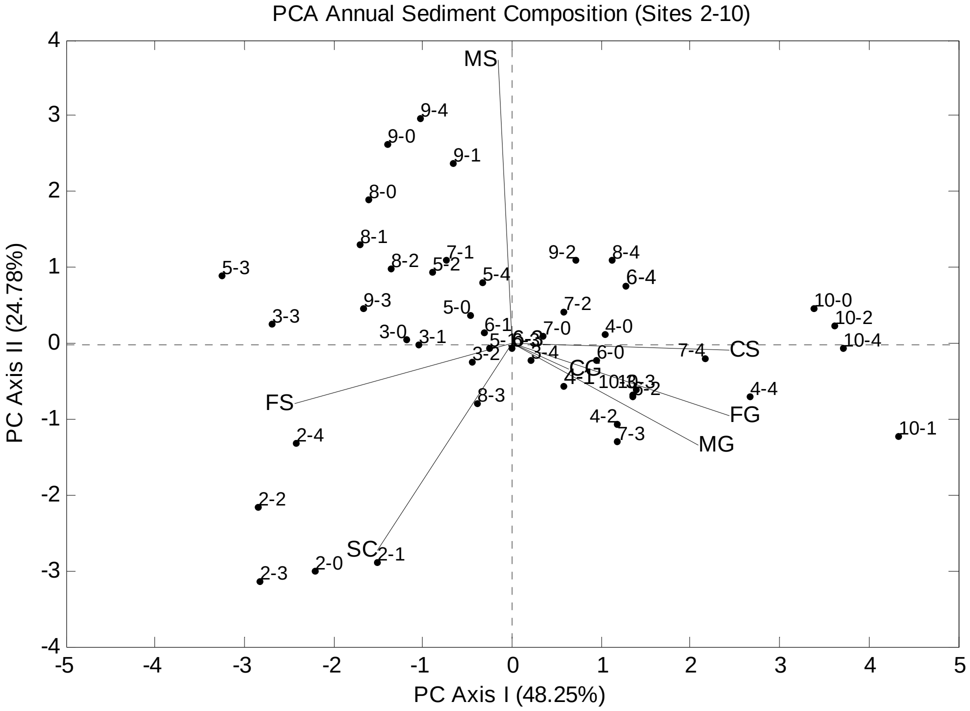

Figure 4.2 Results of the Principal Component Analysis of the arcsin transformed annual sediment composition with the scaled sediment category eigenvectors together with the first and second principal component axis co-ordinates for each site and year. Object labels indicate the site (first number) and the year (second number), with 0=fiscal year 2000, 1=2001, 2=2002, 3=2003, and 4=2004). Note that SC=silt-clay, FS=fine sand, MS=medium sand, CS=coarse sand, FG=fine gravel, MG=medium gravel and CG=coarse gravel.

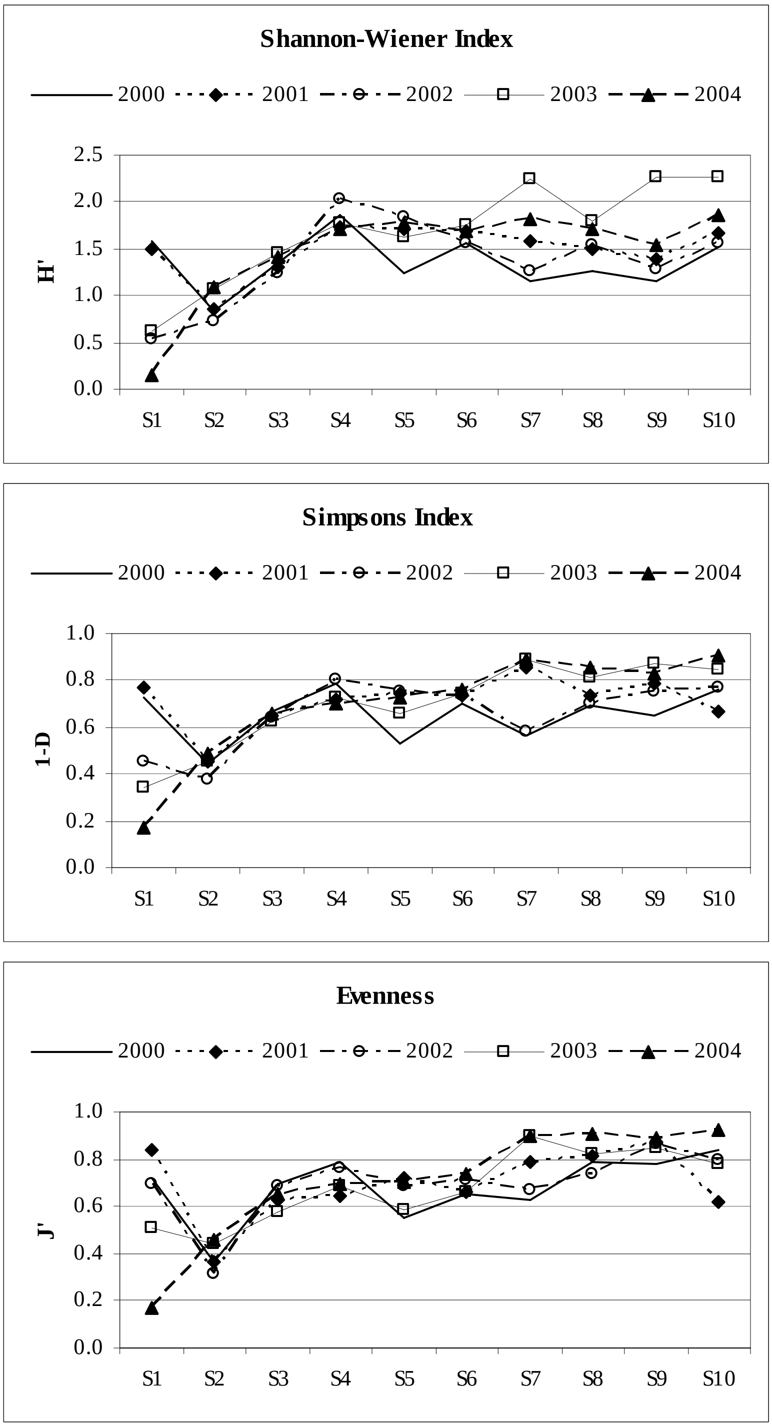

Figure 4.3 Annual mean univariate macrobenthos community measures of Shannon-Wiener Index *H'*, Simpsons Index *1-D*, and Evenness *J'* for all sampling sites.

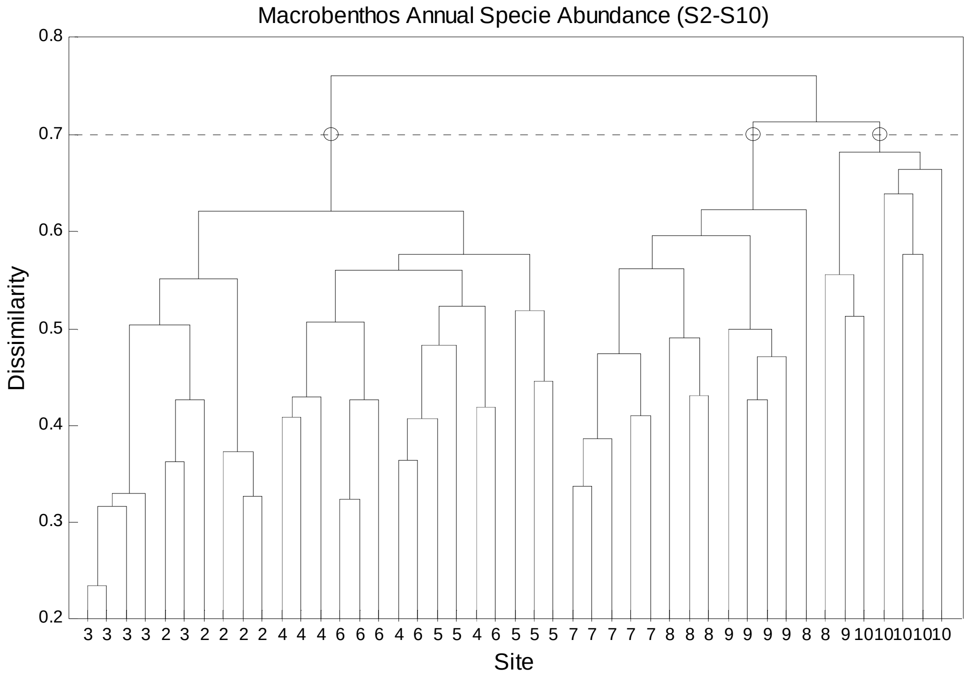

Figure 4.4 Macrofauna mean annual specie abundance similarity cluster analysis dendrogram for sites 2-10. Three main groups are distinguished at an arbitrary level of 0.7 (shown by o).

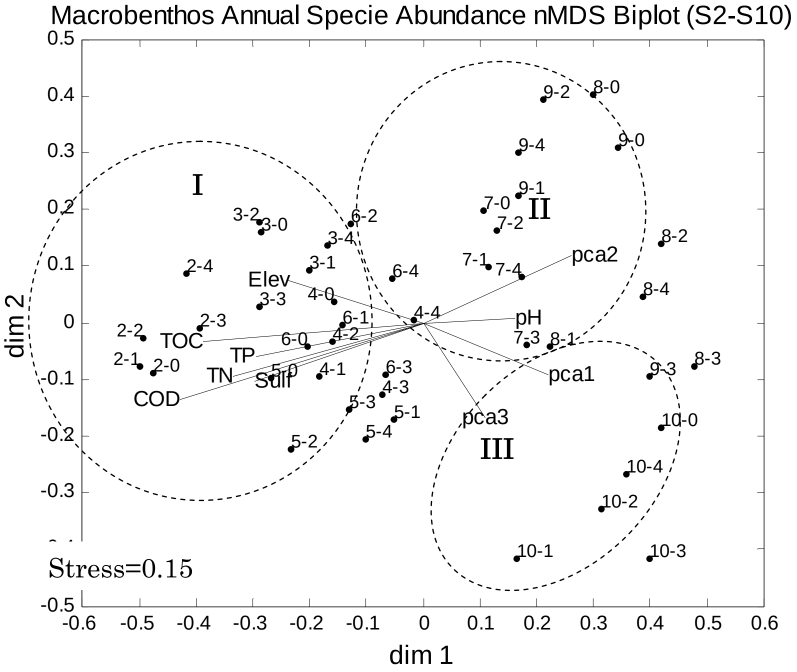

Figure 4.5 Ordination plot of macrofauna mean annual specie abundance for sites 2-10, with the cluster analysis groupings superimposed (I, II and III). Labels indicate the site (first number) and the year (second number, with 0=fiscal year 2000, 1=2001, 2=2002, 3=2003, and 4=2004). Environmental vectors have been scaled by two.

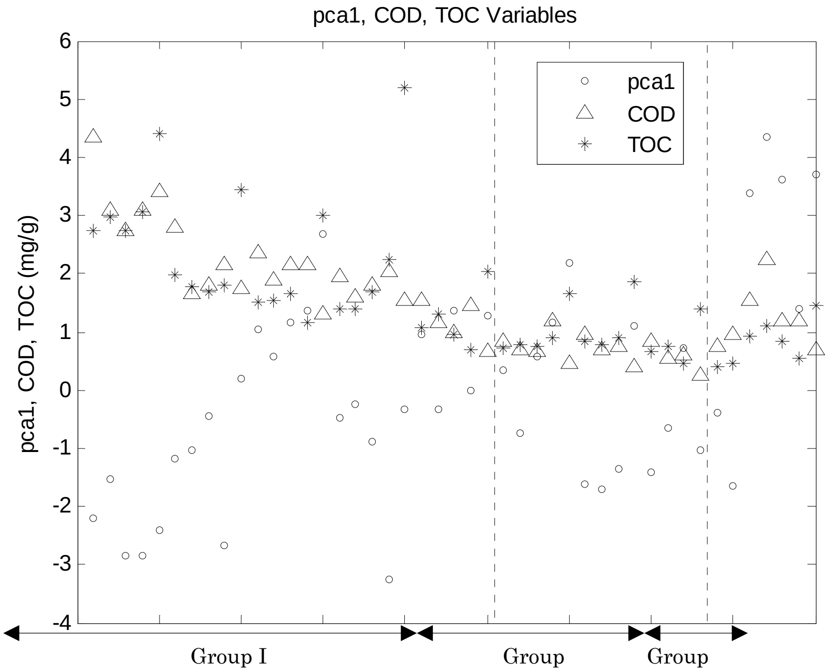

Figure 4.6 Sediment Factor 1 (pca1), Chemical Oxygen Demand (COD), and Total Organic Carbon (TOC) data (COD and TOC plotted on a log scale) for the three groupings determined from the macrofauna abundance multivariate analysis.

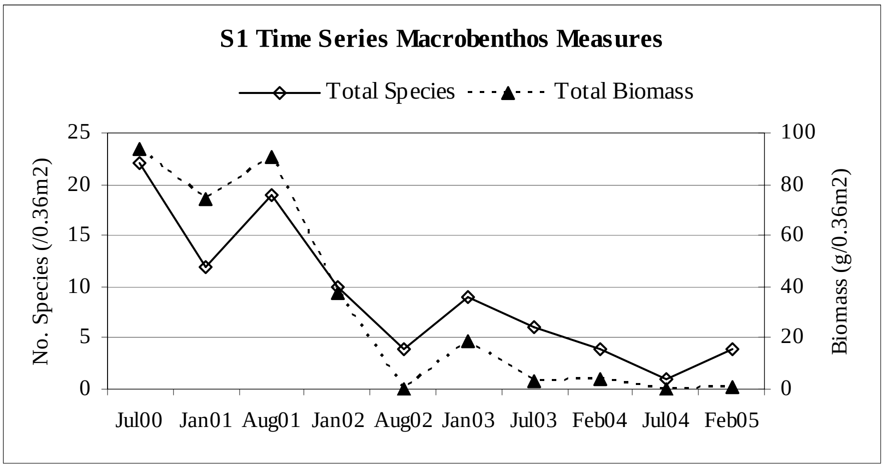

Figure 4.7 Macrobenthos total number of species and total biomass time series at site S1.

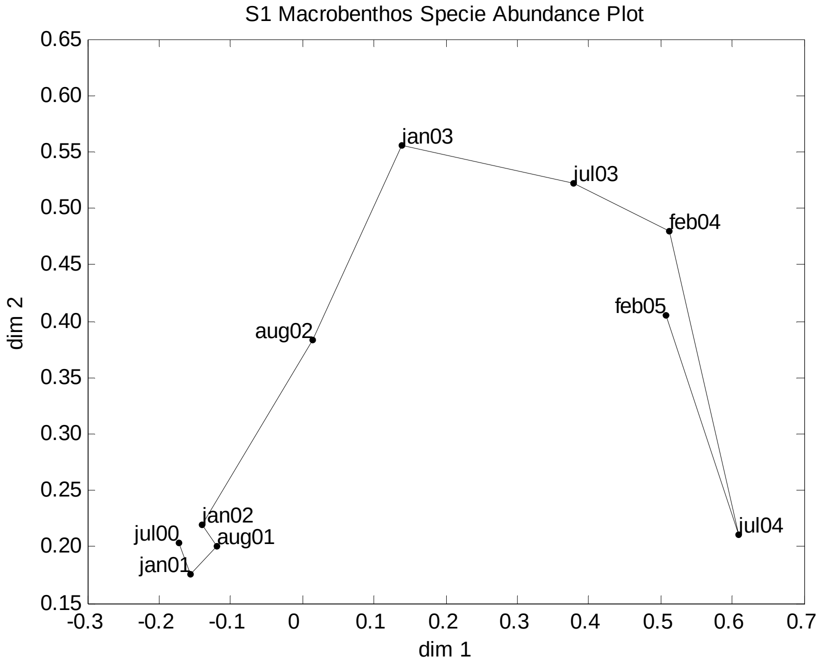

Figure 4.8 Site S1 macrobenthos specie abundance nMDS plot, with labels indicating months and year of sample (*e.g.* jul00=July 2000).

5. GRID METHODOLOGY AND APPLICATION

In order to manage and analyse dissimilar and sometimes sporadic data, the use of a grid system can be very advantageous. Through a grid system, the data management of a wide range of spatial data such as ground surveys, maps and modelling data can be undertaken. It can also be used to examine the dependencies between different elements. For the physical, chemical and biological data available for Awase wetland, it proved to be a very useful methodology for a very diverse data set.

5.1 Grid System

A grid system was applied to the intertidal region of Awase at 50m x 50m spacing, using the Universal Transverse Mercator (UTM, Zone 52) datum system. A secondary grid system was also applied to the wider region incorporating both intertidal and subtidal areas at 100m x 100m spacing. The edge co-ordinates for both grids are given in **Table 5.1**, and **Figure 5.1** displays the grid systems. The Surfer program (Golden Software) was used for gridding and contouring, with both Nearest Neighbour and Kriging methods applied, depending on the type of data and coverage. Surfer was used to collate and evaluate various types of spatial data including nautical charts, insitu surveys, maps and aerial photographs. Subsequently relationships between different abiotic factors (e.g. bathymetry) could then be compared with ecological features (e.g. varying habitats).

The parameters included in the gridded dataset were bathymetry, median sediment grain size (D50), sediment silt-clay fraction, shear stress rank, wave exposure rank, water quality, benthic zones, biotic presence/absence coverage for Kubiremidoro, Tokagehaze, Birds, coral area, mangrove area, seagrass and macroalgae area. The ranking or threshold criteria applied for all parameters are summarized in **Table 5.2**. The following sections describe the details for each parameter.

5.2. Physical Data

5.2.1 Bathymetry

The bathymetry of Awase wetland has been repeatedly surveyed between 1999 and 2003, and was combined to produce the input data set, with the contoured output shown previously in **Figure 2.3**. Depth delineations applied to the grid are shown in **Table 5.2**.

5.2.2 Sediment Grain Size

Sediment median grain size (D_{50}) and silt-clay fraction were based on sediment grain composition results from core samples taken between September and October 2001, when comprehensive sediment sampling was undertaken throughout the wetland region. **Figure 5.2** displays the sampling locations utilized in the input dataset, with **Figure 2.5** shown previously illustrating the contoured data. Since sediment composition data throughout the wetland was only available for this date, the year 2001 was selected as the basis for all grid data input unless otherwise stated. Median grain size delineations applied are shown in **Table 5.2**.

5.2.3 Shear Stress

Assessment of a bottom shear stress due to wave and current was restricted to maximum values, which typically occurred during typhoon season (July-October). The shear stress distribution of three modelled typhoon cases (Okinawa General Bureau et al., 2002; typhoon details given in **Table 5.3**) were overlapped. Due to the fact that wave magnitude and directional differences greatly affect the shear stress results, a rank method was selected. A shear stress rank was then applied based on the maximum magnitude (of all three cases) for each grid cell as follows: 1 = <20dyn/cm^2; 2 = 20-40dyn/cm^2; 3 = ≥ 40 dyn/cm^2 (see **Figure 5.3**).

5.2.4 Wave Exposure

In the absence of comparative wave data across the region, it was assumed that incorporating a rank based on directional wave exposure would assist in identifying differences due to wave effects on the intertidal zone. The predominant wave direction of SSE (see **Appendix A**) formed the premise for the wave exposure ranks applied to each grid cell, with three ranks defined from lowest to highest exposure to SSE direction as follows: 1 = <123.75°, >191.25°; 2 = 123.75-146.25° (SE), 168.75-191.25° (S); 3 = 146.25-168.75° (SSE). Note that the wave exposure rank was applied only to the tidal flat area (i.e. not subtidal region).

5.3 Water Quality

There is a lack of available comprehensive water quality data throughout Awase wetland, including both intertidal and subtidal sites. Subsequently a field study was conducted between 3-5 October 2005 to test the premises that a) subtidal water quality was homogeneous and good, b) poor water quality occurs at incoming freshwater channels. Conditions during the study were dry, with no rainfall occurring prior to or during the investigation. The field study consisted of a subtidal water quality survey of vertical profiles at 20 offshore stations (see **Figure 5.4** for locations) during flood and low tides on 4 October using a Conductivity, Temperature and Depth (CTD) instrument measuring depth, salinity, temperature, Chlorophyll-a, turbidity, and Dissolved Oxygen (DO). Very little variation in the subtidal parameters was evident between the sites, with homogeneity throughout the water column. The mean subtidal water quality values are presented in **Table 5.4**.

Additionally in the field study, insitu deployment on 3 and 4 October of 13 Salinity and Temperature (S/T) sensors within the tidal flat, mangrove region and freshwater channel exits was undertaken, with sampling every 10 minutes (see **Figure 5.4** for deployment locations). All sensors were retrieved on 5 October. Concurrently instantaneous CTD measurements were during the flood and ebb tides at 20 sites on 4 October across the tidal flat, mangrove region and freshwater channels (see **Figure 5.4** for locations), measuring depth, pH, salinity, temperature, DO, turbidity and Oxidation Reduction Potential (ORP). Results from both S/T and CTD sensors showed great variation between the sites, with poor water quality associated with the freshwater channels and immediately downstream, and good water quality present at the seaward tidal flat sites. Sampling of the deep hole located in the middle of the tidal flat was problematic due to access, and only limited measurements could be made in this region. The pH, DO, salinity and ORP results for each site were then standardized and analysed using Principal Component Analysis and cluster analysis (group average linkage). Three groups were distinguished (**Figure 5.5**), and were statistically found to be significantly different (ANOSIM test, $p<0.0001$). **Table 5.5** indicates the mean parameter values for each group.

Following the results of the field study, three ranks were then applied to the grid to indicate water quality: 1=poor (high exposure to freshwater flows), 2=fair (medium exposure to freshwater flows), 3=good (low exposure to freshwater flows). It should be noted that previous studies conducted during rainfall events (monitoring between 4 February 2004 to 25 March 2004) were also taken into consideration for potential effects of freshwater outflows onto the tidal flat, with the ranks reflecting potential impact (i.e. 'fair' water quality rank was attributed to a grid point if it would be potentially influenced by freshwater flows after rainfall event). Gridpoints within the deep hole were attributed with a 'fair' water quality ranking, despite apprehension that perhaps the deeper waters could be of 'poor' water quality, but without any supporting data this is only speculation.

There is a decided lack of nutrient and COD information for the freshwater channels. It is anticipated that the freshwater flows would have greatly enhanced nutrient loading. During the field study, it was noticed that automatic water quality samplers were located at all freshwater discharge channels and entry culverts to the tidal flat. This information would be of great benefit in providing a basis for calculating loading values to the mangrove region and the tidal flat. Further testing of the water quality of the deeper waters of the deep hole must also be undertaken.

5.4 Sediment Quality

Sediment quality was measured only at the intertidal zone sampling sites (S1-S10), and as such it was not possible to extrapolate a sediment quality ranking over the entire wetland region. The possibility of assigning sediment quality to sediment composition and in particular to silt-clay content was examined, with stepwise regression isolating COD, Sulfide and Chla as the highest combination to silt-clay fraction ($R^2=0.38$, $p<0.0001$), but the correlation was too low for spatial extrapolation. COD was the highest correlated single variable ($R^2=0.28$, $p<0.0001$).

The use of a sediment index would be greatly beneficial to further delineate habitat suitability, and more extensive sediment quality sampling is recommended to achieve this.

5.5 Biological Fauna

5.5.1 Macrobenthos

With the exception of the ten seasonal sampling sites (S1-S10) located toward the upper zone of the tidal flat (see **Figure 2.9**), macroinvertebrate sampling was only undertaken in the mid and lower intertidal zones nine years ago in February and August 1996. Whilst phylum biomass is available from the macrobenthos sampling in 1996, the full dataset was not accessible and so community assemblage could not be determined. There was also a question of biotic variability from the 1996 data, given the large temporal interval. Thus this data could not be analysed with the current macrobenthos data from sampling sites S1-S10.

Multivariate analysis of the community structures of the seasonal sampling site data was conducted (see **Section 4.4.3**). The use of benthic zones were decided upon after extensive statistical analysis revealed that there were three distinct benthic community assemblages present amongst the sampling sites, together with one anomalous site (S1). As such, the tidal flat was distinguished into benthic zones, representing benthic community homogeneity within each zone. **Figure 5.6** displays the delineated benthic zones across the intertidal region, with Zone I representing the mangrove region, Zone II in brackish waters of changed macrobenthos, Zone III of unknown benthos, Zone IV in finer sediments behind the deep hole and Gastropod dominant, Zone V in sandy sediments and Annelid and Arthropod dominant, and Zone VI in coarser sediments of lower elevation and Annelid dominant. The benthic zones were then applied to the grid.

It should be noted that no benthic data was available for Zone I (mangroves) or Zone III (unknown, except for sampling of three sites in 1996 suggesting the presence of Bivalves and Gastropods). Zone I is expected to have a very unique benthic community and so cannot be evaluated without any available data. It is recommended that macrobenthos sampling be conducted in the mangrove region to remedy this situation. Zone III will be assessed using Suitability Indices (SI results) to suggest possible benthic assemblage similarity with other zones on the tidal flat (**Section 6.2**).

Ideally the use of a benthic index should be adopted as the benthic indicator. Whilst there are many definitions of the Benthic Index of Biotic Integrity (B-IBI) applied (e.g. Van Dolah et al., 1999; Jackson et al. 2000; Thompson and Lowe, 2004), the underlying principle remains the same that variation in the structure of benthic assemblages can be an effective indicator of benthic habitat quality across a region. The principles behind IBI include a multimetric set of benthic parameters used for the assessment, including indicators of the benthic community structure (such as number of species and abundance), higher taxa and indicator species. It is recommended that the approach of Van Dolah et al. (1999) be adopted for determination of a benthic index for Awase tidal flat, where the benthic metrics used include: total abundance, number of species, 100-% abundance of two most dominant taxa, % abundance of pollution sensitive taxa. From the data available for this study, determination of a benthic index was not achievable. The macrobenthos classification needed to be lower to enable determination of possible pollution sensitive taxa. It is recommended that this be undertaken in the future, and the benthic index calculated for Awase tidal flat.

5.5.2 Tokagehaze

Tokagehaze are located within one small region on the tidal flat (see **Figure 2.6**). Presence and absence conditions were used to indicate Tokagehaze location, with the ranks attributed as 0=absent and 1=present.

5.5.3 Birds

Low tide and high tide bird surveys from August 2000 (summer), November 2000 (autumn) and February 2001 (winter) were combined (shown previously in **Figure 2.15**), with presence and absence conditions used to indicate total bird presence, and the grid ranks attributed as 0=absent and 1=present.

5.6 Biological Flora and Habitat

A map locating the biological elements mentioned below was shown previously in **Figure 2.6**.

5.6.1 Kubiremidoro

Seven Kubiremidoro surveys were undertaken between April 2002 and April 2004. The results were overlapped, with the region of Kubiremidoro habitat determined as the maximum perimeter where Kubiremidoro was present during the surveys (including sparse density), to ensure all possible habitat was incorporated. Presence and absence conditions were used to indicate Kubiremidoro habitat, with the ranks attributed as 0=absent and 1=present.

5.6.2 Mangroves

Mangroves were recorded as potential habitat (so this included the entire mangrove region since they were previously present also in the northern part of the domain), with presence and absence conditions used to indicate habitat, and the ranks attributed as 0=absent and 1=present.

5.6.3 Seagrass and Macroalgae

The results from the aquatic vegetation survey undertaken in November 2001 were used for the 100m grid dataset. Ranks were attributed to the three categories of macroalgae, small seagrass and large seagrass as follows: 0=absent, 1= <10% coverage, 2= 10-50% coverage, 3= >50% coverage. The presence and absence of large seagrass (with presence denoting any coverage) was also applied to the 100m grid to represent seagrass habitat, with the ranks attributed as 0=absent and 1=present. For the 50m grid dataset, results from four surveys (November 2001, November 2002, June 2003 and November 2003) were overlaid, with presence and absence conditions used to indicate where aquatic vegetation could be located on the tidal flat, with the ranks attributed as 0=absent and 1=present.

5.6.4 Coral

The results of a coral survey undertaken in June 2003 were incorporated into the 100m grid dataset. Presence and absence conditions were used to indicate coral, with the ranks attributed as 0=absent and 1=present.

5.7 Linkages

With the development of the grid system, the linkages between different physical variables such as bathymetry, hydrodynamics, water quality and sediment composition, could then be compared with biological elements (e.g. different habitat types). The development of Suitability Index plots of abiotic variables for indicators in **Section 6.2** formalises the analysis of inter-disciplinary relationships between many of the variables, and will be discussed in **Section 6.2**. Additional conclusions drawn from the grid analysis include:

- In the subtidal region, much of the higher shear stresses occur in the shallow waters between -2 and 0m, with the maximum shear stress regions occurring in unvegetated areas. In the intertidal zone, higher shear stresses occur in more open, exposed areas at elevations greater than +0.5m.
- Bird distribution at low tide is predominant in benthic zones I, III, IV and V, and at high tide in zones I, II, and IV. The high tide regions also correspond to the highest elevations in the tidal flat. The benthic regions identified at low tide are representative of the feeding areas and indicate the dominant food supply for birds. This requires further investigation between individual bird specie and preferred benthic organisms.

Table 5.1 Intertidal and subtidal grid details. Grid co-ordinates are given in UTM datum (Zone 52).

Grid Region	Grid Details	x Direction	y Direction
Intertidal	Minimum	382800	2909000
	Maximum	386500	2911300
	Spacing	50	50
Intertidal + Subtidal	Minimum	382800	2707900
	Maximum	387200	2911300
	Spacing	100	100

Table 5.2 Ranking criteria for grid dataset. * denotes intertidal region only.

Parameter	Criteria	Description/Rank
Depth (m)	> +3.0	Intertidal
	+2.0 – +3.0	Intertidal
	+1.5 – +2.0	Intertidal
	+1.0 – +1.5	Intertidal
	+0.5 – +1.0	Intertidal
	0.0 – +0.5	Intertidal
	-2.0 – 0.0	Subtidal
	-4.0 – -2.0	Subtidal
	-6.0 – -4.0	Subtidal
	-8.0 – -6.0	Subtidal
	<-8.0	Subtidal
Median Grain Size (mm)	<=0.063	silt-clay
	0.063-0.25	fine sand
	0.25-0.50	medium sand
	0.50-1.0	coarse sand
	1.0-2.0	very coarse sand
	>2.0	gravel
Shear Stress (dyn/cm^2)	0-20	1
	20-40	2
	>40	3
Wave Exposure*	< SE, >S (50m)	1
	SE, S (50m)	2
	SSE (50m)	3
Water Quality	Poor	1
	fair	2
	Good	3
Birds, Tokagehaze, Kubiremidoro, Benthic Zones	Absent	0
	Present	1
Coral, Mangrove Large Seagrass	Absent	0
	Present	1
Macroalgae, Small Seagrass, Large Seagrass (% coverage)	Absent	0
	< 10	1
	10 – 50	2
	> 50	3

Table 5.3 Modelled typhoon case studies, with results used in determination of shear stress rank. H_o refers to inshore peak/significant waveheight, T_o refers to peak/significant wave period, S_{max} is the coefficient applied in the wave modelling.

Case	Typhoon Date	Wave Direction	H_o (m)	T_o (s)	S_{max}
1	H15.10	SE	1.10	16.0	75
2	H14.5	SE	2.30	5.3	10
3	H16.9	SSE	2.38	4.8	10

Table 5.4 Mean and standard deviation of subtidal water quality parameters measured on 4 October 2005, averaged throughout the water column and over all sampling sites. DO refers to Dissolved Oxygen, and Chla refers to Chlorophyll-a.

	Salinity (psu)	Temperature (degC)	DO (mg/L)	Chla (ug/L)	Turbidity (ppm)
Mean	34.58	29.03	6.37	0.35	1.04
Standard Deviation	0.04	0.25	0.26	0.09	0.53

Table 5.5 Mean water quality parameters for each tidal flat group measured on 3-4 October 2005. DO refers to Dissolved Oxygen, ORP refers to Oxidation Reduction Potential, and *n* is the number of sites in each group.

Group	Water Quality	pH	DO (mg/L)	Salinity (psu)	ORP (mV)
1 (*n*=13)	Poor	7.25	4.51	16.58	-73.08
2 (*n*=9)	Fair	6.46	5.12	29.41	146.67
3 (*n*=18)	Good	7.40	5.50	33.79	73.78

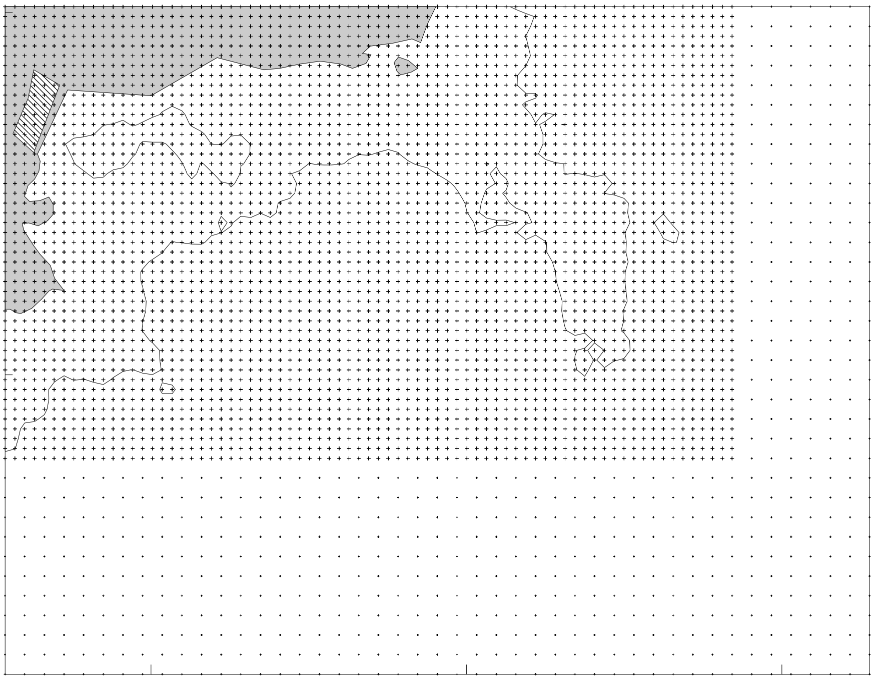

Figure 5.1 Basemap showing intertidal 50m grid and intertidal +subtidal 100m grid.

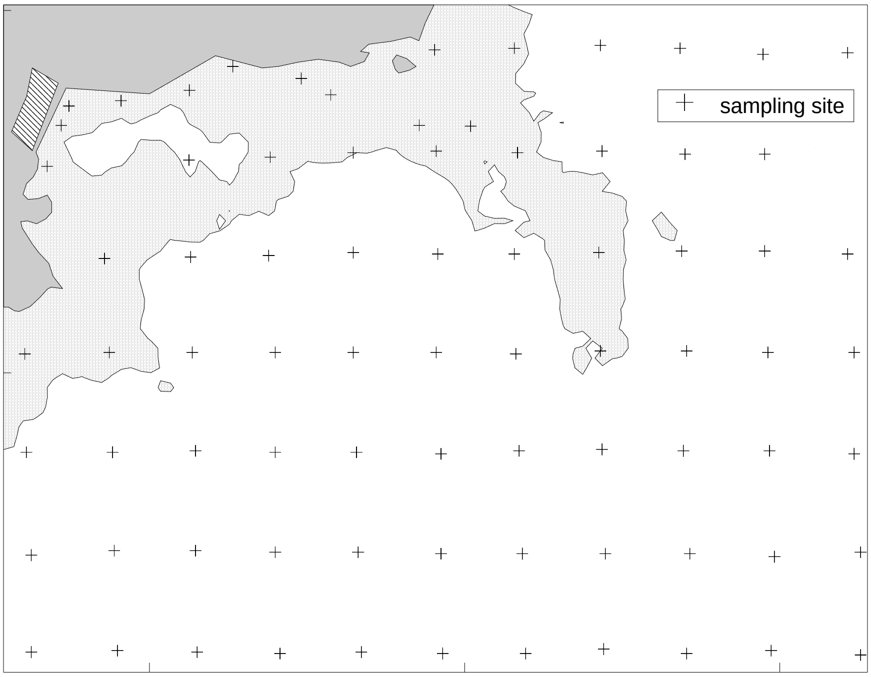

Figure 5.2 Sediment sampling sites in 2001 (Heisei 13).

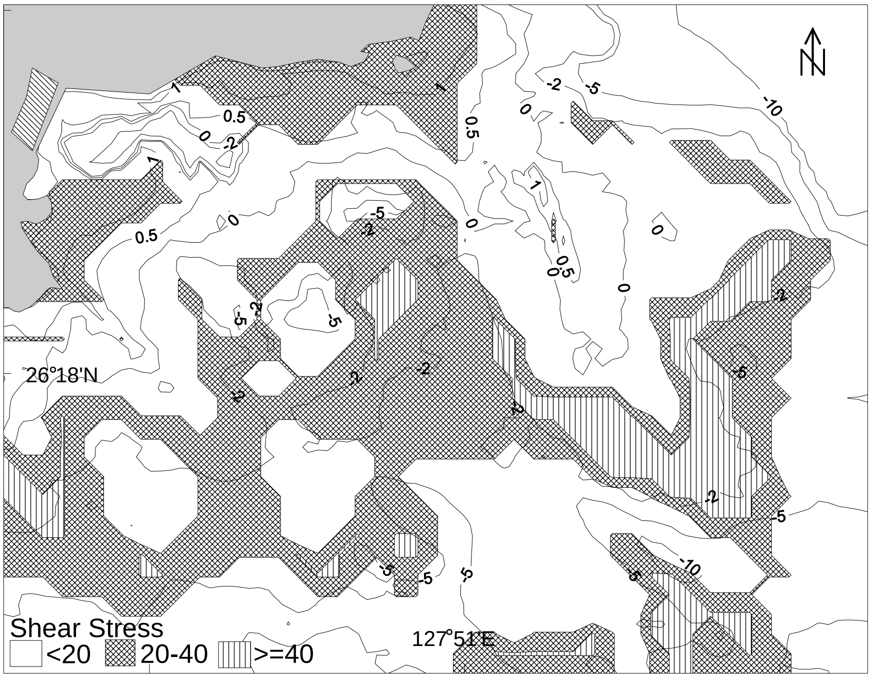

Figure 5.3 Shear stress contours (dyn/cm^2) with bathymetry data.

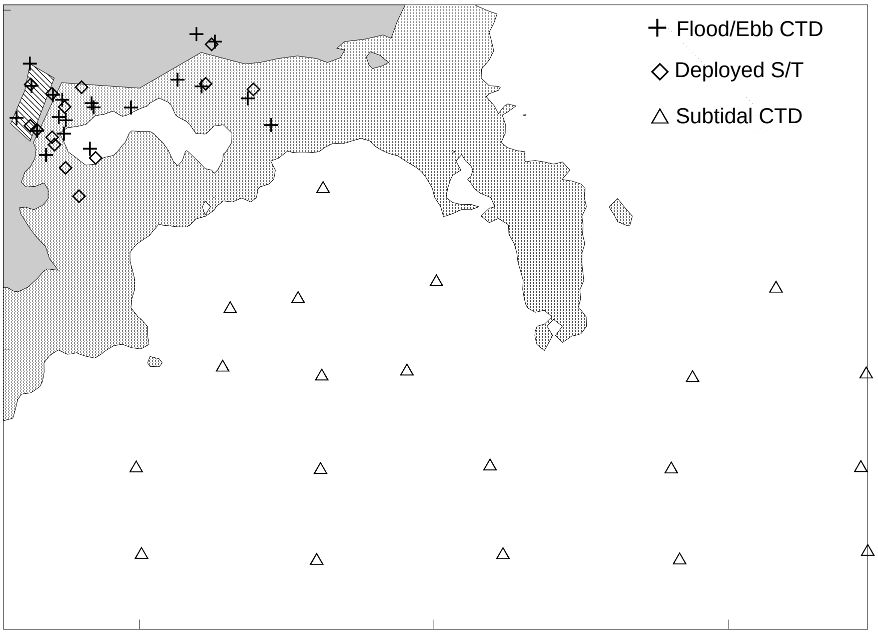

Figure 5.4 Water quality sampling sites from field study on 3-5 October 2005.

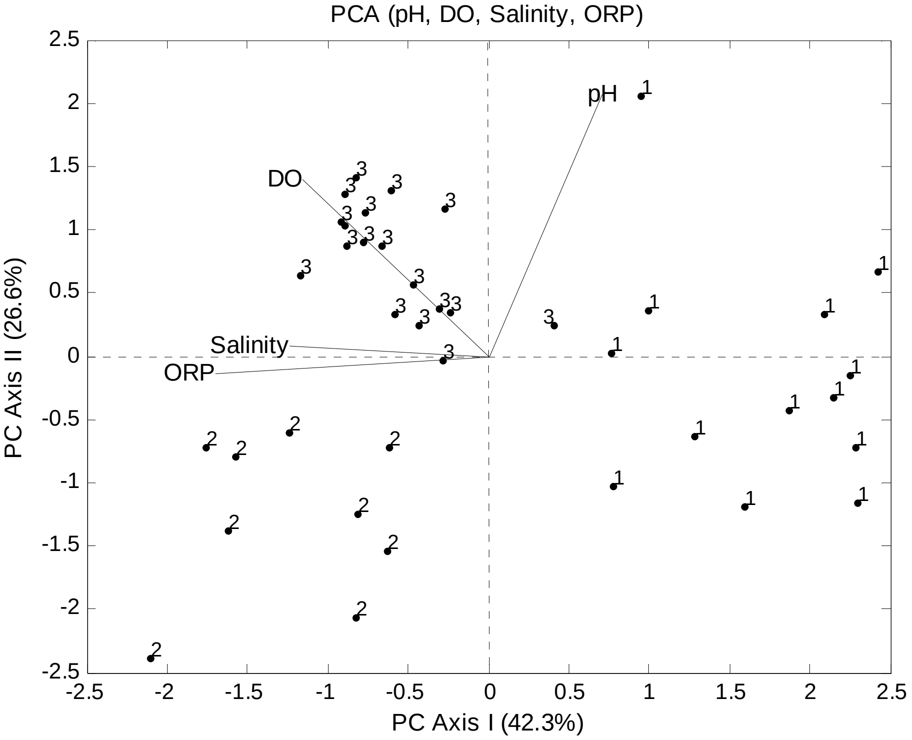

Figure 5.5 Principal Component Analysis results of the standardized water quality parameters pH, Dissolved Oxygen (DO), and Oxidation Reduction Potential (ORP) measured at Awase sampling sites on 4 October 2005, with the scaled eigenvectors. The three water quality rank groupings are indicated by the notation 1, 2 and 3.

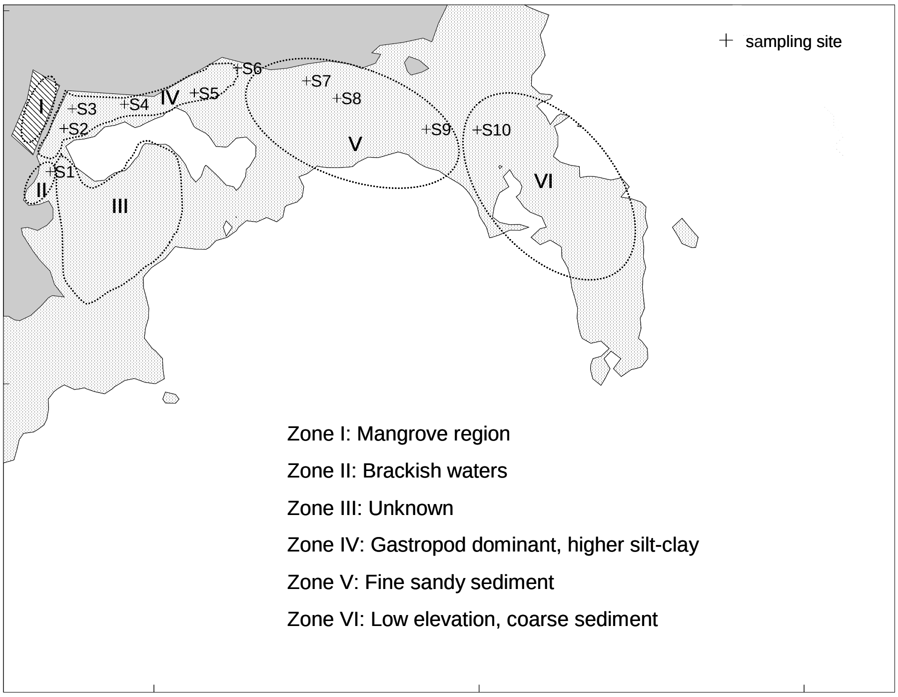

Figure 5.6 Zones indicating macrobenthos homogeneity. The intertidal sampling sites are also shown.

6. ENVIRONMENTAL INDICATORS AND HABITAT SUITABILITY INDEX

6.1 Indicators

Biotic and abiotic indicators are essential to characterize the current ecological status of Awase wetland and to track future or significant change, particularly with the future landfill development. An indicator may reflect biological, chemical or physical qualities of the ecological condition. In the situation of Awase wetland, the indicators must also provide information that is useful for management decisions. The indicators selected for Awase wetland focus on environmental condition or state.

A total of 11 indicator categories are recommended covering endangered species, habitat extent and quality, and physical parameters (see **Table 6.1**). The indicators include Kubiremidoro, Tokagehaze, mangrove area, large seagrass area, seagrass specie (e.g. Thalassia hemprichii), coral area, Benthic Index or community assemblage, sediment properties (grain size, TOC, TN), water quality (Salinity, Dissolved Oxygen), freshwater discharge and quality (flow, Dissolved Oxygen, COD, Nutrients), waveheight, period and direction. All indicators provide important information regarding the status of the environment at Awase wetland. Losses of habitat and population, shifts in assemblages and sediment composition, increases in nutrients, variations in water quality all indicate changes in environmental characteristics. The only indicator that is not susceptible to environmental change are the wave conditions, but it was included because it was deemed very necessary for interpretation of other wetland elements and indicators (e.g. changes in sediment composition). Consideration was also given to the possible use of birds and hill hermit crabs as indicators, but it was deemed that insufficient background data of the hermit crabs existed to ascertain changes to the populations. For birds, the use of macrobenthos as an indicator was provident since it is the dominant food source for birds at the tidal flat, and there was uncertainty regarding historical quantification of bird populations and behaviour, and there was inherent greater difficult in assessment.

At this point, calculation of the Benthic Index was not possible and hence the use instead of benthic zones of relative homogeneous community assemblages determined for Awase. However the aim should be to attain a benthic index because macrobenthos is a very suitable measure of the ecological status of the intertidal zone, and a good baseline history has already been established. It should also be noted that whilst a seagrass specie is recommended as an indicator and is essential as a measure of subtidal habitat quality, this indicator was not selected for further analysis. The reason behind this decision was a lack of available data to the authors regarding specific seagrass specie behaviour in the Awase coastal zone. However extensive information exists regarding seagrasses in Awase due to ongoing monitoring and transplanting experiments, and it is recommended that upon the outcome of such trials, a suitable seagrass specie is selected. In the interim, large seagrass area is the representative indicator of seagrass status that will be further investigated.

6.2 Habitat Suitability Index (HSI)

The habitat quality for selected evaluation species is recorded with an index, the Habitat Suitability Index (HSI). The HSI is defined as a numerical index that characterizes the capacity of a given habitat to support a selected specie (U.S. Fish and Wildlife Service, 1981). The methodology is based on the presumption that habitat quality and quantity can be numerically described. The HSI index is determined from an evaluation of key habitat components to provide essential life fundamentals for the selected specie. HSI models produce an index from 0 to 1.0, with an index value of 1.0 representing optimal habitat and decreasing values referring to less suitable habitat. HSI is determined from Suitability Index (SI) plots, which rate the carrying capacity of the environmental factor.

Suitability indices (SI) for the specie and habitat indicators Kubiremidoro, Tokagehaze, benthic zones II-VI (benthic zone I was not included due to no available data in the mangrove forest), mangrove area, large seagrass area and coral area were determined. The results were based primarily on available field data at Awase, together with assumed knowledge of optimal conditions. SI plots were determined for the abiotic parameters of depth, median grain size (D50), shear stress rank, and water quality rank and where data was available, silt-clay fraction. The suitability index for each parameter ranged between 0 and 1.0 (most optimal). **Figure 6.1** displays an example of the SI plots for large seagrass area. The SI plots for the remaining selected indicators are displayed in **Appendix C**.

The calculation of HSI for the selected specie and habitat indicators of Awase wetland consisted of the combination of SI results for depth, substrate, and water quality (**Eq.5**). There are several methodologies for calculating HSI from SI curves (e.g. minimum factor rating, averaging), but in this case a decision was made to combine three factors because all applied factors were considered to be of equal importance and influence to biotic elements.

$$HSI = \sqrt[3]{SI_{depth} * SI_{substrate} * SI_{WQ}} \qquad (5)$$

where $SI_{substrate}$ was averaged from SI_{D50} and $SI_{shearstress}$ and in some circumstances $SI_{siltclay}$ (for Tokagehaze and benthic zones IV-VI, where the silt-clay content was of importance for distinguishing characteristics). WQ refers to water quality.

HSI was determined for each pixel in the 100mx100m grid setup over the study area, and then visualised using Surfer and Nearest Neighbour gridding technique. **Figure 6.2** shows an example of the contoured HSI map for large seagrass, with **Appendix D** containing the HSI maps for each selected indicator. The optimal areas were calculated based on the HSI threshold value of 0.9, except for when maximum indices were less than 1.0 for Tokagehaze and Benthic Zone II, then a lower HSI threshold value was applied (0.8 and 0.7 respectively). For large seagrass and coral areas, applying the threshold value at 0.9 produced an optimal area of high similarity to surveys of recent coverage, thus creating the benchmark for assessing future change.

Conclusions drawn from the HSI maps include:

- The identification of no suitable habitat area for mangroves within the Awase wetland, suggesting that rehabilitation of the current area is essential for the ongoing survival of the mangroves. This is of great importance because the mangrove region currently serves as a buffer and filtering region between the incoming poor water of the freshwater channels and the tidal flat, and is a dynamic environment providing habitat for many species.
- The results from Benthic Zone III, Zone IV, and Zone V suggest that the unknown region (Benthic Zone III) has similarities with the benthic communities of Zones IV and V. The central region of the main foreshore toward the deep hole of Zone III has habitat suitability for the benthos assemblage of Zone IV, whilst the region closer to the southern boundary suggests habitat suitability for the benthic community of Zone V. It is recommended that sampling of this unknown region be undertaken to test these findings and to better understand the macrobenthos distribution across the tidal flat.
- Results from Benthic Zone VI propose further areas of macrobenthos community similarity in lower elevation, coarse sediments across the intertidal region. These areas have not been sampled.

6.3 Impact of Landfill Development

In order to assess the impact of the landfill development on the habitat areas, the loss of optimal habitat area (i.e. above threshold value applied previously) due to the construction was determined (Areanet=Areapre-landfill–Areapost-landfill). **Table 6.2** presents the area loss of optimal habitat for the selected indicators and also visually displayed in **Figure 6.3**. Large losses in optimal habitat (> 20%) are recorded in large seagrass area, benthos Zones IV and VI, and Kubiremidoro, with significant losses in benthos Zone V (>10%). It should be remembered that these losses are only for the selected indicators. Other key habitats that will also be affected include macroalgae and small seagrass areas, which have substantial coverage in the lower intertidal zone and the upper subtidal zone (see **Figure 2.6**). The effect of loss of macrobenthos and tidal flat habitat can be also of importance for the bird populations that use Awase wetland.

Figure 6.4 displays the relative percent contribution of each component to total optimal habitat area for pre and post-landfill development. Little variation is seen in the magnitudes with the exception of benthic zone IV which shows a significant relative reduction after the construction. Nevertheless, total shape of fraction keeps similarity pre and post-landfill development. This suggests that the impact of the landfill is not building up on specific species group, but spread across (minimized) through the system of the wetland.

Table 6.1 List of environmental indicators for Awase wetland.

Indicator	Class
Kubiremidoro	Endangered Species
Tokagehaze	Endangered Species
Benthic Index/Community Assemblage	Habitat Quality
Mangrove area	Habitat Extent
Seagrass area	Habitat Extent
Coral Area	Habitat Extent
Seagrass specie	Habitat Quality
Sediment Properties (Grain size, TOC, TN)	Sediment Quality
Water Quality (DO, Salinity)	Water Quality
Freshwater discharge and quality (Nutrients, DO, COD)	Hydraulics, Water Quality
Waveheight, period and direction	Hydraulics

Table 6.2 Based on HSI threshold values of 0.9, except for * calculated using 0.8 and ** calculated using 0.7 due to lower maximum indices. All areas are given in hectares (ha). The terms pre-landfill and post-landfill refer to before and after landfill development respectively.

Indicator	Optimal Area (pre-landfill)	Optimal Area (post-landfill)	Loss (ha) Optimal Area	% Loss Optimal Area
Kubiremidoro	17.1	13.2	3.9	23.0
Tokagehaze*	1.6	1.6	0	0
Benthos Zone II**	0.9	0.9	0	0
Benthos Zone III	58.5	53.0	5.5	9.4
Benthos Zone IV	58.5	22.1	36.4	62.1
Benthos Zone V	23.1	20.6	2.5	10.6
Benthos Zone VI	48.4	37.9	10.5	21.7
Mangrove area	0	0	0	0
Large Seagrass area	180.3	142.7	37.6	20.9
Coral area	58.3	57.1	1.2	2.1

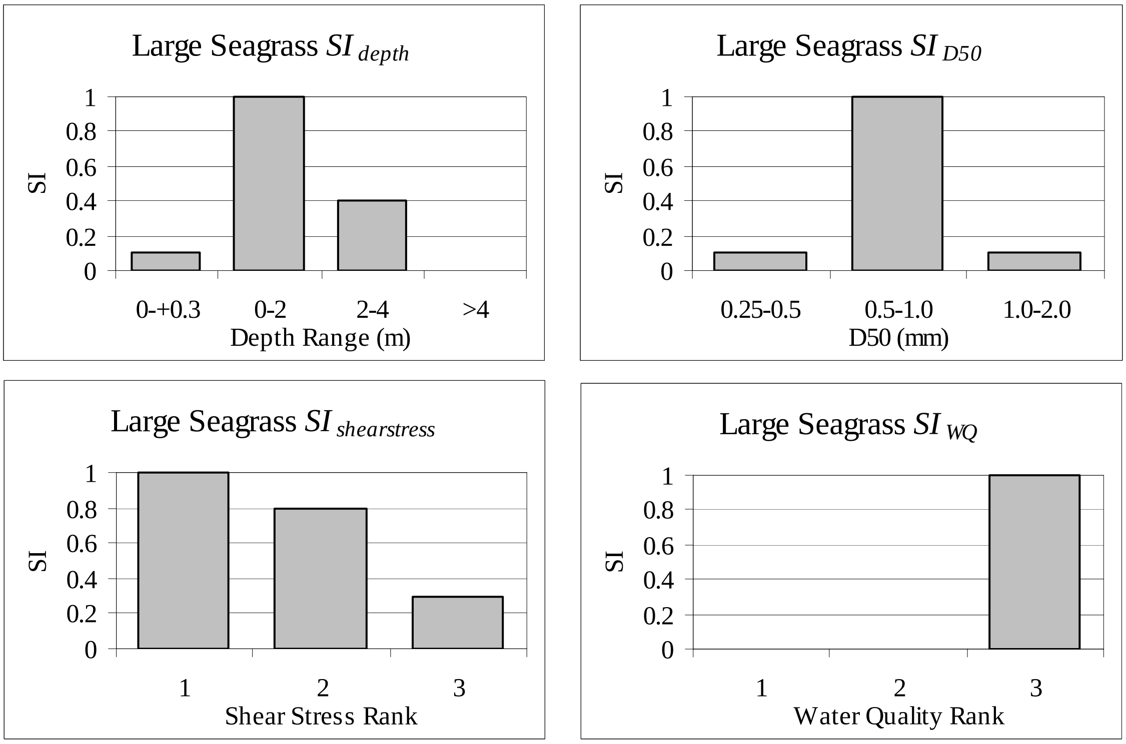

Figure 6.1 Suitability Index Plots for large seagrass area.

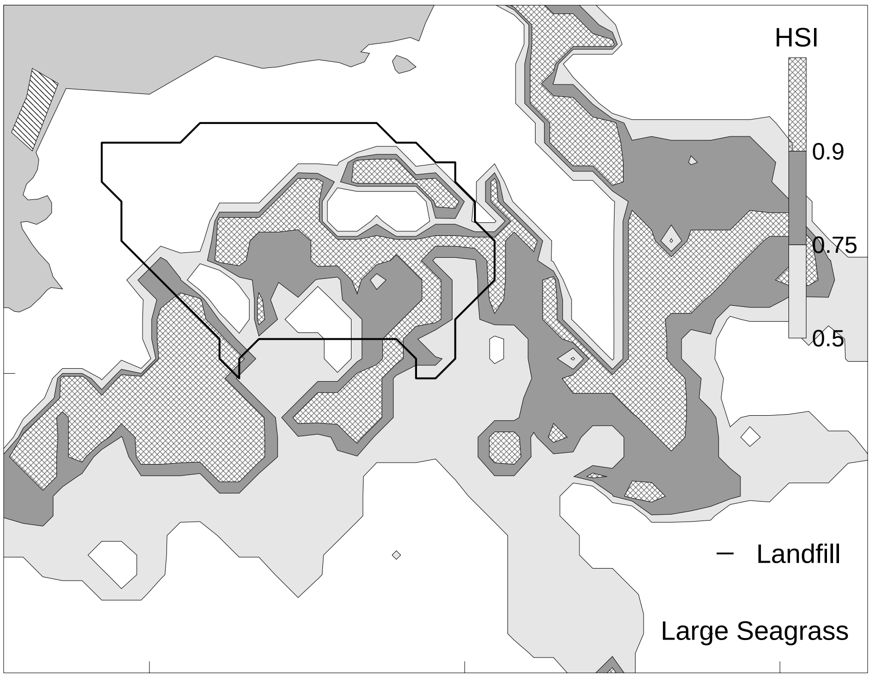

Figure 6.2 Contour map of HSI values for large seagrass, with landfill area shown.

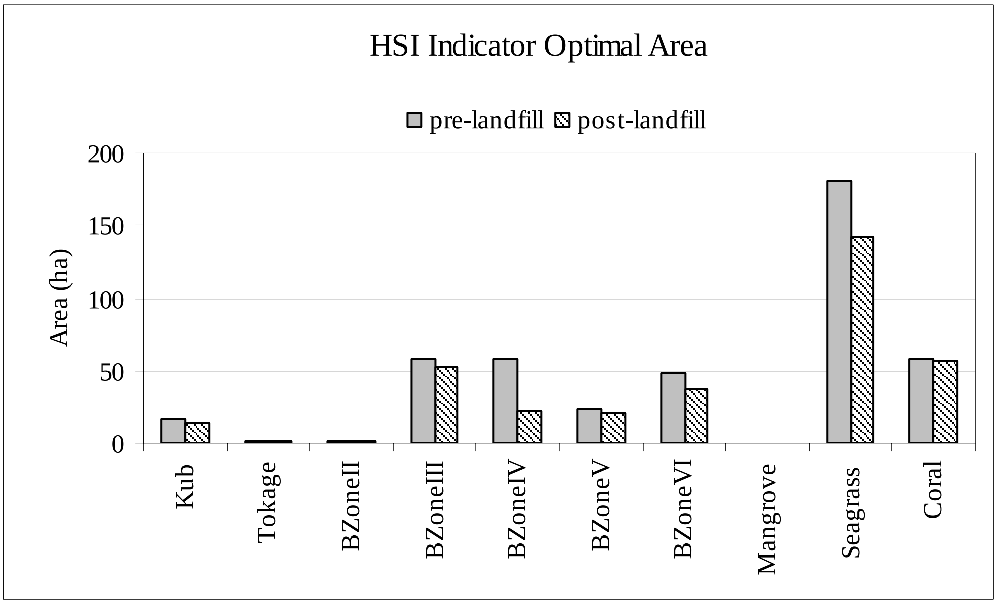

Figure 6.3 HSI optimal areas pre and post landfill development for selected indicators based on the threshold value of 0.9 (except for Tokagehaze and Benthic Zone II with threshold values of 0.8 and 0.7 applied respectively). Note that Kub refers to Kubiremidoro, Tokage to Tokagehaze, and Seagrass to Large Seagrass area.

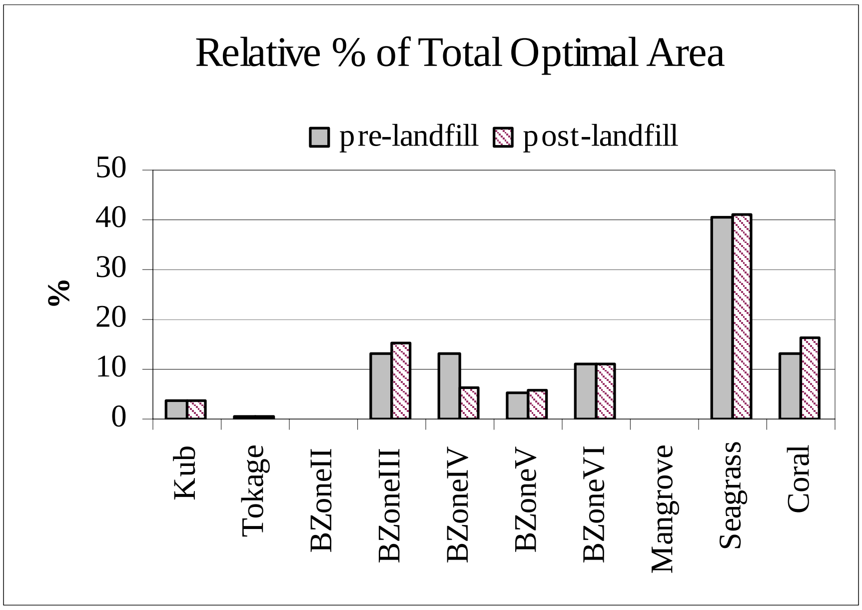

Figure 6.4 Relative percent contribution of each component against total optimal area pre and post landfill.

7. MANAGEMENT AND RECOMMENDATIONS

7.1 Adaptive Management Methodology

A flexible, adaptive management procedure should be adopted in order to allow the process to change or evolve in response to varying factors. The adaptive management process is based on the following: specify and quantify management objectives; appropriate management applied to achieve objectives; monitoring of features to assess the objectives success; review and modification of management if objectives are not met (see **Figure 7.1**). It is proposed that the adaptive management iterative approach be adopted for the management of Awase wetland.

7.2 Goal

The chief environmental goal for Awase wetland is for a healthy ecosystem that maintains the current diversity of habitat types along with the associated resident animal and plant communities and ecological functions, that is self-sustaining (i.e. requiring minimal intervention) and is resilient to stresses. The system will also continue to accommodate human use of natural resources.

7.3 Objectives

Objectives provide more specific descriptions of the components and processes that are necessary to achieve the overall goal for Awase wetland.

Proposed objectives include (no prioritization):

A. Ensure conditions necessary to support and protect biodiversity.
B. Protect and/or restore conditions necessary to increase populations of endangered or valuable species.
C. Protect and/or restore wetland functions.
D. Ensure conditions necessary for resilience of either species or ecosystem.
E. Protect the natural trophic structure of communities.
F. Improved assessment of the natural patterns of transport of essential materials (sediments, nutrients, water).
G. Protect water quality.
H. Provide for human use (harvest, recreation, aesthetics).

7.4 Strategy

Monitoring is essential to measure the effectiveness of the management procedures, and key indicators provide a focal point for the monitoring. Performance standards (or success criteria) are measurable attributes of the indicators identified through the research that can quantify and assess the current condition of a feature and can be used to determine if the management objectives are being met.

The environmental indicators determined in Chapter 6 provide the focus for monitoring and evaluation of the state of Awase wetland. **Table 7.1** summarizes the monitoring strategy for each indicator, together with a suggested performance standard that represents a threshold for action. In determination of the performance standards, consideration was given to possible natural variability of the indicator. Thus change in seagrass areas was given a higher threshold criteria of 15% due to variation in coverage between past in-situ surveys, whereas other habitats such as coral and mangroves have more stable coverage and require intervention at a lower threshold level of 10% change in area. The chemical indicators (i.e. water quality and sediment quality) do not have baseline levels for comparison, and thus the threshold criteria of ±2 standard deviations was deemed the most suitable range. Once future data becomes available, specific concentrations should be adopted instead.

If action is required, the results and management must be reviewed, and if necessary altered or adapted. If further action is still required, then the original objectives must be reconsidered. In the case of Awase wetland, the major impact on the wetland will be due to the future construction of the landfill development. Therefore the current status of the wetland forms the baseline from which post-development impacts can be assessed (e.g. change in sediment grain size from current condition or loss in habitat area coverage from current average). Hence it assumed that the average current condition is the benchmark against which future measurements are assessed for all quantified indicators.

A more comprehensive list of desirable parameters (including frequency and analysis/use) that should ideally be monitored at Awase wetland is presented in **Appendix E**.

7.5 Landfill Development Impact

The construction of the offshore landfill development incurs a highly significant loss of habitat and abundance, with the results of the HSI analysis highlighting losses to large seagrass (and will also greatly affect small seagrass and macroalgae), benthos and Kubiremidoro. Large losses in optimal habitat (> 20%) are recorded in large seagrass area, benthic zones IV (Gastropod dominant) and VI (Annelid dominant), and Kubiremidoro (green algae), with significant losses (>10%) in benthic zone V (Annelid and Arthropod dominant). The relative proportion of optimal area for the each species (groups) doesn't change except for a special type of benthic zone IV. Mitigation measures suggested by the EIA are justified and must be implemented, however further measures should be taken.

Transplanting trials of seagrass and Kubiremidoro have been undertaken. The succession of targeted seagrass species are gradual and marginal after two years monitoring. To offset or minimize the impact, further countermeasure such as environmental mitigation (*e.g.* by controlling wave force, sediment improvements, and / or water quality control) will be needed.

Seagrass habitat is of great importance for many organisms and seagrasses serve many functions within the ecosystem. Kubiremidoro is a valuable and sensitive specie and so this direct loss of potential habitat is of extreme significance. The importance of macrobenthos in the food web means that a significant loss could affect the trophic links and thus the potential reduction of benthos biomass due to the loss of intertidal zone area could impact on birds, with a reduction in the amount of available food. In summation, the impact of the future landfill development is highly significant, and will culminate in potentially large effects on Awase wetland. Thus further monitoring of the highly affected elements must be undertaken and adaptive management is required.

7.6 Additional Features Requiring Attention/Protection

1. The mangrove forest needs further assessment and management action to ensure its longevity. From aerial photographs, it appears that sedimentation (and subsequent increasing elevation) has dried out the northern area of this region. If confirmed, this would necessitate management action such as the use of sediment traps upstream in order to reduce the incoming sediment load. It is imperative to maintain the mangrove region, as it is an important ecosystem and serves a crucial function as a filter of the poor water quality from the incoming freshwater flows.
2. The vegetated land with direct connection to the tidal flat is an essential feature supplying habitat for hill hermit crabs and roosting areas for birds. It is vital to maintain and protect these regions.

7.7 Recommendations for Further Investigation

In addition to the monitoring strategy specified for the selected environmental indicators, additional investigation and subsequent analysis is required to further understand the wetland. Below is a list of recommended attributes or processes that are essential for this undertaking, yet currently the data remains unavailable:

- Sediment grain size and sediment quality sampling in the mid and lower zones of the tidal flat, and in the subtidal region.
- Benthic biota sampling in the mid and lower zones of the tidal flat.
- Measurement of the freshwater nutrient loadings and discharge under dry and wet conditions (ascertaining nutrient inputs to the wetland).
- Water quality, sediment composition and sediment quality sampling of the deep hole located in the intertidal zone.
- Assessment and quantification of the energy flow through the system (food web cycle). Local information is required regarding the feeding habits of the dominant species at Awase (i.e. trophic interactions).
- Investigation into material cycling (e.g. Nitrogen), with comprehensive sediment and water column measurements.

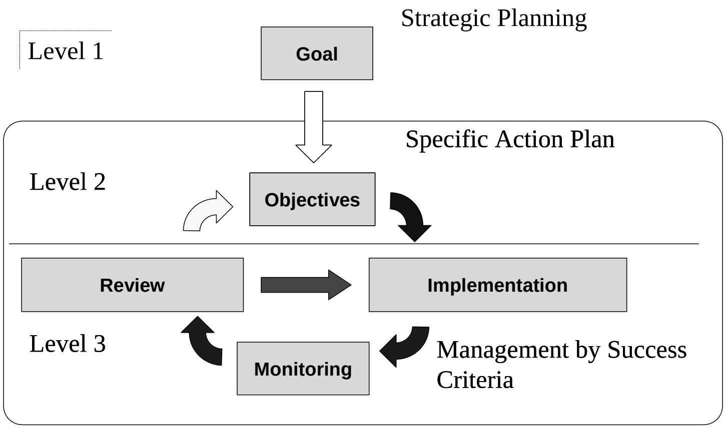

Figure 7.1 Schematic diagram showing adaptive management methodology (adapted from Furukawa *et.al.* 2005).

Table 7.1 Environmental indicators, monitoring strategy and performance standard.

Indicator	Objective	Monitoring Strategy	Performance Standard
Kubiremidoro	A, B, D	Seasonal surveys (strong seasonal effects - one survey during month of peak population)	Presence/absence. Trends in abundance, distribution and density. Substantial decrease in coverage during peak annual population (more than 10% - based on historical average due to large fluctuation and seasonal variability).
Tokagehaze	A, B, D	Seasonal surveys	Presence/absence. Trends in abundance, distribution and density. Substantial decrease in number of individuals (-2 standard deviations).
Benthic Index/Community Assemblage	A, B, D, E, H	Seasonal surveys	Substantial change in benthic community assemblages (or Index, if determined).
Mangrove area	A, C, D	Annual survey, including elevation.	Substantial decrease in mangrove coverage (more than 10%). Rise in elevation (more than 0.1m).
Seagrass area	A, C, D	Annual survey	Substantial decrease in seagrass coverage (more than 15%).
Coral Area	A, C, D, H	Annual survey	Substantial decrease in coral coverage (more than 10%).
Seagrass specie	A, D, E	Annual survey	Coverage. Trends in abundance, distribution and density. Substantial decrease in seagrass specie density or biomass (-2 standard deviations).
Sediment Quality (Grain size, TOC, TN)	A, F	Annual survey	Substantial changes in sediment grain size (change in median grain size category). Increases in sediment TOC, TN (+2 standard deviations).
Water Quality (DO, Salinity)	A, F, G	Seasonal survey (over spring tidal cycle for intertidal zone and mangrove area)	Decreases in DO (-2 standard deviations), substantial change in Salinity (±2 standard deviations).
Freshwater discharge and quality (Nutrients, DO, COD)	F, G	Dry conditions and wet weather events must be recorded, together with continuous time series discharge data (obtain monthly averages).	Increases in Nutrients, COD (+2 standard deviations), decreases in DO (-2 standard deviations).
Waveheight, period and direction	F	Continuous time series (obtain monthly averages, histogram and typhoon events).	No performance standard.

8. CONCLUSION

At Awase wetland there are a wide range of habitats and biotic communities. The tidal flat supports a large macroinvertebrate population including Molluscs, Annelids and Arthropods that are important prey for the shorebirds that feed in the intertidal zone. Awase wetland is also of great importance to the wider environs of Nakagusuku Bay, with the tidal flat and vegetated shallow waters providing good shelter and breeding areas for juvenile fish and other organisms.

Research into the key abiotic and biotic features of the wetland has been undertaken based on the available data, with additional investigation into the tidal flat macrobenthos and environmental conditions. The macrobenthos community structure was found to vary across the tidal flat, and could be clustered into three groups. The sediment environment was found to greatly influence the spatial distribution of the macrofauna community. A decreasing COD and nutrient gradient along the tidal flat dictates the primary spatial distribution of the benthic community, with the sediment grain size also an influential factor.

This study has shown a methodology for combining and analyzing a disparate collection of available physical, chemical and biological data, and assessing the current environmental status of Awase wetland. Through this research, relevant environmental indicators (biotic and abiotic) have been identified for both intertidal and subtidal regions of the wetland, with suitability indices developed for specie and habitat indicators using the methodology of Habitat Suitability Index. Maps of optimal habitat were then developed for the region. The impact of the landfill development on the present environment status was then evaluated, with significant losses in optimal habitat for seagrass, benthic fauna and Kubiremidoro being predicted. Nevertheless, the shape of species groups fraction keeps similarity between pre and post-landfill development. This suggests that the impact of the landfill is not building up on specific species group, but spread across (minimized) through the system of the wetland.

Management objectives, indicator monitoring strategy and performance standards have been developed based on the available data. Further research is recommended into areas identified as lacking in pertinent data. It is only through an understanding of the elements and dynamics that this very important wetland can be managed effectively and efficiently.

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