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A survey strategy and environmental monitoring network for an estuary supporting finfish cage culture

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The Huon estuary, in southeastern Tasmania, is an important location for finfish, and to a lesser extent shellfish, farming. The Huon catchment is a lightly populated rural and forested region in a cold temperate climate which supports agriculture (horticulture and livestock), forestry, and tourism. The estuary (40 km in length) is microtidal, with a stratified to partially mixed water column. Effective design of sampling procedures for either monitoring or interdisciplinary studies is essential for resolution of the key time and space scales, and the operational programme must be relevant for events and processes in both the water column and the sediments. We chose to track seasonal changes in physical, chemical, and biological parameters by doing quarterly samplings of the water column at a grid of stations (63 in all) that encompassed the entire estuary from a freshwater end-member to a designated marine boundary. More rapid events were captured by monitoring (both autonomous instrument systems and manual sampling), at hourly to weekly intervals, at a small representative subset of the estuarine stations. Underway measurements from the research vessel were used to map transient surface and near-surface features. Sediments are long-term integrators of processes in the water column and therefore an intensive spatial survey of the sediment characteristics has been made to characterize the long-term influence of human activities. Knowledge gained from field observations of the baseline study has been used to outline an autonomous monitoring network that will derive the environmental information critical for the prudent management of the waterway for both its natural and commercial values.

Key words: environmental monitoring, estuary, mariculture, sediments, water quality.

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Introduction

Survey design is often neglected in environmental research. It tends to be considered perfunctorily at the outset of a study, and is then adjusted *ad hoc* throughout the operational phase when early results indicate shortcomings. The two extremes to designing an estuarine survey are: (i) a statistical approach that presumes almost no knowledge of the system, and seeks to make randomized observations over space and time, from which inferences might then be tested by statistical analyses, and (ii) a process-oriented design that uses understanding of estuarine systems to influence the planning of a sampling strategy (e.g. if salinity is considered a master variable, the salinity gradient should be sampled comprehensively so that the effects of estuarine mixing are reflected in other parameters).

Favouring one of these approaches at the expense of the other is likely to lead to flawed survey design. At the very least some conditions could be oversampled, and effort wasted. Nevertheless, we concentrate here on the influence of natural system processes in arriving at a survey strategy, because that influence is often overlooked. The ideal design would also consider stochastic factors (e.g. what disposition of sampling stations, frequencies of measurement, degree of replication, and

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statistical methods are needed to detect patterns or changes that are considered important). Statistical elements of survey design in environmental studies are dealt with well in several primary texts (Gilbert, 1987; Keith, 1988; Ellis, 1989; Thompson, 1992).

Reports on survey design in estuarine studies usually have a narrow perspective. Their attention has often been weighted toward a particular scientific discipline, or influenced by budgetary or regulatory considerations. Only a handful of reports on study design have had a broad interdisciplinary basis (Nittrouer and DeMaster, 1996; Harris and Crossland, 1999 and references therein), grappled with the estuary as a dynamic system (Morris *et al.*, 1982; Morris, 1985; Kjerfve and Wolaver, 1988), or dealt with the estuary as the axis for myriad interactions influenced by its catchment, sediments, neighbouring coastal waters, and the atmosphere (Morris, 1985; Schoer and Duwe, 1986).

Here, we present the basis for our survey strategy for the Huon estuary study, which considers the entire estuary as a system and is aimed at evaluating its present status and functioning. Special attention is paid to issues relating to finfish aquaculture in the lower estuary (such as water quality, microalgal dynamics, and organic matter in sediments) and emphasis is placed on the temporal and spatial scales relevant to nutrient cycling and microalgal blooms.

We begin with a description of the Huon estuary and its catchment, and review past investigations. The basic elements of our survey strategy are then presented, and their part in an integrated, interdisciplinary scientific investigation of the waterway is discussed. Toward the end, we consider opportunities and advantages of an automated monitoring system, once system understanding has been obtained from an initial baseline study.

Study site

The Huon river estuary and its catchment are located in southeastern Tasmania (Figure 1) between latitude 42°45′S and 43°45′S, in a maritime climate that is dominated by zonal westerlies producing changeable, cool temperate conditions. The catchment area is about 3130 km^2. The annual average rainfall varies from in excess of 2000 mm in the west to slightly under 800 mm in the east. Rainfall is relatively uniform throughout the year, peaking in the months July–October. Most of the central catchment is forested with native hardwood. The western catchment is also well vegetated, but with its higher relief, it is a mix of moorland, wet scrub, and pockets of hardwood trees. This vegetation cover protects the excellent water quality of the upper Huon river and tributaries but, because of run-off from the moorland, the waters are strongly coloured with humic substances. Forestry operations cause intermittent increases in turbidity and nutrient concentrations in rivers. Land is cleared for farming and settlements in the east and along the shores of the estuary. The region is sparsely settled, with a total population of about 13 000. Agricultural and urban run-off contribute to some deterioration of water quality.

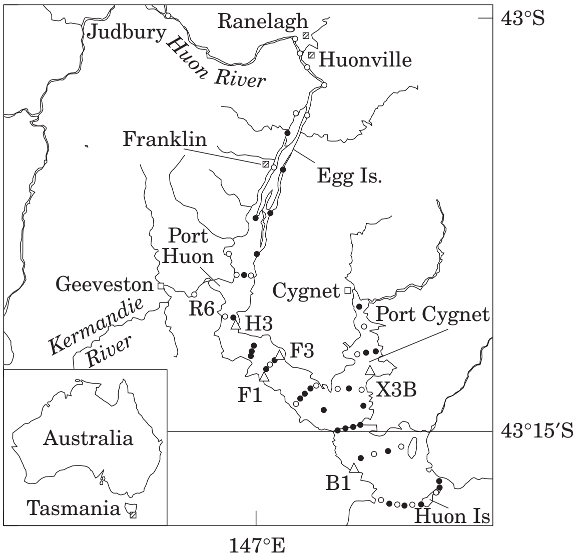

Figure 1. Sampling sites in the Huon estuary (Tasmania): (●) physical, (○) chemical, and (△) biological stations.

The mean annual flow of the Huon river (estimated just upstream of Judbury) is 87 m^3 s^{-1}, with monthly average flows varying from 30–40 m^3 s^{-1} (January–March) to 125–130 m^3 s^{-1} (July–August). The Kermandie river is also an important tributary discharging to the middle estuary (2% of the total discharge, but 8% and 25% of the nitrogen and phosphorus load, respectively, to the estuary in 1997).

The Huon estuary, like others in southern Tasmania, has been formed from the drowning of a river valley. It is characterized as a microtidal salt-wedge estuary. The deeper saltwater layers can penetrate under low river flow as far as Ranelagh, some 40 km upstream from the mouth of the estuary at Huon Island. The estuary can be partitioned into three geographic regions: (i) a deeper marine zone in the lower half, (ii) the Port Cygnet arm, and (iii) a shallow brackish zone in the upper half. The Port Cygnet arm is situated mid-way up the lower estuary; it is shallow, but marine-dominated with very little freshwater input from the Agnes and Nicholls Rivulets. The upper estuary shoals rapidly from 10 m at Port Huon to a mean depth of around 4 m on the western side, and 2 m on the eastern side of the Egg Islands.

Other features of the estuary are presented in Table 1. Historical water quality data, although sporadic and not comprehensive, indicate no serious water quality problems in the Huon region (including the estuary). A

Table 1. General characteristics of the Huon estuary.

Length	Upper estuary	19 km
	Whole estuary	40 km
Mean depth	Upper estuary	2–3 m
	Lower estuary	17.7 m
Volume	Upper estuary	0.04 km^3
	Whole estuary	1.28 km^3
River flow	Typical	90 m^3 s^{-1}
Mean tidal amplitude at Huonville Bridge		0.9 m
Tidal excursion	Calculated	~0.6 km
Flushing time	Calculated	≤7 d

recent issue for environmental management has been the introduction of *Gymnodinium catenatum* to the waterway in the 1970s (McMinn *et al.*, 1997). This dinoflagellate is one of the causative organisms of paralytic shellfish poisoning, and blooms of this species have resulted in closures of shellfish farms in the estuary for periods of weeks and longer almost every summer and autumn since 1986.

Earlier hydrographic surveys in the Huon estuary (e.g. Woodward *et al.*, 1992) established some of the broad physical and chemical characteristics of the water body. These included the limit of penetration of saltwater being adjacent to the township of Ranelagh, and the complex hydrodynamical features of the middle estuary around the elbow below Port Huon. A recent compendium of historical and current environmental information on the Huon river and catchment also proved invaluable in early planning.

Development of a survey strategy

Preliminaries

Decisions as to what measurements to make were determined mainly by the objectives and the need for fundamental measurements for mixing indices, water quality, sediment properties, and conditions for microalgal growth. The specific study objectives relevant to this were:

- determine the sources, distribution, and cycling of nutrients (including those from fish farming) in the estuary, and relate nutrients and physical parameters to microalgal dynamics;
- evaluate the processes (and their rates) that contribute organic matter to sediments from fish farming and natural sources, and the significance of this organic matter in the cycling of nutrients through the sediments;
- test the usefulness of different methods for monitoring the environmental quality of sediments and water column to: (i) provide a scientific basis for the design of a monitoring framework for both industry and environmental managers, and (ii) give technical advice on optimizing such a framework to address both localized impacts and general estuarine conditions.

From the outset, we decided to develop a number of observational strategies to cover the important spatial and temporal scales. Not all time and space scales are necessarily of interest. If it is decided that certain scales of variation are not relevant, they can be treated as noise. However, sampling strategies must take account of this noise and ensure that the desired signal does not end up masked, aliased, or biased (an element of statistical survey design).

Concurrently, we aimed for an interdisciplinary study – integrating physics, chemistry, and biology – to improve understanding of the ecological functioning of the estuary. The benefits of such an approach have been advocated previously (PERP, 1983). Full details of the Huon Estuary Study programme – its design, observational procedures, and results – are provided in the study report (HEST, 2000). Our study began with a pilot hydrographic survey of the entire estuary over 3 d in March 1996, comprising 59 sites (86 stations in all with repeat casts) that were each profiled using an oceanographic conductivity–temperature–depth (CTD) sensor. The main objective of this preliminary fieldwork was to characterize the estuarine structure. The distribution of stations (i.e. spatial resolution) was determined on the basis of earlier studies in the Huon estuary and in the neighbouring Derwent estuary, which is a close analogue (Edgar *et al.*, 1999; HEST, 2000).

Geographic coverage

We adopted the traditional approach of a survey of the whole estuary, where "geographical sites are fixed according to the salinity gradient, and spanning the entire salinity range, including freshwater sampling" (Morris, 1985). A survey of the entire estuary gives valuable information on: (i) mixing processes, and behaviour of dissolved and particulate matter over the estuarine gradient, (ii) broad geographic distribution of properties, and, if three-dimensional sampling is used in stratified areas, (iii) differences may also be discerned in properties (e.g. transport processes, chemical reactivity, and microalgal distribution) between surface and deeper layers, and possibly inferred for sediment–water exchange of solutes.

The marine boundary was fixed across the opening to D'Entrecasteaux Channel, where Huon Island is located (Figure 1). The freshwater end-member was selected at a gauging station (automated turbidity measurement) at Judbury, just upstream of the first shallow rapids. It was sampled by hand from the river bank, as was a freshwater end-member on the Kermandie river.

A dense array of physical measurements was required to resolve complexity in the distribution of salinity and temperature noted historically (Woodward *et al.*, 1992),

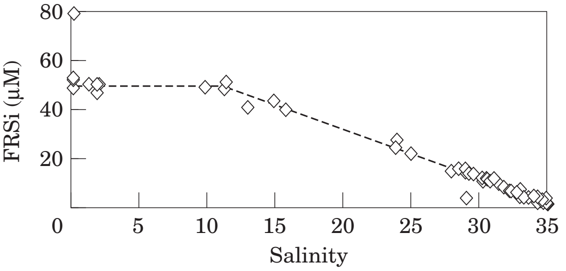

Figure 2. Relation between filterable reactive silicon (FRSi) and salinity (October 1996): the different slopes of the mixing relation indicate an input mid-estuary at Port Huon from the Kermandie river (see Figure 1; FRSi concentration in freshwater station R6 is off-scale at 257 μM).

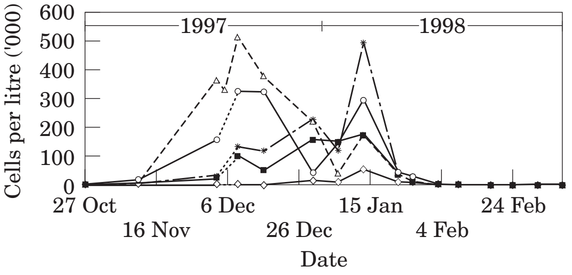

Figure 3. Weekly/fortnightly monitoring data for cell counts of the toxic dinoflagellate *Gymnodinium catenatum* at the biological stations: (◆) B1, (★) F1, (▲) F3, (●) H3, (■) X3B.

and in the pilot survey. Sixty-three stations in all constituted the balance struck between sufficient resolution and operational capacity in both the field and laboratory. Of these, 30 were also chemical stations (water quality measurements and plankton net hauls), and five chemical stations were upgraded to biological stations (enhanced characterization of microalgal ecology). Station locations were fixed for all surveys. The many locations of interest (e.g. point source inputs, aquaculture operations) throughout the estuary were influential in station selection, as was the utility of a station grid for developing box inverse models.

In a salt-wedge estuary, it is common to take just samples from the two layers – surface and bottom. However, because *in situ* fluorescence measurements during the pilot survey suggested that phytoplankton biomass could be concentrated at or near the halocline, we opted also to sample at the fluorescence maximum. This would provide a sample with maximal biological imprint.

An example of results from a spatial survey is presented in Figure 2. The plot of filterable reactive silicate against salinity reveals an input of this nutrient to the middle Huon estuary from the Kermandie river.

Temporal scales

Spatial surveys

We chose to carry out the comprehensive spatial surveys at quarterly intervals to track seasonal changes with respect to biological activity. Shorter-term events (e.g. tides, microalgal blooms, peak river flows, storms, and fluctuations in coastal currents) would thus be missed. Therefore, additional data collections were deemed necessary.

Monitoring at key stations

Weekly intervals are useful to track succession in microalgal blooms (although not the history of an individual bloom), and approximately match the period of short-term cycles in weather. However, manual sampling and subsequent laboratory measurements were only manageable on a weekly or fortnightly rotation if they were done at a subset of stations. The five biological stations of the spatial survey were selected as the key stations. Although they are all located in the middle and lower estuary, they bracket the region in which aquaculture is found. Moreover, the Huon estuary can be classified as a biochemical estuary (Church, 1986): its small tides and low concentration of suspended particulate matter cause the geochemical (particulate) processes affecting solutes in the upper estuary to be overwhelmed by the biological activity in the lower estuary. This is an additional reason to focus on the lower, marine end of the waterway.

The five key stations could all be sampled from a small boat in about 3 h, giving a weekly or fortnightly snapshot of the estuary under close to synoptic conditions. An example of microalgal cell counts from weekly monitoring at the biological stations is given in Figure 3.

Autonomous continuous profilers

In attempting to glean information on conditions that influence the genesis of the bloom of an individual phytoplankter, it is necessary to have data down to hourly intervals, and often over the full water column. Similarly, the onset of oxygen-depleted conditions in the vicinity of fish cages in warmer months of the year is strongly influenced by microbial decomposition of organic matter. Monitoring hourly or more frequently may prevent sudden fish kills.

Instrumentation to provide this frequency of data over the full water column grew out of an earlier demonstration project at a fish farm in the Huon estuary. The subsurface package consisted of a CTD profiler, light sensor, an *in situ* fluorimeter, and a prototype underwater spectroradiometer. The package was deployed at a depth of 3 m, and measurements were made and recorded at 30-min intervals (60 min for the spectroradiometer). It could be made to record a depth profile on manual command.

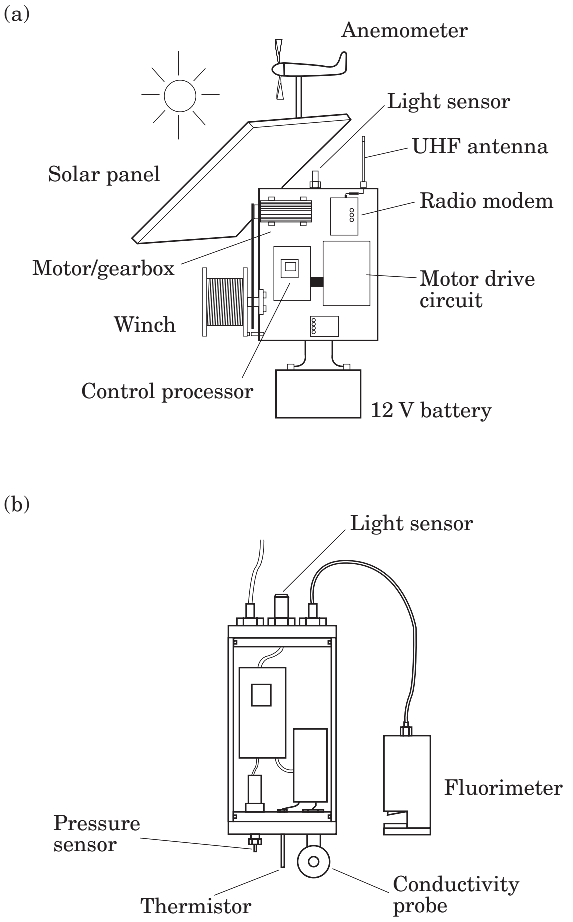

Figure 4. Cutaway drawing of automated continuous profiler showing (a) surface unit that is mounted on a pontoon, and (b) sensor unit deployed by winch. Its use in an operational configuration is depicted in Figure 8.

A key lesson from this experimental work was the importance of resolving vertical variation. Not only was this important to follow changes in physical characteristics of the water column, but also vertical migration of dinoflagellates can only be tracked by measurements over the full water column.

Two automated continuous profiling systems were developed in house (Figure 4). Each system raises and lowers a sensor package at intervals of 1 h, obtaining data with a vertical resolution of ~0.5 m. The controller-logger unit and winch were mounted on a moored pontoon. These profiling systems were deployed with CTD, fluorescence, turbidity, light and dissolved oxygen sensors. Figure 5 is an example of output depicting microalgal biomass fluctuations (measured by *in situ* fluorescence) at a station in the lower estuary.

Mapping of surface water properties

The spatial surveys took 3 d, operating in sequence of daily steps in the lower, middle, and upper regions of the estuary. Variations in conditions at time scales of 1 d or less are lost within the survey data. On occasions, we took rapid physical (CTD only) profiles of the water column at all 62 estuarine stations in 1 d (~8 h). However, the tidal influence would still be present in these data.

To survey the whole estuary rapidly and with improved geographic coverage, we developed an intake system for use while the vessel was moving forward at constant speed (typically 12 m s^{-1}), with intake pipes mounted on the side of the hull at depths of 0.5 and 1.0 m. The intake manifold distributed water to flow-through cells of deck-mounted CTD units of the same type as used for profiling the water column. The entire estuary from the mouth to just below Huonville could be mapped in 2–3 h, depending on survey track. Using time as a reference, the sensor data were concatenated with simultaneously collected GPS information to provide maps of salinity, temperature, and *in situ* fluorescence. A compact flow-analysis instrument is under development to add nutrients to the array of mapped variables.

Although this mapping is limited mostly to the surface layer (depending upon the depth of the pycnocline), it is these waters, as a buoyant brackish plume in the estuary, that are most changeable. They are influenced by transient forcing by winds, waves, and short-term fluctuations in local run-off (HEST, 2000).

Sediment sampling and analysis

Estuaries act as a natural filter, retaining within their sediments much organic matter and minerals supplied naturally by rivers. Concentrations are often several orders of magnitude higher in the sediment than in the overlying water column, thus simplifying the analysis. A single estuary-wide survey will often suffice for gathering the required information.

Surface sediments provide an integrated picture of inputs over time frames of a few years. Hence, they may give an indication of local inputs in the context of an estuary-wide baseline, and also provide a better view of long-term average inputs than a sequence of snap-shot surveys of the water phase. Sediment cores provide a record down their length of estuarine conditions over years to decades and longer, depending on sedimentation rate. The gradient with depth, especially for porewaters, yields estimates of the fluxes of solutes in or out of the sediment.

One of the key issues in the Huon estuary is the high content of organic matter in the sediments, its origins and susceptibility to degradation. Much of it is derived from freshwater inputs of terrestrial origin, such as that derived from sub-alpine moorland and other peaty soils, with additional inputs from autochthonous phytoplankton and localized inputs from salmon farms, sewage treatment plants and stormwater drains (HEST, 2000).

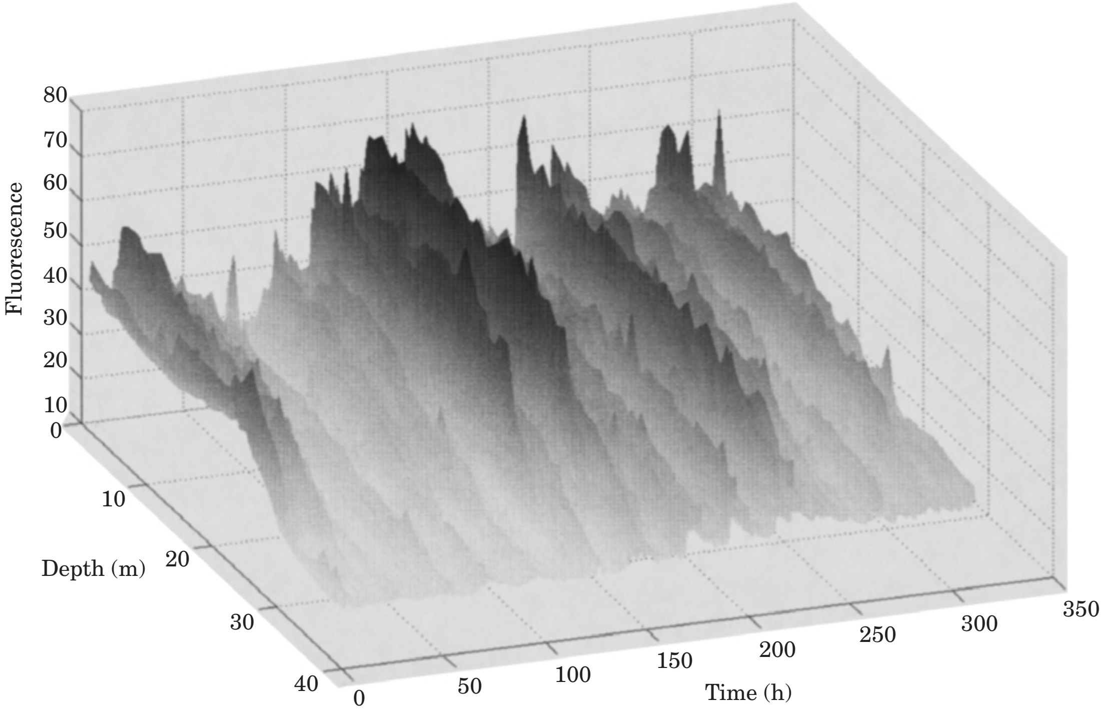

Figure 5. Relation between *in situ* fluorescence output (uncorrected), depth, and time from the continuous profiler deployed in the middle estuary (31 Oct 1997 to 12 Nov 1997): fluorescence profiles indicate short-term fluctuations in biomass during the austral spring.

Organic matter from these diverse sources has very different compositions. All samples were referenced to a primary set of characteristics (grain size, colour, loss on ignition, etc.), and then a subset was used for further chemical and biochemical measurements to resolve microbial processes and to characterize the long-term influence of natural and human activities (HEST, 2000). Much of the terrestrial material consists of high molecular weight tannin-like compounds, which seem to be degraded very slowly. Its demineralization probably does not contribute greatly to nutrient loads. In contrast, organic nitrogen in sediments (Figure 6) at higher levels in the middle and lower estuary is derived from marine sources, as indicated by its $\delta^{15}N$ signature (HEST, 2000). Presumably, the organic nitrogen is derived from sedimenting microalgae, and might be remineralized relatively easily to be returned to bottom waters.

Relevant time and space scales

The preceding survey and monitoring methods were selected to acquire the necessary observational data to meet the objectives. Figure 7 provides a diagrammatic representation of the coverage of time and space scales.

A re-assessment of the relevant time and space scales would be required if the purpose for studying or monitoring the estuary were to be different. For example, operational monitoring within the confines of a fish-farm lease would have a different set of objectives. The domain for gathering data would mostly be restricted to the farm lease, and perhaps waters immediately adjacent. Observations would be needed for each cage, or at the least, for each cage group in a limited area. Measurements would need to span the entire water column, or at least a set of discrete depths. They are likely to include temperature, salinity, dissolved oxygen, and *in situ* fluorescence or some other means by which to automatically monitor microalgal biomass. Frequency of observation would need to be hourly or better.

If, on the other hand, observational data were required for interactive environmental management of the entire estuary as a *system* (for commercial uses, such as aquaculture, as well as for its ecological sustainability), a different approach is needed.

An automated monitoring network

Here, we consider briefly the elements of an environmental monitoring network comprising an array of autonomous field stations reporting to a base station, where logged environmental data are processed and stored. The purpose of the proposed network is to provide information to aquaculture industry (finfish and

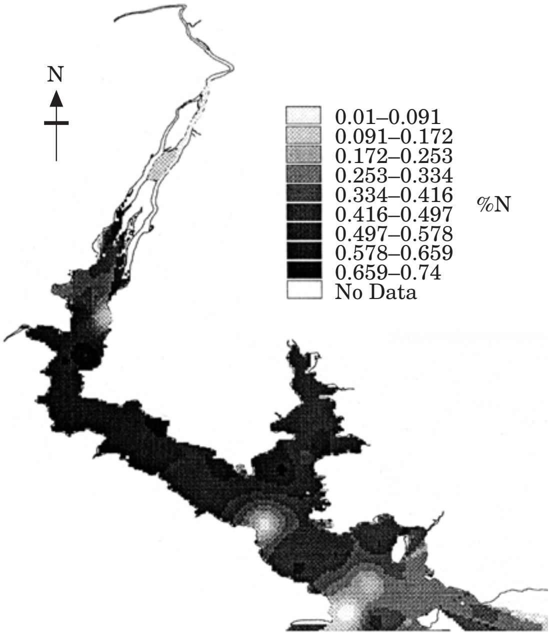

Figure 6. Percent nitrogen determined in surface sediments of the Huon estuary (survey: 13–14 May 1997).

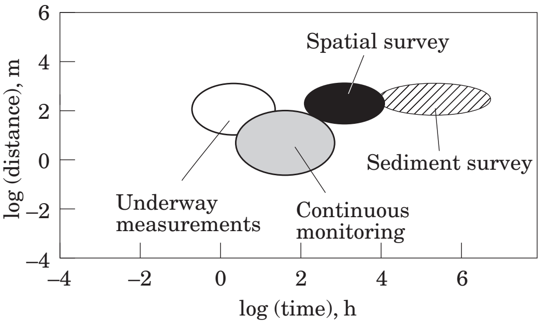

Figure 7. A representation of the different time and space scales covered by the different observational procedures used in the Huon estuary study. See text for explanation.

shellfish) for their effective operation of marine farms, while at the same time monitoring the environmental health of the estuary.

The establishment of such a network relies definitively on the gathering of fundamental baseline information so that the physical and ecological functioning of the estuary is known in outline, and its current status is recorded. Such information is now available for the Huon estuary (HEST, 2000).

Because the natural processes and human activities in the catchment may affect the health of the estuary (the natural ecosystem, as well as aquaculture operations) it is necessary to look at the catchment as the geographic unit. The monitoring needs to be considered in two parts: the estuary itself, and the catchment and its streams.

Salinity, temperature, and dissolved oxygen would need to be measured in the estuary at all stations. The preference is that these variables be monitored as a continuous vertical profile, rather than at a subset of discrete depths. These *core* measurements are the basis for following estuarine dynamics, and are as relevant for estuary-wide management as they are for aquaculture farm operation. Because microalgal blooms are an issue, *in situ* chlorophyll fluorescence measurements throughout the water column are probably needed at a subset of estuarine stations and sensor systems.

A second tier of measurements might also be considered. Although they may be less critical on the whole, this would depend on circumstances and location. They could be implemented intermittently by temporarily upgrading an existing field station:

- Meteorological measurements (especially wind velocity and direction) are valuable for their influence on the hydrodynamics of water bodies, but only a subset of stations would need to be instrumented.
- Direct measurement of currents by current meters are useful to establish such matters as the dispersal of wastes from sea cages holding finfish, and they can be used to validate model estimates of currents. Nevertheless, a conventional current meter records at just one point. An acoustic Doppler current profiler yields more information because it measures over a depth range. However, implementation of a hydrodynamic model of estuarine circulation seems a better tool for environmental management. Given routine access to an array of salinity and temperature data, a model provides estuary-wide coverage. A variety of applications can be considered, such as simulation of observed conditions, or prediction of the effects of atypical or modified conditions.
- Similarly, nutrient measurements are useful when tracing sources, estimating loads, or investigating their biogeochemical cycling. However, from a management perspective, ephemeral injections of nutrients (and patchiness in their distribution) in a water body as large as the Huon estuary might be very difficult to observe reliably from a restricted number of monitoring stations. Excess nutrients, especially nitrogen, are readily assimilated by microalgae. Dilution away from the source in the wider estuary can also challenge methods of nutrient analysis. If possible, the place to measure inputs of nutrients is in the discharge stream, rather than in the estuary near the point of entry. For sources within the estuary, such as salmon farms, this is not possible. Nevertheless, nutrient monitoring is useful and necessary to follow broad-scale changes in nutrient concentrations.
- Microalgal biomass is the more amenable environmental indicator of aquatic eutrophication for seasonal to longer intervals. A useful surrogate for microalgal biomass is chlorophyll *a*; fluorescence

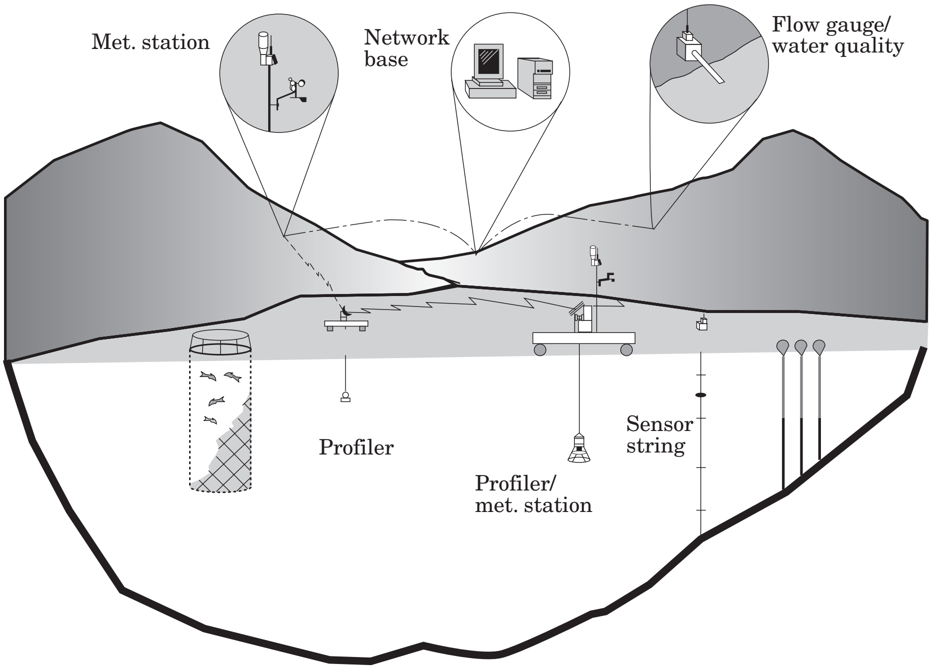

Figure 8. Depiction of an automated environmental monitoring network providing operational data for mariculture industry (finfish and shellfish) and also information for environmental management of the estuary. The array of monitoring elements is only indicative of the system.

measurements might be made weekly at a selected number of sites, or intermittently at automated field stations by upgrading instrumentation (e.g. continuous monitoring for 1 d per month).

- The frequency of core measurements should be hourly, in relation to operational monitoring for fish farms. We envisage automated continuous profilers located in the middle and lower estuary and a third in Port Cygnet (because this part appears to be functionally different from the main arm of the estuary) as a minimum deployment. The continuous profilers can also serve as a reference station for associated sensor strings. The sensor strings provide measurements at a series of discrete depths to extend the coverage of estuarine data. They are relatively inexpensive and robust, and thus suited to operational deployment in and around aquaculture leases. It is anticipated that data from the sensor strings would be telemetered to the network base station via the continuous profiler platforms.

The estuarine components of the monitoring network are depicted schematically in Figure 8, which also shows the basic elements of the catchment part of the network. Here we are looking at monitoring the effect of run-off on estuarine conditions. The two priority measurements are stream flow and turbidity. The first determines the volume of water discharged from a tributary over a set period, which is essential for load calculations. Sharply increasing flows are often an early warning of deteriorating water quality. Turbidity is a useful record because it is related to the suspended solids concentration in the stream, but it has enhanced value because turbidity may be a surrogate for nutrient (N and P) concentration and also for the extent of faecal contamination. Measurement of rainfall in the catchment is discretionary for estuarine management, and finfish and shellfish farming. Its advantage is that it can provide earlier warning of increased (local) discharge.

Monitoring stations are needed on the main tributaries: the Huon and Kermandie rivers. Turbidity and stream flow (at different locations) are already gauged on the Huon river. This situation points to the advantages of incorporating existing infrastructure into monitoring networks if at all practicable. The small and transient nature of the flow of other minor tributaries makes them difficult to instrument. Rainfall measurement in some of these catchment areas, particularly those of Port Cygnet, could provide some workable information on local peaks in discharge.

An environmental monitoring network provides operational data that can be used directly as supplied (e.g. dissolved oxygen for fish-farm operations). However, the data may get added value by further processing. Derived data products may represent the integration of several types of data reported by sensors, or some other synthesis from the raw data, or they could be extended to the development or use of mathematical models. Some examples of derived data products are:

- Toxic algal bloom forecasting: synthesis of the probability of microalgal blooms from water temperature, immediate history of rainfall and windspeed, and *in situ* fluorescence (the triggers for the toxic dinoflagellate *Gymnodinium catenatum* have been discussed by Hallegraeff *et al.*, 1995).
- Environmental health monitoring for shellfish culture: coupling rainfall distribution over catchment, resulting freshwater inflow and turbidity with the known record of waterborne concentrations of pathogenic organisms (*Escherichia coli* and others) to provide early warning of unsafe water quality for harvesting.
- Microscale dissolved oxygen and toxicant (e.g. free ammonia, hydrogen sulphide) prediction in and around finfish farms: using a combination of dissolved oxygen, temperature, salinity, turbidity (and possibly *in situ* fluorescence) data along with nested hydrodynamic model, fish excretion algorithms, and baseline information on sediment characteristics provides a concept of a tool for fish farms by which to estimate acute and chronic hazards to fish stock.

The opportunities for environmental monitoring networks will grow rapidly with experience of their application in the field. Their value to the community is not limited to the estuary, but can be extended to integrated catchment management – nor is it constrained to aquaculture. Other obvious uses are improved flood warning services, microclimate forecasting and, for the broader community, an environmental database into which other position-referenced information can be entered.

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