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Water quality of the Madang Lagoon, Papua New Guinea: A status report

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Very little is known about the water quality parameters of marine ecosystems in Papua New Guinea (PNG). While several studies converge in classifying these ecosystems as among the richest in the world in terms of marine biodiversity (Pearse, 1988; Rau, 1988; Gosliner et al., 1996; Maniwavie, 2000; Karlson et al., 2004), relatively little can be said about the status of their waters, although water pollution and pressures on marine

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environments are increasingly becoming a concern among coastal people in PNG.

The importance of the Madang Lagoon lies in its highly heterogeneous, diverse and rich reef system (Pearse, 1988; Maniwavie, 2000; Jenkins, 2003). The Lagoon was designated a priority area for conservation (Alcorn, 1993), which led Wetlands International to assist some communities along the Lagoon to establish protection regimes (Fig. 1) (Jenkins, 2003). Currently, the natural resources of the Lagoon are threatened. Coastal population growth, intensive agriculture, urban development and intense logging activities are aggravated by minimal planning for waste disposal and the lack of water purification systems (Fig. 1) (Hunnam et al., 2001; Benet Monico, in preparation). Consequently, there is an intention to develop an Integrated Coastal Zone Management Plan for the Lagoon. In this context, the Water Quality Monitoring (WQM) aims at defining a baseline for a suite of physical and chemical water quality indicators, and at identifying warning signals if any problems were already evident. This study represents the first extensive water quality assessment conducted in the North Coast of PNG, and describes a robust and easy method that could be applied in similar conditions.

The Madang Lagoon (5°S 145°E) is the largest Lagoon in the North Coast of PNG (approximate area 50 km^2). It is bordered on its seaward edge by a narrow barrier reef

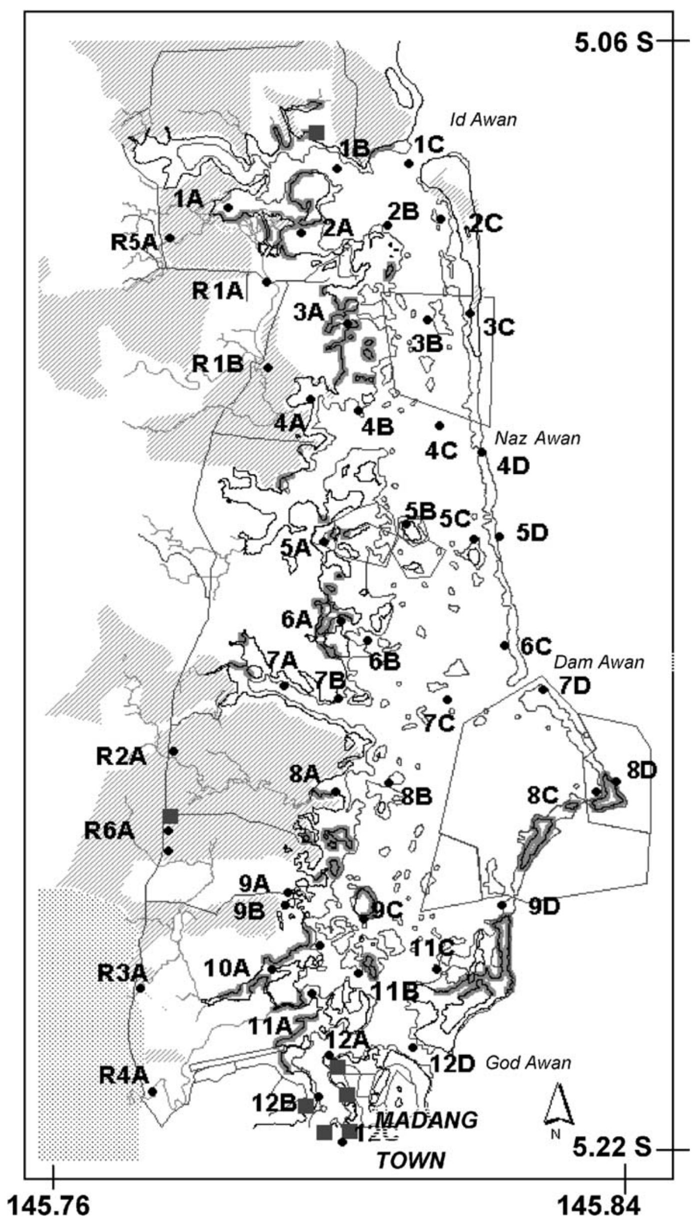

Fig. 1. Map of the Madang Lagoon. Sea sampling sites (black dots) are labeled as nA to nD and river sampling sites as Rn. The map indicates all protected areas (boxes), mangrove habitats (thick grey lines) and coral reef habitats (thin grey lines) in the Madang Lagoon area. Also, it locates industry (square dots), logging concessions (dotted areas) and agricultural land (stripped areas) occurring along the Lagoon. Passages connecting the Lagoon with the open sea are labeled in italics.

with four major passages that link the Lagoon to the open sea (Fig. 1). The barrier reef is steep-sided on the seaward side, dropping to seabed depths of 400 m–1 km (Jebb and Lowry, 1995). The Lagoon is even in depth (30–40 m), and its bed is a thick layer of silt clay with numerous shallow patch reefs and coral rubble islands. The inner coastline is greatly dissected. It has shallow fringing reefs, mangroves and sea grass habitats (Fig. 1). The Lagoon harbors spawning aggregation sites, nursery areas and holoturian and burrowing fauna (Rau, 1988; Pearse, 1988). The climate includes precipitation of about 3000 mm per year and is strongly influenced by El Niño Southern Oscillation (ENSO) events (Jebb and Lowry, 1995). Surface marine temperatures of 27–30 °C are among the highest known in tropical regions. Visibility is generally poor by tropical oceanic standards, rarely exceeding 20 m. The New Guinea Current (NGCU), at a depth of 200 m, has high salinity, low tritium and high dissolved oxygen concentration and dominates the oceanography of the northern New Guinean waters (Tsuchiya et al., 1990). NGCU upwellings occur when changes in the direction of surface currents, as observed in the Madang Lagoon (Jenkins, 2003). Two major rivers discharge into the Lagoon: the Biges and the Meiro (Fig. 1). During heavy rain, water coming from the Gum and Gogol rivers, located to the south of the Lagoon, also enters the Lagoon through God Awan passage reducing visibility and causing localised siltation.

In coastal waters, organic matter, nutrients, microorganisms, metals and toxicants are the most critical contaminants. Most of these occur naturally in the sea. Information on the natural background level of these contaminants is key to designing management plans to prevent the accumulation of these substances to the level of pollutants, which might impact on marine ecosystems and human health (UNEP, 1982).

In order to investigate the level and variation of contaminants in Madang Lagoon, a total of 41 sites within the Lagoon (nA to nD) and eight sites on rivers and creeks (R1A to R6B) were sampled between May 2002 and April 2003 (Fig. 1). The Lagoon was divided into 12 transects (1–12). Several points along each transect were sampled (A-coast to D-ocean) to assess changes in the parameters across the width of the Lagoon. The physical parameters plus dissolved oxygen (DO) were measured up to six times both at surface and 15 m depth. Temperature, pH, conductivity and salinity were measured with a field-based YSI 63 meter. DO was measured with a field-based YSI 58 meter. Calibration of both meters was done according to manufacturer guidelines. Water clarity (the inverse of turbidity) was measured using a Secchi disc. The range of other chemical parameters that could be included in this study was constrained by the limited testing facilities available at the National Analytical Laboratories in Lae. Biological Oxygen Demand (BOD), phosphates and a suite of trace metals (arsenic, cadmium, copper, lead and mercury) were measured three times using standard techniques. Water samples for analysis of BOD and phosphorus were collected in 500 ml polyethylene bottles, pre-rinsed with sample before complete filling. Sediment samples for metals analysis were collected from the Lagoon bottom or the nearest beach into a polythene bag using a plastic scoop. Each sample bag was placed into a second sealed bag for storage, to avoid cross-contamination of samples. Water samples for faecal coliforms analysis were collected in 250 ml sterile bottles, which were opened and closed beneath the water surface, and immediately sealed with Teflon tape. All water samples were kept in an Esky chillbox, and cooled with ice while sampling. After sampling, all bottles were stored at <5 °C overnight, and flown to Lae the following morning in a refrigerated Esky. No field blanks or internal standards were included in this monitoring programme, although in the longer term, including these in the protocol would permit the detection of accidental contamination or laboratory discrepancies.

To analyse the data, sampling sites were grouped according to the three different natural environments existing at the Madang Lagoon: (1) river outlets, (2) coastal areas without rivers, and (3) inshore and offshore sites. Trigger values for management responses were calculated in relation to the average values of the indicators assessed for each of the environments. The lack of previous water quality studies along the North Coast of PNG has hindered the identification of an appropriate reference systems, thus impeding the derivation of low-risk trigger concentration values with which to compare the current results (NWQMS, 2000). With studies of coral reef and fish suggesting that the Lagoon is a moderately pristine area, the Lagoon itself was defined a reference site. Mean values of replicates (medians when high variability was observed) were calculated for the physical parameters and DO at each sampling site. Sites with fewer than four observations were excluded. The mean (or median) was calculated for each category at surface and 15 m depth. Low-risk trigger values for each category were defined as the mean ± one standard deviation (or median and 80th percentile and 20th percentile). Mean (or median) values for individual sampling sites far outside the low-risk trigger value would be considered as warning signals of potential pollution. The low number of replicates for metals, chemical and microbiological parameters precluded this type of statistical approach. Therefore the interim trigger values described in the Australian NWQMS Guidelines were used as a generic indication of a good water quality situation (NWQMS, 2000). The data obtained have been interpreted in the light of these threshold values. Samples falling outside the interim trigger value in more than one of the surveys are highlighted in the discussion below and this forms the basis for the ongoing development of this monitoring protocol.

Table 1 summarises the low-risk trigger values of the measured indicators for the three categories at both surface and 15 m depth. These values were similar to the interim trigger values listed in the Australian Guidelines for coastal and open waters (data not shown) (NWQMS, 2000).

Table 1
Low-risk trigger values calculated as the mean ± one standard deviation for temperature and pH, and the 80%ile–20%ile of the median for DO, conductivity and salinity for the three natural environment categories found at the Madang Lagoon

	T (°C)		pH		Dissolved oxygen (% sat)		Conductivity (mS cm^{-1})		Salinity (ppt)	
	Mean ± st. dev		Mean ± st. dev		(20%ile–80%ile)		(20%ile–80%ile)		(20%ile–80%ile)	
	Surface	15 m	Surface	15 m	Surface	15 m	Surface	15 m	Surface	15 m
River outlet ($n = 7$)	30.86 ± 0.61	–	7.8 ± 0.21	–	80.85 (75.2–84.9)	–	39.83 (32.7–54.4)	–	23.58 (21.5–28.3)	–
Coast ($n_s = 15/n_d = 12$)	30.07 ± 0.83	29.18 ± 0.39	7.97 ± 0.17	7.85 ± 0.22	87.65 (81.4–91.9)	95.4 (85.2–107)	52.7 (49–55.8)	56.6 (56.2–57)	32.75 (31.4–33.6)	34.4 (34.2–34.5)
Inshore/offshore ($n = 19$)	29.39 ± 0.52	29 ± 0.26	8.08 ± 0.07	8.02 ± 0.09	92.3 (88.3–93.9)	107.15 (98.8–114.8)	54.9 (54.5–55.5)	56.4 (56.2–56.8)	33.6 (33.3–33.8)	34.4 (34.3–34.6)

s-surface, d-depth.

In agreement with previous data, Madang water temperatures ranged from 29 to 31 °C (Jenkins, 2003; Tamata et al., 1993). Deep water temperatures were consistently lower than their surface counterparts (Table 1). Temperature declines from the coast to the ocean, because of less water movement and greater depth. River outlet points have greater temperature variation due to the influence of the river (Fig. 2(A)). Water temperature tends to decrease when heavy rain had occurred the night before sampling. In tropical climates, where temperature variation is low, changes in temperature may have important effects on the growth and reproduction of the biota and enhance coral bleaching (NWQMS, 2000; Hoegh-Guldberg, 1999), although critical temperatures are specific to each ecosystem (Brown et al., 2000). The NWQMS guidelines indicate a maximum permissible increase of 2 °C over the temperature for optimal growth, which in the case of Madang Lagoon is unknown. Points 9A and 9B had average temperatures of 32.2 °C, almost two degrees above the set trigger value for coastal waters. Two factors may contribute to this observed deviation: (1) the sampling site 9B is located in a narrow and shallow harbour and water at this point is very static; and (2) the sampling point 9 A is at the outlet of a small creek carrying hot water from the food processing industry near to it.

pH trigger values increased slightly from river outlets to inshore–offshore waters, both at the surface and 15 m (Table 1). Little pH variation was observed among inshore–offshore sample sites (Fig. 2(B)). Changes in pH can cause direct adverse effects on aquatic organisms, and may also alter the toxicity or speciation of several pollutants (NWQMS, 2000). No significant departures from these conditions were found in sea values. In rivers, sites R6A and R6B were found to have very low pH values, reaching 4.5 in one of the surveys. Such low pH values were not seen in any of the other points, and are well below the interim trigger value for freshwaters (NWQMS, 2000). They may be indicative of leaching or dumping of liquid wastes into the river system.

Whilst the Lagoon's surface waters were strongly influenced by freshwater input, stratification effects kept deep water more constant (Table 1). River outlets and surrounding waters had low and very variable salinity values ranging from 1.7 ppt to 33 ppt (Fig. 3(A)). Conversely, coastal and inshore–offshore sites had consistent and higher salinity values across the Lagoon, in agreement with other studies (Furnas and Brodie, 1996). Accordingly, conductivity was also variable and low in river outlets and higher and more consistent in coast and offshore–inshore sites (Fig. 3(B)). Lower values of both salinity and conductivity correlated with precipitation on the mountain ranges. Most aquatic biota can tolerate a range of conductivity, but marine biota is especially sensitive to decreased salinity (the ionic composition). Near the coast these parameters are episodically subject to changes due to enhanced freshwater runoff. Consequently reefs and corals near the coast, such as those at Madang, may have a higher

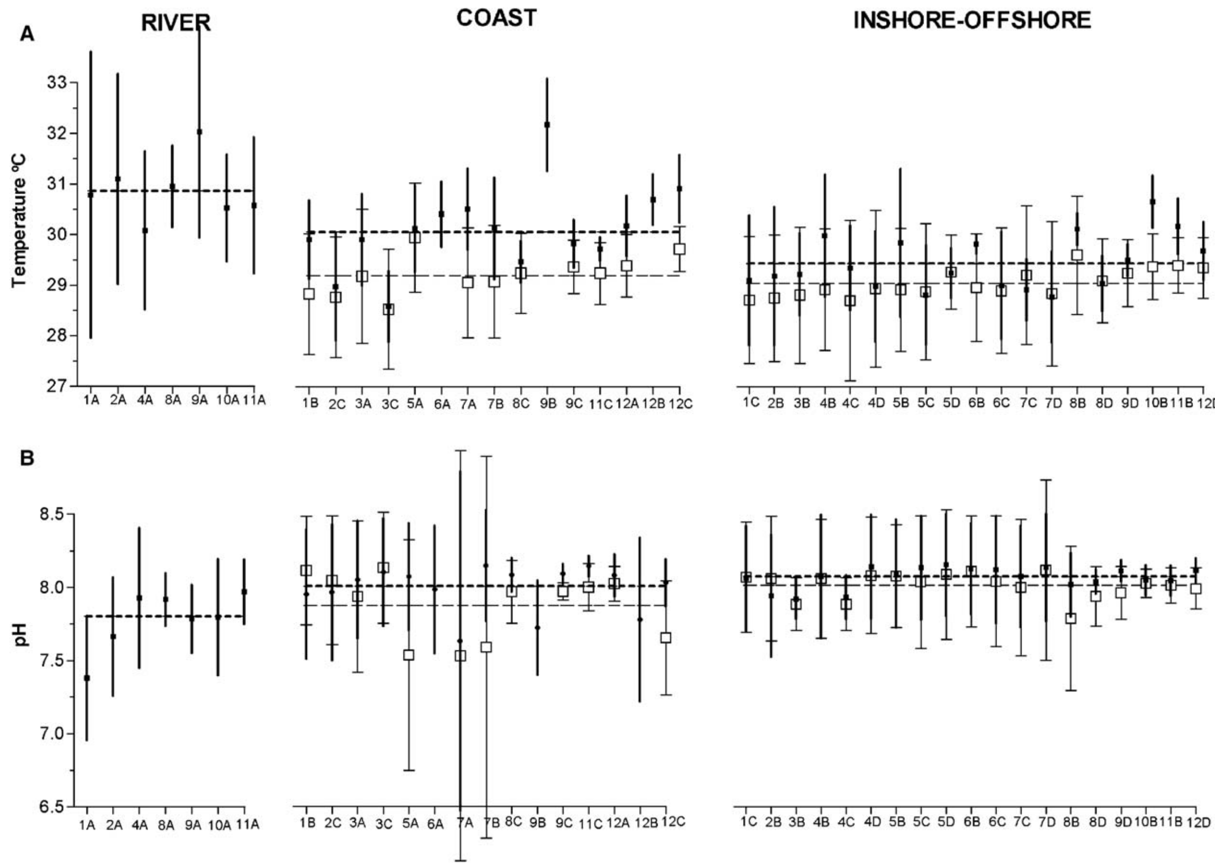

Fig. 2. Box-plots of the mean and standard deviations of replicates at each sampling point for Temperature—°C (A) and pH (B) at both surface (■) and 15 m depth (□). Sampling sites are grouped in the three natural environment categories: river outlets, coast and inshore–offshore. Trigger value (overall mean) represented for surface (--) and 15 m (—).

resilience. Points 9B and 12C had median salinity well below the trigger value calculated for coastal points (Fig. 3(A)), and therefore should be taken into consideration for further surveillance. Strong variability in conductivity readings was also observed in rivers. Although most of the values were below 400 μS cm^{-1}, well within the NWQMS guidelines recommend threshold of 1500 μS cm^{-1} readings ranged from 140 to 41,000 μS cm^{-1}. The high variability may be attributable to natural geology and hydrological variability, local contamination at the sampling sites, and possibly to the suspended solids that affected meter readings.

The large degree of DO variability observed in the Madang Lagoon might reflect the influence of organic matter in the water and its decomposition rate, since DO readings were higher in coastal sites close to vegetation such as river outlets and seagrass beaches (Fig. 4). The median value of DO at 15 m is higher than the surface median (Table 1), but only three sets of observations for DO at 15 m were recorded, so no statistical treatment is appropriate, and DO at 15 m has therefore not been represented in Fig. 4. Low DO concentrations have adverse effects on many aquatic organisms, and can cause sediments to release nutrients and toxicants to the water column. Points 9A and 9B have surface median DO values very markedly lower than the identified trigger value, with only ~50% saturation. This generally indicates high levels of organic matter or rapid biological activity. It could be attributed either to the natural characteristics of these sites (rich in mangroves and seagrass), or to the organic contents of the water discharged by the food processing industry (point 9A). DO readings in the rivers are generally very low, with site R6A plummeting to <10% saturation on two different sampling days, representing a significant water quality concern.

Visibility in the Lagoon was generally poor by tropical standards, ranging from ≪1 to 21 m, although readings above 15 m were rare. At river outlets, turbidity was highest. Changes in light penetration have a critical effect on marine biota. The particulate matter can bury hard corals as it sediments out from the water column and alter the structure and nutrient dynamics of reef surfaces (Bilger and Atkinson, 1995). Water clarity is highly dependent on rainfall. Seven years of sampling in the Great Barrier Reef have shown that the peak for sediment input carried by rivers happens at the beginning of the wet season (Mitchell et al., 1996) and very similar behaviour was observed in this study. Extensive plumes of silty water were

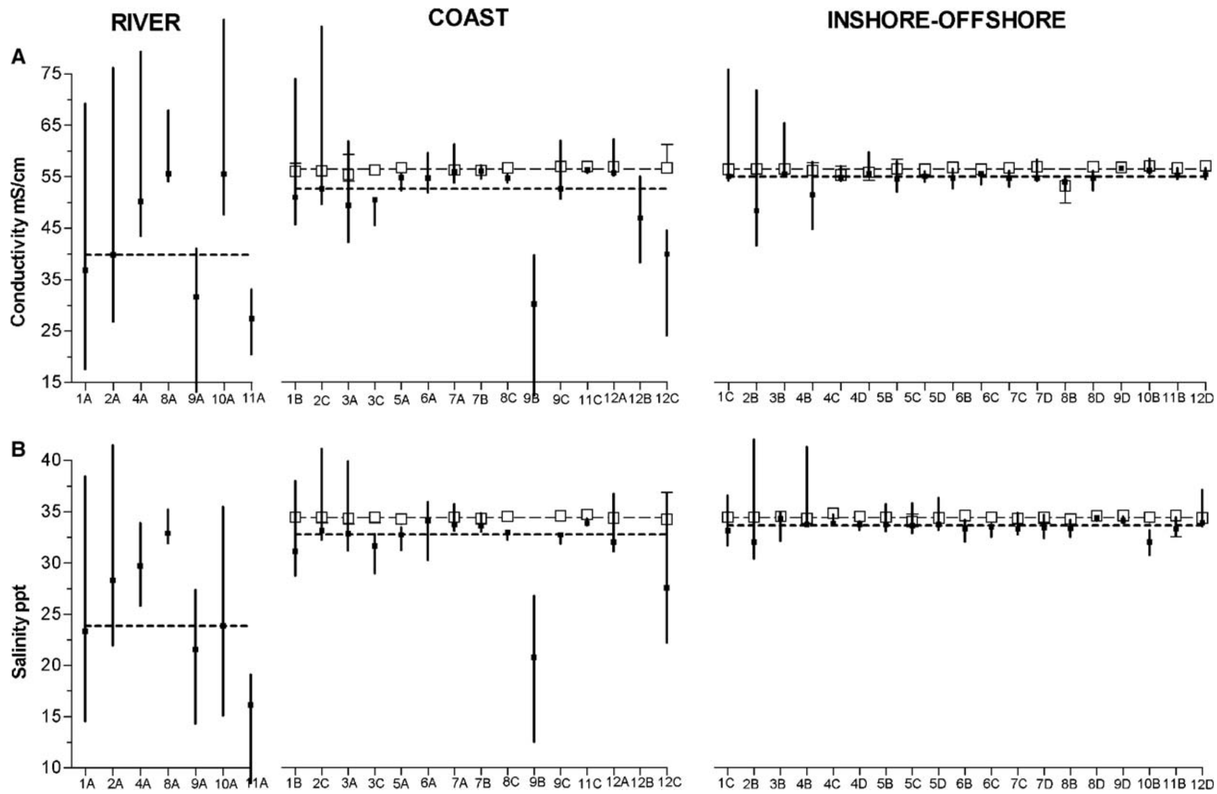

Fig. 3. Box-plots of the media and first and third quartiles of replicates at each sampling point for conductivity—mS/cm (A) and salinity—ppt (B), at both surface (■) and 15 m depth (□). Sampling sites are grouped in the three natural environment categories: river outlets, coast and inshore–offshore. Trigger value (overall media) represented for surface (--) and 15 m (––).

observed in the Madang Lagoon on the days after heavy rains in the Adelbert Ranges, which were associated with a decrease in water clarity, as previously described by Jebb and Lowry (1995). Oil spills coming from the wharf at the northern end of the Lagoon have been repeatedly reported by local people, and the impact of these was also observed at times during sampling.

Dissolved phosphorus was analysed in just two of the six surveys. The analytical laboratory's limit of detection for dissolved reactive phosphorus was 50 μg L^{-1}, which is close to the accepted NWQMS trigger values (55 μg L^{-1}). At Madang Lagoon, dissolved phosphorus concentrations ranged from <50 to 245 μg L^{-1}. River concentrations were generally higher than in the sea (around 100 μg L^{-1}) and

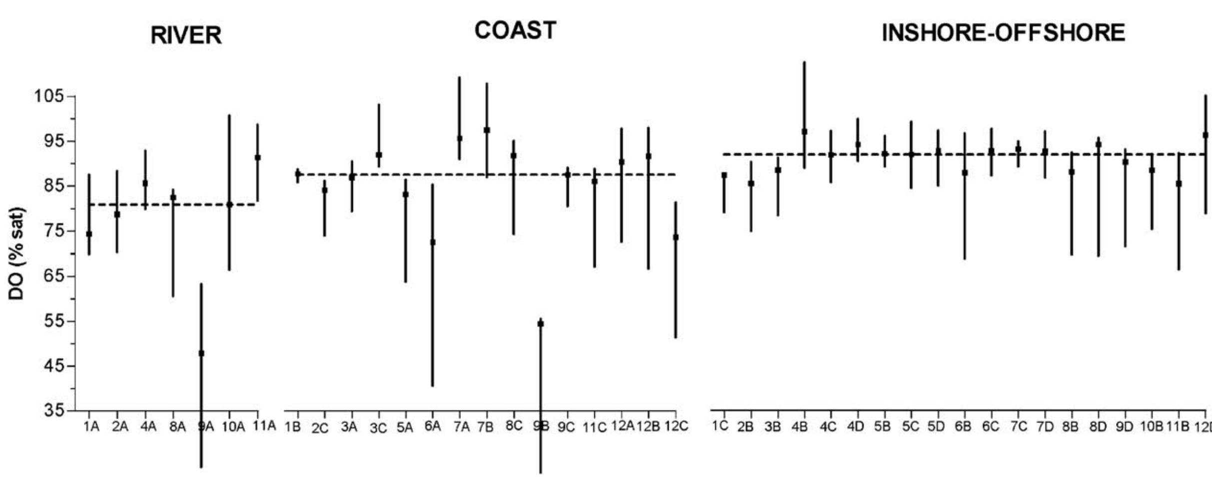

Fig. 4. Box-plots of the media and first and third quartiles of replicates at each surface sampling point for dissolved oxygen (% of saturation). Sampling sites are grouped in the three natural environment categories: river outlets, coast and inshore–offshore. Surface trigger value (overall media) (--).

Table 2
Faecal coliform counts and BOD in the Madang feeder river sites

Sample	River	Faecal coliforms (counts/100 ml)			BOD (mg/l)		
R1.A	Biges, *N*	2000	82	30	not sampled	7.37[b]	3.86[b]
R1.B	Biges, *S*	2800	500[c]	30	not sampled	<1	3.04
R2.A	Nagada	8900[c]	150	1150[c]	1.76	<1	2.9
R3.A	Miss	69000[c]	3600[c]	6200[c]	1.72	<1	3.2
R4.A	Meiro	6700	140	not sampled	1.8	<1	not sampled
R5.A	Marrain	1400	1370[c]	625[c]	1	1.06	3.08
R6.A	Siar Creek1	9000[c]	0	107000[c]	1.62	10.4[a]	109.05[a]
R6.B	Siar Creek2	560	70	0	1.7	<1	3.66

[a] Highly polluted.
[b] Semi-polluted.
[c] Unacceptable levels.

Table 3
Metals range found in the Madang Lagoon

Metal ($\mu g\ g^{-1}$)	As	Cd	Cu	Pb	Hg
This study	1.5–34	0.1–2.2	0.7–77	0.2–138	0.04–0.24
NHMRC limits[a]	20	3	60	300	1

[a] ANZECC (1992) admissible trigger levels for metals.

higher than the accepted trigger values for freshwater ($37\ \mu g\ L^{-1}$). Sample R6A contained $4149\ \mu g\ L^{-1}$ in one survey, a very high concentration for a natural aquatic system.

As expected in this relatively pristine environment, almost all surface values for BOD_5 along the Madang Lagoon were $\leqslant 2\ mg\ L^{-1}$, indicative of unpolluted waters (Clark, 1986). River samples, on the other hand, showed a different picture (Table 2). R1A (Biges River, North) had BOD_5 values falling in the category of semi-polluted to polluted waters. Similarly, BOD_5 values at R6A were indicative of highly polluted waters.

The World Health Organisation's faecal coliforms (FC) criterion for marine bathing waters is <350 FC in 100 ml of water (WHO, 1983). In Madang Lagoon, the variation in FC counts was very high, not only between points but also at the same point in different surveys (Table 2). In one of the surveys, FC counts were significantly higher than in the other surveys, and the possibility of problems in sample processing could not be excluded. Most of the assessed sites in the Madang Lagoon had coliform counts lower than the WHO threshold. Only points 1A and 12B had values higher than 350 (ranging from 90 to 3250 counts per 100 ml) in more than one survey. In most of the sampled rivers, FC counts tend to be higher than the recommended trigger value in at least one of the surveys (Table 2). The Marrain, Miss and Nagada rivers and Siar Creek were of greatest concern since high values (>1000 counts) were observed repeatedly.

High variability in As, Cd, Cu, Pb and Hg concentrations and the low number of surveys only allow general conclusions to be drawn. However these metals should be included in the routine monitoring programme and these surveys show that this is feasible with the protocol proposed. In general metal concentrations were lower than the ANZECC (1992) admissible trigger levels for metals in sediments (Table 3).

This study gives the first assessment of the water chemical quality of the Madang Lagoon, and the protocol developed for this assessment is robust enough to be carried out in the field using the facilities available, and also intensive enough to capture the broad-scale characteristics of the Lagoon. Interim low-risk trigger values are calculated as indicators of good quality.

The data described above indicate that the Lagoon is still in a relatively pristine state, with most indicators generally at natural concentrations for this type of system. Most of the indicators, especially those inshore and offshore, had concentrations within the trigger levels determined by the survey campaigns or lower than the NWQMS or WHO interim trigger levels. However, signs of pollution were found in the neighbouring of the food processing industry (points R6.A, 9A and 9B). Therefore, these points have been flagged as a key location for a future monitoring programme. Nevertheless, the biological assessment currently under way at the sampling sites should complement the water quality monitoring programme. To make the water quality assessment protocol operational as a monitoring tool for integrated management of the Lagoon, the recommendations are to:

1. Continue the monitoring for at least a further year to allow a better estimation of the variability of the assessed parameters and to investigate possible trends that would affect the definition of the baseline state of the Lagoon.
2. Conduct further investigations and monitoring of the identified sources of pollution.

3. Daily water checking should be done at one or two points, to establish the seasonal behaviour of the physical parameters.
4. Consolidate the water quality monitoring with other biodiversity and resource use surveys planned for Madang Lagoon to either confirm or reject the assumption that the current state of the Lagoon is a fair reference state. A more integrated approach including biological assessment would give a more complete picture of changes in reef health than from the monitoring of contaminants alone.

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