

The effects of rainfall on the distribution of inorganic nitrogen and phosphorus in Discovery Bay, Jamaica

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Abstract

We sought to define the ambient concentrations of inorganic nitrogen and phosphorus in the coastal waters of Discovery Bay, Jamaica, and to investigate the effects of groundwater and rainfall on those concentrations. Ambient nutrient concentrations, in areas away from groundwater sources, were generally low during the 4.5-yr study period, with nitrate, soluble reactive phosphorus (SRP), and ammonium varying between 0.2 and 1 $\mu\text{mol L}^{-1}$, 0.02 and 0.04 $\mu\text{mol L}^{-1}$, and 0.05 and 0.2 $\mu\text{mol L}^{-1}$, respectively. Groundwater nitrate diluted conservatively within the bay, with the average concentration being predicted, from dilution curves, to be 90 $\mu\text{mol L}^{-1}$. Groundwater SRP also diluted conservatively from a predicted average concentration of 0.6 $\mu\text{mol L}^{-1}$, although there was suggestion of a source of SRP within the bay, presumably recycled phosphorus. Episodic, heavy rainfall events (100–200 mm over a few days) in the vicinity of the bay were generally linked to immediate decreases in bay salinities but only marginal changes in nutrient concentrations. Two consecutive and very heavy basin-wide rainfall events (>200 mm over several days) that occurred within 4 months of each other resulted in salinities that gradually decreased, whereas nitrate concentrations increased by factors of 2–5; these elevated concentrations were sustained for 3–4 months. Increases in ammonium and SRP also occurred but were not sustained. Dissolved inorganic nitrogen:SRP ratios suggest that the system can become phosphorus-limited following very heavy rainfall.

The coral reef at Discovery Bay, Jamaica, is one of the most studied reefs in the Caribbean (Liddell and Ohlhorst 1981; Goreau 1992; Szmant 2002). Starting in the mid-1980s the reef shifted to a macroalgae-dominated system. The cause of the shift has been variously attributed to the devastation caused by Hurricane Allen in 1980, the 1983–1984 Caribbean-wide mortality of *Diadema antillarum* (Liddell and Ohlhorst 1986; Liddell and Ohlhorst 1987; Hughes 1994), over-fishing (Munroe 1983; Jackson 1997), a coral disease epidemic (Aronson and Precht 2001), and elevated nutrient concentrations (Lapointe 1997, 1999). Similar shifts to macroalgal dominance have occurred elsewhere in the Caribbean and to a lesser extent around the world (Hodgson 1999; Aronson and Precht 2001; McClanahan et al. 2002; and references therein).

Before Hurricane Allen, the Discovery Bay reef was dominated by the fast-growing branching corals *Acropora palmata* (6–12-m depth) and *Acropora cervicornis* (5–15-m depth), and the massive coral *Montastraea annularis* (5–30-m depth) (Woodley et al. 1981), although this coral dominance (>50% coral cover; Hughes 1994) may have been unusual as there had been no hurricane damage to the reef for several decades (Woodley 1992). Recent reports (Woodley 1999; Aronson and Precht 2000; Edmunds and

Carpenter 2001) suggest that although the coral cover is increasing slowly from the 1990s-low of <5% (Hughes 1994), the recovery may be hampered by the synergistic effects of multiple stressors such as nutrients, diseases to corals and sea urchins, over-fishing, hurricanes, sedimentation, coral bleaching, and pollution (Hughes and Connell 1999).

Corals are known to exist under a variety of conditions, including widely ranging nutrient concentrations (Hughes and Connell 1999; Kleypas et al. 1999). Szmant (2002) exhaustively summarized the argument that nutrient enrichment on coral reefs is responsible for macroalgal blooms and concluded that whereas nutrient pollution can cause localized effects, widespread effects remain unsubstantiated. Further, nutrient enrichment experiments have usually shown that elevated nutrients by themselves do not adversely affect coral health. For example, Miller et al. (1999) found that nutrient concentrations comparable to the threshold levels suggested by Lapointe (1997) had negligible effects on algal abundance, and the 2-yr-long ENCORE (Enrichment of Nutrients on a Coral Reef Experiment) nutrient enrichment experiments (Koop et al. 2001) demonstrated that the effects of elevated nutrients were subtle, with nutrient-enriched reefs being visually similar to control reefs.

Only a few nutrient studies have been published for Discovery Bay, and they are of limited value because they were conducted for periods of a few months (D'Elia et al. 1981) or days (Lapointe 1997). Because long-term monitoring data are unavailable, understanding factors that affect the spatial and temporal variability of nutrient concentrations and descriptions of ambient conditions themselves remain uncertain. Further, identifying the sources of nutrients to Discovery Bay is difficult because submarine vents and groundwater seepage are thought to

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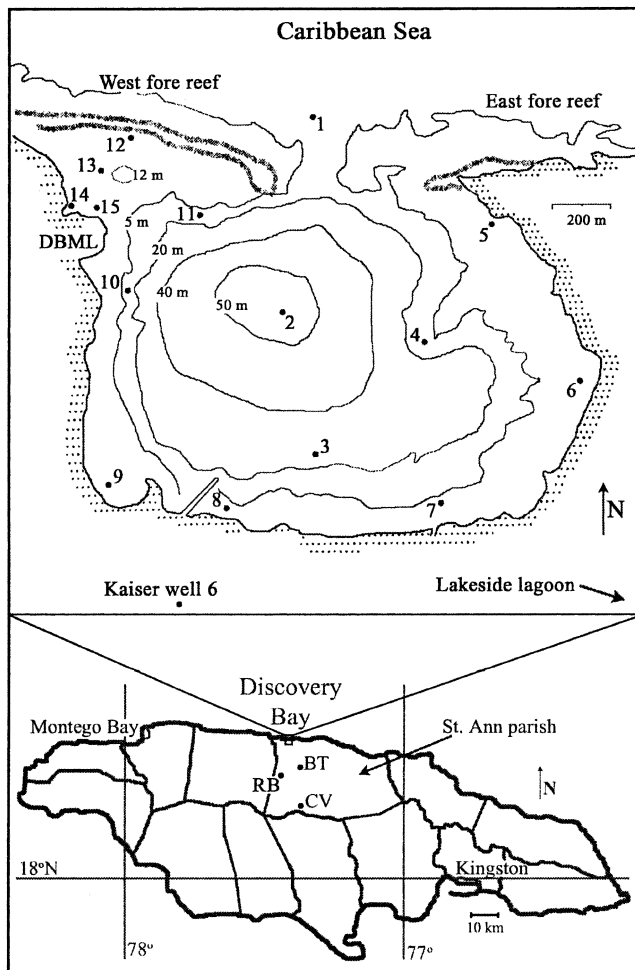


Fig. 1. Map of Jamaica with detail of the Discovery Bay marine and terrestrial sampling sites. CV, Cave Valley; BT, Browns Town; RB, Rio Bueno; DBML, Discovery Bay Marine Laboratory.

predominate, and these are difficult to quantify. Thus, whereas there is an extensive amount of information available on the ecology of the Discovery Bay reef, the lack of nutrient data at the appropriate temporal and spatial scales has generated considerable controversy about the relative importance of top-down versus bottom-up processes affecting coral reef condition, especially related to the presence of macroalgae on the reef (Hughes et al. 1999; Szmant 2002; Lapointe 2004, and references therein).

The purpose of this study was (1) to quantify the ambient concentrations of dissolved inorganic nitrogen and phosphorus in bay surface waters over an extended

timeframe at multiple locations throughout the bay and in brackish waters produced from submarine vents and a near-surface shoreline fissure as they mix with the bay waters and (2) to interpret these results using available historical nutrient and rainfall data and changing land-use patterns.

Methods

Description of study area—Discovery Bay is a small coastal basin (approximately 1.5 km²) on the north coast of Jamaica protected by a fringing reef system (Fig. 1). The western section of the reef crest is partially exposed, especially at low tides (normal tidal range approximately 30 cm), whereas the eastern reef crest is just below the water surface. The bay reaches a depth of >50 m, has steep submerged cliffs short distances from shore, and seagrass-covered sandy plateaus on the eastern and southern edges and in the northwestern quadrant. There is a small, drowned, 13-m-deep sinkhole in the northwestern quadrant, which is currently not a source of freshwater to the area. A 120-m-wide, 12-m-deep ship channel through the reef provides bauxite-exporting ships access to the bay. The surrounding hills are porous limestone uplifted from the sea and consist of extensively faulted early-to-middle Miocene carbonate rocks (Hine et al. 1991; Gayle and Woodley 1998).

The township of Discovery Bay is in the parish of St. Ann, which approximately equates to the Dry Harbor hydrologic basin. Population information (STATIN 1976, 1986, 1996, 2002) is given in Table 1. Rainfall in St. Ann between 1969 and 2003 ranged from 1,200 mm yr⁻¹ to 2,300 mm yr⁻¹ and was variable at and between rainfall data collection stations; rainfall events were typically localized, heavy, and of short duration (STATIN Annual Reports 1970–2001; National Meteorological Service). During storms, rain can fall heavily for several days.

There is no regular surface-water flow to the bay, but there are many freshwater-bearing submarine vents and rocky shoreline fissures (D'Elia et al. 1981; Bonem 1988). Waters from the vents rise quickly to the surface to produce thin (millimeters) patches of brackish water that are clearly visible in the early morning when the bay is normally calm. Wind (4–9 m s⁻¹; Porter, 1985), which frequently rises at about 11:00 h and lasts through most of the afternoon, mixes the brackish surface with deeper saline waters before the surface patches build up again overnight.

Water sampling and analysis—Sampling sites were selected (Fig. 1; Table 2) to measure the effects of inflowing

Table 1. Population data 1970–present (STATIN, 1976, 1986, 1996, 2002).

Census year	Jamaica	St. Ann Parish	St. Ann Rural	Cave Valley	Browns Town	Discovery Bay
1970	1,848,500	122,000	87,600	1,100	5,500	1,800
1982	2,176,000 (18%)	137,700 (13%)	99,100 (13%)	1,400	6,400	1,200
1991	2,380,700 (9%)	149,400 (8%)	112,800 (14%)	1,800	8,200	2,100
2001	2,599,300 (9%)	166,100 (11%)	121,500 (8%)	1,700	8,200	2,500

% are the % growth from previous census.

Table 2. Marine sampling sites.

Site number and type*	Longitude	Latitude	Description	Water depth (m)
1 s	77°24.610'	18°28.240'	500 m to sea of ships channel	200
2 s	77°24.708'	18°27.653'	Center of bay	80
3 s	77°24.699'	18°27.537'	South bay ships marker	30
4 s,v	77°24.262'	18°27.617'	East bay ships marker	30
5 s	77°24.330'	18°27.764'	East back reef by east shore	5
6 s	77°24.287'	18°27.565'	Puerto Seco Beach	2
7 s	77°24.447'	18°27.389'	Portside restaurant	2
8 s	77°24.750'	18°27.395'	Dry river east of Kaiser pier	2
9 s	77°25.034'	18°27.513'	Pilots bay west of Kaiser pier	3
10 s,v	77°25.026'	18°27.703'	To sea of Columbus Park	20
11 s,v	77°24.910'	18°27.919'	Southern edge of western section of bay	20
12 s	77°25.002'	18°28.043'	West back reef	2
13 s	77°25.057'	18°27.960'	Center of western section of bay	5
14 s,f	77°25.080'	18°27.951'	At fissure in rocky limestone shore	0.5
15 v	77°25.002'	18°27.955'	Laboratory boat channel	1.5

* s, surface; v, vent; f, fissure.

freshwater (sites 4, 10, 11, 14, and 15) and other potential sources of nutrients (sites 5 and 6, beaches; 7, a restaurant; 8 and 9, boating activities) and to quantify the nutrient concentrations in the various freshwater sources in the vicinity of the bay (Table 3).

Samples (except vent samples) were collected in pre-cleaned (1 mol L⁻¹ hydrochloric acid, distilled water, and at-site water), 1,000-mL polycarbonate bottles and stored on ice until delivered to the laboratory.

Bay surface samples (sites 1–14; Fig. 1) were collected between 08:00 h and 10:00 h at 10–20-cm depths, operating from a small boat (sites 1–13) or land (site 14). A Hydrolab H₂O water quality multiprobe, calibrated according to the manufacturer's procedures (Hydrolab 1995), was used to record salinity while sampling. Surface samples from near the shoreline fissure (site 14), in addition to those mentioned above, were collected on an almost daily basis between 13 May and 25 June 2002, biweekly from 08 October through 11 December 2002 and 04 February through 17 June 2003, and then weekly until 17 November 2003.

Submarine vent samples were collected from sites 4, 10, 11, and 15 between June 1999 and February 2000, January 2002 and February 2003, and August 2003 and October 2003 using SCUBA techniques and specially prepared pre-cleaned (see above) flow-through bottles (two 500-mL polycarbonate bottles joined at their bases). The bottles were held as far into the vents as possible, and water flowed through them for 30–60 s before the top and bottom were

capped. Samples were also collected slightly above and around the vents whenever vent-mouth samples were collected. The samples were transferred to 1,000-mL pre-cleaned polycarbonate bottles upon return to the boat and handled as above.

Freshwater samples were occasionally collected at sites in the vicinity of the Discovery Bay township (Table 3; Fig. 1) from either 1 m from the bank at 20-cm depth (Lakeside Lagoon and Rio Bueno) or from taps. Water flowed from taps for 30 s before bottle rinsing and sample collection.

Samples were filtered (0.45 μm) upon returning to the laboratory and ammonium (NH₄⁺) analyses started immediately. Soluble reactive phosphorus (SRP) and nitrate plus nitrite (hereafter referred to as NO₃⁻) analyses were either completed within 24–48 h with samples being kept refrigerated between analyses, or frozen for later analyses (vent and fissure samples only). Salinities and conductivities (using a refractometer and, since August 2002, a conductivity meter) on all samples were recorded to cross-check field salinities.

Nitrate, SRP, and NH₄⁺ were analyzed manually (Parsons et al. 1984). Low-nutrient seawater (Kirkwood 1994), prepared using water collected from about 1 km offshore, was used to prepare all NO₃⁻ and NH₄⁺ operating standards and for any required sample dilutions. Deionized, distilled water was used for SRP standards.

Approximately 20% of the samples were collected in duplicate, and approximately 20% of all collected samples

Table 3. Freshwater sites data.

Site	Longitude	Latitude	Nitrate* (μmol L ⁻¹)	NH ₄ ⁺ * (μmol L ⁻¹)	SRP* (μmol L ⁻¹)
DBML laboratory tap	77°25.040'	18°27.949'	83±12 (15) 66–112	0.06±0.03 (16) 0.03–0.12	0.24±0.09 (16) 0.14–0.40
Kaiser well 6 tap	77°25.119'	18°27.009'	87±2 (15) 65–113	0.05±0.03 (16) 0.03–0.13	0.24±0.09 (16) 0.13–0.38
Lakeside lagoon	77°22.997'	18°27.681'	83±9 (10) 73–100	0.15±0.1 (12) 0.02–0.31	0.16±0.08 (12) 0.09–0.32
Rio Bueno head waters	77°24.959'	18°25.634'	81±10 (6) 69–94	0.17±0.09 (6) 0.09–0.33	0.19±0.11 (6) 0.08–0.40

NH₄⁺, ammonium; SRP, soluble reactive phosphorus; DBML, Discovery Bay Marine Laboratory.

* Mean concentration±SD (number of samples), range.

Table 4. Data quality.

Analyte	Accuracy* (%)	Spike recovery (%)	Analytical precision ($\mu\text{mol L}^{-1}$)	Sampling precision ($\mu\text{mol L}^{-1}$)	Detection limits ($\mu\text{mol L}^{-1}$)
NH_4^+	61	(102 \pm 9)	\pm 0.01	\pm 0.03@0.3 \pm 0.1@>0.6	0.05
Nitrate	75	(97 \pm 8)	\pm 0.03@1 \pm 0.5@80	\pm 0.04@1 \pm 1@80	0.07
SRP	84	(93 \pm 7)	\pm 0.01	\pm 0.01	0.01

* The percentage of results that agree with the accepted value ($z=\pm 2$; Wells and Cofino 1997) when the total error is 20% or less; 9 exercises, 44 samples. The inter-laboratory data indicate that although our data are usually within 20% of the accepted values, extreme values should be considered with caution.

were analyzed in duplicate. Accuracies were assessed through participation in nine Quasimeme (Wells and Cafino 1997) laboratory proficiency exercises during the study period and spike recoveries. Analytical and sampling precisions were calculated from duplicate data (Taylor 1987). Detection limits were estimated from calibration curve statistics (Miller and Miller 2000; Table 4).

Results

Rainfall—Rainfall within the watershed is spatially and temporally highly variable. Three of the watershed's National Meteorological Service rainfall stations were selected to characterize the high (Cave Valley; 640 m), mid (Browns Town; 430 m), and low (Discovery Bay; sea level) altitudes of the watershed (Fig. 1). Monthly rainfall at these stations through the 4.5 years spanning the study period (Fig. 2; no data for Cave Valley before November 2000) documented no clearly defined annual wet or dry seasons although heavy rain tended to fall in May–June and September–October. Detectable rain (>1 mm) fell on about 1 in 5 days at all stations, but heavy rain (>25 mm) fell on only 1 day in 12.5, 20, and 30 days, respectively, at the three stations, with <10% of those events being sustained for >1 day.

In late May 2002 very heavy rain fell across the entire island, causing severe flooding. In particular, 624 mm of rain fell at Cave Valley in 11 days, 206 mm at Browns Town in 5 days, and 131 mm at Discovery Bay in 4 days. This was followed by another major flood in late September 2002 when 488 mm of rain fell at Cave Valley

over 6 days, 280 mm at Browns Town over 4 days, and 312 mm at Discovery Bay over 3 days. No other event of these magnitudes has occurred in the watershed in the past 5 years, although the 5–10-day heavy rains that fell in January, late April to early May, and November 2001 caused severe local flooding.

Nutrient concentrations and salinities: surface waters—The concentrations of nutrients in Discovery Bay (Table 5) varied considerably (Figs. 3–5) during the study period. Concentrations at site 1, an open coastal-water site (Fig. 1), were significantly lower (between 90% and 95% confidence) than the concentrations at the center of the bay (site 2), whereas salinities were significantly lower (90% confidence) within the bay. Concentrations within the bay tended to be higher, but not significantly so, closer to shore (sites 5–11). Nitrate and SRP concentrations at sites 12 and 13 in the shallow northwestern quadrant were significantly higher than the highest average concentrations in the main section of the bay (site 10 for NO_3^- , 99% confidence; site 9 for SRP, 97.5% confidence) but no significant differences were detected between the ammonium concentrations. The salinities in the northwestern quadrant were significantly lower than in the main section of the bay (99.5% confidence). The brackish waters at the shoreline-fissure site 14 clearly had the highest nutrient concentrations of all the surface sites sampled. These observations are consistent with a freshwater source of nutrients to the bay. The effects of the freshwater flow were most easily seen in the shallower northwestern quadrant of the bay.

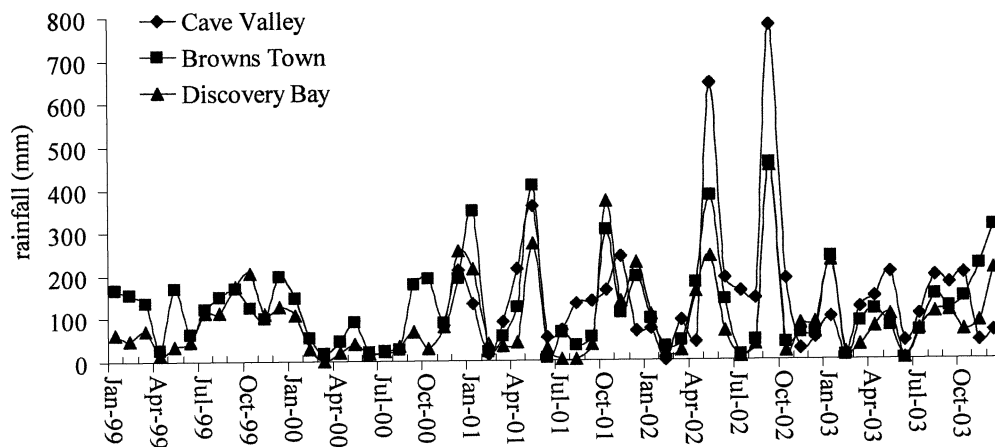


Fig. 2. Monthly rainfall at Cave Valley, Browns Town, and Discovery Bay for 1999–2003.

Table 5. Summary statistics for determined parameters in bay surface samples: mean \pm SD (number of samples), range.

Site	Salinity	SRP ($\mu\text{mol L}^{-1}$)	$\text{NO}_3^- + \text{NO}_2^-$ ($\mu\text{mol L}^{-1}$)	NH_4^+ ($\mu\text{mol L}^{-1}$)	DIN:SRP
1	35.94 \pm 0.69 (27) 34.5–36.9	0.024 \pm 0.007 (28) 0.020–0.050	0.50 \pm 0.44 (27) 0.05–1.63	0.05 \pm 0.02 (27) 0.03–0.10	24.3 \pm 20.0 (27) 3.3–85.5
2	35.75 \pm 0.68 (26) 34.4–36.7	0.030 \pm 0.017 (28) 0.020–0.082	0.71 \pm 0.50 (28) 0.13–1.93	0.07 \pm 0.04 (27) 0.03–0.18	30.2 \pm 20.2 (28) 4.0–79
3	35.66 \pm 0.64 (26) 34.4–36.6	0.033 \pm 0.014 (27) 0.020–0.068	0.82 \pm 0.58 (27) 0.11–2.46	0.09 \pm 0.07 (26) 0.03–0.30	30.6 \pm 20.0 (27) 5.2–88
4	35.66 \pm 0.70 (27) 34.2–36.6	0.030 \pm 0.020 (27) 0.020–0.087	0.79 \pm 0.52 (28) 0.14–2.24	0.09 \pm 0.07 (27) 0.03–0.31	31.0 \pm 18.4 (27) 3.8–69
5	35.65 \pm 0.68 (27) 34.4–36.8	0.031 \pm 0.016 (27) 0.020–0.083	0.77 \pm 0.55 (28) 0.18–2.39	0.08 \pm 0.05 (27) 0.03–0.23	29.5 \pm 16.7 (27) 6.0–54
6	35.66 \pm 0.69 (27) 34.3–36.7	0.037 \pm 0.019 (28) 0.020–0.100	0.90 \pm 0.55 (28) 0.16–2.50	0.11 \pm 0.06 (27) 0.03–0.26	29.1 \pm 15.4 (28) 5.4–75
7	35.58 \pm 0.66 (27) 34.2–36.5	0.040 \pm 0.017 (28) 0.020–0.080	0.99 \pm 0.62 (28) 0.14–2.91	0.13 \pm 0.09 (27) 0.03–0.38	29.1 \pm 13.9 (28) 3.8–58
8	35.62 \pm 0.66 (27) 34.3–36.7	0.042 \pm 0.024 (28) 0.020–0.110	0.90 \pm 0.53 (28) 0.30–2.48	0.14 \pm 0.14 (27) 0.03–0.68	28.5 \pm 17.1 (28) 6.3–88
9	35.61 \pm 0.65 (27) 34.2–36.6	0.043 \pm 0.018 (28) 0.020–0.090	0.96 \pm 0.56 (28) 0.28–2.47	0.14 \pm 0.09 (27) 0.03–0.31	27.7 \pm 15.6 (28) 5.7–62
10	35.53 \pm 0.66 (27) 34.2–36.5	0.040 \pm 0.016 (27) 0.020–0.079	1.01 \pm 0.56 (28) 0.27–2.53	0.12 \pm 0.07 (27) 0.03–0.30	30.8 \pm 15.0 (27) 6.9–60
11	35.44 \pm 0.68 (27) 34.1–36.4	0.033 \pm 0.013 (28) 0.020–0.070	0.98 \pm 0.59 (28) 0.24–2.60	0.11 \pm 0.07 (27) 0.03–0.26	32.6 \pm 13.2 (28) 15–58
12	34.78 \pm 1.02 (27) 32.8–36.2	0.055 \pm 0.020 (28) 0.020–0.090	1.60 \pm 1.11 (28) 0.14–4.81	0.17 \pm 0.12 (26) 0.03–0.41	33.5 (18.8, 28) 3.8–67
13	34.15 \pm 1.32 (27) 31.3–35.9	0.062 \pm 0.021 (28) 0.020–0.100	1.85 \pm 1.13 (28) 0.32–4.95	0.17 \pm 0.11 (25) 0.03–0.41	34.9 \pm 19.8 (28) 8.5–73
14	26.60 \pm 2.80 (27) 14.8–29.9	0.27 \pm 0.20 (28) 0.11–0.79	28.4 \pm 10.1 (28) 11.8–47.7	0.56 \pm 0.77 (27) 0.03–3.01	150 \pm 83.6 (28) 24–326

DIN, dissolved inorganic nitrogen.

Before September 2002, nutrient concentrations did not show any clear temporal trends (Figs. 3–5). Nitrate, NH_4^+ , and SRP concentrations at sites 1–11 averaged 0.5, 0.1, and 0.04 $\mu\text{mol L}^{-1}$, respectively. Nitrate concentrations seldom exceeded 1 $\mu\text{mol L}^{-1}$, whereas NH_4^+ and SRP were often not detectable and seldom exceeded 0.2 $\mu\text{mol L}^{-1}$ and 0.1 $\mu\text{mol L}^{-1}$, respectively. From October 2002 the NO_3^- concentrations gradually increased at both the coastal and bay surface sites, peaked in January 2003, and then gradually fell to pre-October 2002 levels by May 2003. The concentrations of NH_4^+ and SRP also increased but not to the same magnitude nor for the same extended time. This dramatic increase in NO_3^- concentrations (to approximately five times those found before this event) followed the 25–30 September 2002 flood rains and was possibly a result of the accumulated effect of the 20–30 May 2002 and September rains, as the May rains themselves did not lead to any clear increases in nutrient concentrations in the surface waters.

The gradual increases in surface SRP and NO_3^- concentrations from August 2003, also seen at shoreline-fissure site 14, may be a result of the consistent rainfall in the latter half of that year.

Throughout the bay surface-water monitoring period, samples were collected under calm conditions (early mornings) from depths of about 20 cm, well below and thus avoiding the thin surface patches of brackish water

often present in the vicinities of the submarine vents (Fig. 1; Table 2). The salinity variations during the sampling period generally reflect short-term (1–5 days before sampling) and long-term (months) rainfall patterns. During the 30 days preceding most sampling occasions, very little rain fell (Fig. 6a, the rainfall during the 30 days before sampling; Fig. 6b–g, the 30-day period broken down into 5-day intervals; sampling dates are given on the x-axis).

The drop in salinity at most sites in January 2001 followed heavy rain at Browns Town (202 mm) and Discovery Bay (78 mm) on the two days preceding sampling, and the lower salinities observed in May 2002 followed heavy rainfall at Cave Valley (554 mm during the preceding 8 days), Browns Town (254 mm during the preceding 2–5 days) and Discovery Bay (131 mm during the preceding 2–5 days), with the effect of the former event, which was closer to the time of sampling, being more pronounced. Direct rainfall on the bay and surface runoff may have been important. Nitrate concentrations increased slightly with these decreases in salinities (Figs. 3–5). Heavy rain falling 6–30 days before sampling (November 2001 and June and October 2002) had no observable effect on either salinities or nutrients.

The high salinities observed at most sites on the fourth sampling occasion (04 October 2000; Fig. 3) followed 7 months of dry weather (Fig. 2).

The sustained low salinities at the coastal (site 1) and main bay sites (2–10) between February and September

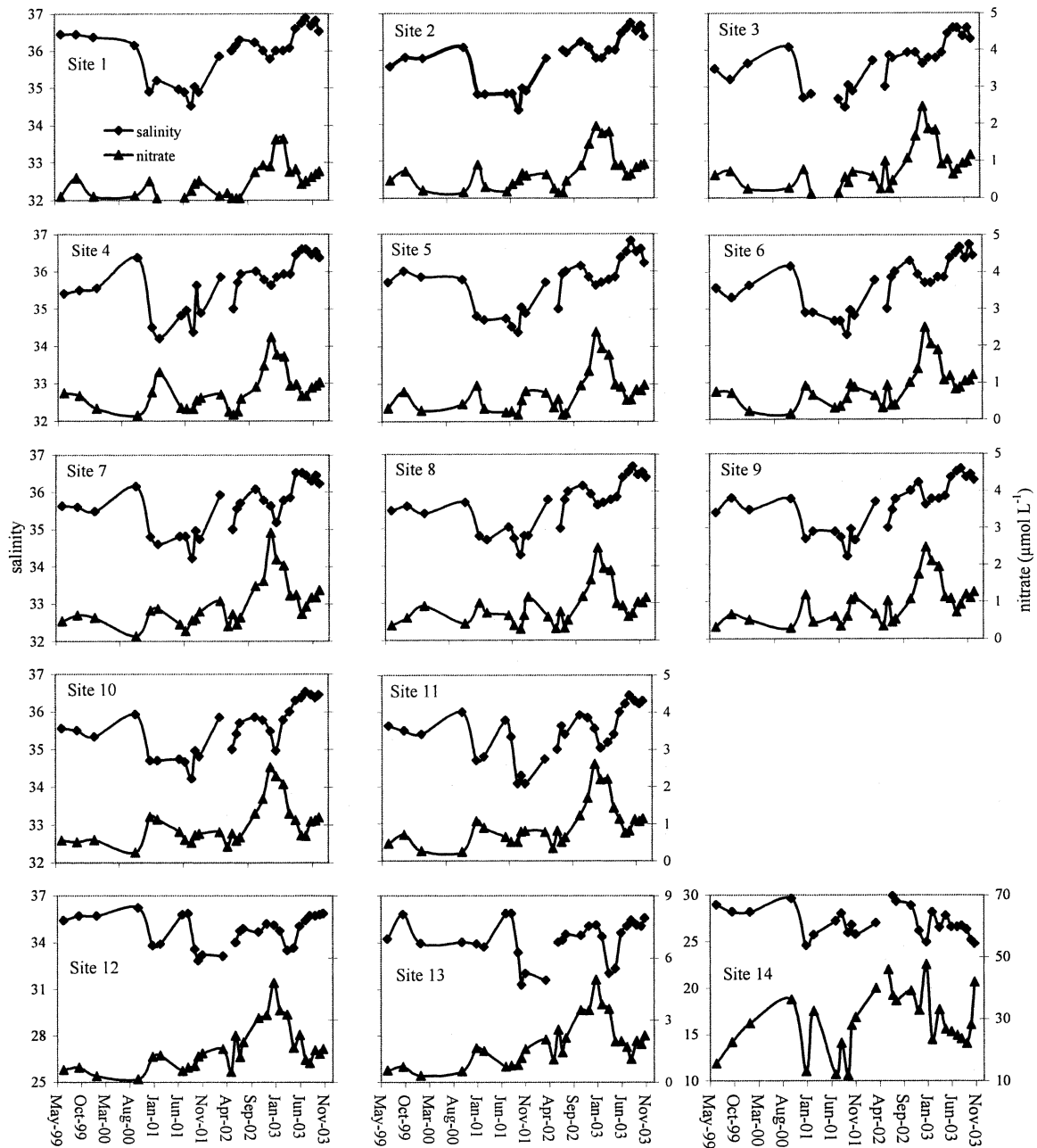


Fig. 3. Nitrate ($\mu\text{mol L}^{-1}$) and salinity in Discovery Bay surface waters. Note the varying scales for sites 12–14.

2001 followed two heavy rainfall events, at the beginning of the year and in April (Fig. 2), and the further slight salinity drops observed on the ninth sampling occasion (19 September 2001) followed moderate in-land rains over the preceding 2 months. The very heavy rains in May and September 2002 were likely reflected in the slight but sustained salinity drops between December 2002 and May 2003. The moderate rainfall in the latter half of 2003 may have accounted for the gradual decrease in salinities after August.

These results suggest that heavy rain ($>100 \text{ mm d}^{-1}$) close to the coast had an immediate but short-term effect on bay salinities, whereas sustained heavy and short, very

heavy rainfalls ($>200 \text{ mm}$) over the watershed took longer to have an effect, but resulted in lower salinities for several months. Sustained dry periods likely led to elevated bay salinities.

Nutrient concentrations and salinities: submarine vents—Samples collected from the mouths of the various vents within the bay were brackish, with salinities varying between about 15 and 25, indicating that initial freshwater mixing occurs within the aquifer below the bay. Similar salinities (18–26) were reported by D'Elia et al. (1981) from their 1979–1980 study. These brackish waters rise quickly to the surface with minimal lateral mixing.

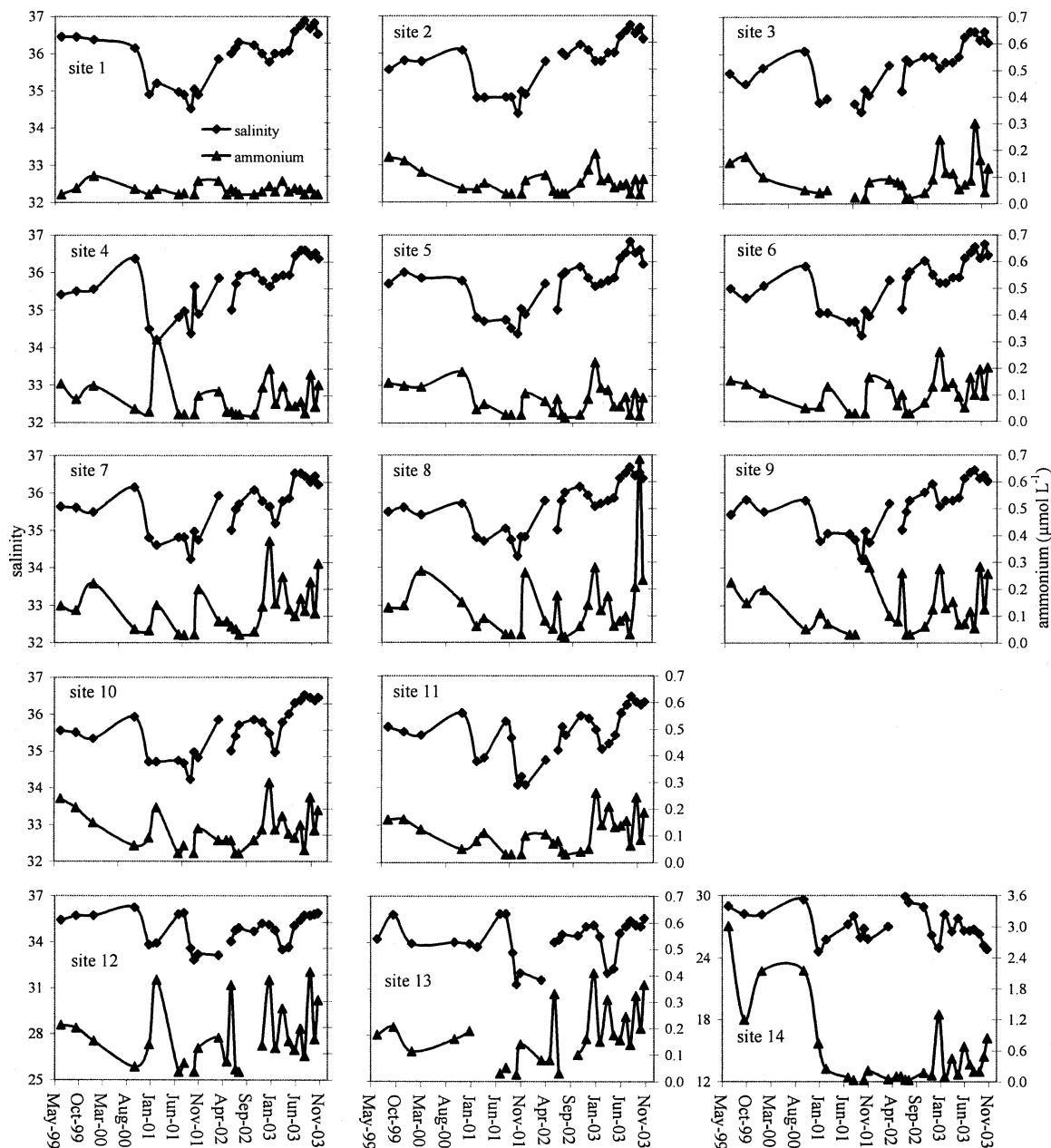


Fig. 4. Ammonium ($\mu\text{mol L}^{-1}$) and salinity in Discovery Bay surface waters. Note the varying scales for sites 12–14.

The NO_3^- , NH_4^+ , and SRP concentrations and salinities for all of the samples collected within the vicinities of the four vents during the 1999–2003 period (Fig. 7) document that freshwaters flowing to the bay carry these nutrients, particularly NO_3^- at relatively high concentrations compared to those normally found in the bay (Table 5). For NO_3^- , the correlation with salinity was highly significant ($r^2 = 0.91$ at the 95% confidence level) showing that within the timeframe of the mixing processes NO_3^- behaved conservatively. The intercept suggests that the concentration of NO_3^- in groundwater averaged $91 \mu\text{mol L}^{-1}$ over the 4 years. The correlation for SRP, although not as good ($r^2 = 0.57$ at the 95% confidence level), suggests a 4-yr average groundwater concentration of $0.6 \mu\text{mol L}^{-1}$. There

is no apparent correlation between NH_4^+ and salinity, the variability possibly reflecting changing groundwater concentrations and a source of ammonium within the bay, as suggested by Lapointe (1997). Ammonium has been shown to seep from the sands in the southern and eastern sections of the bay (Gordon-Smith unpubl. data).

Nutrient concentrations and salinities: surface fissure—Site 14, the shoreline-fissure site, is similar to the submarine-vent sites although the flow of brackish water to the bay occurs close to the surface. This site is easily accessible from shore and was monitored intensively, starting on 13 May 2002 (Fig. 8). The water was brackish (Fig. 8b) with salinities normally varying between 24 and 30. Nitrate and

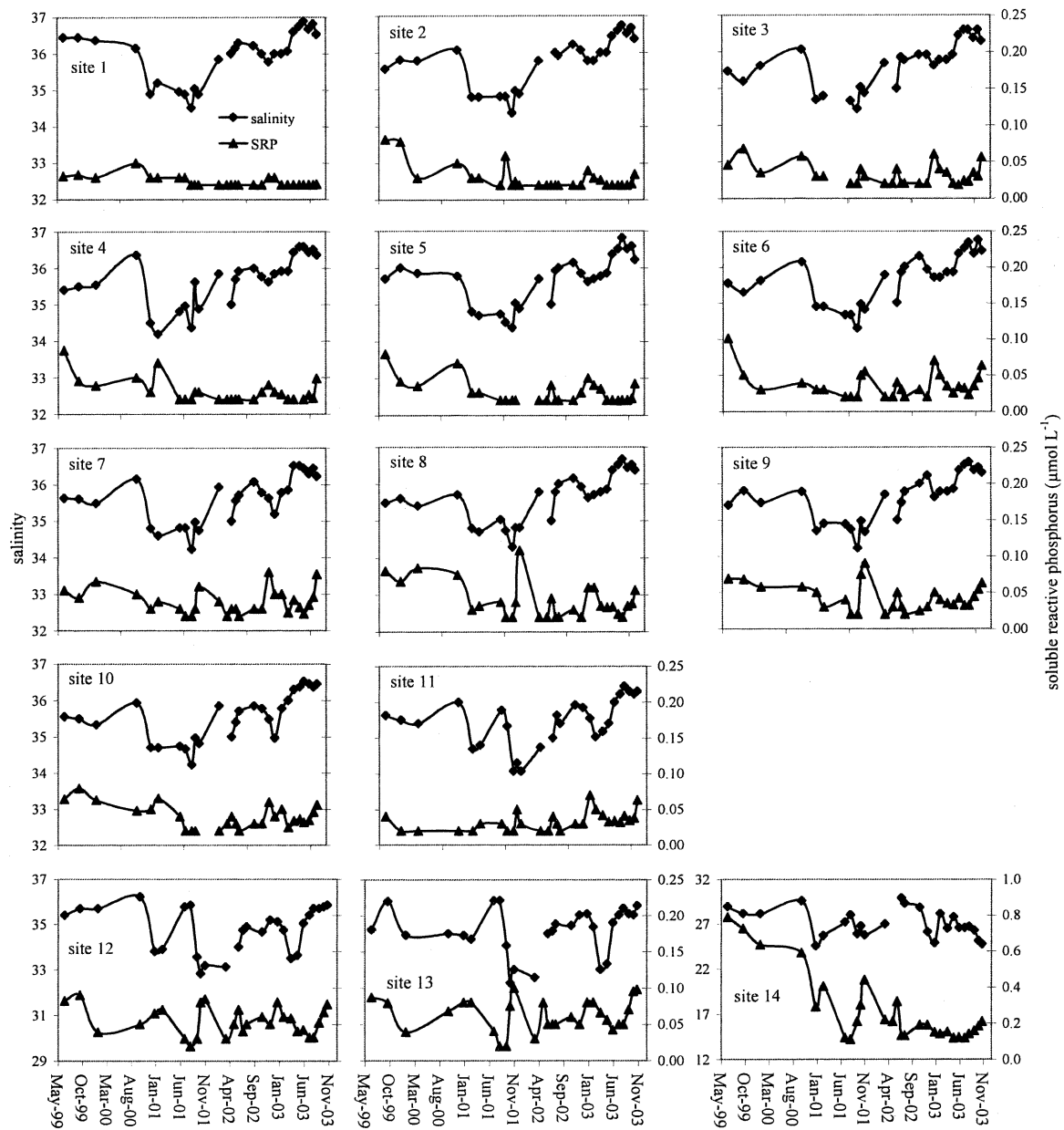


Fig. 5. SRP ($\mu\text{mol L}^{-1}$) and salinity in Discovery Bay surface waters. Note the varying scales for sites 12–14.

SRP concentrations (Fig. 8c,e) increased over the more usual ranges ($20\text{--}32 \mu\text{mol L}^{-1}$ for NO_3^- and $0.1\text{--}0.2 \mu\text{mol L}^{-1}$ for SRP) and salinities decreased immediately following the May and September 2002 and May 2003 heavy rainfalls (Fig. 8a), with the NO_3^- changes in May 2002 being particularly dramatic. The rapid and sustained response of salinity to rainfall at this site, compared to the suggested slow and sustained responses at other sites, may be attributable to these samples being taken within the plume of the brackish water. The increases in NO_3^- , NH_4^+ , and SRP concentrations in early 2003 coincided with the maxima in the nutrient peaks at other monitored sites within the bay. The gradual increases in the concentrations of all nutrients toward the end of 2003 followed a slight

drop in salinity that possibly resulted from the moderate rainfall that fell in the second half of the year (Fig. 2).

Discussion

Understanding how and why nutrient concentrations vary across space and time in nearshore waters is a critical element in discussions related to the condition of reefs, especially to discern the relative impacts of natural versus anthropogenic sources. Our results confirm that groundwater from submarine vents and shoreline fissures contribute substantially to the nutrient dynamics of Discovery Bay (D'Elia et al. 1981; Lapointe 1997), but our longer-term dataset leads us to conclusions that are quite different than

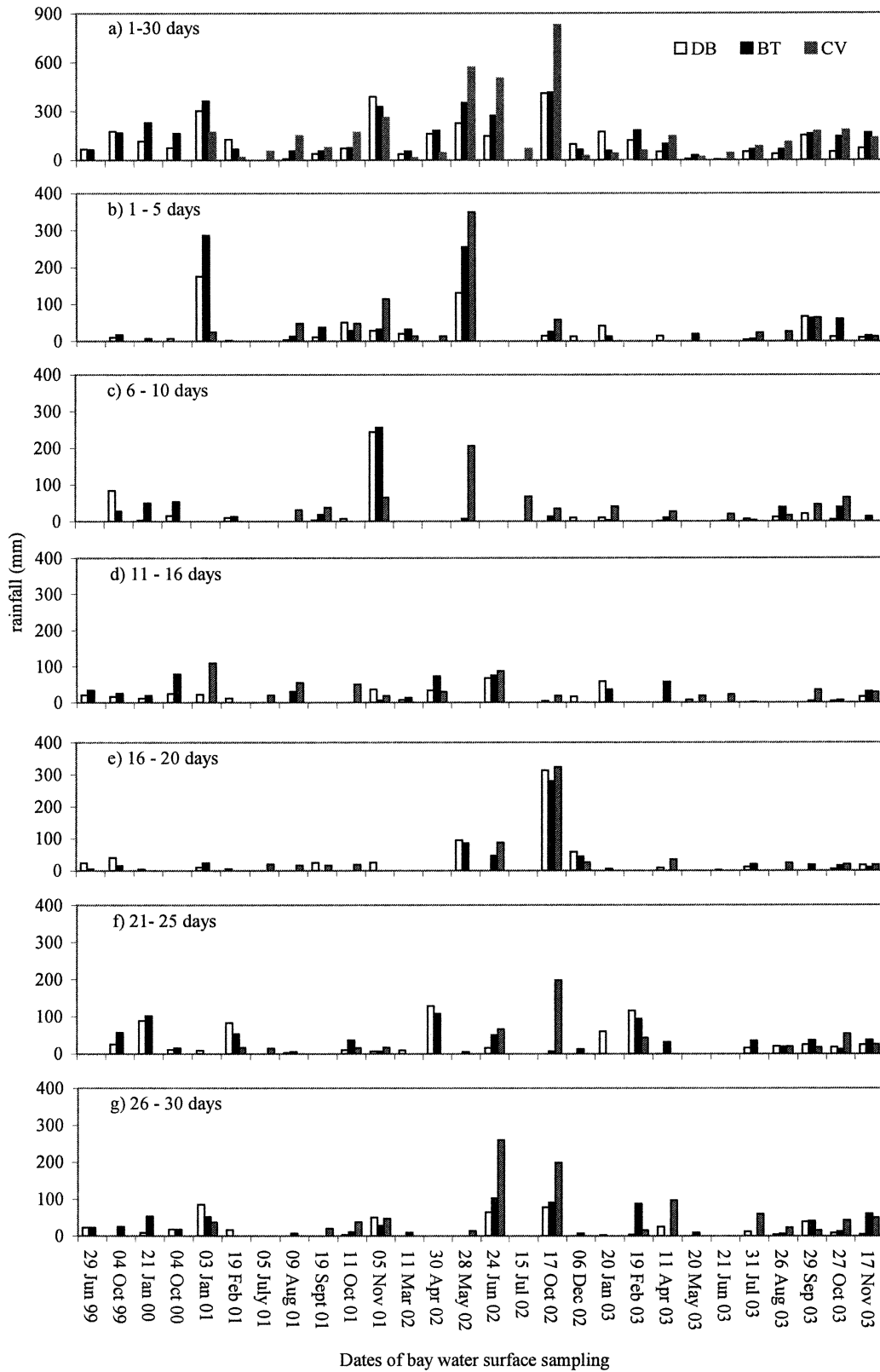


Fig. 6. Integrated rainfall in the days preceding surface water sampling trips. (a) 1–30 days, (b) 1–5 days, (c) 6–10 days, (d) 11–15 days, (e) 16–20 days, (f) 21–25 days, (g) 26–30 days.

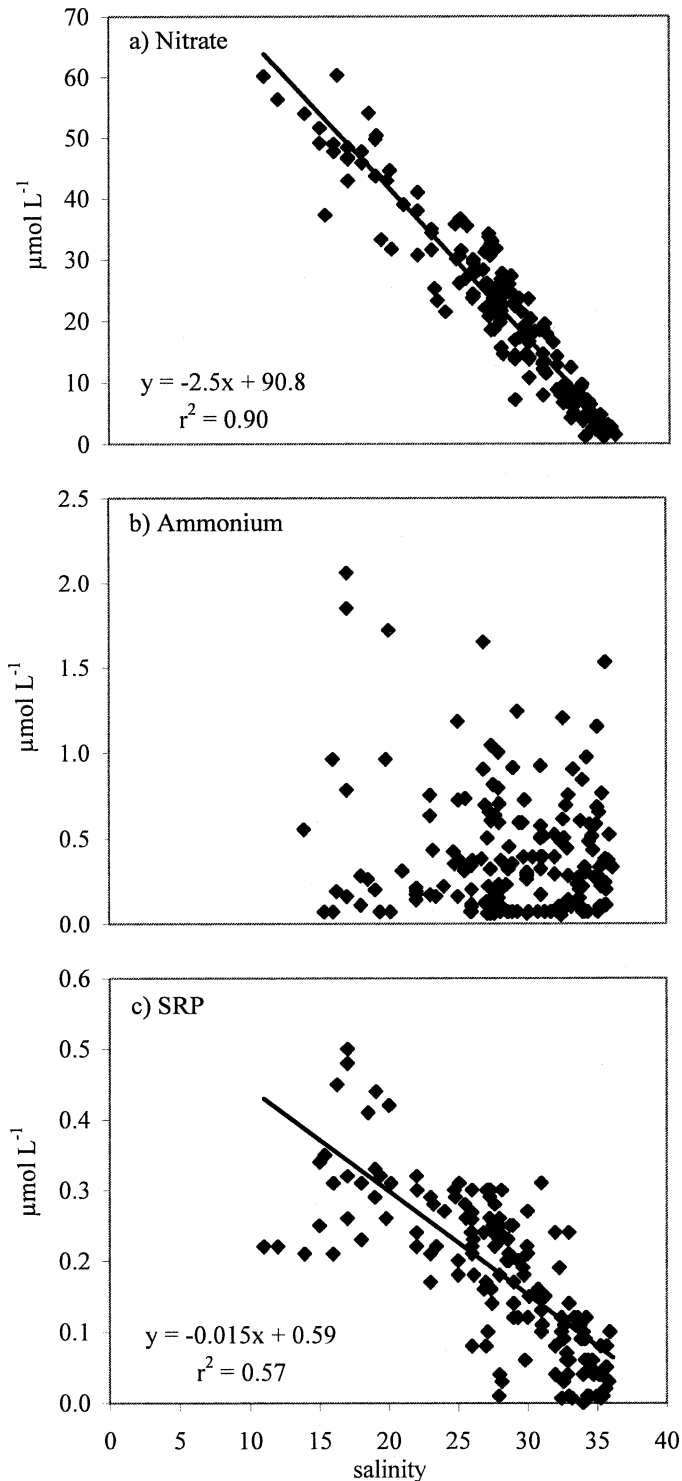


Fig. 7. Nutrient-salinity plots for vent samples. (a) Nitrate, (b) ammonium, (c) SRP.

Lapointe (1997), who claimed that nutrient concentrations measured over the short term were the result of an aquifer enriched because of pollution from anthropogenic sources.

Potential sources of nutrients to the bay—The groundwater flow of nutrients to the bay may be enhanced with

nutrients from rainwater, N₂ fixation, upwelling from offshore waters, and inflow from coastal waters.

D'Elia et al. (1981) found NO₃⁻ concentrations in rainwater at Discovery Bay to vary between 2 µmol L⁻¹ and 10 µmol L⁻¹, somewhat similar to dissolved inorganic nitrogen (DIN) concentrations reported for Bermuda and Tahiti (Cornell et al. 1995). Concentrations are unlikely to be very different now given the minimal changes in population (Table 1) and land-use practices in the vicinity of the bay. Following heavy rainfall events across the 1.5-km² bay (≥ 50 mm d⁻¹ that occurred at Discovery Bay on 24 occasions between January 1999 and December 2003, average 80 mm d⁻¹), the associated NO₃⁻ will be rapidly diluted within the upper meter or so of bay water by the daily wind-driven mixing. At the maximum concentration found by D'Elia et al. (1981) this would increase the upper 1-m layer NO₃⁻ concentration by about 0.8 µmol L⁻¹, or approximately double the NO₃⁻ concentrations within the major section of the bay on about 5 days of each year. Cornell et al. (1995) reported that dissolved organic nitrogen (DON) concentrations in rainwater in Tahiti and Bermuda were comparable to DIN concentrations and that the DON was of relatively low molecular weight and probably biologically available. If we assume that the DON in Discovery Bay rainwater is comparable to the DIN concentrations, then the concentrations of bioavailable nitrogen in the surface waters may approximately double whenever ≥ 25 mm of rain falls on any 1 day (about 12 days per year). There is no comparable data available for SRP. Given our earlier observations, it is probable that increases in nutrient concentrations resulting from nutrients in the rainwater will only be detectable within the 2–3 days after the events.

Upwelling of nutrient-rich waters along the north coast of Jamaica has never been reported and tidal exchange of bay and coastal waters will tend to dilute the bay waters with the nutrient-poor coastal waters (site 1, Table 5). Nutrient fluxes from sediment have been shown to be small (Gordon-Smith unpubl. data) with NH₄⁺ being the dominant nitrogen species. Nitrogen fixation, which can be important over seagrass beds and in systems where terrestrial sources of nitrogen are low (Fourqurean et al. 1993), may be relevant to Discovery Bay, but no data are available to quantify this.

We conclude, therefore, that the continuous flow of vent water is probably the major source of nitrogen, and possibly phosphorus, to the bay.

Groundwater nutrient concentrations—In our studies, the conservative mixing behaviors in the vicinities of vents and fissures (Fig. 7) led to predictions of groundwater NO₃⁻ and SRP concentrations of 91 µmol L⁻¹ and 0.6 µmol L⁻¹, respectively. The NO₃⁻ prediction is consistent with data from freshwater sites within the Discovery Bay area (NO₃⁻ varied from 65 µmol L⁻¹ to 113 µmol L⁻¹, Table 3) but the SRP prediction may be slightly high (SRP varied from 0.08 µmol L⁻¹ to 0.40 µmol L⁻¹ in freshwaters, Table 3); the salinity-SRP data may be better represented by

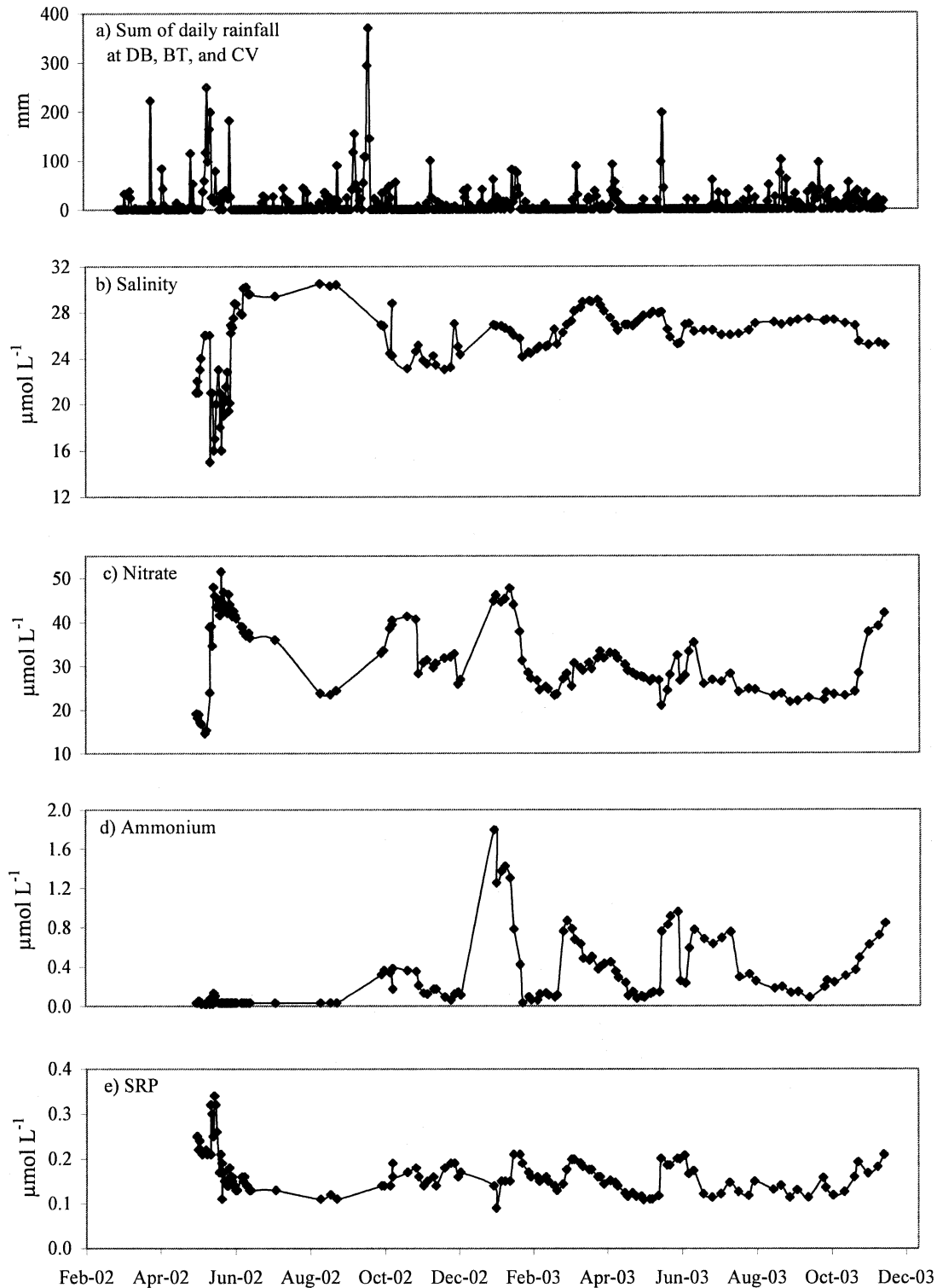


Fig. 8. The variations of salinity and nutrients at a rock fissure compared to daily rainfall. (a) Sum of daily rainfall at Cave Valley, Browns Town, and Discovery Bay, (b) salinity, (c) nitrate, (d) ammonium, (e) SRP.

a convex nonconservative curve consistent with a within-bay source of phosphorus. The above predictions were made by pooling all the vent data (186 samples collected from four sites during 14 sampling exercises, some extending for several days). By considering the data from

each vent separately, the predictions for NO_3^- are 81 (site 4, $n = 55$), 89 (site 10, $n = 36$), 91 (site 15, $n = 78$), and 103 (site 11, $n = 17$) $\mu\text{mol L}^{-1}$, suggesting that the vent waters are from similar, if not a common, subterranean estuary.

D'Elia et al. (1981), using data collected on six occasions between 16 August 1979 and 28 February 1980 and daily salinity–nutrient plots, predicted that the concentration of NO_3^- in the source waters, although varying considerably from day-to-day, fell within the 88–250 $\mu\text{mol L}^{-1}$ range. Phosphate, urea, and NH_4^+ concentrations did not correlate with salinity. Nitrate concentrations in freshwater sites at that time ranged from 61 $\mu\text{mol L}^{-1}$ to 157 $\mu\text{mol L}^{-1}$ (no SRP data reported). Lapointe (1997) reported data from a 1987 transect starting close to a shoreline fissure (site 14 in the present study, Fig. 1) and extending out over the west fore-reef (four sites, sampled at surface and depth). The surface waters were of lower salinity than deeper waters and there were significant correlations between both SRP and DIN ($\text{NH}_4^+ + \text{NO}_3^- + \text{NO}_2^-$) and salinity (SRP = $-0.018(\text{salinity}) + 0.77$; $r^2 = 0.61$; DIN = $-2.25(\text{salinity}) + 84.8$; $r^2 = 0.80$; both at the 95% confidence level and calculated herein from the reported data). The DIN was dominated by oxidized nitrogen (91–99%) with a clear trend to higher NH_4^+ with higher salinity. The predicted freshwater concentrations of 85 $\mu\text{mol L}^{-1}$ and 0.8 $\mu\text{mol L}^{-1}$ for DIN and SRP, respectively, agree with the results from D'Elia et al. (1981) and the present study.

The agreement between the predictions of our work and the above two studies suggests that the concentrations of nutrients in the freshwaters entering the bay have not, on average, changed during the 35 years that the studies span. There have been minimal population increases within the watershed since 1970 (8–14% per decade or about 1,000 persons per year across all of rural St. Ann; Table 1; Fig. 1); no major shifts in land-use practices (bauxite mining and small farming); and no changes in sewage collection systems, with homes, schools, etc. all relying on septic tanks or soak-away pits. There are, therefore, no reasons to suspect that anthropogenic inflows to the aquifers changed during the decades. Lapointe (1997), however, noted that his 1987 DIN concentrations in the western back-reef area (approximately site 13 of this study) were between two and four times those of D'Elia et al. (1981) and thus concluded that there had been an increase in nutrient concentrations in that area during the time between their studies (1979–1987). He supported this by reference to some of his similar, but unpublished, 1988–1989 data. The absence of rainfall data for the time periods of the Lapointe and D'Elia et al. studies (unfortunately the nation's daily rainfall data before 1992 were lost in a Meteorological Services office fire) makes interpretation of Lapointe's high concentrations difficult, but, the similarities of the predicted zero salinity concentrations from all three studies and the agreement between our data and those of D'Elia et al. (1981), suggest that Lapointe's small dataset may have biased his results.

Potential for nutrient limitation in the bay—DIN:SRP ratios (Fig. 9; Table 5) vary considerably from site to site. D'Elia et al. (1981) reported a groundwater ratio of about 625 but assumed that the concentration of SRP in

groundwater at that time was equivalent to the concentrations in their brackish waters ($\sim 0.2 \mu\text{mol L}^{-1}$), which both Lapointe's (1997) data and our data show is an underestimate. The present groundwater ratio, calculated from the zero salinity intercepts, is about 150.

The Redfield nitrogen:phosphorus (N:P) ratio of 16 in phytoplankton is frequently used as a guide to biological productivity, with ratios less than this indicative of N limitation. Atkinson and Smith (1983) found that for benthic marine plants, ratios >30 and <10 indicated P and N limitations, respectively. Entsch and coworkers (1983) reported an average N:P ratio of 45 for several algae associated with coral reefs and suggested that P limitation is indicated by ratios in plants >60 . Fourqurean et al. (1993) suggested that concentrations of inorganic nutrients are poor indicators of nutrient availability as they are normally quickly used by phytoplankton and do not reflect the bioavailable pool, which is better reflected by total dissolved N (TN) and P (TP). Guildford and Hecky (2000) agreed and suggested that TN:TP ratios <20 imply N limitation, whereas P limitation is indicated by N:P ratios >50 . In the absence of TN and TP data we have used the DIN:SRP range of 10–30 suggested by Atkinson and Smith (1983) to indicate biological nutrient balance.

The DIN:SRP ratio (Fig. 9) observed at site 14 averaged around 70 (range 24–202) before the increases in concentrations that occurred in mid- to late-2002, after which it rose to around 200. The ratios at the bay sites averaged between 17 and 27, with many values <20 , before the NO_3^- increase and then rose to average between 40 and 48.

Thus, while inflowing freshwater to Discovery Bay was rich in NO_3^- , the bay waters were in approximate biological balance and only approached phosphorus limitation under extreme freshwater flow regimes and even then for only short periods. This in turn suggests that there must have been a phosphorus source within the bay that was able to balance the inflow of nitrogen from the freshwater, a suggestion that is consistent with the possibly non-conservative SRP–salinity plots discussed earlier. The phosphorus pool was probably maintained by efficient use of recycled phosphorus. This contrasts with D'Elia et al.'s (1981) suggestion that SRP contamination of groundwater could lead to eutrophication because it appears that the system is seldom enriched in DIN.

Nutrient dynamics and the condition of coral reefs in Discovery Bay—Our results documented that heavy, widespread rainfall events significantly increased the concentration of NO_3^- , and to a lesser extent SRP, in the bay waters and, by extension, across the reef and that in severe cases elevated NO_3^- concentrations were sustained for several months. The effects were most noticeable in the shallow northwestern quadrant of the bay. In reaching these conclusions we considered rainfall across the hydrologic basin and not just in the vicinity of the study area, and over several days, even months, before sampling occasions. Rainfall limited to the immediate vicinity of Discovery Bay,

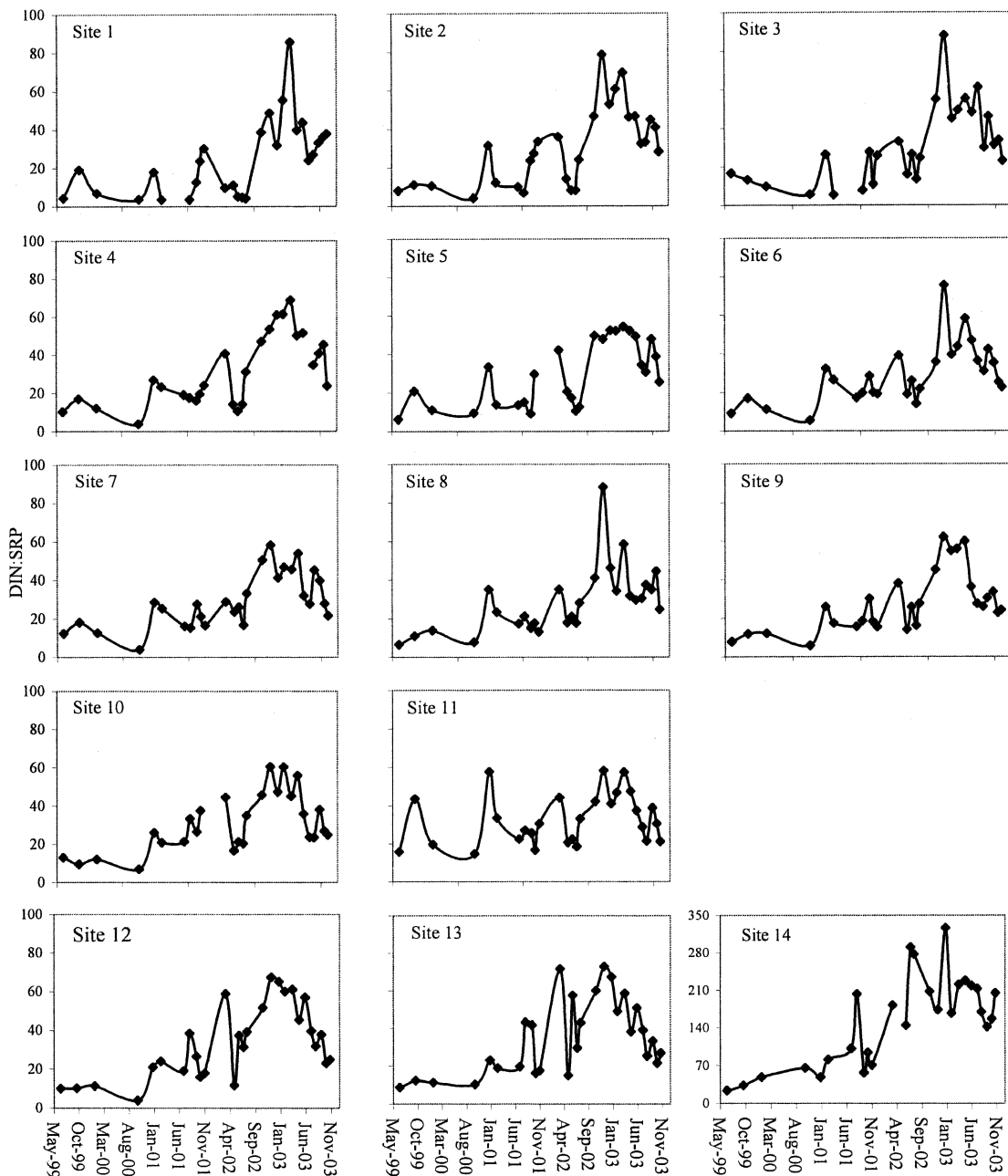


Fig. 9. DIN:SRP ratios for Discovery Bay surface samples.

where there is no channeled surface runoff, appears to only affect nutrient concentrations for short periods and even then only after heavy rainfall events, probably because such localized events will have only minimal effects on the aquifer. However, heavy rainfall ($>100 \text{ mm d}^{-1}$) across the hydrologic basin had a greater effect, although it did not become apparent until several weeks after the events, and only after very heavy rainfall ($>200 \text{ mm d}^{-1}$ over several days) are elevated nitrate concentrations sustained. Ammonium and SRP concentrations rose slightly after heavy

and very heavy rain, but the elevations were not sustained. Thus, when considering nutrient dynamics in this embayment, where groundwater discharge dominates surface-water flow, it is clear that rainfall patterns must be considered and that using local annual or even monthly rainfall averages and not including data from across the hydrologic basin may generate misleading results.

Our 4.5-yr dataset shows that in Discovery Bay's surface waters, NO_3^- and SRP concentrations seldom exceed $1 \mu\text{mol L}^{-1}$ and $0.1 \mu\text{mol L}^{-1}$, respectively, even in the

northwest quadrant where freshwater can often be detected. This contrasts the results of earlier studies that failed to consider rainfall patterns: it takes very significant rainfall to raise the NO_3^- concentrations above $1 \mu\text{mol L}^{-1}$, and phosphorus only becomes limiting after such infrequent rainfall events.

Extreme rainfall events and, hence, nutrient concentrations exceeding the suggested thresholds for macroalgal overgrowth of coral reef communities (Lapointe 1997) have been occurring on an irregular basis for centuries, including during the 1950–1980 period when corals dominated the reef. Our results therefore do not support the suggestion that bottom-up control via nutrient enrichment was the causal factor for the 1980s phase shift from corals to macroalgae on the Discovery Bay reef.

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