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Predicting and managing the effects of hypersalinity on the fish community in solar salt fields in north-western Australia

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Summary

Five concentrator ponds (CPs) of a solar salt field in Port Hedland, Western Australia were sampled by seine and gill nets over a 12-month period in order to describe the fish community and examine relationships between diversity, abundance and catch per unit effort (CPUE) with salinity. Salinity varied between 40.2 and 113.7‰ during the sampling period. Forty-one species of fishes were recorded from the CPs, with fewer species recorded from CPs of higher salinity. A significant inverse relationship was identified between salinity and the number of species (diversity) captured in gill nets, indicating that one species is lost with every 16‰ increase in salinity. A significant relationship between salinity and CPUE was also identified with gill-net samples, indicating a reduction of 1 kg h^{-1} with every increase in salinity of 5.5‰. As CPs are connected by one-way flaps, fish movements are only possible into CPs of higher salinity. Thus, reductions in diversity, abundance and CPUE suggested fish mortalities, likely as a result of maximum or rapidly changing salinities exceeding the tolerance ability of individual species. As fish kills are not infrequent events in solar salt fields and result in economic losses due to loss of production and clean-up costs, the results may allow managers to identify high risk species and times of year of fish kills by using salinity measurements. Commercial, indigenous and/or recreational fishing opportunities are viable options for reducing fish biomasses within the CPs and are discussed. Although absolute salinity values were higher than those recorded from tropical Australian estuaries, salinity deviations within each CP are similar to other estuaries and the effect on the ichthyo-community is likely to be similar.

Introduction

Solar salt fields are large producers of salt, the majority of which is used for industrial purposes (e.g. manufacturing of plastics; C. Sanderson, pers. comm., 2000). In Western Australia there are several large solar salt fields in dry tropical regions, where rainfall is relatively low and evaporation rates are high. Typically, salt water enters a salt field via a bank of large pumps (approximately 1000 mm inlets) from adjacent tidal creeks into the first of a series of extensive, shallow concentration ponds (CPs). Evaporation then increases the salinity from ambient to >200‰, before being pumped to crystallizer fields where salt crystals are eventually harvested (Burnhard, 1991; Thomas, 1991).

The pumping of large volumes of salt water into the CPs also results in the movement of small/juvenile fishes and invertebrates from adjacent creeks into the first CP. Fishes and invertebrates that survive the pumping process are unable to leave the CP system due to one-way valves. Aquatic animals can either remain within a single CP or move unidirectionally into CPs of increasing salinity (LeProvost, Semeniuk & Chalmer (Consultants), 1990). Due to the large areas of the CPs involved in the solar salt process (usually several thousand hectares) and large volumes of water pumped into the first CP, the abundance and biomass of fishes within these systems can be considerable (Burnhard, 1991; Molony and Parry, 2002). Some taxa within the CPs are important in maintaining water clarity (e.g. filter-feeding fishes, *Artemia*), thereby increasing evaporation rates and the efficiency of salt production (Burnhard, 1991). Other species of fishes and biota within salt ponds do not necessarily contribute to water clarity or the salt production process but may have commercial, recreational and/or indigenous values (Molony and Parry, 2002).

As salinity and other water parameters (e.g. dissolved oxygen) vary within the CPs, conditions can become unsuitable for certain species of fishes and mortalities of fishes have been recorded within the CPs of solar salt fields (Molony and Parry, 2002; B. Molony, pers. obs., 2002). Fish kills impact on the efficiency of salt production as pumping is stopped until carcasses have been removed (S. Simmons, pers. comm., 2002), thereby imposing an economic loss. Understanding the effects of changing salinities on fish communities within salt fields can provide managers of solar salt fields with information to develop strategies to predict and reduce the intensity of fish kills, minimizing downtime and maintaining salt production. The current study examined the relationships between salinity and the fish community within the Dampier Salt CPs at Port Hedland, specifically the number of fish species (diversity), abundance and biomass (catch per unit effort, CPUE) sampled by seine and gill nets. The relationships between salinity and individual fish species were also examined to determine the approximate maximum salinity tolerance of individual species. The overall objective was to identify relationships between the fish community and salinity in the CPs, in order to allow salt producers to identify high risk periods and develop management options to reduce the impacts of fish kill events.

Methods

Sampling sites

Sampling occurred within the Dampier Salt CPs located approximately 30 km north-east of Port Hedland (20.31°S, 118.58°E), Western Australia. There are nine CPs ranging in size from approximately 381 to 1225 ha, covering a total area of approximately 7273 ha (Fig. 1). Water is pumped from two mangrove-lined tidal creeks (Ridley and Rock Cod Hole) into

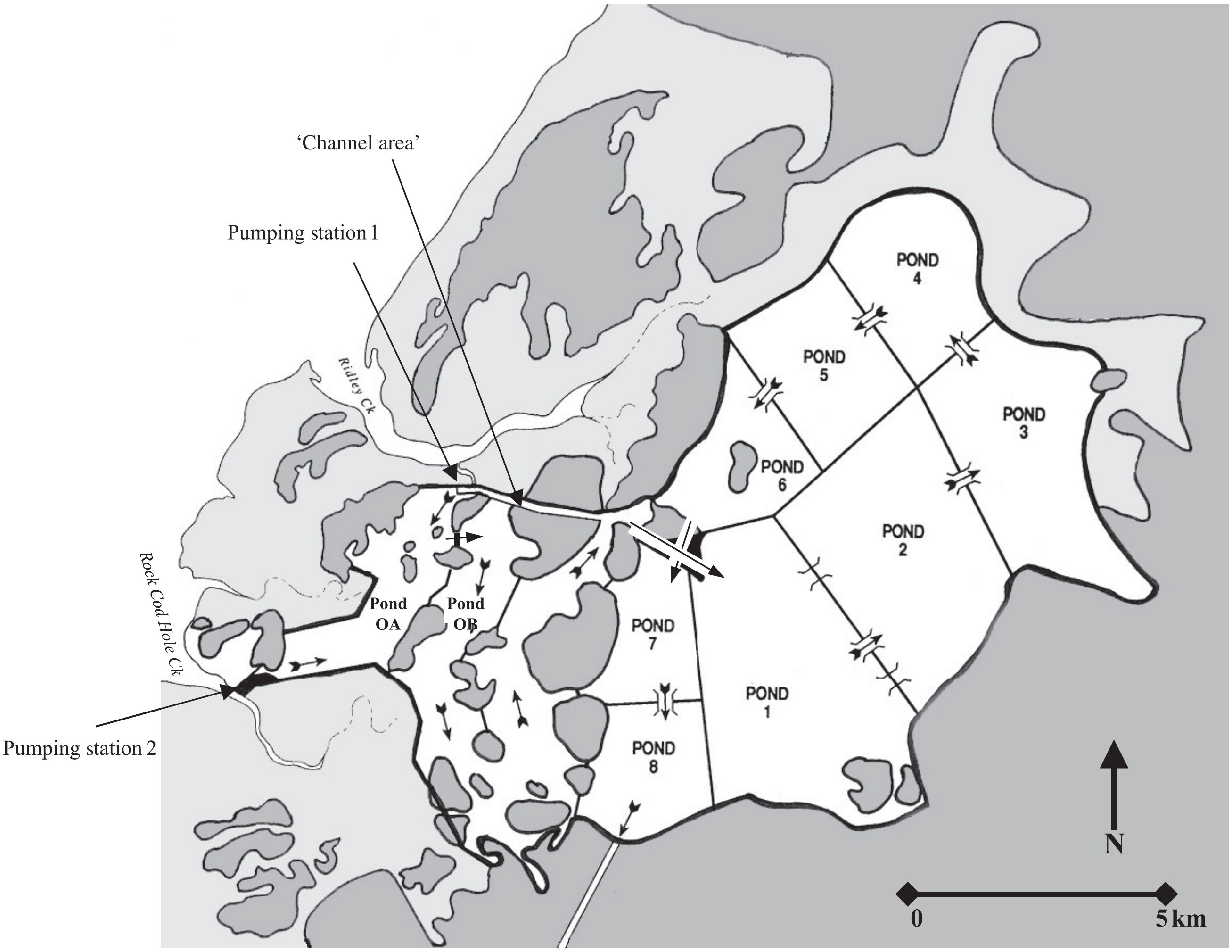

Fig. 1. Map of the Dampier Salt concentrator pond area showing the two creeks, pumping stations and the direction of waterflow through the system (modified from LeProvost, Dames & Moore (Consultants), 1996)

CP OA on high tides around the spring phase of the lunar cycle (tidal fluctuations of approximately 7 m occur in this region). Up to 12 pumps may operate at any one time with each pump capable of pumping more than 10 m^3 min^{-1} through large diameter outlets fitted with non-return valves. The CPs have

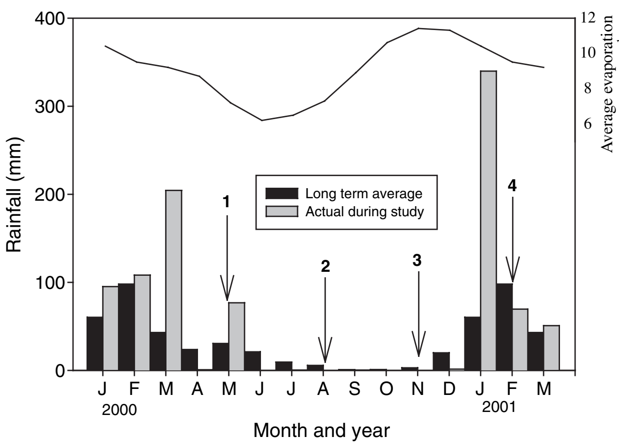

Fig. 2. Rainfall and average daily evaporation rates from Port Hedland airport (Western Australia) throughout the study period (data from the Bureau of Meteorology). Arrows indicate sampling periods during the study

an average depth of 0.7 m but some areas within the CPs may exceed 3 m. Sediments range from fine muds to coarse sands. Walls separating each CP are constructed from granitic rocks and small areas of mangroves exist within the system in CPs OA, OB and 1. CPs are linked to the next CP in the concentration series by a single point, several metres wide fitted with a one-way valve. However, a long channel links CP OB and CP 1. Water moves unidirectionally through the system from CP OA to CP 8 by two pumping stations (intakes) on CP OA and a pumping station linking CP 6–CP 7. The salt fields are in the dry tropics of Western Australia where the average rainfall is low (mean = 311 mm per annum) and falls mainly in the first quarter of the calendar year (Fig. 2). Evaporation rates are also relatively high due to favourable prevailing winds (Fig. 2).

Sampling methods

Four sampling periods were selected to reflect the range of climatic conditions typical of the dry tropics in Western Australia. The four periods were May–June 2000 (early dry season, 'autumn'), August 2000 (dry season, 'winter'), November 2000 (pre-wet season, 'spring') and February 2001 (post-wet season, 'summer'; Fig. 2). During a preliminary visit to the site in February 2000, fish were observed in CPs OA, OB,

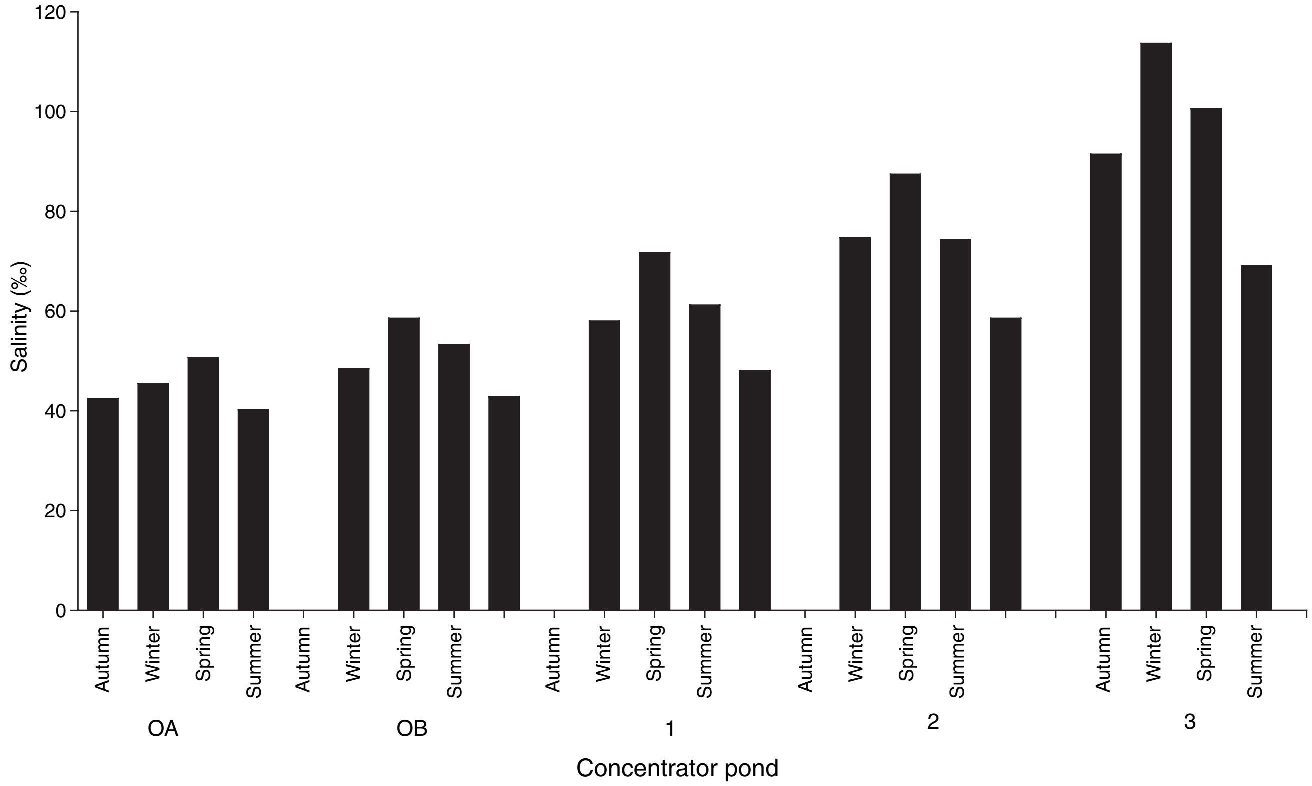

Fig. 3. Salinity recorded from the concentrator ponds at each sampling occasion. Each bar represents mean values of three readings during each sampling period as supplied by Dampier Salt

1 and 2. Sampling through this project focussed on these four CPs, plus CP 3 using seine and gill nets.

During each sampling period, each CP was given 3 units of effort at two locations. A unit of effort consisted of three seine-net hauls and three gill-net sets, with each gill-net set consisting of three separate gill-nets. The seine net (40 m long × 2 m deep, 25 mm wing mesh, 9 mm cod-end mesh) was used to target small species of fishes close to the banks of the CPs. Three gill nets (each 30 m long × 2 m deep, with 50 mm, 100 mm or 150 mm monofilament nylon mesh) were used simultaneously. Each unit of effort consisted of using all three gill nets for three, 1-h sets. On re-setting, the position of gill nets assured that all nets were sampled independently of each other. The exception to the soak time occurred in CPs 2 and 3 due to the relatively low number of fishes. In these CPs, gill nets were set in the late afternoon and retrieved early the following morning, giving a soak time between 15 and 18 h. Seine nets were not used in CPs 2 and 3 due to the lack of suitable banks. An additional unit of effort was expended in CP OB due to the large size of this CP (Fig. 1).

The total weight of fish from each seine-net shot was measured in the field (±0.1 kg). On return to the laboratory, all fish captured by seine and gill nets were identified to species using the guides of Allen (1985), Allen and Swainston (1988) and Heemstra and Randall (1992), and total length (TL; mm) and wet weight (g) recorded.

Fish kill events were defined by reductions in diversity (as the number of species recorded within each CP), reductions in abundance (numbers per species within each CP and total abundance) and/or reductions in CPUE when compared to the previous sampling trip, without corresponding increases of diversity, abundances or CPUEs in CPs of higher salinity (i.e. to discount movement of fishes into CPs of higher salinities). Some observations of fish kills within individual CPS were also provided by salt field staff.

Data analysis

Data were converted to CPUE for each net type. Briefly, the total weights or numbers of fishes were divided by the soak time of the gill nets (CPUE kg^{-1}), or the number of the seine-net shots (3) for each site within each CP (CPUE kg $haul^{-1}$). For overnight gill-net soaks in CPs 2 and 3, catch and effort was standardized by dividing catches by soak time (h). Mean values and error estimates were calculated for each gear type within each CP.

Diversity (number of fish species) and salinity, or CPUE and salinity from each net type (seines or gills) were regressed against salinity to identify significant relationships. The maximum salinity from which each species of fish was recorded was used to determine the maximum salinity tolerance for each species within the CPs.

Results

Rainfall was relatively high during the sampling period (Fig. 2) with higher than average rainfall recorded in March and May 2000 and in January 2001. However, daily evaporation rates were similar to the long-term averages and thus the pattern of salinity change in the CPs was expected to follow a similar trend of other years, as confirmed by Dampier Salt staff. Dampier Salt manage high rainfall periods by closing the connections among CPs and cease the pumping of creek water into CP OA, until evaporation causes the salinity in creek waters and CPs to return to pre-determined levels.

Salinity

The salinity of the water in the CPs increased from CP OA to CP 3 (Fig. 3). In CP OA the water pumped into the system was iso-saline with water within the two creeks (approximately 40‰). Salinity reached approximately 114‰ in CP 3 in the tropical winter (August 2000). Although the salinity within the system is dictated by the salinity of the water within the creek and slowly increases due to evaporation in the CPs, the effects of rainfall (Fig. 2) resulted in a rapid decline in salinity between spring and summer samples. Declines in salinity were also observed in most CPs between winter and spring samples as additional water is pumped into the system during this time of year as ambient creek water is at its maximum salinity. CP OA did not show a decline in salinity between winter and spring samples due to the buffering effect of large volumes of water being pumped in from the creeks and the relatively small annual range in salinity in CP 1 (10.5‰).

Fish community

A total of 41 species of fishes were identified from seine and gill-nets samples in the CPs (Table 1). More species were recorded from seine samples than from gill-net samples except in summer (Fig. 4). The number of species and biomass were generally highest in CPs OA or OB, although some individual species were more abundant in CP 1 (Table 1). The number of species peaked in summer in CPs OA, OB and 1, but fewer species were identified from CPs with higher average salinities (i.e. CPs 2 and 3; Fig. 4). Six species of fishes had an indigenous value to local communities as food fishes (Table 1), although most species had some economic value as well as being important fodder species (e.g. *Allanetta mugiloides*) for other species of fishes and birds (e.g. sea eagles, *Haliaetus leucogaster*; pers. obs.) that inhabit the area.

The abundance of fishes varied throughout the sampling period and among CPs. Seine-net samples were dominated by small planktivorous fishes in all CPs although predatory species were dominant in terms of biomasses. Similar mean numbers of fishes were sampled by seine nets from CPs OA, OB and 1 at all times (Fig. 5a). The only exception was during autumn 2000 when higher numbers of fishes were recorded from CP 1. The mean CPUE of fish collected by seine net varied throughout the year (Fig. 6a) with the highest CPUE recorded from CP OA in autumn 2000.

Table 1
Species of fishes captured during the project, with information on distribution by abundance and biomass within the concentrator ponds (CPs) and the highest salinity in which each species was captured

Species (family)	n	Highest abundance	Highest biomass	Highest S‰ recorded
Allanetta mugiloides	11 579	OB	OB	71.7
Apogon ruppellii	6660	1	OA	71.7
Ilisha striatula[1]	3634	OB	OB	61.2
Stolephorus spp.[1]	2172	1	OB	71.7
Gerres oyena[1]	1605	OA	OA	61.2
Arramphus sclerolepis[1]	889	OB	OB	71.7
Amnitaba caudovittatus[1]	725	OB	OB	91.4
Elops hawaiiensis[1,2]	340	1	1	113.7
Sillago vittata[1,2]	266	OA	OA	61.2
Acanthopagrus latus[1,2]	147	OA	OA	71.7
Chanos chanos[1,2]	147	OB	1	113.7
Valamugil buchanani[1,2]	130	OB	OB	91.4
Sillago analis[1,2]	128	OA	OB	58.6
Leiognathus equulus[1,2]	112	OA	OB	48.9
Scomberoides commersonnianus[1,2]	110	OB	OB	71.7
Leiognathus bindus[1,2]	83	OB	OB	53.3
Ambassis vachellii[1,2]	33	OB	OA	53.3
Arius thalassinus[1,2]	28	OA	OA	71.7
Platycephalus indicus[1,2]	28	OA	OA	71.7
Bathygobius fuscus[1,2]	24	1	OA	71.7
Dexillichthys muelleri[1,2]	24	1	1	61.2
Selenotoca multifasciata[1,2]	16	OB	1	71.7
Epinephelus coioides[1,2,3]	8	OA	OA	50.7
Gnathanodon speciosus[1,2,3]	7	OA	OA	58.6
Pelates quadrilineatus[1,2]	7	OA	OA	50.7
Scomberomorous semifasciatus[1,2]	5	OA	OA	50.7
Caranx ignobilis[1,2,3]	4	OA, OB	OB	53.3
Pomadasys kaakan[1,2]	4	OA	OA	50.7
Sillago sihama[1,2]	4	OA	OA	50.7
Anodontostoma chacunda[1]	3	OB	OB	53.3
Syphraena jello[1,2]	3	OA	OA	42.5
Cymbacephalus nematophthalmus[1,2]	2	OA	OA	42.5
Epinephelus malabaricus[1,2,3]	2	OA, 1	OA	58.6
Lates calcarifer[1,2,3]	2	1	1	58.0
Lutjanus argentimaculatus[1,2,3]	2	OA, 1	1	61.2
Terapon puta[1,2]	2	OB	OB	42.8
Tylosurus crocodiles	2	OB, 1	1	58.0
Acanthopagrus palmaris[1,2]	1	OA	OA	40.2
Platycephalus endrachtensis[1,2]	1	OB	OB	58.6
Scatophagus argus[1,2]	1	OA	OA	42.5
Siganus lineatus[1,2]	1	OA	OA	40.2

[1]Species with commercial value, including ornamental value.
[2]Species with recreational fishing value.
[3]Species with indigenous value.

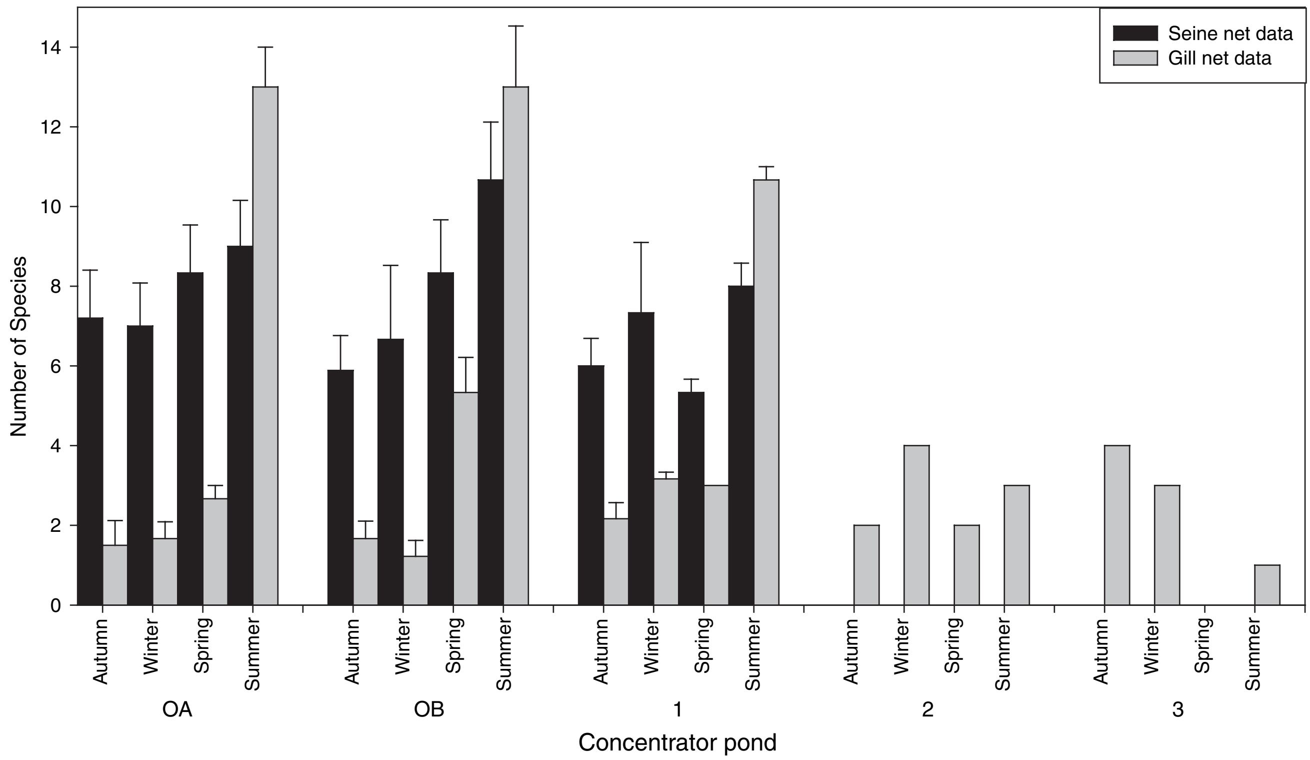

Fig. 4. Mean number of species recorded from each concentrator pond (CP) by seine and gill nets. Seine nets were not used in CPs 2 and 3. Bars represent mean values of nine seine hauls or three gill-net sets (of three nets). Error bars represent 1 SEM. Standard errors are not available for gill-net data from CPs 2 and 3 as only a single overnight set of three gill nets were used at each time (see text)

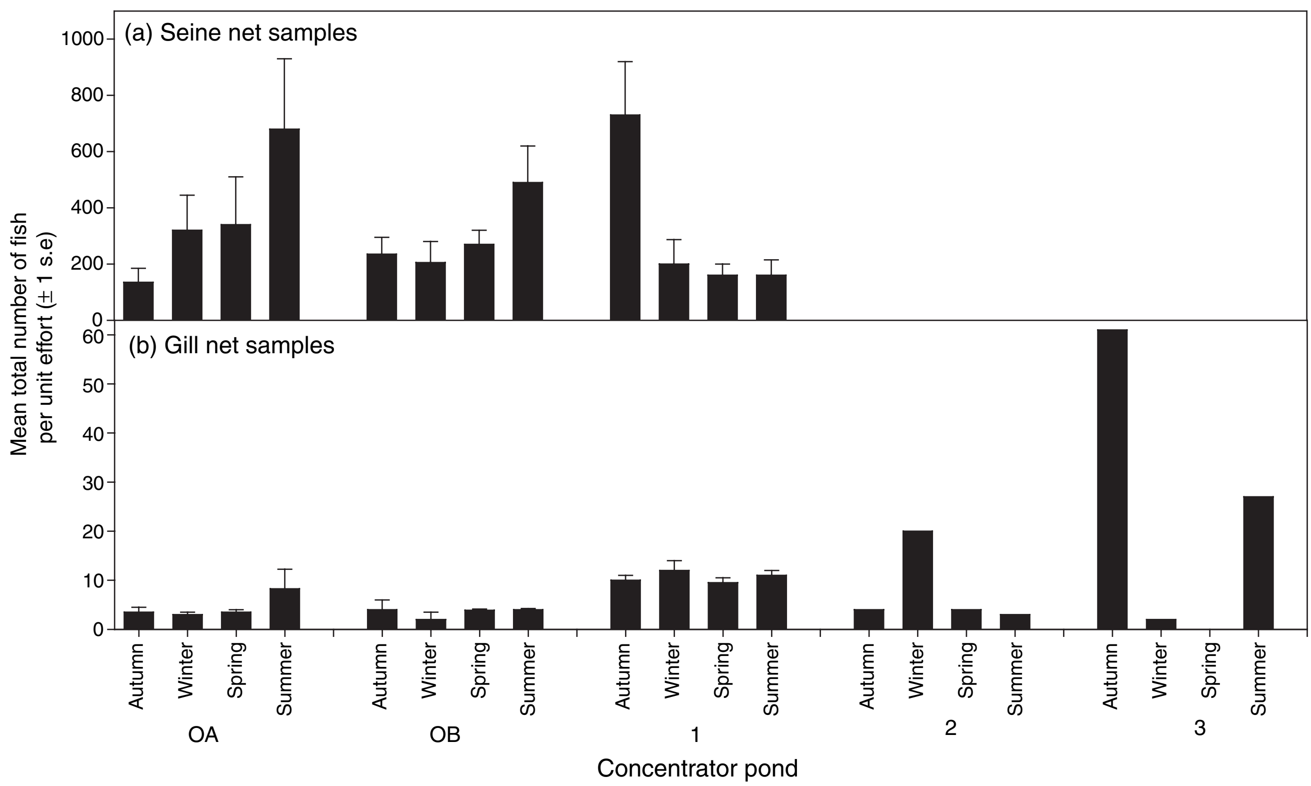

Fig. 5. Mean total number of fishes per unit effort from each concentrator pond (CP) by seine and gill nets. Seine nets were not used in CPs 2 and 3. Error bars represent 1 SEM. Standard errors are not available for gill-net data from CPs 2 and 3 as only a single overnight set of three gill nets were used at each time (see text)

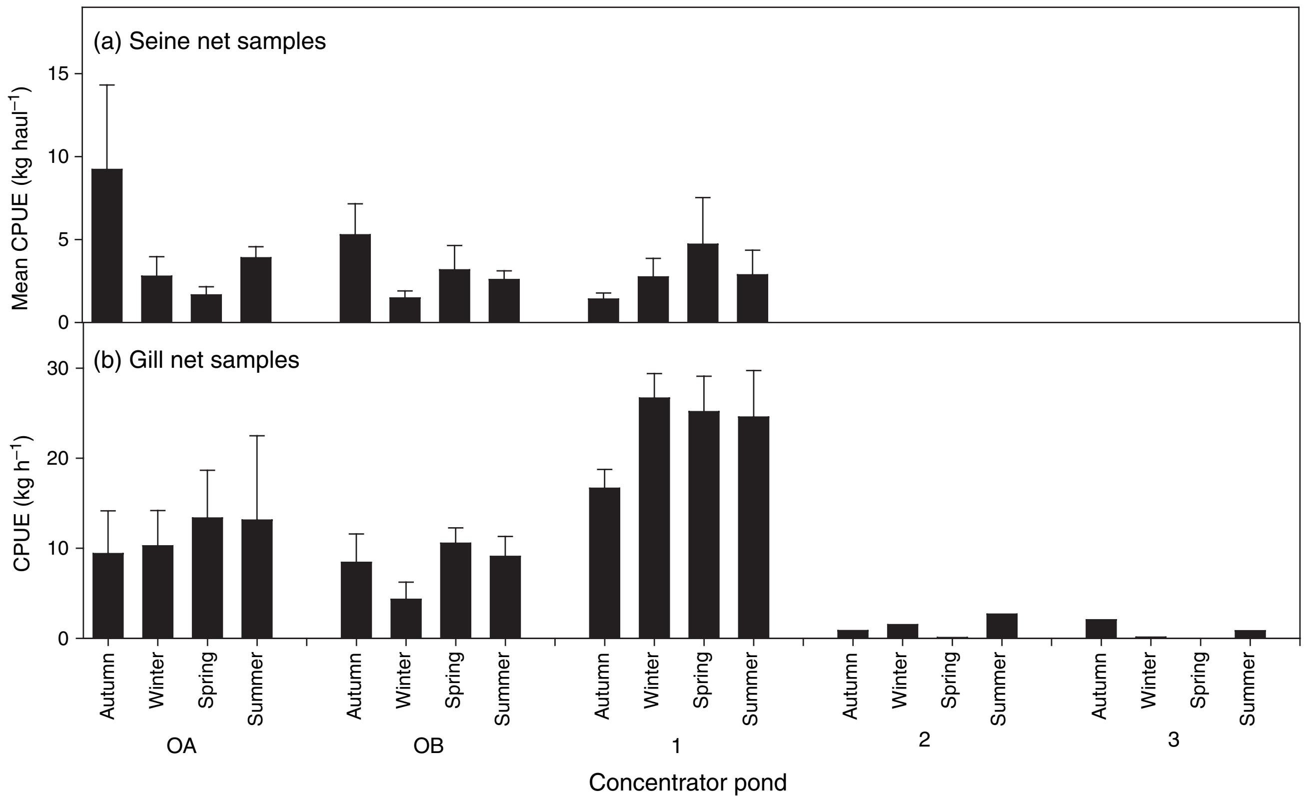

Fig. 6. Catch per unit effort (CPUE) from seine nets (CPUE kg $haul^{-1}$) and gill nets (CPUE kg h^{-1}) throughout the study. Error bars represent 1 SEM. Standard errors are not available for gill-net data from CPs 2 and 3 as only a single overnight set of three gill nets were used at each time (see text)

Gill-net samples were dominated by larger fishes that either fed at low trophic levels (e.g. *Chanos chanos*) or on other fishes (e.g. *Elops hawaiiensis*). Relatively few species were recorded from the CPs for most of the year, with more species recorded during summer 2001 (Fig. 4). In CPs of higher salinities, the highest numbers of species were recorded in winter in CP 2 and in autumn in CP 3.

Gill-net samples produced far fewer fishes than seine-net samples (Fig. 5b). Most gill-net samples produced <20 fish per shot. Gill-net samples from CP 3 generally consisted of more individuals and were dominated by *El. hawaiiensis* and *Amniataba caudovittatus*. However, longer soaks were used to sample CPs 2 and 3 and the larger number of fishes is likely to reflect soak time. When CPUE h^{-1} was calculated (Fig. 6b) the largest catches were consistently made in CP 1. Few fish were captured by gill nets during spring 2000 from CP 2, with no fish captured from CP 3.

Salinity and fish diversity

The number of species declined with increasing salinity in both seine and gill-net samples (Fig. 7). There was a significant relationship between the number of species and salinity for gill-net samples (number of species $= -0.062 \times S‰ + 7.71$, $r = 0.64$, $P = 0.003$), indicating a reduction of one species for each increase in salinity of 16‰. There was also a negative relationship in seine-net data, but this was not significant.

Salinity and individual species

The distribution and numbers of individuals of each species varied throughout the study among CPs with different salinities. The distribution of all species could be broadly divided into two groups based on their presence at higher salinities. The first group included species which displayed their highest abundances and greater size ranges in CPs of relatively low salinity (i.e. OA, OB and 1) and were not recorded in CPs of high salinities (e.g. *Am. caudovittatus* and *Scomberoides commersonnianus*; Fig. 8a,b). In contrast, the second group of species was recorded throughout all sampled CPs at most times, up to salinities of 114‰ (e.g. *El. hawaiiensis* and *C. chanos*; Fig. 8c,d). Although *El. hawaiiensis* and *C. chanos* were generally most abundant in CP 1, large numbers were also sampled in CP 3 in May 2000.

Fish kill events

Two periods of fish kills were identified by reductions in diversity, abundance and CPUE of fishes between sampling periods: between autumn and winter when maximum salinities were reported in most CPs (Fig. 3); and between winter and spring as major declines in salinity were recorded in most CPs. Between the autumn and winter samples, major declines in CPUE were reported in CPs OA, OB and 3 (Fig. 6), with major reductions in the total number of fish sampled in CPs 1 and 3 (Fig. 5). Major reductions in the numbers of species sampled were reported between the winter and spring samples in CPs 1, 2 and 3 (Fig. 4), with major declines in CPUE recorded in CPs 2 and 3 (Fig. 6). In addition, a reduction in the total number of fishes sampled in CP 2 was also reported between winter and spring (Fig. 5).

CPUE and salinity

The CPUE of all fishes for both seine (kg $haul^{-1}$) and gill nets (kg h^{-1}) declined with increasing salinity (Fig. 9), although the

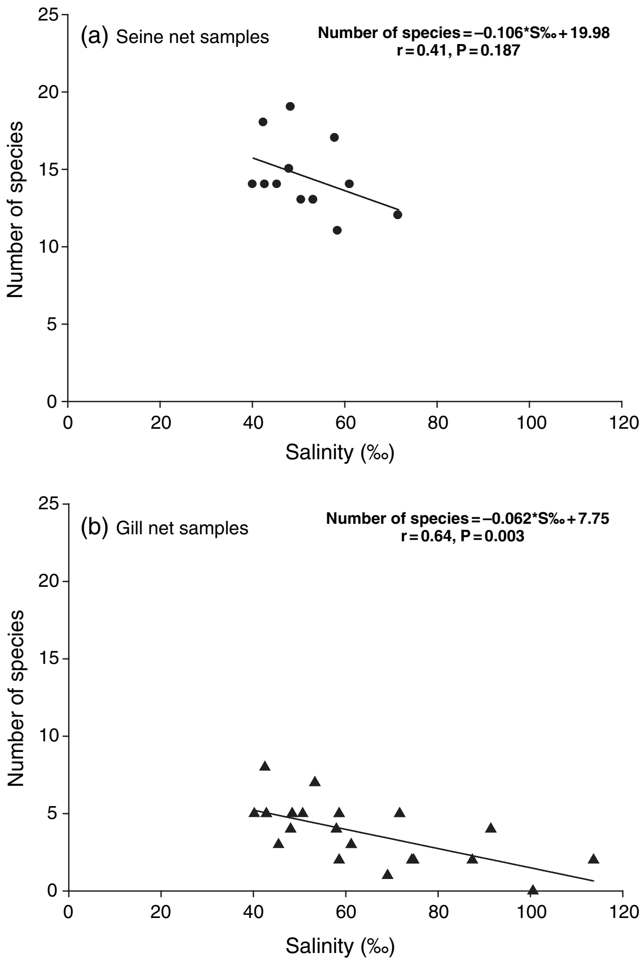

Fig. 7. Number of species sampled as a function of salinity by, (a) seine nets and (b) gill nets. Each point represents the total number of species sampled by gear type within each concentrator pond (CP) at each sampling time. Regression equation, coefficient and significance is also presented in each figure

relationship between seine-net CPUE and salinity was non-significant. Extremely high CPUEs were recorded from CP 1, likely due to the structurally complex channel that links CP OB to CP 1 that supports a high biomass of large fishes, especially *Valamugil buchanani*. When gill-net CPUE data from CP 1 were removed, a significant linear relationship was evident (CPUE = $-0.1807 \times S_{‰} + 17.29$, $r = 0.821$, $P < 0.0001$), indicating that gill-net CPUE decreased by 1 kg h^{-1} with every 5.5‰ increase in salinity.

Discussion

The salinity of water within the CPs increased from CP OA to CP 3 but varied within each CP throughout the project (Figs 2 and 3). Generally, salinity increased slowly due to evaporation but decreased rapidly due to significant rainfall, although declines in salinity between winter and spring were the result of additional pumping of creek water before summer rainfall interrupts pumping into the system. However, salinities within CPs OB, 1, 2 and 3 were always higher than ambient salinities within adjacent creeks (i.e. hypersaline).

From the present study, *C. chanos*, *El. hawaiiensis* and *A. caudovittata* appear to be the most saline-tolerant species, recorded in waters up to 113.7‰. However, most other species tolerated salinities between 50 and 70‰. Only seven species were not recorded in waters above 50‰, a relatively high level of salinity compared to many tropical estuaries (e.g. Sheaves, 1996a,b, 1998; Sheaves and Molony, 2001). Only two species were recorded in salinities above 100‰ and no species were recorded in waters exceeding 113.7‰.

Large numbers of the yellowtail trumpeter, *Am. caudovittatus*, were recorded from all CPs during the current study, except for CP 3 in August and November (Fig. 8). *Amniataba caudovittatus* are common in temperate and tropical Australian estuaries (Allen and Swainston, 1988) and they have been recorded in previous studies in salinities up to 35‰ (Potter et al., 1984; Wise et al., 1994) and above 50‰ (recorded as *Amphitherapon caudavittatus*; Lenanton, 1977). The sampling of *Am. caudovittatus* from salinities up to 91.4‰ in the present study extends the range of salinities that this species can tolerate. *Amphitherapon caudovittatus* is a benthic predator that feeds on polychaete worms and small crustaceans (Wise et al., 1994). However, from samples collected from the Dampier Salt CPs, large *A. caudovittatus* were found to contain only fishes and thus may be a piscivore in this unique environment. It may be that the benthic food sources on which this species relies are not present in the high salinities of the CPs and that a switch to more common food sources occurred.

Seine catches were dominated by small species of fishes (e.g. *Illisha striatula*) that are likely to have a short life history (e.g. *Ambassis*; Molony and Choat, 1990) and recruit throughout the year in tropical estuaries (Molony and Sheaves, 1998). Thus, the reproduction of small, short-lived fishes within the CPs may be possible, at least in CPs with relatively low salinity (e.g. CPs OA and OB). However, larger species also recorded from seine-net samples typically have an offshore migration prior to spawning (e.g. *Epinephelus coioides*; Sheaves, 1995), thus reproduction within the CPs is unlikely. Thus, while some smaller species may be self-recruiting within the CPs, many of the larger and commercially or recreationally important species must recruit to the CPs from adjacent creeks via the pumping process.

Gill nets, due to their passive nature and large meshes, captured mobile and relatively large species. Predatory pelagic species, such as *El. hawaiiensis*, tended to dominate the catches, although recreationally important species (e.g. *S. commersonnianus*) dominated catches in CP OB. As expected, the number of species declined in CPs of higher salinity, although large numbers and weights of *El. hawaiiensis* were recorded in all CPs, including CP 3. Gill-net samples revealed that the most abundant, large species in the CPs was *El. hawaiiensis* and not *C. chanos* as recorded in other studies on solar salt fields (e.g. Burnhard, 1991). Although *C. chanos* was captured in most CPs, it was never recorded in CP 2, suggesting that *C. chanos* was spawning in CP 3 as fish cannot move into ponds of lower salinity (LeProvost, Semeniuk & Chalmer(consultants), 1990).

Fish kills (identified by major declines in the number of species, number of fishes and/or CPUE) were observed during periods of major salinity change. Between autumn and winter the maximum salinities were recorded from most CPs. Based on the maximum salinity of capture (Table 1), salinities in many CPs were likely to have exceeded the maximum tolerable salinity for many species. In CP 3, the absence of fish from samples suggests that 113.7‰ exceeds the salinity tolerance of all fishes in the region. The second period of decline in the three metrics occurred between winter and spring as salinity started to decline rapidly, initially due to additional pumping

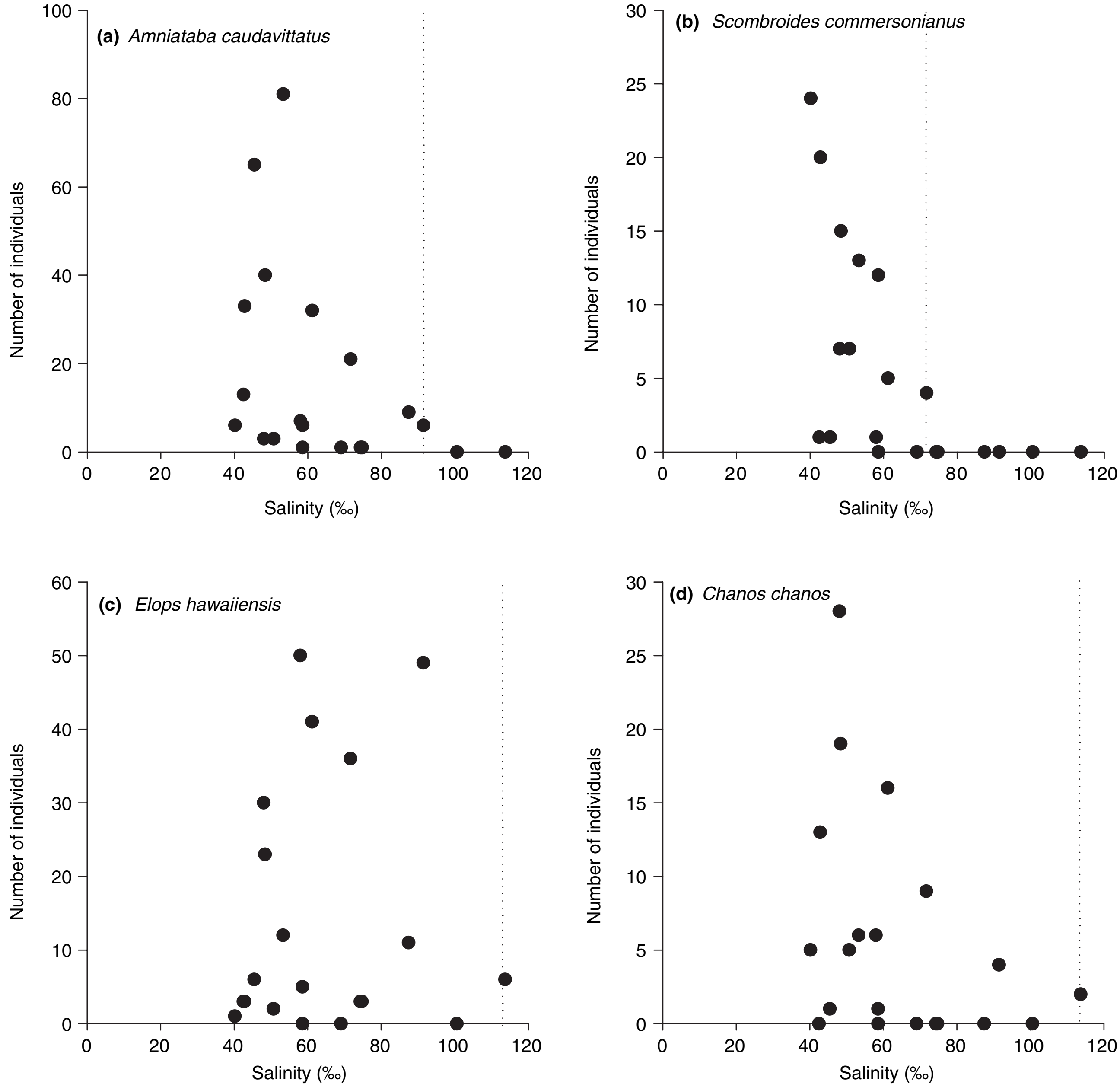

Fig. 8. Influence of salinity on abundance of four common species of fishes from the concentrator ponds (CP). (a) *Amniataba caudavittata*, (b) *Scombroides commersonnianus*, (c) *Elops hawaiiensis*, (d) *Chanos chanos*. Vertical dotted lines indicate maximum salinity in which each species was captured. Each point represents total number of individuals for each species sampled within an individual CP at each sampling time (n = 19 points per species). Total number of individuals for each species are provided in Table 1

and then due to intense summer rain (Fig. 2). It is likely that these fish kills were due to the rate of salinity change exceeding individual species' ability to physiologically respond.

A significant relationship was identified between salinity and fish diversity with gill-net samples indicating that one species was lost for each increase in salinity of 16‰ within the range of salinities examined (40.2–113.7‰), a relative effect of a 20% reduction in diversity with each increase of 16‰. Similarly, a significant relationship was also identified indicating that gill-net CPUE declined by 1 kg h^{-1} with every increase in salinity of 5.5‰.

Although salinity was the most obvious physical variable in the current study, salinity alone may not explain changes in fish diversity, abundance and CPUE or the relatively low number of species recorded. Interactions between salinity and other variables (e.g. temperature, dissolved oxygen) are also likely to be important in limiting the species present in the CPs, both directly or indirectly (e.g. starvation due to the loss of prey species). Fish within the CPs must also be able to survive the pumping process; thus the fish community within the CPs may be composed of robust species that recruit into the CP OA as small or juvenile fish. The diversity of habitat within the CPs is also limited, dominated by open, sandy areas with little structure. In contrast, tropical estuaries are structurally diverse (e.g. rocky outcrops, sand banks, channels, extensive areas of mangrove, etc.; Robertson and Blaber, 1992; Sheaves, 1996b) and thus some species that survive the pumping process may be habitat limited, although many small species were found associated with available structures within the CPs (e.g. *Ep. coioides* in the rock-lined channel linking CPs OB and 1;

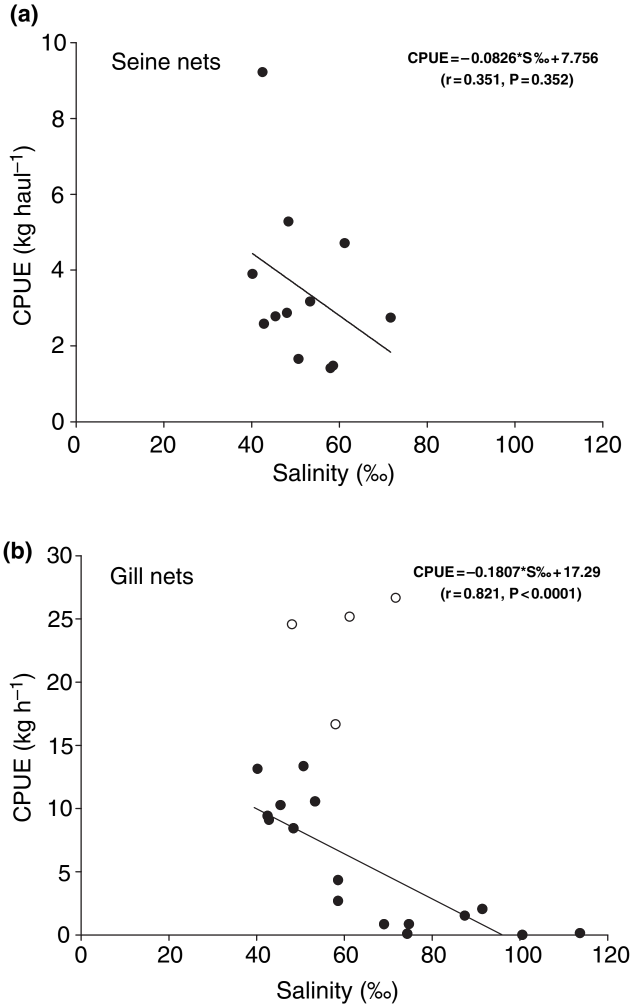

Fig. 9. Catch per unit effort (CPUE) as a function of salinity from (a) seine-net samples and (b) gill-net samples. Gill-net samples from concentrator pond 1 (○) were excluded from the regression (see text). Regression equation, coefficient and significance is also presented in each figure

Acanthopagrus latus associated with rock walls in CPs OA and OB). Thus, a combination of factors is likely to be involved in determining the species present and their abundances in the CPs, although salinity is likely to be the major variable.

Although maximum salinities within the CPs exceeded salinities recorded in most tropical estuaries, hypersaline waters (in excess of 50‰) have been recorded previously from tropical Australian estuaries at certain times, due to tidal inundation of salt flats and the re-dissolution of salt crystals (Sheaves, 1996a, 1998; Sheaves and Molony, 2001). Further, the maximum salinity deviation recorded in the current study (CP 3–45‰) was similar to the maximum salinity deviation recorded from a tropical Australian estuary (39‰; Sheaves and Molony, 2001). Thus, the salinity challenges faced by fishes in the CPs may be similar to those in hypersaline estuaries. For example, CP 3 had the highest salinity of any CP surveyed throughout the project (69–113.7‰), but salinity was reduced by 31‰ within 11 weeks (November 2000 to February 2001; Fig. 3). The actual decline was likely to be much more rapid due to extremely high rainfall in January 2001 (340 mm of rain in a 9-day period; maximum daily rainfall of 177 mm; Bureau of Meteorology, 2001). The hypersaline conditions and subsequent rapid decline in salinity were likely to have resulted in restricting the diversity and abundance of fishes (and other organisms) within the CPs, supporting previous reports of the impact of salinity deviations in structuring the ichthyo-community in tropical estuaries (Sheaves, 1996a, 1998; Sheaves and Molony, 2001). Thus, the relationships between salinity and community diversity described in the current study are likely to be broadly applicable to tropical fish communities in estuarine systems that experience hypersaline conditions.

The overall result of the current project is that salinity from the CPs can be used as a proxy to broadly monitor fish diversity and CPUE in gill-net samples and thus the relative abundance of fishes can be readily estimated by the salt field managers. Coupled with the maximum salinities from which each species in the CPs was recorded (Table 1), managers may be able to use salinity measures to identify species of fishes at risk prior to periods when fish kills in CPs are likely. This information permits the potential use of management interventions to remove fishes prior to periods when fish kills are likely to occur (e.g. the tropical summer). For example, selective harvesting of fish by gill nets may be applied to the CPs late in the calendar year to reduce fish biomass prior to periods of highest risk of a fish kill event. The removal of fish prior to a fish kill will not only reduce costs and economic loss through lost salt production caused by shut-downs, but harvested fish may be sold for human consumption or other uses (e.g. bait). Commercial or indigenous harvesting (via gill nets) or recreational fishing targeting prized predatory species (e.g. *Epinephelus* spp., *El. hawaiiensis*, *Lutjanus argentimaculatus*) could be considered to reduce fish biomasses with minimal impact to the benthic structure of the CPs. Harvesting by local indigenous peoples may allow continued access to traditional areas now covered by the CPs, while commercial and recreational fishing may provide additional revenue to salt producers and the region. Further, the design of the CPs means that fishing opportunities are not limited by wind, weather or tidal conditions (as in boat- and land-based fishing) as land-based access is possible around all CPs at all times of the year.

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