Temperature, Dissolved Oxygen and Stratification in a Tropical Reservoir, Lake Tinaroo, Northern Queensland, Australia

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Abstract. Thermal and oxygen depth profiles in Lake Tinaroo were measured monthly at six sites over a two-year period from May 1988 to July 1990. Lake Tinaroo exhibits thermal layering throughout most of the year. Partitioning of the water column into an oxygenated epilimnion and a deoxygenated hypolimnion was well established by October each year. Breakdown of stratification occurred in late May to June and persisted until September. From October to May multiple thermoclines (diurnal, parent) developed, particularly during still weather. Localized disruption of stratification by oxygenated, cool, denser inflows during flood events in the catchment occurred during the rainy season. Thermocline tilting was noted after prolonged periods of south-easterly winds, with a deeper thermocline/oxycline at the north-western end of the lake. South-westerly winds had a corresponding effect on the north-east of the lake. The distribution of oxygenated water and deoxygenated water, affected by seasonal stratification, thermocline tilting, upwelling and flood-mediated disruption of stratification, is of importance to recreational fisheries and the location of water intake points for urban and domestic use. Lake Tinaroo has thermal characteristics of outer tropical rather than equatorial tropical lakes, owing in part to altitude effects.

Introduction

Studies on the limnology of outer tropical lakes are limited (Mackey 1991) and few tropical impoundments have been studied to date. A notable exception is the extensive study of Parakrama Samudra, Sri Lanka, in 1979–80 (Scheimer 1983). The thermal characteristics of temperate lakes and impoundments and some large equatorial lakes have been well studied (Ryanzhin 1989, 1990). The wet–dry tropics are characterized by a short rainy season and a long dry season when rainfall is minimal. The erratic rainfall pattern over much of Australia limits the applicability in Australia of international experience with issues such as eutrophication (Johnstone 1994). Physical limnology in tropical Australia has been little studied (De Deckker and Williams 1986), with the exception of the Alligator Rivers Region in the Northern Territory (e.g. Hart and McGregor 1980; Walker and Tyler 1984). Russell (1987) studied some aspects of the limnology of tropical impoundments and lakes in Queensland for suitability for recreational fisheries, finding Lake Tinaroo to be the only one of five lakes likely to support a viable recreational fishery. Finlayson *et al.* (1980, 1984) studied the hydrobiology of man-made lakes in north-western Queensland. These lakes are generally shallower than Lake Tinaroo, and smaller. Lake Moondarra was found to be a warm polymictic lake, owing to climatic influences such as rainstorms that induced partial mixis in much of the lake (Finlayson *et al.* 1980). However, the normal condition for Australian lakes is warm monomictic (Williams and Wan 1972). Knowledge of the behaviour of impoundments is important because of the influence of stratification on nutrient pathways, phytoplankton production, fisheries and water quality. Tinaroo Falls Dam, impounding Lake Tinaroo, was constructed in 1959 primarily for irrigation. The uses now include irrigation, provision of domestic water supplies for townships in the catchment and along the Barron River downstream, supply of water for hydroelectric power generation and, increasingly, recreational pursuits (e.g. boating, angling and water-skiing).

As a result of increased domestic and recreational demands, issues regarding water quality for domestic consumption, fisheries and health have arisen. A basic understanding of the thermal characteristics, as determined by local conditions, is essential for provision of potable water and economical water treatment. Recent large-scale blooms of cyanobacteria, particularly in southern Australia, have raised awareness of water quality problems associated with thermal structure and nutrient availability in waterbodies (Jones 1994). The prospect of Lake Tinaroo becoming eutrophic has prompted studies to identify and quantify nutrient inputs, assess the current trophic status of the lake, and elucidate nutrient pathways (Hlaing 1991; Littlemore *et al.* 1991). The present project forms an integral part of these studies. Apart from their bearing on water quality, the thermal characteristics and behaviour of the lake are important in the development and management of recreational fisheries developed through stocking programmes (MacKinnon and Cooper 1987), as fish

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distributions are markedly influenced by thermal structure and nutrient inflow patterns (Cadwallader and Lawrence 1990).

This paper presents the results of a two-year study concentrating on thermal regime and associated circulation and stratification patterns in Lake Tinaroo. Particularly, understanding of seasonal stratification and internal seiches is important in the development and implementation of appropriate management strategies.

Materials and Methods

Study Environment

Lake Tinaroo (17°10′S,145°35′E) is in the upper section of the Barron River catchment on the Atherton Tableland about 40 km south-west of Cairns, at an altitude of 670 m (Fig. 1). At full supply level (FSL) the storage holds 407 000 ML and covers an area of 3320 ha. Maximum depth is 41 m and mean depth 12·2 m. The storage exists mainly to supply irrigation and hydroelectric schemes, but it is also a major regional recreational resource and supplies domestic water for several townships. The 54 500-ha catchment includes a variety of vegetation and land-use categories: rainforest, sclerophyll forest, plantation forest, grazing, dairying, intensive agriculture, horticulture and the urban centres of Atherton, Yungaburra, Kairi and Tinaroo.

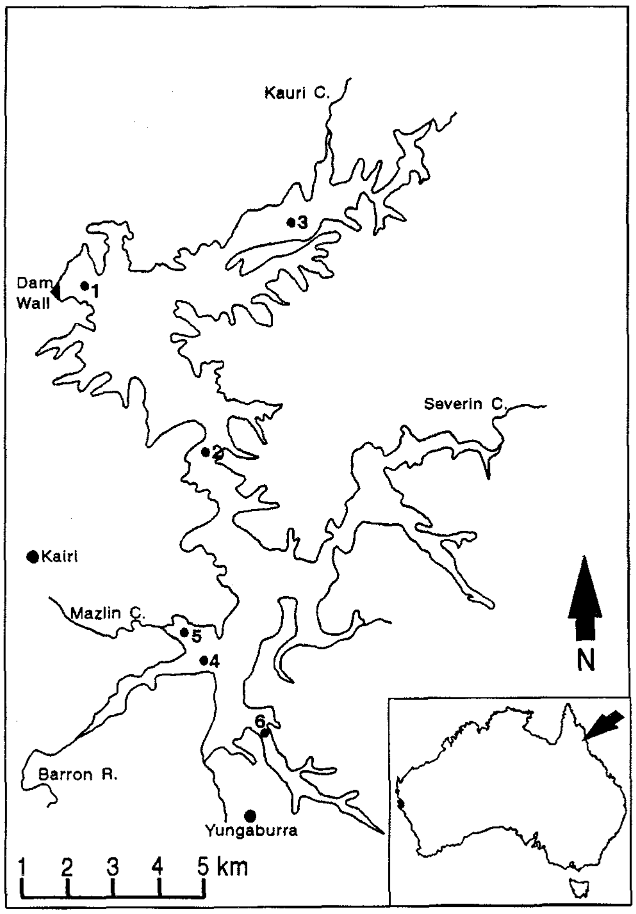

Fig. 1. Lake Tinaroo, showing sampling sites.

Climate

The Atherton Tableland has a monsoonal tropical climate with a well defined rainy season. Within this general pattern, local climates vary greatly owing to the diversity in altitude and topography (Tracey 1982). Weather data representative for Lake Tinaroo, collected from the Queensland Department of Primary Industries' Kairi Research Station adjacent to the lake, are plotted in Fig. 2. The longest axis of the lake is approximately parallel to prevailing south-easterly winds.

Sampling Sites

Locations of sampling sites are indicated in Fig. 1. Sites 1 and 2 were in deep open-water areas over the original course of the Barron River and were 40 m and 30 m deep, respectively, at FSL. Sites 3 and 4 were in major arms of the lake at intermediate depths (23 m and 22 m at FSL, respectively). Sites 5 and 6 were in shallow water near the entries of tributary streams, 16 m and 14 m deep at FSL, respectively. Site 5 was 200 m downstream of the point where the Mazlin Creek tributary entered the storage. Site 6 was located in the Wright's Creek arm at the southern end of the lake.

Sampling Procedures

Profiles of dissolved oxygen and temperature were measured monthly at all six sites from May 1988 to July 1990 with a calibrated YSI Model 54 ABP dissolved-oxygen meter. Supplementary profiles were made arbitrarily to clarify short-term changes. Sampling was carried out between 1000 and 1400 hours. Readings were taken at 1-m intervals from the surface to 10 m depth and at 2-m intervals from 10 m to the bottom of the water column. To ensure accuracy of temperature readings, surface (10 cm)

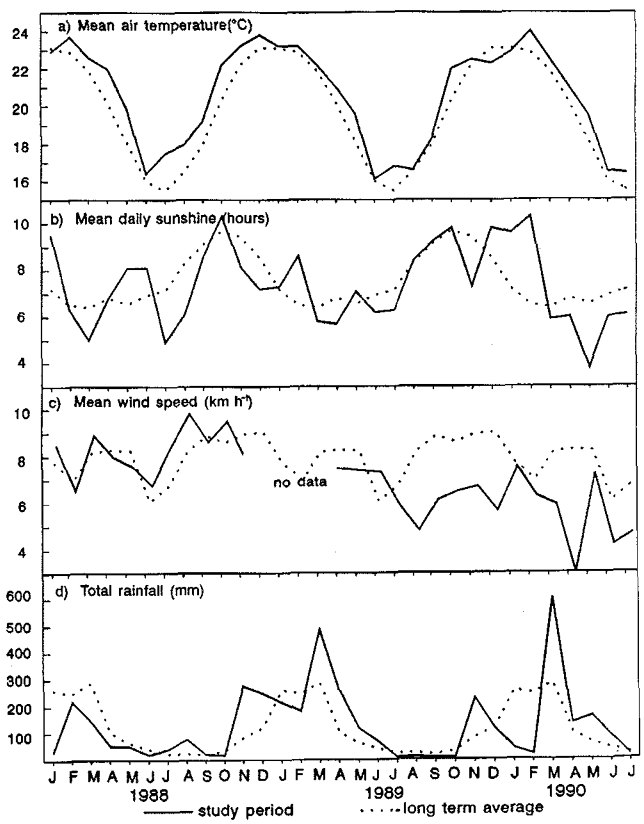

Fig. 2. Climate data from Kairi Research Station, 1988–90.

temperature values at each site were checked with a calibrated mercury thermometer. The temperature of water samples taken at 1 m above the bottom with a 3-L van Dorn sampler was measured with the mercury thermometer immediately on collection to confirm bottom temperature readings from the probe.

Results

Temperature Regime

In open-water sites, annual maxima of 29–30°C in the top 0.1 m of the water column were recorded early in both summers before the onset of the rainy season. Temperature variation in surface and bottom waters at Site 1 is shown in Fig. 3. Bottom water temperature was stable at 20–21°C from November to April and rose to a maximum of 21–22°C in late May or June when seasonal stratification first broke down to allow mixing throughout the water column. Bottom temperatures declined during the winter circulation period, reaching a minimum of around 19°C in late July to early August. Surface temperatures rose sharply between August and October and declined rapidly from March to May.

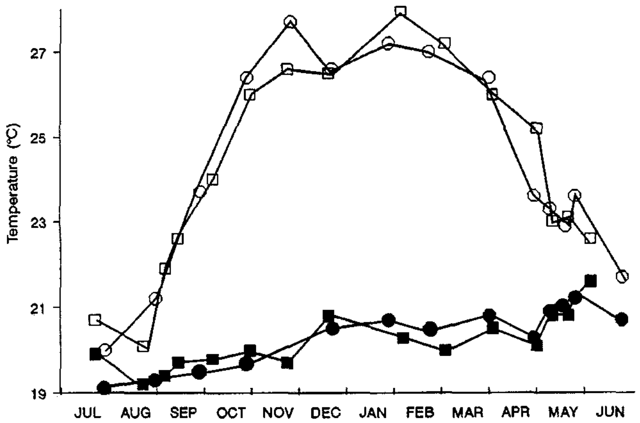

Fig. 3. Water temperatures at Site 1 over two years: (○) surface and (●) bottom, July 1988–June 1989; (□) surface and (■) bottom, July 1989–June 1990.

Stratification and Circulation Patterns

Profiles of temperature and dissolved oxygen at Site 1 show that the deeper parts of the lake were thermally stratified for much of the year, with a warm oxygenated surface layer (epilimnion) overlying a cooler, denser and deoxygenated hypolimnion (Fig. 4). For approximately three months during the coolest part of the year this strong stratification broke down and the entire water column mixed sufficiently to become well oxygenated throughout. During stratification the base of the epilimnion was often indicated more clearly by oxygen concentration than by temperature. Thermal gradients as small as 0·2°C m^{-1} sometimes marked boundaries between water masses with markedly differing oxygen concentrations. Stratification of the water column persisted in both years of the study until the temperature differential between surface and bottom waters was <2°C (May profiles, Fig. 4). In both years seasonal stratification developed during September in association with rising surface temperatures and was established by October. Partition of the water column into an epilimnion that remained responsive to heat flux at the surface and a hypolimnion with essentially constant temperature occurred rapidly (Fig. 5).

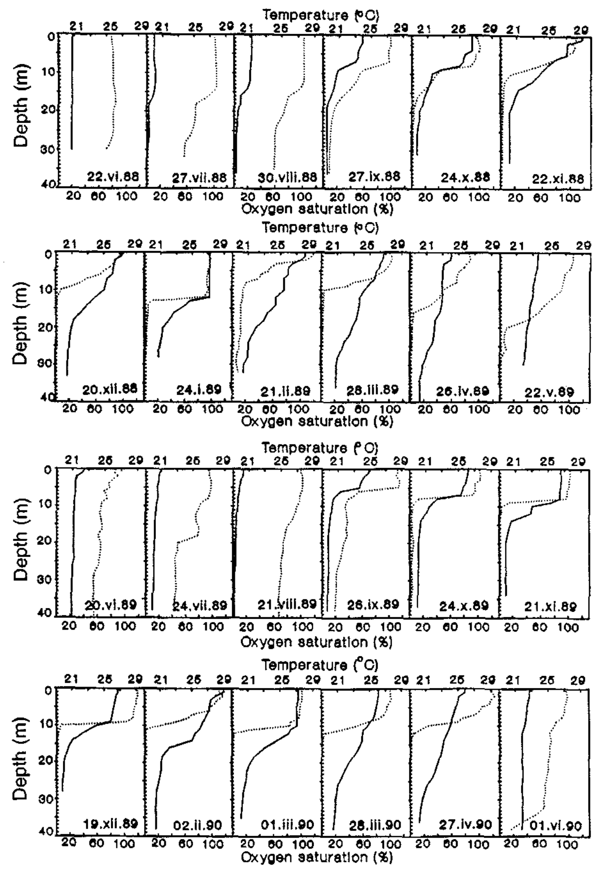

Fig. 4. Monthly profiles of (solid lines) temperature and (dotted lines) oxygen saturation at Site 1, 1988–90.

Seasonal Stratification at Shallower Sites and Effects of Flood Inflow

The seasonal stratification pattern described above for deep-water sites was modified at shallower sites. Summer flood runoff entering the storage had particularly marked effects on temperature and oxygen profiles at shallower sites (Fig. 6). In 1989–90 stratification was poorly developed until September, when hypolimnetic anoxia developed and bottom water temperatures remained relatively constant.

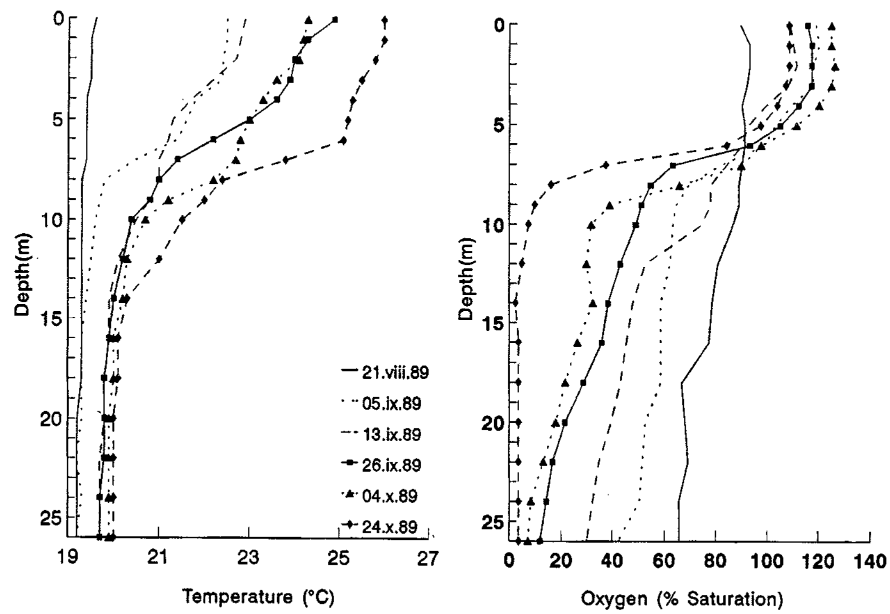

Fig. 5. Temperature and oxygen profiles showing development of stratification at Site 2, August–October 1989.

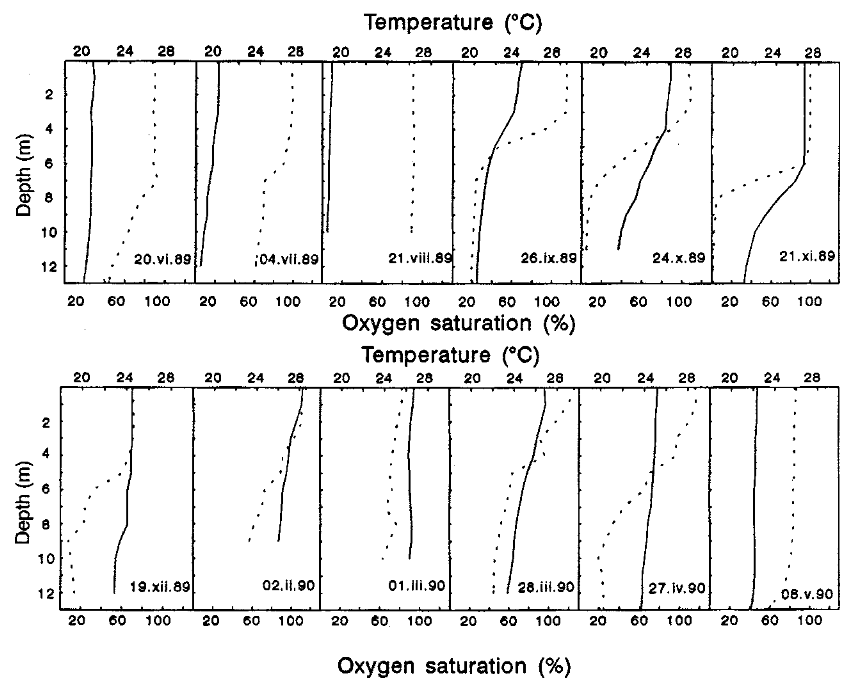

Fig. 6. Monthly profiles of (solid lines) temperature and (dotted lines) oxygen saturation at Site 6, 1989–90.

During this period stratification at Site 6 was apparently continuous. However, runoff from local thunderstorms in late December mixed the entire water column. For the rest of the rainy season stratification was weakly developed, with a relatively small vertical temperature differential and partially oxygenated conditions at the bottom.

Sites 3 and 4, of intermediate depth, also showed differing stratification patterns between the two summers (Fig. 7). During 1988–89, with the lake at low water levels, thermal structure was similar to that observed in shallow Sites 5 and 6 in 1989–90. Stratification persisted only until December, when increased inflows became visible in successive monthly profiles as a dense underflow, bringing oxygen to the hypolimnion (Fig. 7, 20.xii.88 to 26.iv.89). During 1989–90 stratification at Sites 3 and 4 was similar to that at deep Sites 1 and 2, with a true hypolimnion present for most of the summer. Major flood runoff in March–April 1990 disrupted stratification and oxygenated the entire water column. Seasonal thermal structure did not redevelop subsequently, though a distinct epilimnion remained as shown by the presence of a parent thermocline and associated oxygen discontinuity. Flood inflow that disrupted seasonal stratification at Sites 3 and 4 was detectable as a metalimnetic density current in deeper water at Site 2 but did not disrupt stratification. No effect on temperature or oxygen profiles at Site 1 was detected.

Progressive Changes during Seasonal Stratification

Though becoming less obvious and more variable in depth as summer progressed, discrete parent thermoclines were present in most temperature profiles (Fig. 4) and oxygen data show that they maintained a significant dampening effect on vertical mixing throughout this time. In contrast to the steadily increasing depth of the seasonal

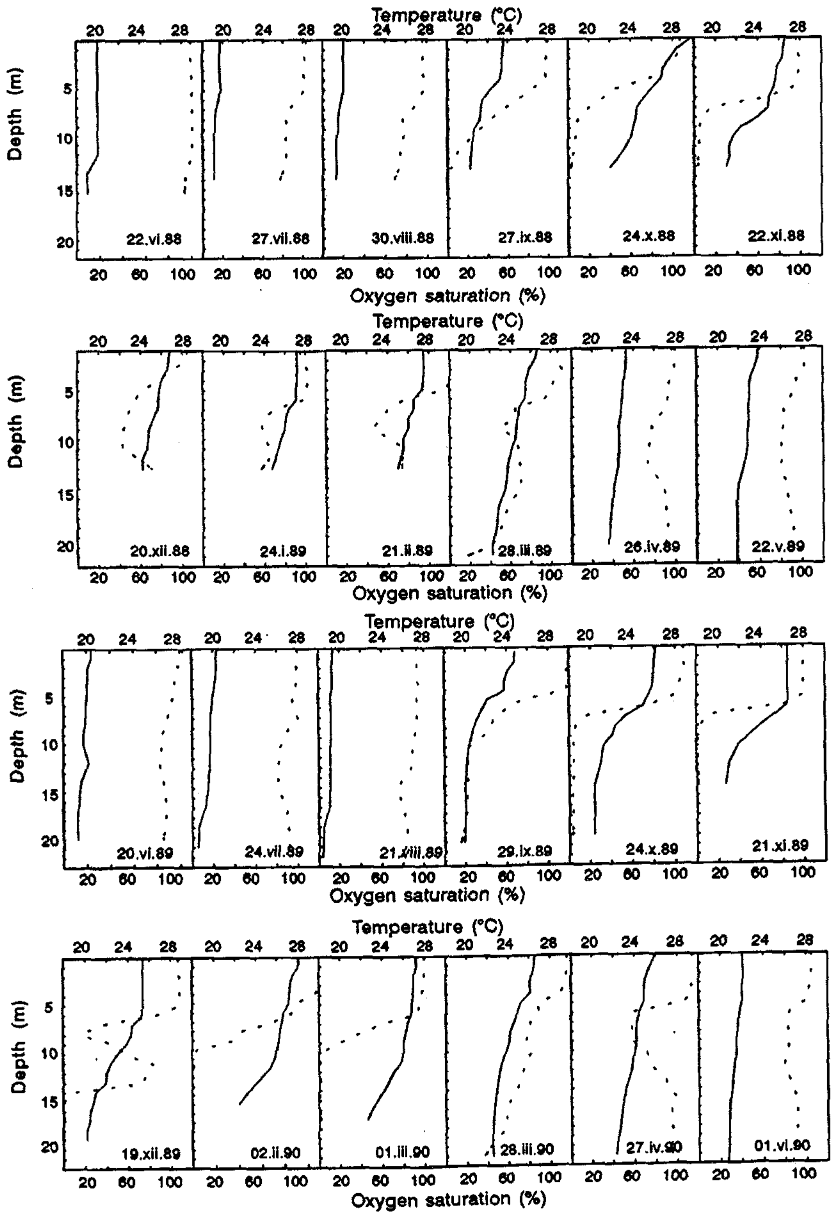

Fig. 7. Monthly profiles of (solid lines) temperature and (dotted lines) oxygen saturation at Site 4, 1988–90.

thermocline, there was no marked increase in average depth of parent thermoclines until just before seasonal overturn. During May, when the seasonal thermocline had deepened to reach the bottom of the lake, there was a rapid increase in depth of the surface mixed layer and a reduction in surface dissolved oxygen (Fig. 8) to annual minima. In the three winters of the study, surface mixing progressed to the bottom of the water column between the last week of May and the third week of June. Mean temperature of the water column at first turnover was around 21°C.

Most temporary deepening of the epilimnion was dampened by the seasonal thermocline. Such deepening occurred during a period of cool, windy weather before the December 1988 sampling (Figs 4 and 9), reflected in lowered epilimnion temperatures, multiple parent thermoclines and relatively low epilimnion oxygen saturation, but with no observed effect on the hypolimnion.

On one occasion, however, between the January and February samples in 1989, some mixing occurred throughout the water column, significantly deepening the seasonal thermocline and transporting oxygen to the bottom of the lake (Fig. 4). It is likely that a combination of weather phenomena brought about this partial mixing at around the end of January. At this time daily air temperatures and sunshine hours decreased to their lowest values in three months, presumably causing considerable loss of heat at the surface and creating ideal conditions for deepening of the mixed layer. At the same time a sustained period of moderate south-easterly winds that had caused marked tilting of the thermocline (Fig. 9) and thermocline sharpening (Lewis 1973) (Fig. 5) ended abruptly. Seiches and turbulence at layer boundaries almost certainly followed cessation of the sustained winds, and such movements combined with surface-layer deepening were probably responsible for considerable interchange of water between layers and 'smearing' (Lewis 1973) of the seasonal thermocline.

Horizontal Variability in Profiles

Fig. 10 shows surface temperature differentials between Sites 5 and 6. These sites were always sampled consecutively within a 30-min period before 1100 hours. Similar differentials existed between other sites, where sampling time was more variable. Surface water was warmer at Site 5 on all but one occasion when wind direction at 0900 hours was from the south-east or north-east quarters. On all dates when conditions were recorded as calm or westerly wind, the surface water was warmer at Site 6.

Thermocline Tilting and Upwelling

The data on both temperature and dissolved oxygen suggest that upwelling occurred several times during the study. Evidence for upwelling of cool deep water to the surface is clear in profiles for Site 6 on 19.xii.89 (Fig. 6). Tilting at the base of the epilimnion is illustrated in Fig. 9. During periods of south-easterly to easterly winds the oxycline was deeper at Site 1 than at upstream sites (Fig. 9). During periods of light winds (22.xi.88 and 02.ii.90) there was little difference between sites. South-westerly winds before 20.xii.88 moved surface water to the north-east at Site 3, whereas northerly and westerly winds before 21.ii.89 deepened the epilimnion at both Sites 2 and 3.

Inter-seasonal Differences in Stratification

Differences, apparent in Fig. 4, existed between the two stratification periods of the study. In the first summer, a

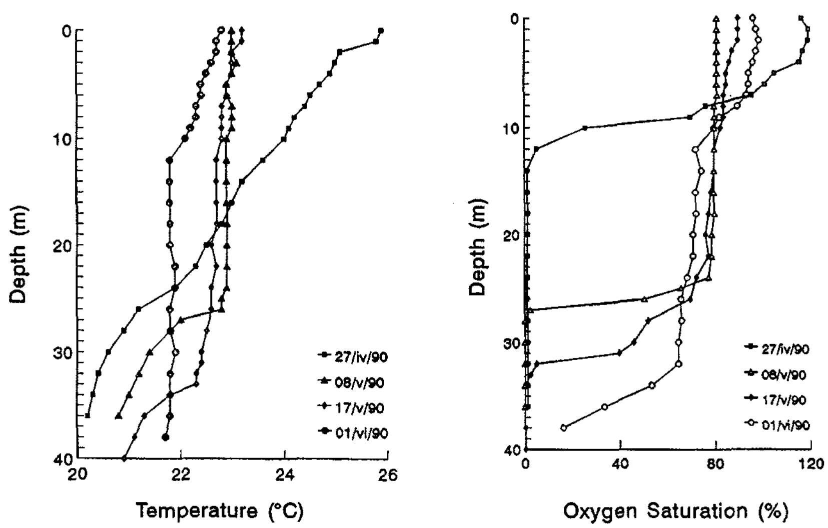

Fig. 8. Temperature and oxygen profiles showing progression to turnover at Site 1, April–June 1990. Oxygen saturation demonstrates turnover more distinctly than does temperature.

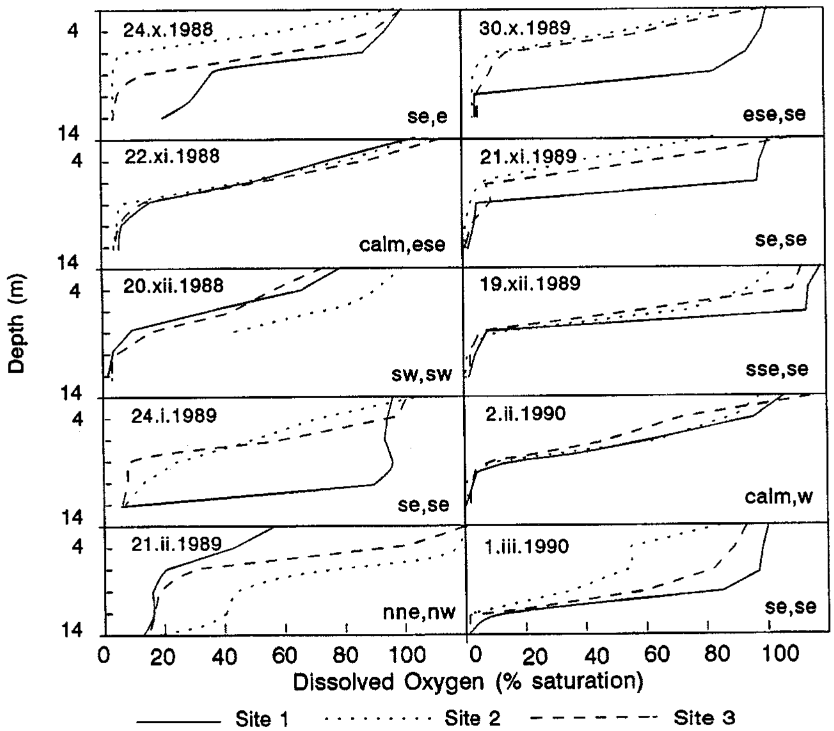

Fig. 9. Wind-induced seiches evidenced by oxycline tilting, dependent upon wind direction. Wind directions indicated were observed at Kairi Research Station on two days preceding sampling.

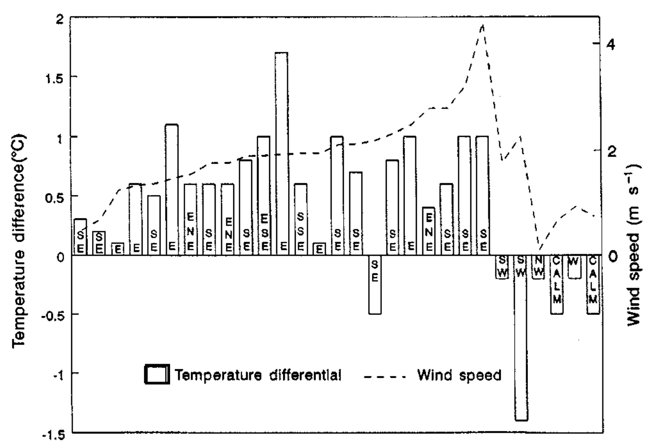

Fig. 10. Temperature differential (Site 5 minus Site 6) in relation to wind speed and direction.

broad metalimnion was present from October and thermal and oxygen gradients at the base of the epilimnion were generally less abrupt than in the following summer, suggesting more frequent surface-layer deepening in 1988–89. The parent thermocline was located at similar depths in both summers.

Winter Mixing Period

In the three cool seasons of the study, first turnover occurred between the last week of May and the third week of June, when mean temperature was 21–22°C. Rapid increase in mixing depth saw surface oxygen saturation reach annual minima at this time. Mixing of the entire water column continued for about three months until at least the end of August in both years of the study; however, mixing in the lower water column was sporadic and rarely thorough. Thus, most winter profiles showed a vertical temperature differential of about 1°C and oxygen saturation rarely exceeded 60% in bottom waters. The closest approach to thermal homogeneity occurred in early June 1988, when the temperature differential between 3 m depth and the bottom was 0·3°C and oxygen saturation at 30 m rose to 80%, the highest record at this depth. Weak stratification was evident in most oxygen profiles and some temperature profiles during the winter mixing period (Figs 4 and 5). Two distinct processes combined to produce this layering. During calm weather periods vertical mixing did not extend below 15–20 m and a weakly developed epilimnion was delimited by discontinuities in oxygen saturation. This weak stratification was destroyed during cool, windy weather.

Horizontal temperature differences were evident throughout the winter circulation period, with temperature

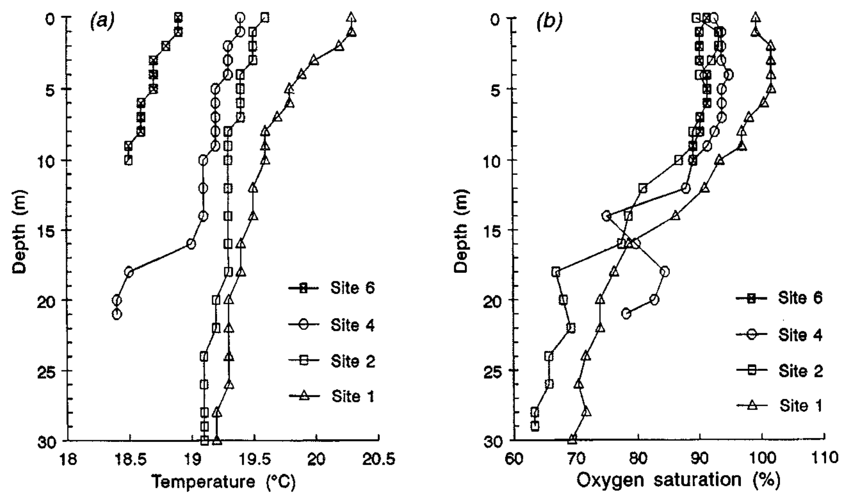

Fig. 11. Profiles of *(a)* temperature and *(b)* oxygen saturation for August 1989. Surface waters at upwind sites are cooler than those at downwind sites.

increasing from upstream to downstream sites (Fig. 11). Horizontal surface flow resulting from prevailing south-easterly winds (strongest during the daytime warming period), greater diurnal temperature variation in shallow waters, and gradual mixing of chilled bottom water during the process of downslope flow probably combined to produce these temperature gradients.

Dissolved Oxygen

Once seasonal stratification became established the hypolimnion rapidly deoxygenated (Figs 4 and 5). The upper part of the dissolved oxygen gradient remained closely associated with parent thermoclines throughout the stratification season, even when the latter were poorly developed in late summer (Fig. 7). Slight maxima in oxygen saturation often occurred 1–5 m below the surface. This was most evident early in seasonal stratification, when sunshine hours were longest. Oxygen saturation in the top 1 m (Fig. 12) followed a general seasonal pattern that was complicated by irregular periods of increased surface mixing.

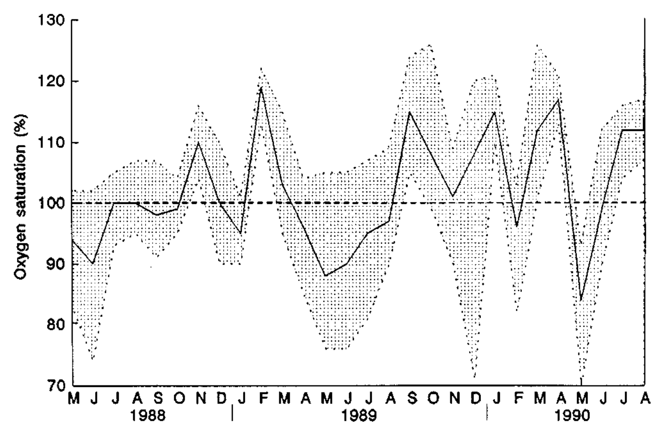

Fig. 12. Mean and monthly range of oxygen saturation at 0–1 m depth.

Discussion

Temperature Regime

Surface minima in July–August varied little (19·9–20·3°C) among the three winters of the study, agreeing with a minimum of approximately 20°C for lakes in the area indicated by Russell (1987). Surface temperatures ≤32°C have previously been recorded in shallow sheltered inlets of the lake (MacKinnon and Herbert, unpublished data), and the lowest surface temperature in the present study (18·9°C) was recorded at shallow Site 6. Differential heating, responsible for higher maxima at sheltered sites, was demonstrated by Bauer (1983) and Imberger (1985), and the lower minima result from radiative heat loss in shallow water.

Mathematical expressions linking lake temperatures to latitude and altitude are given by Straškraba (1980) and Lewis (1987). Lewis' equation for maximum temperature relates to a subsurface temperature representative of the entire surface mixed layer rather than temperature right at the surface, which is subject to considerable transient variation. In both summers of the study, maximum temperature of the upper mixed layer was close to the value obtained from Lewis' equations (Table 1). Mean air temperatures during mid-summer months of the study were within 1°C of 30-year averages and maximum water temperatures were probably also close to average. Minimum bottom water temperature predicted by Lewis' equations is also close to the minimum recorded in this study. However,

Table 1. Temperature predictions and actual recorded temperatures in Lake Tinaroo
Equations are from Lewis (1987). All temperatures are in °C. T_b, minimum bottom temperature; T_r, maximum vertical temperature range; T_m, maximum mixed-layer (epilimnion) temperature; ϕ', latitude; E, elevation (m)

Equations	Predicted temperature	Actual temperature
$T_b = 28{\cdot}9 - 0{\cdot}43\phi' - 0{\cdot}0038E$	$28{\cdot}9 - (0{\cdot}43 \times 17{\cdot}1) - (0{\cdot}0038 \times 670) = 19°$	18·4° (Sites 3 and 5)
$T_r = 0{\cdot}50\phi' - 0{\cdot}80$	$(0{\cdot}50 \times 17{\cdot}1) - 0{\cdot}8 = 7{\cdot}75°$	9·1° (Site 1)
$T_m = T_r + (28{\cdot}9 - 0{\cdot}43\phi')$	$7{\cdot}75 + 21{\cdot}547 = 29{\cdot}3°$	30·0° (Site 3)

the equation for annual vertical temperature range was not as good a predictor of conditions in Lake Tinaroo.

Most recent field studies on thermal structure of tropical lakes have been carried out within a few degrees of the equator (e.g. Antwi and Ofori-Danson 1993; Vyverman 1994). Some of these studies do not emphasize the close proximity to the equator. Distinctive thermal characteristics such as frequent and substantial variations in depth of the surface mixed layer are often referred to as typical of 'tropical' rather than 'equatorial' lakes. Parameters of thermal structure change rapidly very near the equator (Straškraba 1980; Lewis 1987) and in some important respects stratification in lakes of the outer tropics should resemble that of mid-latitude lakes rather than equatorial lakes. Latitudinal changes in seasonality interact with temperature–density effects to produce stratification stability in marginally tropical lakes that is greater than in equatorial lakes of equivalent depth but little different from that of temperate lakes. The distinction in thermal structure between equatorial and marginally tropical lakes is particularly relevant in Australia, which lies well south of the equator and barely approaches the equatorial zone but which has most of its land mass within warm temperate and outer tropical latitudes. Data from Lake Tinaroo suggest that stratification characteristics of some outer tropical lakes more closely resemble those of warm temperate lakes than of equatorial lakes. Though Lake Tinaroo is well inside the Tropic of Capricorn, altitudinal effects produce a temperature regime similar to that of low-altitude lakes nearer to the tropic. Stratification characteristics of Lake Tinaroo are likely to be representative of outer tropical lakes worldwide and lakes throughout central Queensland.

Stratification and Circulation Patterns

Lake Tinaroo conforms to the warm monomictic category of Hutchinson (1967), as do several other Queensland lakes of similar mean depth (Timms and Midgley 1969; King and Everson 1978; Russell 1987). Duration of seasonal stratification (September–May) approximates that of lakes at similar latitudes in northern Queensland (Hawkins 1985; Russell 1987), Africa (Talling 1969; Marshall and Falconer 1973*a*; Payne 1986) and South America (Barbosa and Tundisi 1989). The fundamental monomictic pattern in the lake was complicated by non-seasonal partial mixing (shown by temporary increase in hypolimnetic oxygen saturation in February 1989, Fig. 4) and by intermittent weak stratification during the winter mixing period. The tendency to remain stratified at small temperature differentials is characteristic of deep (>5 m) tropical lakes (e.g. Beadle 1981; Melack and Fisher 1983; Lewis 1987; Vyverman 1994) owing to increased change in density at higher water temperatures (Bauer 1983). The warm monomictic category for Lake Tinaroo is in disagreement with the arrangement of Northern Hemisphere thermal lake classes of Ryanzhin (1994), whereby Lake Tinaroo would be classified as warm polymictic on the basis of altitude and latitude. However, shallower sites did demonstrate a warm polymictic pattern of stratification owing to seasonal rainfall influences (see below). Williams and Wan (1972) believed that warm monomictic is the normal condition for Australian lakes, and the findings of the present study support this.

Variation in surface heat flux and/or increased wind action led to occasional short-term deepening of the mixed layer beyond the usual depth range of the parent thermocline (the 'atelomixis' of Lewis 1973) and left relic thermoclines that persisted after a new parent thermocline had become re-established at a shallower depth (e.g. profiles for 21.xi.89, Fig. 4). These remnant thermoclines, analogous to the 'squall thermoclines' of Lewis (1973), gradually lost individual definition through internal mixing processes (Imberger 1985), but their cumulative effect created a metalimnion (transition zone between the well mixed epilimnion and the stagnant hypolimnion). The metalimnion contained a broad thermocline (the 'seasonal thermocline' of Imberger 1985) that is comparable to the 'storm thermocline' of Lewis (1973). Parent thermoclines are analogous to the 'breeze thermoclines' recognized by Lewis (1973) in Lake Lanao, but in Lake Tinaroo they were generally more strongly established and not easily displaced by minor daily variations in wind action. Their relatively constant position in Lake Tinaroo reflects the greater vertical temperature differential, which gives greater stability and proportionally less stability change in response to a given heat loss.

Seasonal Stratification at Shallower Sites and Effects of Flood Inflow

Density currents are a common feature in both smaller lakes (Marshall and Falconer 1973*a*; Orr 1983; Hawkins

1985) and larger lakes (Begg 1970). Atypical rainy-season oxygen profiles reported for the Koombooloomba Dam impoundment (near Lake Tinaroo) (Russell 1987) almost certainly indicate intruding density currents. Data from Sites 3 and 4 suggest that major tributary arms of medium depth in Lake Tinaroo conform to the discontinuous warm polymictic category in the revised classification of Lewis (1983). At least two other tropical Queensland lakes of similar depth appear to be discontinuously polymictic owing to summer flooding (Finlayson *et al.* 1980; Finlayson and Gillies 1982). Flood runoff does not necessarily break down stratification (and may intensify thermal stratification) but does result in oxygen profiles atypical of stratified lakes.

Progressive Changes during Seasonal Stratification

Over the course of seasonal stratification in Lake Tinaroo the metalimnion gradually thickened through internal mixing processes. In Lake Calado (Brazil) density gradients damped wind mixing in early summer, but similar wind speeds in late summer resulted in greater mixing (MacIntyre and Melack 1988). Similarly, in Lake Tinaroo a general weakening of the development of the parent thermocline and thickening of the oxycline suggested that surface-layer deepening became more frequent during the course of stratification. Both gradual warming of the metalimnion throughout the stratification period and cooling of the surface layer owing to seasonal changes in surface heat flux in late summer contributed to loss of definition of parent thermoclines. As parent thermoclines became progressively less well defined the seasonal thermocline became the most obvious thermal discontinuity and moved deeper, slowly at first and more rapidly later in the stratification period as the frequency of mixed-layer deepening events increased. Gradual deepening of the main thermal discontinuity during seasonal stratification is well known in both tropical lakes (Harding 1964; Talling 1969; Begg 1970; Marshall and Falconer 1973*b*) and temperate lakes.

The combination of weather parameters leading to partial breakdown of stratification in January–February 1989 was somewhat unusual. However, the lake is occasionally subject to weather extremes caused by tropical cyclones and its response to weather anomalies observed in this study suggests that heavy cyclonic weather may result in holomixis.

Horizontal Variability in Profiles

Surface temperature variations of up to 2°C among sites on the one day were common. Because of the time lag between measurements the possible influence of diurnal warming on these variations cannot be discounted but was probably slight as no trends related to sampling order were noted and sometimes the earliest readings were higher. Wind-induced surface currents were probably the prime cause of horizontal differentials. The data suggest a relationship between wind speed and the size of the differential when winds were below about 2 m s^{-1}. No such relationship is apparent at greater wind speeds, possibly because increased vertical mixing by wave action disrupts the laminar surface flow.

Thermocline Tilting and Upwelling

Accumulation of wind-driven surface water at the downwind end of the lake caused downward displacement of the parent thermocline in this area and compensatory displacement of the hypolimnion. This led to thermocline tilting and occasional upwelling of hypolimnetic water in upwind areas, as observed in previous studies (Talling 1969; Eccles 1974; Green *et al.* 1976). This has implications in the siting of water intakes for urban centres, because of the odours and tastes associated with anaerobic water. Sites in the southerly areas of the lake currently have problems of this nature with water supplies, possibly owing to upwelling. Water intakes sited at the northerly end of the lake might be less likely to experience these problems. However, scums resulting from cyanobacterial blooms, should they occur, would tend to accumulate in the downwind regions.

Inter-seasonal Differences in Stratification

The most likely cause of the differences among years was large-scale variation in weather patterns. Mean wind speed at Kairi Research Station (Fig. 2*c*) during the final months of 1988 equalled or exceeded long-term average speed (wind data for the later part of this summer were unavailable), whereas during the following summer wind speed was generally below average. This is consistent with the observed occurrence of a La Niña event (high Southern Oscillation Index values and trade winds stronger than average) during late 1988 and an El Niño pattern (low SOI values and light winds) during 1989–90 (D. Gaffney, National Climate Centre, personal communication).

Winter Mixing Period

A minor fish kill observed in June 1988 may have been caused by partial deoxygenation of surface waters and/or upwards transport of toxic compounds such as H_2S formed in the anaerobic hypolimnion. Fish kills resulting from rapid destratification have been noted in other tropical lakes (Green *et al.* 1976; Beadle 1981; Vyverman 1994). Annual minimum bottom temperatures at deep-water sites in Lake Tinaroo at times of winter mixing were appreciably below those on the surface at the same sites (Fig. 3). This cannot be explained in terms of wind-induced surface mixing, and the lower bottom temperatures probably resulted from downslope flow of cold water from tributaries and/or surface water chilled at night in shallow marginal areas where radiative heat loss caused greater temperature change. A dense bottom layer formed by such downslope flow has been demonstrated in large African lakes by Talling (1963, 1969) and Eccles (1974). Increases in dissolved oxygen towards the bottom of winter profiles at Site 4 support the hypothesis that formation of a colder bottom layer is due to inflow of cold, oxygenated water forming a density current at the bottom of the lake.

Dissolved Oxygen

Supersaturation (>100%) occurred at most sites early in seasonal stratification, presumably because increasing temperature, sunshine duration and nutrient concentrations following winter circulation stimulated photosynthesis. An analogous spring peak in primary production is well known in temperate lakes. Saturation levels then tended to fall over the mid-summer months, probably because loss of nutrients to the hypolimnion and reduced sunshine duration limited photosynthesis (Littlemore *et al.* 1991 reported higher nutrient concentrations in deeper water in Lake Tinaroo). This apparent trend was masked to a large extent by irregular increases in mixing depth returning nutrient-rich water to the surface layer and stimulating photosynthesis. The non-seasonal partial mixing event in early 1989, for instance, resulted in a marked increase in oxygen saturation. Saturation levels increased again in March–April, probably owing to increased frequency of mixed-layer deepening returning nutrients. This was followed by a rapid decline of oxygen saturation to annual minima as seasonal turnover brought large amounts of deoxygenated water to the surface, which may have diluted the phytoplankton in the euphotic zone. Opinions vary as to whether hypolimnetic deoxygenation occurs primarily through uptake at the mud–water interface or uptake in the water column (Westlake 1980). In Lake Tinaroo oxygen concentration declined at a similar rates at all depths below the parent thermocline, suggesting that uptake in the water column was at least as great as that at the bottom. The oxycline was very compact during early summer, reflecting the effective dampening of vertical mixing during this period of rapid heat gain. Gradients of up to 6·7 mg O_2 L^{-1} m^{-1} (or >90% saturation) were exhibited at this time. Surface oxygen saturation and surface temperatures at Site 6 were markedly lower than at other sites in profiles for December 1988, January and December 1989, and February 1990. This suggests upwelling at the southern end of the lake at these times. Nutrient analysis of surface and bottom water samples taken concurrently with monthly temperature and oxygen profiles provide supporting evidence for events outlined above (Littlemore *et al.* 1991).

The extent and persistence of oxygen supersaturation in surface waters has also been used to assess trophic status. In tropical lakes photosynthesis and nutrient recycling in surface waters is rapid and slight supersaturation is not unusual, but sustained high supersaturation can indicate eutrophy. Hawkins (1985) found that surface oxygen saturation levels >120% were common in the Solomon Dam impoundment, northern Queensland (20°S), and Marshall and Falconer (1973*a*, 1973*b*) found persistent surface supersaturation of up to 180% in an African lake at the same latitude as Lake Tinaroo. Both of these lakes were prone to nuisance blooms of algae and clearly eutrophic. Saturation levels exceeding 120% were only occasionally recorded in Lake Tinaroo, mainly at the start and end of seasonal stratification and usually at only a few sampling sites at any one time. This suggests a mesotrophic rather than eutrophic state.

Hypolimnetic anoxia *per se* is not a meaningful indicator of trophic status in tropical lakes where high water temperatures can cause hypolimnetic anoxia even in oligotrophic lakes. However, the rate of depletion of dissolved oxygen during stratification can indicate lake trophic status (Hutchinson 1967) because the rate at which oxygen is consumed by decomposers is greatly influenced by the rate of primary production (and by the volume of the hypolimnion relative to the euphotic zone) (Payne 1986). In Lake Tinaroo the oxygen depletion rate or areal hypolimnetic oxygen deficit (AHOD) was estimated at around 1300 mg O_2 m^{-2} day^{-1} in early summer (MacKinnon and Herbert, unpublished results). The data of Cornett and Rigler (1980) and modelling by Lewis (1987) suggest that lakes of similar depth to Lake Tinaroo at higher latitudes (hypolimnetic temperatures around 4°C) would have average AHOD values of around 500 mg O_2 m^{-2} day^{-1}. Values calculated for Lake Tinaroo would thus indicate eutrophy in a cool temperate lake, but when allowance for higher hypolimnetic temperature (20°C) is made on the assumption that Q_{10} for decomposer activity is $\geqslant$2·0, the AHOD values for Lake Tinaroo suggest a mesotrophic state.

Characteristics of dissolved oxygen in the lake indicate that the storage is mesotrophic with a tendency to eutrophy. The inevitability of population increases in the catchment clearly indicates a need for careful control of nutrient inputs. Modelling of nutrient flows in the catchment and development of decision support systems is directed towards control of water quality in the lake (Gourley *et al.* in press).

General Discussion

The effects of latitude on stability are reflected in the extent and frequency of mixed-layer deepening and in the complexity of thermal structure in the epilimnion. The 8°C vertical differential in Lake Tinaroo dampens surface mixing much more effectively than does the 2°C range over a similar depth in Lake Valencia, Venezuela, at 10°N (Lewis 1983). Variation of epilimnion depth from 5 to 12 m in Lake Tinaroo during seasonal stratification is less than the variation of 5 to 30 m in Lake Valencia. In Lake Tinaroo on most occasions only one persistent parent thermocline was discernible at the base of the mixed layer and its relatively constant depth resulted in a close relationship with the oxycline. In equatorial lakes with greater frequency and vertical extent of mixed-layer deepening, relic parent thermoclines are more common and the relationship of the parent thermocline to the oxycline is often far less evident. The presence of persistent multiple parent thermoclines distinct from the seasonal thermocline is not generally reported for temperate lakes, which usually have a single persistent thermocline. However, Imberger (1985) reported a well developed parent thermocline in Canning Reservoir, Western Australia (32°S), showing that such thermoclines are not solely a tropical feature. The (sometimes) small temperature differentials that mark parent thermoclines may have led to their being overlooked in some studies and may have contributed to uncertainty regarding the precise relationship between thermal and oxygen stratification. Mackey (1991), for instance, found difficulty in determining the depth of the surface mixed layer of a lagoon in central Queensland and stated that maximum oxygen and temperature gradients occurred at different depths. The profiles presented by Mackey (1991) suggest that the upper part of the oxycline was often associated with a small thermal discontinuity that was probably a parent thermocline. Progressive development and deepening of the seasonal thermocline out of direct contact with surface mixing phenomena show that internal turbulence phenomena not directly examined in Lake Tinaroo are important to the overall structure of the water column and may have an important bearing on nutrient transport.

Relationships between the oxygen and temperature patterns shown in this study and other parameters sampled on the same monthly schedule (nutrient and chlorophyll *a* analyses, and Secchi disk readings) are somewhat unclear. The rapid uptake and efficient cycling of nutrients at high water temperatures means that the monthly sampling regime was not appropriate for monitoring biological and chemical responses to transient events such as mixed-layer deepening, or upwelling in marginal areas. Nevertheless, the general relationship between surface-layer deepening events and oxygen saturation in surface waters suggested that such events subsequently stimulated photosynthetic oxygen production. Some surface samples taken during windy periods with sharpening of the parent thermocline and active erosion of the metalimnion had elevated phosphate concentrations (MacKinnon and Herbert, unpublished data). Understanding the effects of these events upon water quality will be necessary for consideration of siting of water intakes for domestic use. Closer study of nutrient cycling and entry into the lake will be required to limit deleterious effects on water quality due to algal blooms.

Thermal structure has important effects on the distribution and abundance of fish. During stratification fish are effectively confined to the surface mixed layer by oxygen requirements. Thermocline tilting, upwelling and probable seiche action complicate the situation and habitable parts of the lake bottom probably change over periods of hours to days. Fish distribution, particularly of territorial demersal species such as sleepy cod (*Oxyeleotris lineolatus*), would undoubtedly be sensitive to such changes. Thermocline tilting/upwelling events probably also affect movements of more mobile mid-water species such as barramundi (*Lates calcarifer*) and sooty grunter (*Hephaestus fuliginosus*), which are stocked in Lake Tinaroo (MacKinnon and Cooper 1987). Horizontal temperature gradients in surface waters may also direct fish movements towards preferred temperature areas. The distribution of macquarie perch in Lake Dartmouth, Victoria, is influenced by the temperature of inflow water (Cadwallader and Lawrence 1990). Research on behavioural responses of fish to the thermal and oxygen structure of lakes could enhance angler catches and improve the cost-effectiveness of stocking programmes, particularly in the case of barramundi, which are prized by anglers but expensive to stock and difficult to catch in Lake Tinaroo.

Acknowledgments

We thank Peter Cooper, Paul Clayton and Dave Bull for field assistance. Water Resources Commission, Mareeba, provided the oxygen meter. Thanks go to John Russell, L. Cogle, R. Pearson and D. Griffiths for comments and criticisms of the manuscript. This project was funded by the National Landcare Program and the Queensland Department of Primary Industries.

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Manuscript received 4 December 1995; revised and accepted 2 April 1996