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THE DEVELOPMENT OF TEMPERATURE STRATIFICATION IN FRESHWATER WETLANDS

Michael Waters[1,2] and David A Luketina[1]

1. Water Research Laboratory, School of Civil and Environmental Engineering
University of New South Wales, Manly Vale, NSW, AUSTRALIA

2. Current address, Manly Hydraulics Laboratory, Department of Public Works and Services,
Manly Vale, NSW 2093, AUSTRALIA

ABSTRACT

Temperature measurements were conducted in a small wetland to determine the extent of vertical and lateral stratification in vegetated and open water areas. Isolated thermistors were used on a long term basis to determine the seasonality of the temperature structure of the wetland. Distinct summer and winter patterns of vertical and lateral stratification were observed. During summer, lateral stratifications lasted over many days and were at times quite strong, up to 4°C between the open water and the wetland. During winter stratifications still occurred, however, these were generally only diurnal and were relatively weak. A temperature microprofiler was used to determine the temperature structure of the wetland in detail for a period of one week. Profiles obtained were not consistent with predictions from theoretic calculations. Differences between observed and theoretic profiles most likely arose due to horizontal convection.

INTRODUCTION

Hydrodynamic processes in a wetland play an important role in regulating chemical, biological and geomorphic processes in wetlands, yet they have received little attention to date (Roig, 1994).

Should buoyantly stable stratification occur within a wetland, this may drastically affect hydrodynamics, especially by inhibiting mixing in the vertical. In freshwater wetlands, temperature is expected to be the main mechanism by which buoyantly stable stratification would occur.

This paper relates the techniques used and results obtained for a series of experiments carried out in a wetland consisting of the emergent macrophyte *Typha orientalis* in a sidearm of Manly Dam, Sydney, whereby significant, buoyantly stable temperature stratifications were observed to occur.

BACKGROUND

Dale and Gillespie (1977) found that stratification in the water column in the presence of wetland vegetation can be significantly greater than in water without vegetation. According to their study, temperature differences of up to 3°C occurred in beds of the submergent macrophyte *Potamogeton richardsonii* within 600 mm of the water surface under average radiation loadings of 870 Wm^{-2} over 7 hours. Under the same conditions, no significant temperature difference developed in an open water container. In these experiments, the temperature structure of the water was primarily affected by:

- Plant matter above the water surface intercepting radiation (the plant canopy) hence reducing the depth averaged temperature in the water column; and
- Plant matter below the water surface preventing light penetrating deeper into the water column, causing temperature stratifications to develop that were higher than in the unvegetated containers.

In wetlands containing the emergent macrophytes *Typha orientalis* and *Schoenoplectus validus*, Waters and Luketina (1995) found that these mechanisms were valid. The plant canopy was also found to inhibit the heat and momentum transfer at the air-water interface by reducing the wind speed immediately above the water surface.

To investigate these factors in detail, a series of experiments were undertaken in a small wetland in a sidearm of Manly Dam. The wetland examined was located in a drowned creek bed to the North of the dam. Figure 1 shows a plan of the site.

The wetland is approximately 250 m^2 in area. The average depth of water in the wetland is approximately 1.0 m. The site is directly connected to the main impoundment of the lake and consists of two distinct regions: a large region dominated by the emergent macrophyte *Typha orientalis*, and a small open water region that is separated from the lake by the *Typha*, as shown in Figure 1.

Experiments were conducted in two phases, long term monitoring, and intensive monitoring. The techniques used for these two phases of monitoring are described separately below.

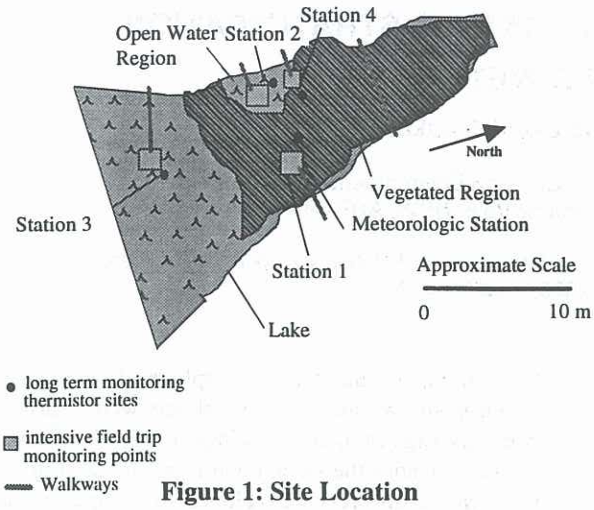

Figure 1: Site Location

LONG TERM EXPERIMENTS

Long term monitoring equipment used at the two sites consisted of: a meteorologic station recording rainfall, wind speed and direction, air temperature, relative humidity and solar radiation; 14 thermistors for recording temperatures within the water and two in air below the plant canopy; and a water level recorder

The thermistors were accurate to approximately 0.01°C. Details of equipment deployment, specifications, calibration and data reduction are given in Waters (1997). Throughout the long term monitoring, readings were taken from all instruments on an hourly basis.

Thermistors were deployed in four assemblies, as listed in Table 1. A number of thermistors were attached to floats so they remained a fixed distance below the water surface. The remaining thermistors were deployed at fixed depths above the bed.

Two assemblies were deployed in the *Typha*, these were designated as Stations 1 and 4, as shown in Table 1. One assembly was deployed in the sheltered open water section, designated as Station 2 and the remaining assembly was deployed in the shallows of the lake side arm, approximately 4 m from the vegetation, designated as Station 3.

This pattern of deployment was chosen to:

- determine the influence of the lake dynamics on stratification and mixing in the wetland;
- investigate differences between stratification and mixing in the vegetated and unvegetated areas;
- assess the variability of stratification and mixing within a monocultural stand of emergent macrophytes.

Vertical Stratification

Figure 2 shows the degree of stratification observed through the water column from 100 mm below the water surface to 100 mm above the bed. Significant features that can be observed from Figure 3 are summarised below.

- Temperature differences of up to 10°C can occur over the depth of the wetland, despite its shallowness (approximately 1 m deep).
- Stratification often lasts significantly longer than a diurnal cycle. This is especially so through the summer months from late September to March. The longest lived of these stratifications occur at Station 4, where through January the stratification was maintained continuously for over half the month.
- The highest stratifications developed at Station 4 (vegetated station furthest from the lake), then stations 1 (vegetated close to the lake) and 2 (isolated open water area), while the lowest stratifications occur at Station 3 (in the lake).

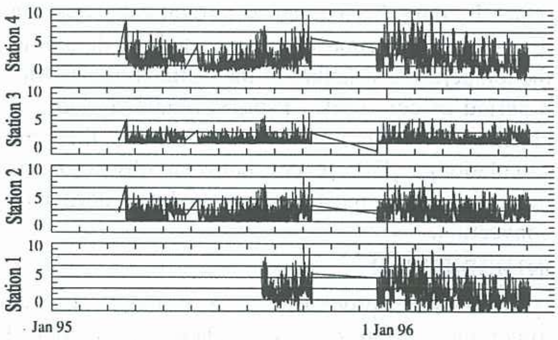

Figure 2: Vertical Temperature Differences

Negative stratifications occur on occasion at Station 4, especially through the winter months from April to August, but occasionally through summer as well. These stratifications were observed to last through the diurnal cycle, especially from April to June. Neither the length of time for which negative stratifications occurred, nor the magnitude of these stratifications were as large as for the positive stratifications.

Note that similar temperature inversions were observed in the temperature profiles taken during the intensive field investigations (Waters, 1997). These temperature inversions most likely arose due to penetrative convection and saline groundwater inflows.

Summer Pattern

Throughout the summer (December to February), Figure 3 reveals the following:

- Depth averaged temperatures at Stations 1, 2 and 4 in the wetland were generally colder than at

Station 3 in the lake, typically by 1 to 4°C.

- Lateral depth averaged temperature differences to Station 3 were higher further from the lake at Station 4, than closer to the lake at Stations 1 and 2.
- Periods of many weeks at a time could pass where the water in the vegetation (Stations 1 and 4) continuously remained colder than the water in the lake (Station 3).

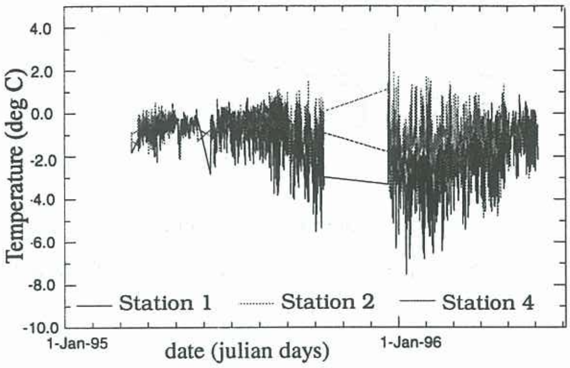

Figure 3: Lateral Temperature Differences to Station 3 at Stations 1, 2 and 4

Winter Pattern

During winter (June to August) Figure 3 reveals the following.

- Depth averaged temperatures at Stations 1, 2 and 4 were generally lower than at Station 3, typically by 0.2 to 0.5°C. This is considerably weaker than the temperature differences of between 1 and 5°C reported above for the summer conditions.
- As for the summer conditions, lateral depth averaged temperature differences to Station 3 were highest in magnitude at Station 4, then at Station 1, then Station 2.
- Water in the lake (Station 3) was often colder than water at Stations 1, 2 and 4, but only for very brief intervals. These colder conditions at Station 3 generally occurred by night. This provides a contrast with the summer conditions where the water in the lake rarely became colder than the water in the vegetated areas (Stations 1 and 4).
- By contrast with the summer conditions the water in the vegetation (Stations 1 and 4) did not remain continuously colder than the water in the lake (Station 3) for periods of more than one week.

Quite clearly considerably stronger density gradients occur during summer than winter.

INTENSIVE INVESTIGATIONS

A one week period of intensive monitoring was carried out at the wetland in February 1995 to determine temperature profiles over the full depth of the water column and the changes that would occur in profiles with diurnal changes in meteorologic parameters.

Temperature profiles were obtained using an fp07 fast response thermistor by allowing the probe to freefall through the water column. Profiles were taken at each site every 60 to 90 minutes.

Solar radiation during this period was high and winds were low.

Temperature Profile Estimation

The development of temperature profiles with time due to solar radiation is described by Beer's law as:

$$T_{E2} = T_{R1} + \frac{\tau\phi\eta t}{\rho C_p} e^{\eta z} \qquad 1$$

where T_{E2} is the estimated temperature at the time of the second reading, T_{R1} is the first recorded temperature, τ is the transmission coefficient, which accounts for canopy absorption and surface reflection; ϕ is the incoming solar radiation, η is the coefficient of extinction, t is the time between the two readings, ρ is the water density, C_p is the specific heat of water and z is the distance from the water surface (positive upwards). τ and η were used as calibration coefficients, allowing matching between the T_{E2} and T_{R2} profiles.

For the open water stations (2 and 3), reflection is less than 10 % while light is at an angle of incidence of less than 45° (Hecht, 1987), hence τ was set at its lower limit value of 0.9.

The calculated τ values used at the vegetated Stations (1 and 4) were based on canopy radiation profiles taken by Waters (1997) which revealed that approximately 60% of light is transmitted through the canopy during the middle of the day. Large variations in τ must be expected, due to the heterogeneous nature of the canopy, so it is of no surprise that solar radiation entering the water column at Station 1 is 30% lower than at Station 4.

Adjusting τ caused the depth averaged temperature to be changed, but only had a small effect on the temperature gradient. η caused the temperature gradient to be changed, but did not drastically change the depth averaged temperature.

Fitting was done primarily by ensuring the estimated and recorded profiles were in agreement in the lower part of the water column, where the effects of turbulence and latent heat on the profiles would be minimal. These profiles are shown in Figures 5a to 5d. Estimates of η and τ obtained are shown, as is the average solar radiation loading that was measured over the period.

Figure 5c, at Station 3 shows that while the general form of the profiles are in agreement, the estimated profile significantly exceeds the recorded temperature over the whole depth of the profile. In this case it was difficult to match the estimated and recorded profiles using physically realistic values of the coefficients η and τ.

From Waters (1997), at Station 3 there was a surface heat flux out of the water of approximately 50 Wm^{-2}. Over the 66 minutes between the readings, this would give rise to a 0.5°C temperature decrease for the first 0.1 m of the water column, explaining the temperature drop in the upper portion of the water column.

However the lower than predicted temperatures in the lower portion of the profile cannot be explained by this surface heat loss, so it seems the only other explanation is that exchange with cooler water from the deeper portion of the lake must have occurred.

Results of scalings performed in Waters (1997) indicate that for a temperature difference between Station 3 and the other stations of 1°C, as is roughly the case here, a convection of the order of 20 m/hr can be expected. At such a speed, the convection could easily penetrate the whole wetland, thereby accounting for the slightly greater than estimated increase in temperature observed in the upper portion of the water column at Stations 1, 2 and 4.

CONCLUSIONS

Large stratifications were observed to occur year round in a 1 m deep wetland. Stratifications were strongest in summer persisting for many days to weeks at a time. The vertical temperature profiles that develop in both the open water and vegetation cannot be explained solely by radiative heating the form of the vertical temperature differences observed would be most easily explained by the presence of horizontal convections.

In *Typha* vegetation that is 8 to 13 m from open water, depth averaged temperatures are typically 1 to 4°C less than in open water in summer (0.2 to 0.5°C in winter). The lateral temperature differences observed are strong enough to give rise to horizontal convection.

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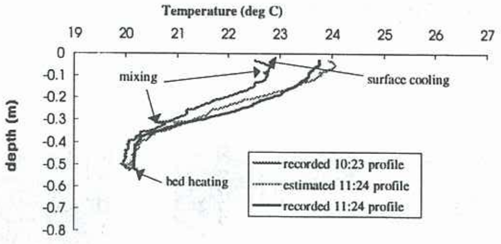
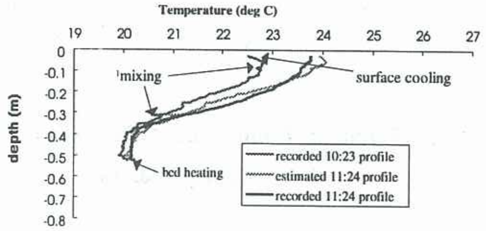


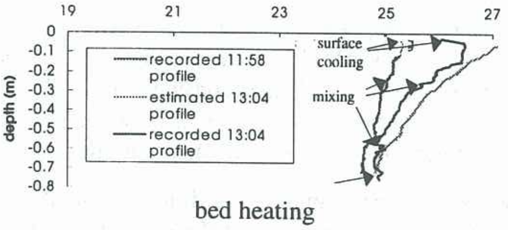
a. Station 1 (vegetated)

$\eta = 5m^{-1}$, $\tau = 0.5$ and solar radiation = 750 Wm^{-2}



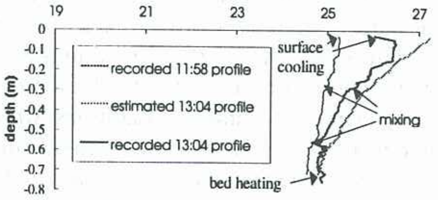
b. Station 2 (open water)

$\eta = 3\ m^{-1}$, $\tau = 0.5$ and solar radiation = 750 Wm^{-2}



c. Station 3 (open water)

$\eta = 3\ m^{-1}$, $\tau = 0.9$ and solar radiation = 910 Wm^{-2}



d. Station 4 (vegetated)

$\eta = 5m^{-1}$, $\tau = 0.8$ and solar radiation = 695 Wm^{-2}

Figure 5: Temperature Profiles in the Wetland