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The impact of controlled tidal exchange on drainage water quality in acid sulphate soil backswamps

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Abstract

Periodic opening of one-way tidal floodgates was undertaken on two coastal flood mitigation drains to promote exchange with estuarine water and improve drain water quality. The drains were located in areas with acid sulphate soils and their drainage water frequently had high acidity and low dissolved oxygen (DO). Tidal exchange via floodgate opening generally raised drain water pH levels through dilution and/or neutralisation of acidity. Increases in DO and moderation of extreme diurnal DO fluctuations were also observed. The magnitude and stability of the improved physico-chemical conditions was highly dependant on the volume and quality of tidal ingress water. Relatively rapid reversion (hours to days) in drain water pH and DO was observed once floodgates were closed again. The rate of reversion following floodgate closure was strongly related to outflow volumes, antecedent drain water quality conditions and groundwater levels. Floodgate opening caused changes in longitudinal drain water gradients and has potential to slow net drainage rates during non-flood periods. However, complex site specific interactions between drain water and adjacent groundwater can also occur. At one location, a 4-day floodgate opening event caused recharge of adjacent acid groundwater during the opening phase, raising the potentiometric groundwater level above local low tide minima. This was followed by tidally modulated draw down of acid groundwater and enhanced acid export in the period immediately following floodgate closure. There are also practical considerations, which limit the efficacy of floodgate opening as an acid management strategy. The low elevation (close to mean sea level) of some acid sulphate soil backswamps, combined with seasonal migration of the estuarine salt wedge, means there is considerable potential for saline overtopping of what is currently agricultural land. This constrains the magnitude and duration of controlled tidal exchange. Also, it is during wet periods that acid drainage outflow to the estuary is greatest. At such times the salinity and acid buffering capacity of estuarine water is often low, thus reducing the capacity of tidal exchange waters to neutralise acidity.

Keywords: Floodgates; Floodplain management; Tidal buffering; Acid neutralisation; Acid sulphate soils
1. Introduction

An extensive network of constructed drains and modified water courses exists on the coastal floodplains of eastern Australia. Construction of drainage schemes was intended to mitigate the negative effects of flooding on agricultural land and facilitate the expansion of agriculture on the floodplains (Pressey and Middleton, 1982; Middleton et al., 1985). Drainage was designed to rapidly remove surface waters after flooding and also exclude saline, tidal estuarine waters from overtopping low lying land. Poor water quality is a common occurrence in these coastal floodplain drains, particularly during and after wet periods. There is substantial documentation of drainage outflow events with high levels of acidity (Sammut et al., 1996, Wilson et al., 1999, Blunden, 2000, Cook et al., 2000) and low dissolved oxygen (Pressey and Middleton, 1982; NSW Agriculture and Fisheries, 1989; Johnston et al., 2003a). The extensive areas of acid sulphate soils (ASS), which underlie the coastal floodplains in eastern Australia (Naylor et al., 1995) are the primary source of acidity in drainage waters (White et al., 1997).

Floodgates are a common feature on coastal floodplain drains. They usually consist of top-hinged, metal flapgates, which allow one-way outflow of drain water, but exclude tidal ingress. Floodgates help maintain low drain water levels, which assists in lowering regional groundwater to local low tide level (Blunden, 2000) where it can then be lowered further through evapotranspiration. Floodgates can also limit small scale flooding from rises in river levels.

By preventing tidal exchange, floodgates promote a stagnant, poorly flushed aquatic environment in the drain and they are known to exacerbate poor water drain quality, particularly high acidity and low dissolved oxygen (Johnston et al., 2003b). In ASS areas, floodgates allow drains to act as reservoir for high acidity waters which discharge during ebb tide cycles (Johnston, 1995; Sammut et al., 1996). The lack of flushing and water quality conditions associated with floodgates also appear to favour the accumulation of iron monosulphides in drain basal sediments in areas with ASS (Sullivan et al., 2002). Coastal floodplain drains are typically exposed to high light levels and also flow through agricultural land, which can favour nutrient and organic matter accumulation. These features, combined with no tidal flushing due to floodgates, can promote eutrophic conditions and episodic algal blooms, which lead to wild diurnal fluctuations in DO and/or low DO accompanying decay of labile organic material (Sammut et al., 1994; Johnston et al., 2003b). There are also other ecological impacts of floodgates (Sammut et al., 1995), which include restriction of fish passage and prevention of access to upstream habitat (Pollard and Hannan, 1994). The fact that floodgates allow drainage to low tide level has greatly reduced both the aerial extent and the ecological integrity of many coastal wetlands (Pressey and Middleton, 1982).

Constructed drainage with floodgates has increased the rate of removal of surface waters from the floodplain, causing a reduction in natural retention/storage times of about an order of magnitude (i.e. ~100 to 10 days; White et al., 1997). This rapid shedding of surface water increases the time period over which evapotranspiration can then act directly on the shallow groundwater – effectively increasing the depth to which evapotranspiration can lower the groundwater table during the dry season (Cook et al., 1999). This indirect contribution of drainage to lowering of groundwater levels has substantial potential to enhance sulphide oxidation and thus acid generation by increasing the exposure of sulphidic sediments to oxygen (Walker, 1972; Dent, 1986).

Controlled tidal exchange with estuarine water by opening floodgates is being increasingly promoted and used as a means of improving water quality in drains (Haskins, 1999; Indraratna et al., 2002; Johnston et al., 2003b). Sea water contains acid buffering agents, mainly bicarbonate and carbonate, and has the capacity to neutralise around 2–2.5 mmol H+ L−1. The buffering reaction of bicarbonate with a strong acid, such as H2SO4 from acid sulphate soils, and formation of weak carbonic acid can be represented by Eq. (1).

\[ \text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{CO}_3 \]  

(1)

The concentration of marine derived buffering agents in estuarine water is strongly related to the salinity regime in the estuary (Indraratna et al., 2002). In the Clarence River estuary the salinity regime varies greatly according to the highly seasonal freshwater inflows (Manly Hydraulics Laboratory, 2000). The net acid neutralisation capacity of tidal ingress waters entering a drain during a given flood tide cycle will be dependent on both the concentration of buffering agents within the ingress water and the ingress volume. The efficient utilisation of this acid neutralisation capacity will depend partly on adequate mixing and there is potential for slug displacement to occur within the drain.

Recent research has shown that controlled tidal exchange in drains can be a reasonably effective means of neutralising/diluting acid drain water (Indraratna et al., 2002). However, chronic discharge of highly acid groundwater following rainfall events can still overwhelm the buffering capacity of tidal ingress water (Indraratna et al., 2002). DO levels in both floodplain drains and estuaries typically display a high degree of dynamism over a variety of time scales (i.e. daily, annually, episodic flow event based). Thus the effects of controlled tidal exchange on DO concentrations in drain water are likely to be variable, depending on the timing of opening events.

Given the heterogeneity of physical and chemical properties typically associated with ASS (Dent, 1986), further field investigations of controlled floodgate opening on acid buffering dynamics are required in drains from a variety ASS landscapes and hydrological contexts. There is also a need to examine the effects of controlled floodgate opening on other important water quality parameters such as DO. The study described in this paper aims to assess changes in drain water quality, particularly acidity and dissolved oxygen, associated with controlled floodgate opening in two drains in ASS backswamps. It also aims to relate these to observed changes to antecedent hydrological conditions, drain flow volumes and local hydrological processes.
2. Methodology

2.1. Study sites

The study sites, Blanches drain and Maloneys drain, are located on the lower Clarence River floodplain on the central east coast of Australia (29°30’S, 153°15’E) (Fig. 1). Both sites drain water from ASS backswamps to the estuary. The estuary is a mature barrier system (Roy, 1984) with a floodplain area >2600 km² which is underlain by an estimated 330 km² of high risk acid sulphate soils (Tulau, 1999). The backswamps are infilled Holocene estuarine embayments (Roy, 1984; Lin and Melville, 1993) with relatively flat topography and surface elevations mostly <0.2 m Australian height datum (AHD; 0 AHD = mean sea level). Both backswamps contain highly acidic sulphuric horizons close to the ground surface (0.2–0.3 m depth), which are underlain by sulphide sediment at about 1 m depth (Lin and Melville, 1993; Milford, 1997).

Blanches drain is located on Everlasting Swamp (Fig. 2) and drains an ASS backswamp area of ~600 ha, plus a proportion of an upland catchment. The main drain is over 3.5 km

![Fig. 1. (a) Clarence River catchment and (b) lower floodplain and study area location adjacent Shark Creek.](image-url)
long and up to 10 m wide and discharges water through a two cell box culvert with outward opening floodgates. This drain was constructed through the natural levee in the 1960’s and discharges directly into the main Clarence River channel. The drain network intersects the sulphuric horizons in the backswamp and the elevation of the drain base in the central channel adjacent the backswamp is approximately $-0.9$ m AHD.

Maloney’s drain is located adjacent lower eastern Shark Creek, a small tidal tributary channel of the Clarence River, and has a catchment containing 208 ha of ASS backswamp and 300 ha of upland. A drainage network constructed in the backswamp conveys water through the distributary levee and discharges into Shark Creek via a single pipe culvert with one-way floodgates (Fig. 2). The drain network is 5.4 km in length and the central channel is up to 8 m wide. The drain intersects the sulphuric horizons in the backswamp and the elevation of the drain base in the central channel is approximately $-1.2$ m AHD.

![Diagram](image_url)

Fig. 2. Blanches and Maloney’s study sites, showing the location of submersible data loggers/flow/drain water level monitoring stations (A and B), piezometers, drains, floodgates and ASS backswamp margin. ASS backswamp boundaries after Milford (1997).

The floodgates at each site can be manually raised by means of winch and pulley systems. Tidal water ingress can occur once the floodgates are raised, depending on relative water levels inside the drain and the adjacent estuary. The mechanism at Blanches drain only allowed the floodgates to be either fully open or fully closed, with no capacity for a partial opening. At Maloney's the mechanism allowed for a variable opening size. The main landuse in both backswamp areas is grazing, though there is some sugarcane on the natural levees at both sites. The climate is sub-tropical and annual rainfall on the Clarence River floodplain ranges from 1100 to 1500 mm. Monitoring was conducted at both sites from December 2000 through to October 2003.

2.2. Meteorological monitoring

Rainfall, solar radiation, temperature, humidity, wind speed and soil temperature was recorded hourly with an EIT E-Tech weather station located near each drain.

2.3. Drain water quality

Hourly measurements of DO, pH, electrical conductivity (EC) and temperature were made with Greenspan CS304 submersible data loggers (SDL). Two SDLs were installed in each drain, one near the floodgates and one near the backswamp margin, designated monitoring stations A and B, respectively (Fig. 2). Each SDL was housed in a slotted 0.1 m diameter PVC pipe, positioned as close to centre channel as possible. The SDLs were cleaned, maintained and calibrated every 28–36 days. Spot measurements of in situ drain water DO, pH, EC, temperature and redox potential (ORP) were recorded at each SDL calibration and at the time and location of sample collection using freshly calibrated portable field equipment (TPS 90FLMV). Redox potential was measured with a platinum tipped Ag/AgCl reference electrode and values are reported as recorded without correction.

Vertical stratification of the water column is known to occur in low flow conditions in ASS drains (Sammut et al., 1994). This has significant implications for monitoring drain water quality using stationary SDLs. There are few ways to avoid this issue other than to use a nested array of SDL at multiple depths or multi-depth samplers. However, opportunistic spot monitoring (at station A) conducted at different depths suggests that the flow associated with floodgate opening and also during discharge events causes enough velocity shear and mixing to prevent substantial stratification of drain water during these times. A comparison of spot measurements with logged SDL values at Maloney’s and Blanches monitoring station A in 2001, 2002 and 2003 is shown in Table 1. This suggests a relatively high degree of accuracy and precision in SDL measurements for pH and EC, but greater variability in DO measurements.

2.4. Sample collection and analysis

Drain water samples were collected at stations A and B opportunistically. Sampling intensities were flow dependant, ranging from daily during high flow/flux periods, to every ~2–10 days during periods of low to intermediate flow/flux and none during prolonged
Table 1
The mean difference between paired spot monitoring and SDL measurements of drain water quality made at station A at Blanches and Maloneys drains during 2001, 2002, 2003

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>DO (μmol L⁻¹)</th>
<th>EC (dS m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Blanches</td>
<td>0.05 (0.08)</td>
<td>6 (6)</td>
</tr>
<tr>
<td></td>
<td>Maloneys</td>
<td>0.11 (0.03)</td>
<td>7 (7)</td>
</tr>
<tr>
<td>2002</td>
<td>Blanches</td>
<td>-0.18 (0.09)</td>
<td>42 (18)</td>
</tr>
<tr>
<td></td>
<td>Maloneys</td>
<td>-0.13 (0.04)</td>
<td>36 (9)</td>
</tr>
<tr>
<td>2003</td>
<td>Blanches</td>
<td>0.07 (0.04)</td>
<td>24 (30)</td>
</tr>
<tr>
<td></td>
<td>Maloneys</td>
<td>0.11 (0.01)</td>
<td>34 (5)</td>
</tr>
</tbody>
</table>

Numbers in brackets are standard errors.

periods of zero outflow. Sampling was timed to coincide with outflow periods where possible to ensure accurate representation of discharge water. Water samples were collected from 0 to 0.3 m below the surface at centre channel using a clean 10 L plastic bucket thoroughly pre-rinsed with the drain water to be collected. Two 250 ml sub-samples were collected in clean (acid rinsed, distilled water flushed) polyethylene bottles thoroughly pre-rinsed with the sample water a minimum of four times. Visible air bubbles were excluded prior to sealing the cap and samples placed in cold storage (approx. 4 °C). One 250 ml sub-sample was analysed for titratable acidity to pH 5.5 within 48 h of sample collection (APHA, 1995 2310B (1995)-including the peroxide oxidation step). Ground-water samples from the sulphuric horizons at Maloneys backswamp, which are referred to in this study, were collected and analysed according to the procedures outlined in Johnston et al. (2003c). A series of estuary water samples were collected from the Clarence River along the salinity gradient during a low flow period in January 2004. Samples were collected in clean (acid rinsed, distilled water flushed) polyethylene bottles thoroughly pre-rinsed with the sample water a minimum of four times and analysed for alkalinity according to Rayment and Higginson (1992).

2.5. Water levels

Drain water levels were monitored hourly near the backswamp margin (station B), immediately inside the floodgates (station A), and outside the floodgates in the adjacent estuary with capacitance probes (Dataflow-model 392, accuracy ±0.01 m). The probes were installed in 5.5 cm diameter slotted PVC pipes and surveyed to AHD. A series of piezometer wells were also installed in the backswamps at each site perpendicular to the drain (Fig. 2). Each piezometer consisted of a 10 cm diameter hand augered hole about 1.4 m deep, with a 5.5 cm diameter slotted and screened PVC pipe inserted. The screened zone was 0.8 m long and positioned to bracket the sulphuric horizon. This was backfilled with clean sand and auger cuttings in the screened zone and then with bentonite to the surface. Each well was surveyed to AHD. Water levels in each piezometer were also logged hourly using capacitance probes. All capacitance probes were cleaned and calibrated every 2–3 months.
2.6. Drain flow and flux calculations

Flow velocity in the drains was measured using Doppler sensors (Starflow-6526-51) with a velocity range of 0.021–4.5 m s$^{-1}$. The scan interval was set for 30 s and the hourly mean, maximum and minimum logged. The Starflow units were located in the centre of the channel at the floodgate culvert (centre of one culvert at Blanches). Culvert dimensions and Starflow locations were surveyed to AHD. The Starflow units also measured drain water level using a hydrostatic pressure sensor vented to the atmosphere. Checks were undertaken using a calibrated current meter in the Doppler field of view under a range of flow conditions (>1 to ~0.1 m s$^{-1}$) and yielded flow velocities within ±10% of the Doppler sensor. Daily drain outflow and inflow volumes ($Q_d$) were derived from the sum of the hourly flow volumes ($Q_h$) using Eq. (2).

$$Q_h = V_h A_h$$  \hspace{1cm} (2)

where $V_h$ is the mean hourly flow velocity, $A_h$ the mean hourly cross-sectional area of water in the culvert.

Because the drainage waters contain varying concentrations of dissolved acidic metal cations (i.e. Fe$^{2+}$, Al$^{3+}$), titratable acidity (TA) was used as the basis for acid flux calculations in this study (Cook et al., 2000). Over short time periods there can be strong correlations between TA and pH (Fig. 3). The hourly acid flux estimates presented in this study were calculated using SDL values to infer ionic concentrations in drain water according to Eq. (3).

$$F_h = (Q_h C_h)$$  \hspace{1cm} (3)

where $F_h$ is the hourly flux estimate and $C_h$ the hourly logger inferred TA. These hourly acid flux estimates were made during a short period before, during and after a single floodgate opening event at Maloney's drain where there was intensive spot monitoring/sampling and a high correlation between the pH values recorded by the SDL at station A and sample titratable acidity (Fig. 3). By fitting a regression equation to the data shown in Fig. 3, the hourly pH values recorded by the SDL at station A were used to infer hourly changes in drain water TA ($C_h$) during this event. This hourly method is better able to account for the rapid variations in drain water chemistry that can accompany tidally modulated outflow periods (i.e. increasing acidity during the ebb tide cycle) and thus provides a more accurate integration of the area under the velocity and concentration curves than daily methods. Other acid flux estimates used in this study are calculated using the methods outlined in Johnston et al. (2004).
Fig. 3. Correlation between drain water pH as measured by the submersible data logger at station A and titratable acidity at Maloney's drain 2 days before, during and 3 days after a floodgate opening event (of 4 days duration), which is shown in detail in Fig. 15.
3. Results and discussion

3.1. Prevailing drain water quality conditions

Both drains experienced prolonged periods with high acid and low dissolved oxygen levels during the period of monitoring (Fig. 4). Maloney's drain water was more frequently and more intensely acidic than Blanches drain, and had mean daily pH values below 5.5 for about 35% of the time at monitoring station A (Fig. 4a). The mean daily dissolved oxygen concentration in drain water at monitoring station A was less than 60% saturation for 80 and 55% of the time at Maloney's and Blanches, respectively (Fig. 4b). Floodgates were opened periodically during the monitoring period under a variety of hydrological conditions (high outflow/low outflow), allowing a number of individual events to be assessed. Most opening events were between 2 and 7 days in duration, though some prolonged (>3 weeks) partial openings occurred at Maloney's drain. Seasonal conditions had a controlling influence on drain water quality and oscillated between wet periods with substantial outflow and generally poor water quality (low pH, low DO), and dry periods with no or minimal outflow, but high pH and variable DO (Fig. 5).

3.2. Changes in drain water pH

The low pH which typically occurred after wet periods in both Blanches and Maloney's drains were a result of outflow of either acid groundwater or surface water from the backswamp acid sulphate soils (Johnston et al., 2004). When antecedent drain water pH was low and floodgates were opened, sharp increases in drain water pH were commonly observed (Fig. 6). Expectedly, pH values during opening periods showed a degree of tidal modulation and there was an increasing lag in the pH response time with increasing distance from the estuary (Fig. 6a and b). A notable and recurring feature was a reversion in drain water pH once floodgates were closed (Fig. 6). This pattern of pH reversion was particularly apparent during a period of regular floodgate opening events at Blanches drain and began to occur immediately following the cessation of inflow (Fig. 7). The pH reversions shown in Fig. 7 are likely a result of continued inputs of acid sulphate contaminated water from the backswamp, as indicated by the sustained low volume outflow.

It is logical to assume that any increases in the pH of acidic drain water due to floodgate opening induced dilution/neutralisation with estuarine water are likely to be proportional to tidal inflow volumes. Detailed analysis of one individual floodgate opening event at Maloney's drain conforms to this hypothesis and shows a strong correlation between the increase in drain water pH and the cumulative inflow volume per flood tide cycle (Fig. 8).

The acid buffering/dilution capacity of tidal ingress waters within a drain can be rapidly exceeded when soluble acidity from the sulphuric horizon is transported to the drain after rainfall (Fig. 9). Fig. 9 shows a period immediately before and after a rainfall event at Maloney's drain whilst the floodgates remained open. Groundwater gradients (the water level difference between well no. 2 and monitoring station B) were influential in the period immediately before and during the initial part of floodgate opening. Both pH and DO levels showed some increase and stabilisation during this initial opening period. A rainfall event on 2 June caused a rise in the backswamp groundwater levels and the development of effluent groundwater gradients adjacent to the drain in the ASS backswamp. Despite the floodgates remaining open for several days after the rainfall event, pH levels experienced a sharp decline at both monitoring stations. DO levels at monitoring station B also decreased.
Fig. 4. Cumulative frequency distribution of (a) mean daily drain water pH and (b) mean daily dissolved oxygen at Blanches and Malneys drains between December 2000 and October 2003. Data for both sites are based on measurements made by submersible data loggers located at monitoring station A.
markedly. While the closure of floodgates on 5 June may have exaggerated or accelerated the observed decreases, they were clearly well underway before floodgate closure. The titratable acidity of sulphuric horizon groundwater at Maloneys can exceed 50 mmol L$^{-1}$ (Johnston et al., 2003c) which is about 25× the acid buffering capacity of pure seawater. Therefore, even small volumes of groundwater seepage can have a large impact upon drain water pH, and also potentially DO due to oxidation of Fe$^{2+}$. The sulphuric horizons at Maloneys backswamp have very high hydraulic conductivity (Johnston et al., 2004) which makes this drain very prone to rapid changes in water quality conditions in response to changing groundwater gradients, regardless of whether floodgates are open or not.

There are several possible explanations for the increase in pH recorded at the monitoring stations during the floodgate openings. These include: (a) dilution with tidal ingress water; (b) neutralisation by acid buffering agents within tidal ingress water; (c) displacement of drain water as a poorly mixed ‘slug’ by tidal ingress water, or any combination of the above. The sulphuric horizon groundwater in the study site backswamps has a distinctive EC:H$^+$ signature, which is very different from that of Clarence River estuarine water (Fig. 10). The EC:H$^+$ signature of drainage water immediately before and during three separate floodgate opening events is also depicted in Fig. 10. A clear shift in EC:H$^+$ characteristics from a signature resembling that of sulphuric horizon groundwater towards that of estuarine water occurred during these floodgate openings (Fig. 10). The observed direction of response during floodgate opening conforms only partially with the theoretical slope of acid neutralisation by 1:1 addition of estuarine water. This suggests that substantial dilution of drain water also took place during these events and may be indicative of displacement type flow.
Fig. 6. Changes in drain water pH in relation to drain water levels at Blanches drain during two separate floodgate opening events. The total volume (ML; 1 ML = m$^3 \times 10^3$) of estuarine water inflow during each day of the floodgate opening event is shown in bold type.
3.3. Changes in drain water DO

Drain water dissolved oxygen at both study sites often displayed large diurnal fluctuations associated with photosynthesis/respiration cycles, particularly during warmer months (Fig. 11). Such behaviour is fairly typical of poorly flushed eutrophic systems. Influx of estuarine water with floodgate opening exhibits some potential to moderate extreme diurnal fluctuations in DO, as evident during the opening event shown in Fig. 11.

Sustained low DO was observed in both drains during a wet period following flooding (Johnston et al., 2003a). During this post-flood period (~February–May 2001) there were a series of floodgate opening events at Blanches drain. Examples of these events are shown in Fig. 12. Rapid, tidally modulated increases in DO are evident during the floodgate opening phase, with the peak of the increase during a given day approximately proportional to the estuarine water influx volume (Fig. 12). Equally rapid declines in DO were observed on these occasions immediately following floodgate closure. The rapid declines were related to the cessation of tidal ingress and the sustained outflow of water with very low DO from the backswamp during this period. At Blanches drain a positive linear correlation ($r^2 = 0.74$) was observed between the mean daily drain water DO and the daily inflow:outflow volume ratio over a 2-month period (Fig. 13).

The DO of eutrophic aquatic environments is highly variable and is influenced by a wide range of biotic and abiotic factors (Stumm and Morgan, 1981). There were a number of occasions when the changes and trends in DO occurring during floodgate opening were
relatively minor and difficult to distinguish from the high levels of background variability (data not shown).

3.4. Flow volumes

Opening floodgates has potential to reduce the net drainage rates and cause net influx of estuarine water by reducing and potentially reversing the mean longitudinal drain water gradient. This was demonstrated by data from Blanches drain (Fig. 14), which shows large openings clearly capable of causing significant net influx and alteration of the mean longitudinal drain water gradient. Slower drainage rates will enhance the retention time of water in floodplain storage basins. However, this effect will largely be confined to the floodgate opening period.

3.5. Interactions with acid groundwater

Detailed monitoring at Maloney’s drain during a floodgate opening event demonstrated that under certain circumstances a short duration floodgate opening has potential to enhance the export of acidity from the drainage system (Fig. 15). The following points outline the sequence of events and key features associated with this opening enhanced acid export. Figures in brackets are derived directly from the Maloney’s system.
Fig. 9. (a) Drain and groundwater levels, (b) drain water pH and (c) dissolved oxygen in relation to (d) rainfall at Maloney's study site during a period before, during and after a floodgate opening event.

- Before floodgate opening the groundwater in the backswamp ASS was close to the minimum ebb tide influenced drain water level (approximately 0.2 m AHD). There was no effluent groundwater gradient and minimal seepage of groundwater to drainage system (Fig. 15a). Drain water at station B was still acidic from previous outflow (Fig. 15b).
- The upper sulphuric horizons in the backswamp have very high $K_{sat}$ (~120 m day$^{-1}$ – Johnston et al., 2004). The shallow groundwater in the backswamp is highly acidic and rich in sulphide oxidation products (Johnston et al., 2003c).
Fig. 10. Changes in drain water H⁺ concentrations in relation to EC, before and during three individual floodgate opening events. Short arrows indicate the direction of change during the floodgate opening phase. The EC:H⁺ signature of sulphuric horizon groundwater (from the Malneys site), and non-acid estuary water (measured during a dry period) are also shown. Dashed lines represent the theoretical change in H⁺ that would occur in relation to EC due to neutralisation of acidity by 1:1 addition of estuary water (based on alkalinity and EC data presented in Fig. 17). The H⁺ concentration of drain and estuary waters is based on pH and the sulphuric horizon groundwater is derived from titratable acidity.

- Floodgates are opened and an influent groundwater gradient develops during the flood tide cycles of the opening phase (Fig. 15a). Recharge of the groundwater potentiometric level occurs in the near drain zone over four days (by ~0.12 at 10 m from the drain) to a point above the minimum ebb tide drain water level (Fig. 15a). Dilution of shallow groundwater with estuarine influx water occurs in the first few meters adjacent to the drain, altering the shallow groundwater chemistry (Fig. 16).
- Floodgates are closed (i.e. set at automatic operation) and effluent groundwater gradients develop during ebb tide cycles, promoting groundwater seepage into the drainage system. Acidity is transported to the drain with this seepage water, enhancing acid export during the period immediately following floodgate closure (Fig. 15b–d). Partial reversion of the near drain shallow groundwater chemistry occurs within several days after floodgate closure (Fig. 16).

Fig. 11. Drain water levels and moderation of diurnal fluctuations in dissolved oxygen saturation during a floodgate opening event at Blanches drain, in relation to solar radiation.
During this opening event there was a net influx of estuarine water and groundwater levels responded to tidal forcing across the backswamp over 300 m from the drain (Johnston et al., 2004). The changes in shallow groundwater chemistry following floodgate opening (Fig. 16) clearly demonstrates there was appreciable dilution of shallow groundwater with estuarine influx water in at least the first few meters adjacent to the drain. While the total amounts of acidic products exported following this opening event were quite small (maximum ~770 mol H⁺ day⁻¹), it demonstrates the principle of near drain zone recharge followed by seepage of ASS groundwater back into the drainage system following a short duration floodgate opening event. The potential for such an interaction to occur in any given drainage system will depend on a number of factors including;
(a) The hydraulic conductivity of the adjacent ASS soils.
(b) The chemistry of both shallow groundwater and estuarine influx water.
(c) The development of effluent groundwater gradients following floodgate closure. This
will be related to the degree of near drain groundwater recharge and the low tide
minima occurring after the event.

An identical opening event at a similar site, but one with low hydraulic conductivity
ASS, and/or a relatively high and stable drain water level with low tidal amplitude after the
floodgate closure, would likely result in far less acid groundwater seepage into the drainage
system.

![Graph](image1)

**Fig. 13.** Positive linear correlation between mean daily drain water dissolved oxygen levels at Blanches drain
(station A) and the daily inflow-outflow volume ratio. Note that inflow only occurred during floodgate opening
events. Based on measurements between 15/3/01 and 19/5/01. Flow volumes measured at station A.

![Graph](image2)

**Fig. 14.** Net drain discharge volume in relation to the mean daily longitudinal drain water gradient at Blanches
drain. Net inflows associated with floodgate opening are indicated by the arrows.
3.6. Estuary water acid neutralisation capacity

Alkalinity in the Clarence River estuary is strongly correlated with the salinity regime (Fig. 17) in a similar manner to that reported in other Australian estuaries (Indraratna et al., 2002). While there is substantial buffering capacity at EC values approaching that of seawater (equivalent to ~2.3 mmol H⁺ L⁻¹), this decreases to less than 0.8 mmol H⁺ L⁻¹ once the EC reaches 10 dS m⁻¹. The EC at monitoring station A at both Blanchies and Maloney's drains was above 10 dS m⁻¹ for about 50% of the time during the study period (Fig. 18a). Higher EC values corresponded with dry periods and small volumes of estuary water leaking into the drain near the floodgates. However, over 95% of both the cumulative acid export and total outflow volumes recorded from both sites took place during wet periods when the mean daily drain water EC was <5 dS m⁻¹ (Fig. 18b and c). Hence, the periods when marine derived tidal buffering capacity is most required for acid neutralisation corresponds with periods when it is least likely to be available.

Fig. 15. Changes in (a) drain and groundwater levels, (b) drain water pH, (c) drain outflow volumes and (d) acid flux rates before, during and after a 4-day floodgate opening event at Maloney’s drain. Negative values for outflow volume represent tidal ingress.

3.7. Overtopping of low lying land

Low elevation ASS backswamps such as Blanches and Maloneyes are about 0.6 m below the maximum high tide recorded at their floodgates (Table 2). Estuarine water with high marine salt concentrations is relatively common at both study sites (Fig. 18a). A key impediment to maintaining a higher frequency, magnitude and duration of floodgate opening events is the risk of saline overtopping adjacent land which is currently used for agriculture. This situation is relevant to a number of ASS backswamps on NSW coastal floodplains, which are situated in similar relative topographic/tidal maxima contexts. Tidal forecast charts are one of the main management tools currently used by landholders to manage the risk of overtopping, i.e. by opening floodgates during neap tide phases only. However, tidal anomalies occur on the NSW coastline and can lead to ocean tides in excess of 0.5 m above predicted levels. This combination of features places significant restrictions upon floodgate management in drains bisecting low elevation backswamps.

Table 2
Approximate backswamp surface elevation ranges at Blanches and Maloneyes in relation to the maximum recorded spring tides in the adjacent estuary during 2001–2003

<table>
<thead>
<tr>
<th>Backswamp Surface Elevation Range (m AHD)</th>
<th>Maximum Recorded Spring Tide (m AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanches -0.1 -0.15</td>
<td>0.73</td>
</tr>
<tr>
<td>Maloneyes 0.0 -0.2</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Fig. 16. Sulphuric horizon groundwater (a) titratable acidity, (b) Cl⁻, (c) dissolved Fe and (d) ORP in relation to distance from the drain before, during and after the floodgate opening event shown in Fig. 15. Samples collected from a transect parallel to the piezometer transect shown in Fig. 2.

Fig. 17. Correlation between Clarence River estuary water EC and alkalinity (expressed as bicarbonate equivalent). Samples collected during a low flow period in January 2004.

Higher frequency and duration of floodgate opening is only likely to be undertaken by landholders when there is a reliable capacity to control drain water levels and prevent overtopping of land. Manual winch gates provide relatively poor control of drain water levels and are subject to operator failure. Other types of floodgate opening devices, such as automatic mini-tidal floodgates, provide automatic closure and far greater drain water level control (Johnston et al., 2003b). Such devices may help overcome the limitations to floodgate opening frequency associated with manually operated systems.
Fig. 18. Cumulative frequency distribution of (a) mean daily drain water EC, (b) acid flux in relation to mean daily drain water EC and (c) flow volumes in relation to mean daily drain water EC at Blanches and Malneys drains. EC data for both sites is based on measurements from monitoring station A.
4. General discussion and conclusions

Floodgate opening can improve in-drain water quality, decreasing acidity, raising DO and moderating diurnal DO fluctuations. Induced changes in drain water quality occur within the context of a highly dynamic and variable aquatic environment over which antecedent seasonal conditions exert a primary influence. The extent and stability of any improvement appears to be largely dependant upon the frequency, magnitude and duration of floodgate opening and the relative interaction between both the volume and quality of drainage outflow water and in-flowing estuarine water. There are also substantial limitations and complexities, particularly in relation to short duration opening events. Improvements can often be followed by relatively rapid reversion to pre-opening conditions upon floodgate closure, depending on antecedent conditions. Prolonged, frequent tidal exchange (i.e. each tidal cycle) is likely to help minimise such reversions and help promote more stable improvements in drain water quality.

This study demonstrated the potential for a short duration floodgate opening event to increase acid export by causing recharge of groundwater levels near the drain during the opening phase and enhanced seepage of acidic groundwater back into the drainage system after floodgate closure. This is most likely to be an issue in ASS soils with very high \( K_{sat} \) and very poor groundwater quality and highlights the importance of appropriate site assessment prior to the adoption floodgate opening strategies.

Floodgate opening can reduce net drainage rates by altering longitudinal drain water gradients and may cause significant net inflow during dry periods. While overtopping of saline tidal water in low elevation ASS backswamps represents a major impediment to controlled floodgate opening, this has the potential to be overcome with automated water exchange device designs that provide a high degree of drain water level control.

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References


