Opening floodgates in coastal floodplain drains: effects on tidal forcing and lateral transport of solutes in adjacent groundwater.

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Abstract

The effects of opening tidal barriers (floodgates) upon tidal forcing and lateral transport of solutes in shallow groundwater adjacent drains was investigated at two sites on a coastal floodplain with contrasting geomorphology, soil texture and sediment hydraulic properties. The site with lower hydraulic conductivity (0.3-0.9 m day^{-1}) soils (Romiaka) also had a higher elevation and effluent trending potentiometric gradients. While floodgate opening at Romiaka enhanced the amplitude of pre-existing tidal forcing in adjacent shallow groundwater, altering potentiometric gradients and causing some salt seepage, lateral solute movement from the drain was highly attenuated (<10 m). The site with very high hydraulic conductivity soils (Shark Creek; ~125 m day^{-1}) had a lower elevation and seasonally fluctuating potentiometric gradients. The introduction of a tidal signal through floodgate opening at Shark Creek caused tidal forcing of groundwater over 300 m from the drain. Floodgate opening at this site also caused changes in groundwater potentiometric gradients, leading to incursion of saline drain water into shallow groundwater over 80 m from the drain. Lateral solute movement was relatively rapid, due to macropore flow in oxidised acid sulfate soil horizons, and caused substantial changes to shallow groundwater chemical composition. Conversely, when groundwater potentiometric gradients were effluent at this site there was substantial lateral outflow of acid groundwater into drains. This study highlights the importance of assessing the hydraulic properties of soils next to drains on coastal floodplains prior to opening floodgates, particularly in acid sulfate soil backswamps, in order to prevent unintended saline intrusion into shallow groundwater.

Additional keywords: salt seepage, hydrodynamics, acid sulfate soils, macropores.

1. Introduction

Thousands of kilometres of artificial drains have been constructed on the coastal floodplains of eastern Australia for agricultural and flood mitigation purposes. The coastal floodplains of eastern Australia are underlain by large areas of acid sulfate soils (Naylor *et al.* 1996) which substantially influence drain discharge water quality (White *et al.* 1997). Many drains have episodic poor water quality and seasonally discharge water with low dissolved oxygen, high acidity and acidic metals cations, into adjacent estuaries (Sammut *et al.* 1996, White *et al.* 1997; Wilson *et al.* 1999; Blunden *et al.* 2000; Cook *et al.* 2000; Johnston *et al.* 2003a).

Most coastal floodplain drains also have one way tidal flapgates (floodgates) near the discharge point. These floodgates allow drainage outflow, but prevent tidal water ingress. This compounds the accumulation poor quality water in the drain (Indraratna *et al.* 2002) and can help lower adjacent groundwater to low tide level. Opening floodgates to allow tidal exchange with estuarine water during non-flood periods has been promoted as a means of improving drain water quality (Haskins 1999; Blunden 2000; Indraratna *et al.* 2002). Opening floodgates may also increase the lateral seepage of saline tidal water into shallow groundwater adjacent the drain (Johnston *et al.* 2003b). This is a concern to floodplain agricultural industries with salt sensitive crops such as sugar cane.

On coastal floodplains there is typically a zone within the aquifer adjacent to tidal channels where mixing between low salinity groundwater and saline tidal water occurs (Reilly and Goodman 1985). Exchange of solutes between natural tidal channels and adjacent groundwater and sediment has been examined in a number of studies (Harvey *et al.* 1987; Harvey and Odum 1990; Harvey and Nuttle 1995; Hughes *et al.* 1998;

Tobias *et al.* 2001). Lateral transport and exchange of solutes in these zones is typically in a highly dynamic state of quasi-equilibrium and is influenced by factors such as sediment hydraulic properties, potentiometric gradients, regional groundwater inputs, precipitation, evapotranspiration, elevation and tidal infiltration. Altering the balance of shallow groundwater inputs or outputs will cause an equilibrium shift, resulting in expansion, contraction and / or displacement of the freshwater - saltwater transition zone (Reilly and Goodman 1985). For example, in a wetland fringing a tidal creek Tobias *et al.* (2001) documented substantial changes in sediment salinity in response to seasonal variation in regional groundwater inputs. Excessive groundwater extraction can also cause extensive lateral seepage of salt into shallow aquifers on coastal floodplains (Howard and Mullings 1996; Mas-Pla *et al.* 1999).

Tidal forcing of adjacent groundwater is a common feature in coastal environments and can be an important mechanism of porewater movement in saturated and intertidal zones (Hughes *et al.* 1998). In shallow unconfined aquifers, tidal forcing can enhance the extent of saltwater ingress and can also alter the configuration of solute concentration contours, particularly near the top of the water table (Ataie-Ashtiani *et al.* 1999). Predictive modelling of saline seepage into unconfined coastal aquifers via tidal forcing is relatively complex. There are a number of potential sources of error, including heterogeneity in sediment hydraulic properties (Beven and Germann 1982; Schultz and Ruppel 2002) and failure to adequately integrate the effects of tidal fluctuations on hydraulic gradients (Serfes 1992). As result, tidally driven subsurface fluxes of groundwater are often ignored in groundwater flux estimates (Tobias *et al.* 2001).

With the exception of Indraratna *et al.* (2002), there have been few published studies examining lateral solute movement and tidal forcing adjacent artificial drains which become newly subjected to tidal influences through floodgate opening. This paper aims to characterise and document the effects of floodgate opening on the extent of tidal forcing and lateral solute transport in shallow groundwater adjacent to several tidal drains with contrasting geomorphology and sediment hydraulic properties. This information will be used to identify key factors which ideally should be assessed as part of any risk management strategy employed by floodgate managers prior to opening floodgates.

2. Site description

The study sites, Romiaka and Shark Creek, are located on the Clarence River coastal floodplain (Fig. 1). The large coastal floodplain (2600 km^2) is situated in an infilled river valley on the east coast of Australia (29^{o}30' S, 153^{o}15' E) and the estuary is regarded as a mature barrier system (Roy 1984). Infilling and formation of the floodplain during the Holocene postglacial marine transgression was characterised by bi-directional sedimentation, with terrestrial sediments accreting in a seaward direction in a low energy basin behind an expanding sand barrier of marine origin at the estuary mouth (Roy 1984). Both study sites consist of unconsolidated Holocene sediments and the aquifers examined in this study are unconfined and located within 1.5 m of the ground surface.

The Romiaka site is located on an alluvial plain on the south-eastern prograding edge of a deltaic island in the lower estuary, and is adjacent to a large tidal channel (Fig. 1c). The site is close to the ocean (6 km) and subject to strong marine influences during its geomorphic evolution, with high tidal energy and inputs of marine sediments from the coastal barrier. Fluvial sediments have been deposited during flood periods on top of largely sandy sub-sediments and the surface elevation of most of the site is 1-2 m Australian Height Datum (AHD; 0 AHD ~mean sea level). The adjacent Romiaka channel is generally saline (>30 dS m^{-1}) depending on seasonal flow conditions, and experiences semi-diurnal tides up to 1.4 m in range during spring cycles. Vegetation at the site is mostly sugar cane with fringing bands of salt marsh and mangroves adjacent Romiaka Channel. There are two main drains at the study site. The first drain (Tidal drain 1 – Fig. 1c), located between the sugar cane and fringing salt marsh, is connected to Romiaka channel and has been subject to tidal influence since it's initial construction (~pre 1980). The second drain is also connected to Romiaka channel and consists of three sections. The lower section is open to the main channel and subject to continual tidal influence (Tidal drain 2). The mid-section is located behind a set of one way tidal floodgates that prevent tidal influence, but which were opened periodically during this study (Transition drain). An upper section is located behind a second set of one way floodgates which remained closed during this study and was not subject to any direct tidal influence (Non-tidal drain).

The Shark Creek site is located in an acid sulfate soil (ASS) backswamp adjacent Shark Creek, a small tidal tributary on the Clarence River floodplain (Fig. 1d). The backswamp is isolated from Shark Creek by a narrow, fringing distributary levee (1 to 3 m AHD). The backswamp is an infilled estuarine sub-embayment with low surface elevations (<0.2 m AHD). The sub-embayment is bounded by sandstone upland to the east and west and is further from the ocean and was subject to less marine influence during infilling than the Romiaka site. A lower energy environment prevailed during infilling stages and backswamp sediments are mostly fine grained (Lin and Melville 1993). Backswamp soil texture in the sulfuric and upper sulfidic horizons is predominantly silty clay to clay, with cumulative particle size analysis showing over

92% (by mass) was smaller than 60 μm (Lin and Melville 1993). The backswamp soils are Hydraquentic Sulfaquepts (Soil Taxonomy, Soil Survey Staff 1998). Sulfidic sediments are typically found within 0.8 to 1 m below the ground surface in the backswamp (Lin and Melville 1993; Johnston *et al.* 2003c) and are overlain by a highly acidic sulfuric horizon with Fe (III) mineral and jarosite mottles. According to Lin and Melville (1993) infilling at this site occurred in three stages, firstly a saline, tidal stage in which a layer of pyrite rich sediments were deposited, followed by a brackish lagoonal phase and finally overbank fluvial deposition of freshwater sediments which formed the distributary levee. The formation of the distributary levee fringing Shark Creek by overbank deposition is an important feature because it effectively isolated the backswamp from direct tidal influence, even though the backswamp elevation is now ~0.4 m below local mean high water. The tidal range in Shark Creek is about 0.7 to 0.9 m during spring tide cycles and the salinity is often less than 10 dS m^{-1}, though it can reach 20-30 dS m^{-1} during low flow conditions. A large network of artificial drains has been constructed in the backswamp. The main drain was excavated through the distributary levee and discharges into Shark Creek via a culvert with floodgates.

3. Methods

3.1. Meteorological monitoring

At each site temperature and rainfall were recorded hourly or every 30 minutes with an EIT E-Tech automatic weather station (Fig. 1c and Fig. 1d). The mean annual ratio of rainfall (P) to evapotranspiration (ET) by the coast at Yamba is 1.19 (30 year mean - assuming ET = 0.8 x pan-evaporation, Australian Bureau of Meteorology, unpub. data). Annual rainfall on the lower Clarence floodplain tends to decrease with increasing distance inland. At Grafton (approx. 40 km from the coast) the ratio of P to ET is 0.81.

3.2. Groundwater and drain water monitoring

A series of 5.5 cm diameter, partially screened PVC piezometer wells were installed at each site perpendicular to the drains. Well location, spacing and screen intervals are provided in Table 1. Water level measurements were recorded in each well every 30 minutes or hour using a Dataflow capacitance probe and 392 logger (precision +/- 0.001 m; accuracy +/- 0.02 m). Dataflow capacitance probes were surveyed to AHD, freshly calibrated prior to installation and cleaned / re-calibrated every 60-90 days. Groundwater electrical conductivity (EC), temperature and water level were also logged at hourly or 30 minute intervals in selected wells using a Greenspan CTDP300 submersible data logger (SDL). The wells housing each CTDP300 consisted of 10 cm diameter PVC with a screened interval situated to bracket the zone in which the greatest water level fluctuations were deemed likely to occur (Table 1). Drain water levels were recorded at drain monitoring stations (Fig. 1c and Fig. 1d) using a Dataflow capacitance probe and 392 logger housed in a slotted PVC pipe surveyed to AHD. Hourly measurements of drain water EC, pH, dissolved oxygen (DO) and temperature were made at each drain monitoring station with a Greenspan CS304 SDL. Each CS304 was housed in a slotted 10 cm diameter PVC pipe and positioned as close to centre channel as possible. EC was measured via a toroidal sensor, pH using a double junction Ag/Cl electrode and DO via a diffusion rod. The SDLs were cleaned, maintained and calibrated every 28-32 days.

3.3. Groundwater field measurements, sample collection and analysis

Groundwater EC and pH was measured *in-situ* in the piezometer wells at the Romiaka site on a regular basis using freshly calibrated portable field equipment (TPS 90FLMV). At the Shark Creek site, groundwater samples were extracted periodically from the sulfuric horizons in freshly excavated 5 cm diameter unlined wells using a hand pump. Groundwater in each well was pumped continuously for several minutes immediately after excavation until largely free of suspended sediment. The pH, EC, ORP and temperature were immediately measured using freshly calibrated portable field equipment (TPS 90FLMV). A minimum of two 250 ml sub-samples were collected in clean polyethylene bottles thoroughly pre-rinsed with the sample water a minimum of 4 times. Visible air bubbles were excluded prior to sealing the cap and samples placed in cold storage (~4^{o} C). One 250 ml sub-sample was analysed for titratable acidity to pH 5.5 (APHA 2310B - including the peroxide oxidation step) within 24 hrs of sample collection. One 250 ml sub-sample was selected for further chemical analysis, and analysed for total Fe and total Al (ICPAES - USEPA 6010), dissolved Fe and dissolved Al (0.45 µm filtration, ICPAES - USEPA 6010), Cl^- and SO_4^{2-} (Ion chromatography - AHPA 4110).

3.4. Soils and hydraulic conductivity

Soil cores were collected at Romiaka adjacent the piezometer transects using a hand auger. Cores were spaced at 0.5, 1.5, 2.5, 4, 6 and 10 m from the drain, profiles described according to McDonald *et al*. (1990) and the soil surface surveyed to AHD. Soil samples were collected at 0.05 m, 0.2 m and every 0.2 m thereafter to a depth of ~1.5 m. Select cores were also sampled at Shark Creek. Soil samples were oven dried at 85^{o} C within 48 hrs of collection and crushed to pass a 2 mm sieve. The EC of a 1:5 water extract was determined for each sample (Rayment and Higginson 1992). Particle size analysis was conducted on select samples from the Romiaka site using the method of Lewis and McConchie (1984).

The saturated hydraulic conductivity (K_{sat}) was assessed using auger hole slug tests (Bouwer and Rice 1976; Bouwer 1989). Tests were conducted in the piezometer wells at Romiaka. At Shark Creek slug tests were conducted in 5.5 cm diameter PVC wells that were placed in freshly hand augured, close fitting boreholes. A rubber collar was placed on the outside of the PVC well immediately above the slotting zone to obtain a tight seal with the bore hole and prevent preferential downward water flow along the well sides. The slotting zone was positioned within the sulfuric horizons. The slug was withdrawn by rapid hand pumping and the water level recovery rate recorded at two second intervals using a freshly calibrated 1.0 m capacitance probe (Dataflow 392). At least three replicate tests conducted in each well and K_{sat} was calculated using the method of Bouwer (1989).

At Shark Creeks the saturated hydraulic conductivity of the upper sulfuric horizons was also assessed using shallow pit bailing methods (Bouwer and Rice 1983). Shallow rectangular pits (about 0.5 m deep and 0.5 m^2) were excavated in each backswamp adjacent to slug test boreholes. Tests were conducted when the backswamp groundwater table was 15 - 30 cm below ground surface. Pit dimensions and the equilibrium water level before bailing were recorded. The water was bailed rapidly using a 10-L bucket to remove ~50-90% of the total water in the pit. Water level recovery was measured every 5 seconds on a ruler with 1-mm graduations. Two tests were conducted in each pit. K_{sat} was calculated according to the methods of Bouwer and Rice (1983),

3.5. EM38 surveying

A number of studies have successfully used EM38 measurements to determine rootzone salinity in areas with shallow saline water tables (Slavich and Peterson 1990; Bennett and George 1995). An EM38 can be used to obtain data over broad areas relatively rapidly. Line transect surveys were conducted perpendicular to the drains using a

Geonics EM38 electromagnetic induction soil conductivity meter, which was operated in accordance with the manufacturers instructions (McNeill 1986). The EM38 has a coil spacing of 1 m and measures apparent soil electrical conductivity (EC_a) in mS m^{-1} in either a vertical (EC_aV) or horizontal (EC_aH) dipole orientation. The mean of the EC_aV and EC_aH readings was calculated to provide a more uniform integration of soil profile EC_a variation (Slavich 1990).

4. Results and discussion

4.1. Romiaka tidal drain 1

The stratigraphy and soil salinity at the piezometer transect adjacent Romiaka tidal drain 1 (R1) are shown in Fig. 2. Soil texture varied substantially down the profile (Fig. 2a). However, while the sandy sub-soils were relatively uniform with an average of 71% by mass (SE = 0.2%, n=12) in the fine to medium-sand size classes (125-500 μm), they still contained a substantial fraction (23%) of finer material (<60 μm). The sandy sub-soils had an apedal massive structure with no visible macropores. The hydraulic conductivity of the sub-soils at transect R1 was relatively low given the texture (Table 2), which may be a result of fines blocking pore spaces around sand grains and the lack of structure.

There was high soil salinity within about 4 m of the drain, particularly in the elevation range of 0.4 to 0.0 AHD, which corresponds with the inter-tidal range and the light clay and peat layer (Fig. 2b). It is possible that this light clay and peat layer may represent a buried salt marsh surface. Soil salinity decreased rapidly between 6 to 10 m from the drain. Spring tides in Tidal drain 1 can exceed 0.8 m AHD, leading to infrequent overtopping and infiltration of saline water within 4-6 m of the drain. Maximum soil EC_e values at this transect (estimated using the method of Slavich and Peterson, 1993) are in excess of 35 dS m^{-1}. There was a good agreement between soil EC (Fig. 2b) and the mean EC_a determined from EM38 measurements (Fig. 2c). This was consistent at all the Romiaka site locations for which paired soil and EM38 sampling was conducted, with a strong positive linear correlation ($r^2 = 0.90$, n=18) observed between mean soil EC (1:5 extract) in the upper 1 m of the profile and mean EC_a.

Tidal forcing of the shallow groundwater in response to the tidal signal in the adjacent drain was observed to a distance of at least 10 m (Fig. 3). The tidal signal was not sinusoidal due to mud flats at an elevation of about 0.1 m AHD located near the drains outflow point. The groundwater level was highly responsive, with fluctuations in excess of 0.3 m per tidal cycle. The amplitude of forcing was attenuated with increasing distance from drain (Fig. 3). Mean potentiometric gradients were effluent during the period of observation (Fig. 4). This is an important feature which effectively limits the extent of salt seepage.

4.2. Romiaka transition drain

The stratigraphy and soil salinity adjacent Romiaka Transition drain (transect R2) are shown in Fig. 5. The elevation of this transect was higher and it had a thicker alluvial topsoil than transect R1 (Fig. 5a). There was also increasing sand content with depth, though the sandy sub-soils were generally coarser near the drain bank (Fig. 5a). Particle size analysis on the sandy sub-soils within 4 m of the drain bank showed an average of 87% by mass (SE = 0.3%, n=9) in the fine to medium-sand size classes (125-500 μm), but finer fractions (<60 μm) were still present and accounted for a mean of 9%. The sub-soils were apedal with a massive structure. The higher hydraulic conductivity at transect R2 compared to transect R1 accords with the slightly coarser nature of the sub-soils (Table 2).

Soil EC at transect R2 was highest within about 4 m of the drain (Fig. 5b) and was substantially lower that at transect R1. Fig. 5b is based on soil sampling undertaken before floodgate opening. The declining trend in soil EC between 6 to 10 m from the drain was similar to that observed at transect R1. The elevation of the saline-fresh transition zone at transect R2 approximately corresponds to the local intertidal range and may reflect long term low volume seepage of salt water from leakage though the floodgates into the transition drain.

Floodgates were opened for total of 57 days over a 71 day period allowing tidal water into the transition drain. Groundwater levels were monitored from about three weeks prior to the first opening. Tidal forcing was evident in groundwater up to 10 m from the drain before the floodgates were opened (Fig. 6a), though the closest possible tidal signal during this time was over 30 m away in Tidal drain 2. This suggests that tidal forcing may be a widespread feature in sandy sub-soils across this site. The amplitude of tidal forcing clearly increased immediately following floodgate opening and was attenuated with increasing distance from the drain (Fig. 6a). This also caused rapid, dynamic changes in groundwater gradients near the drain (Fig. 6b). While the drain water salinity increased from 15 dS m^{-1} to over 40 dS m^{-1} immediately after floodgate opening, there was very little change detected in groundwater EC at 4 m within the first few days of opening (Fig. 6c). Mean potentiometric gradients at transect R2 were effluent during monitoring periods while the floodgates were closed (Fig. 7a). However, floodgate opening caused a substantial change in mean potentiometric gradients, particularly near the drain, leading to influent conditions in the first few meters of the drain bank (Fig.7b).

Direct monitoring of groundwater EC adjacent to the Transition drain was confined to the piezometer wells at transect R2 and another adjacent, but unreported piezometer transect. Indirect monitoring of groundwater EC was undertaken using the EM38. A strong positive correlation was observed between paired groundwater EC and EC_aV measurements (Fig. 8). The regression equation accompanying Fig. 8 enabled the use of data from multiple EM38 transects to infer groundwater EC changes in response to floodgate opening / closure adjacent to the Non-tidal drain, Transition drain and Tidal drain 2 (Fig. 9). While there was a clear increase in groundwater EC over time in response to floodgate opening, increases were mainly confined to the first 4 m of the drain by 57 days (Fig. 9c). It is likely that if the floodgates had been left permanently open, the groundwater EC contours adjacent to the Transition drain would end up with a configuration akin to that observed in Tidal drain 2, which is exposed to, and presumably in dynamic equilibrium with, a continual tidal signal. Minimal change occurred in groundwater EC in either the Non-tidal drain or Tidal drain 2 during the opening period (Fig. 9). Once floodgates were closed again, for about 60 days during a period of flooding, much of the groundwater salts that had accumulated adjacent to the transition drain were leached from the profile (Fig. 9d).

4.3. Shark Creek

The stratigraphy at this site was relatively uniform with distance from the drain. While the backswamp soils were fine textured compared to Romiaka (Fig. 10a), there was very high hydraulic conductivity in sulfuric horizons (Table 2) due to flow through large tubular macropores (Johnston *et al.* 2002). The sulfuric horizons had moderate pedality (angular blocky) with fine, planar fissures evident. Many, medium to coarse tubular macropores with variable orientations were observed, and these were invariably lined with Fe (III) minerals or jarosite. Rapid, sustained inflow of groundwater was observed via these tubular macropores during repeat pit bailing experiments. Soil EC increased down the profile into sulfidic horizon (Fig. 11). EM38 surveying at transect M3 showed substantial increases in EC_a at distances greater than 50 m from drain after periods of floodgate opening (Fig. 10b).

The shallow groundwater was highly responsive to tidal increases in drain water levels, with forcing evident over 300 m from the drain during a four day floodgate opening event (Fig. 12a). During this floodgate opening event there were rapid, tidally modulated increases in shallow groundwater EC at a piezometer 10 m from the drain (Fig. 12b). Incoming tidal water was about 5 dS m^{-1} during this event and at 10 m from the drain the shallow groundwater EC increased from 1.6 to about 2.6 dS m^{-1} over the four days. Incoming tidal water was confined to the drain during this opening event and no surface overtopping occurred. This fast response in groundwater EC to sub-surface tidal infiltration is in marked contrast to that evident at Romiaka in Fig. 6. Shallow groundwater levels across this site are generally quite flat (Fig. 13a), which is partly a function of the high hydraulic conductivity of the sulfuric horizons. However, the floodgate opening event shown in Figure 12 altered potentiometric gradients, creating influent conditions during the opening phase (Fig. 13b) and slightly effluent conditions during the four days immediately after (Fig. 13c).

Floodgates were then opened for a longer period (58 days), but with a restricted opening size which limited the in-drain tidal amplitude to prevent overtopping of the low lying backswamp. Incoming tidal water was approximately 10 dS m^{-1} during this time. Large changes in shallow groundwater chemistry accompanied this longer period of opening. Increases in the $Cl:SO_4^{2-}$ ratio over 80 m from the drain indicates there was substantial infiltration of marine derived Cl^- from drain water into the adjacent shallow aquifer (Fig. 14). There was also an increase in groundwater EC and decreases in both SO_4^{2-} and dissolved Fe (Fig. 14).

In macropore dominated systems, individual pore velocities and solute transport can very rapid and extremely difficult to predict (Bouma 1991). Preferential flow and a degree of segregation in solute transport processes between matrix and macropore domains is also known to occur (Bouma 1991; Harvey and Nuttle 1995). Repeat soil sampling was not undertaken at this location after the longer floodgate opening event. Given that the groundwater sampling strategy employed in this study is likely to have preferentially drawn water from the macropore network, it is uncertain to what extent the changes in shallow groundwater chemistry were mirrored within the soil matrix itself.

Longer term monitoring at this site showed that drain water chemistry was strongly influenced by the seasonally variable potentiometric gradients. During wet periods, when maximum daily groundwater gradients were effluent, there was substantial outflow of acid groundwater to the drain resulting in low drain water pH values (Fig. 15). In contrast, influent groundwater gradients which developed during dryer periods were accompanied by circumneutral pH values.

5. General discussion and conclusions

The difference in the extent of lateral solute transport between the two sites is largely a function of very different sediment hydraulic properties and also the potentiometric gradients that developed in response to floodgate opening. The contrasting soil physical properties between the sites was a very important feature, which in turn was closely related to their different geomorphic history.

Romiaka displayed significant tidal forcing, but limited lateral transport of salt water from the drain. Potentiometric gradients indicate regional groundwater was mostly discharging during the period of monitoring which limited the ingress of saline drain water. The higher elevation of this site (above local high tide) and the fact that long term rainfall is in excess of evapotranspiration, both encourage a higher water table and thus effluent trending gradients. While the higher energy deposition environment at this site associated with proximity to the coastal barrier led to the sub-sediments being coarse textured, the lack of structure and presence of some fines resulted in relatively low - moderate K_{sat} values, further limiting saltwater ingress. A further significant feature of this site is its proximity and exposure to an ongoing tidal signal from the nearby tidal channel. The shallow groundwater at this site was already being influenced by a tidal signal prior to floodgate opening and thus was more likely to be in a state of partial dynamic equilibrium with tidal influences.

In contrast, floodgate opening at Shark Creek backswamp caused extensive and rapid lateral transport of solutes from the drain, as well as substantial tidal forcing across aquifer. While the ASS are fine textured, the sulfuric horizon exhibited a higher degree of structure than the sub-sediments found at Romiaka and also contained an extensive macropore network. This resulted in extremely high K_{sat} values, which according to a theoretical comparison solely on the basis of texture, are approximately equivalent to what might be expected from very coarse, well sorted clean sand or even gravels (Boulding 1995). The lower elevation of the backswamp surface at Shark Creek (below local high tide) and the fact that long term rainfall decreases with distance from the coast, both encourage a lower water table relative to local tides, and thus a greater probability of influent trending groundwater gradients being creating during floodgate opening. The Shark Creek backswamp was cut-off from tidal action by the formation of the natural distributary levee at some point after sea level stabilisation following the last post-glacial marine transgression (Lin and Melville 1993). Despite the high hydraulic conductivity of the backswamp sulfuric horizons, no tidal forcing is evident in the shallow groundwater solely in response to the tidal signal in Shark Creek (i.e. independent of the floodgate opening events). This behaviour points to the possible existence of semi-confining layers with lower hydraulic conductivity existing between Shark Creek and the backswamp, perhaps beneath the natural levee. Therefore, the re-introduction of a tidal signal into this backswamp via artificial drains represents a significant change in the balance of groundwater inputs, as this site is not in dynamic equilibrium with tidal influences.

5.1. Practical implications for opening floodgates

This study highlights the importance of adequate site assessment, particularly of soil hydraulic properties, prior to opening floodgates. This is particularly relevant to ASS backswamps where differences in soil hydraulic properties can be extreme. The hydraulic conductivity of sulfuric horizons is known to be highly variable, owing to the unique chemical and physical ripening processes that accompany drying and oxidation of sulfide minerals, and the potential existence of macropores (Bouma *et al*. 1993). A compilation of recent investigations in a variety of ASS backswamps on coastal floodplains in eastern Australia confirms this variability, with values ranging over three orders of magnitude (Table 3). In unconsolidated floodplain sediments estimates of K_{sat} based on soil texture alone may be highly misleading, as this does not account for variations in soil structure or the existence of macropores. The vertical variation in soil hydraulic properties down the profile relative to the local tidal range is also an important consideration. Previous work has demonstrated the attenuating influence that semi-confining layers can have upon groundwater flux and solute transport (Schultz and Ruppel 2002). The potential existence and effects of such layers at the drain bank face, due to chemical (i.e. Fe III clogging) or physical (smearing, detrital acumulation) processes, requires further attention.

In theory it would be ideal to conduct sophisticated modelling prior to opening floodgates at each site in order to predict the likely extent of tidal forcing and lateral solute movement in adjacent shallow groundwater. However, given the complexity of inputs required, the costs associated with obtaining reliable data and the difficulties of accurately modelling solute transport in macropore dominated systems, this is not likely to be a practical broad scale solution. There are many thousands of kilometres of floodgated drains on coastal floodplains in eastern Australia and floodgate opening is becoming increasingly promoted and used as a water quality management strategy (Johnston *et al*. 2003b). An alternative to predictive modelling may be a simple hazard ranking process. This could be based on information that is either already available or relatively easy to obtain including,

- field based assessment of sediment physical and hydraulic properties
- land surface elevations relative to local tidal range
- local groundwater table ranges
- local climatic data (P, ET)
- before and after EM38 monitoring.

Such information, when combined with a cautionary, adaptive management approach, may prove to be a simple and cost effective means of managing risks of saline seepage associated with floodgate opening.

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Table 1
Piezometer well identification, horizontal spacing and slotting screen intervals.

Location / transect no.	Well no.	Distance[A] (m)	Screen interval (m AHD)
Romiaka site			
R1	R1-1	0.5	-0.58 to -0.98
	R1-2	1.5	-0.44 to -0.84
	R1-3	2.5	-0.42 to -0.82
	R1-4	4.0	-0.45 to -0.85
	R1-5	6.0	-0.47 to -0.87
	R1-6	10.0	-0.39 to -0.79
R2	R2-1	0.5	0.16 to -0.25
	R2-2	2.5	-0.03 to -0.43
	R2-3	4.0	0.05 to -0.35
	R2-3WQ[B]	4.0	0.66 to -0.14
	R2-4	10.0	0.34 to -0.06
Shark Creek site			
M1	M1-1	2.0	-0.40 to -1.20
	M1-2	10.0	-0.36 to -1.16
	M1-3	63.0	-0.24 to -1.04
	M1-4	335	-0.32 to -1.12
	M1-5	410	-0.10 to -0.90
M2	M2-6	2.0	-0.10 to -0.80
	M2-7WQ[B]	10.0	0.12 to -0.58
	M2-8WQ[B]	25.0	0.08 to -0.62

[A] All distances relative to the edge of adjacent drain bank.
[B] Groundwater water quality and water level monitoring well.

Table 2

Mean saturated hydraulic conductivity values at the study sites. See Methods for details regarding the soil horizons these data apply to.

Location	Mean K_{sat} (m day^{-1})	SE[A]	n
Romiaka – R1[B]	0.36	0.08	13
Romiaka – R2[B]	0.89	0.18	16
Shark Creek[B]	125	14	10
Shark Creek[C]	184	37	7

[A] Standard error.

[B] Bouwer and Rice, 1976; Bouwer, 1989.

[C] Bouwer and Rice, 1983.

Table 3

Comparing the hydraulic conductivity of the sulfuric horizons in some ASS backswamps located in coastal floodplain environments in eastern Australia.

Site / Coastal River	K_{sat} range (m day^{-1})[A]	Test method	Source
Pimpama / Pimpama	~0.4	Constant head	(Rassam *et al.* 2002)
McLeods Creek / Tweed	~0.8	Auger hole	(White and Melville 1993)
Broughton Creek / Shoalhaven	~1 - 8	Falling head	(Blunden 2000)
Clybucca / Macleay	13 - 22	Pit bailing[B]	(Morris unpub. data)
Rossglenn / Hastings	~14	Pit bailing[B]	(Aaso unpub. data)
Everlasting Swamp / Clarence	9 - 17	Pit bailing[B] / auger hole[C]	(Johnston *et al.* 2004)
Tuckean Swamp / Richmond	52 - 178	Auger hole[C]	(Johnston unpub. data)
Partridge Creek / Hastings	82 - 272	Pit bailing[B] / auger hole[C]	(Johnston *et al.* 2003d)

[A] Note: This data is provided to demonstrate the variability range of K_{sat} values encountered in coastal ASS in eastern Australia. Caution should be applied when interpreting or extrapolating this data due to the different methods used, different sampling intensities and the high degree of spatial heterogeneity in hydraulic conductivity.

[B] Bouwer and Rice 1983.

[C] Bouwer and Rice 1976.

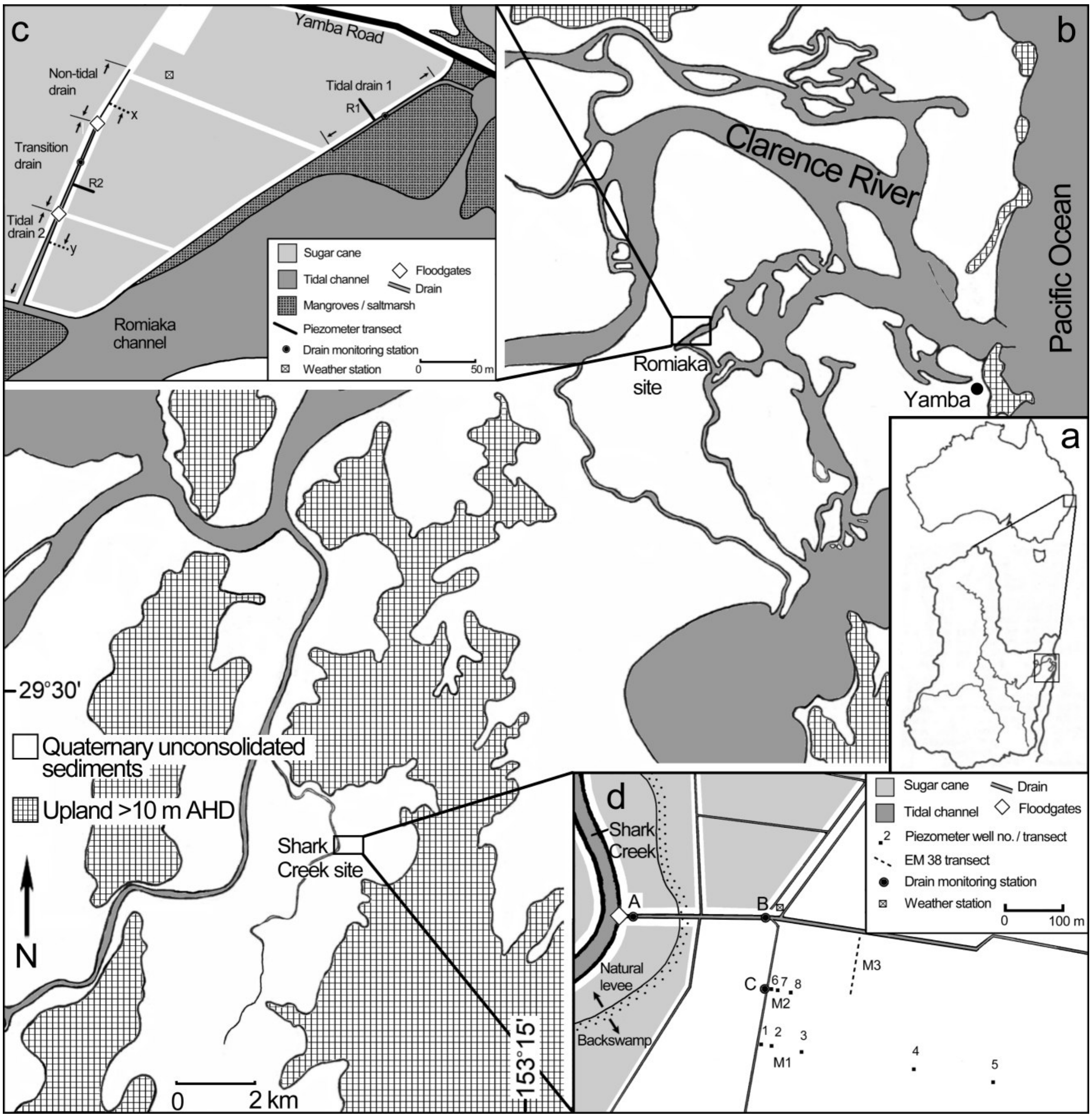

Fig. 1. a) Location of Clarence River catchment, b) the lower Clarence River floodplain – showing unconsolidated Quaternary sediments and upland areas, c) Romiaka and d) Shark Creek study sites.

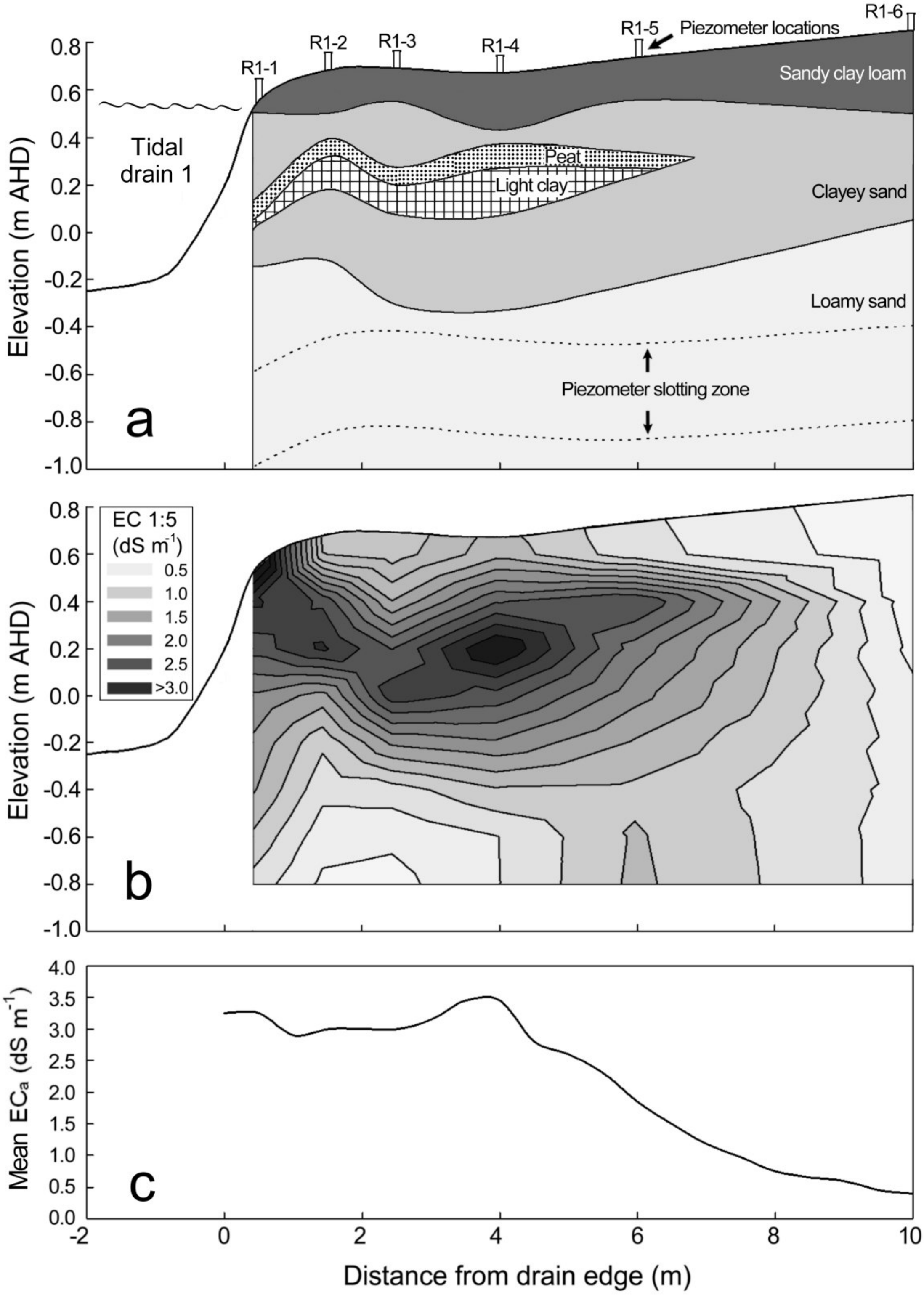

Fig. 2. Romiaka transect R1 a) stratigraphy, piezometer well locations and piezometer slotting zone, b) soil EC (1:5 extract) and c)mean EC_a in relation to distance from the drain. Soil EC contours based on linear interpolation (n = 48).

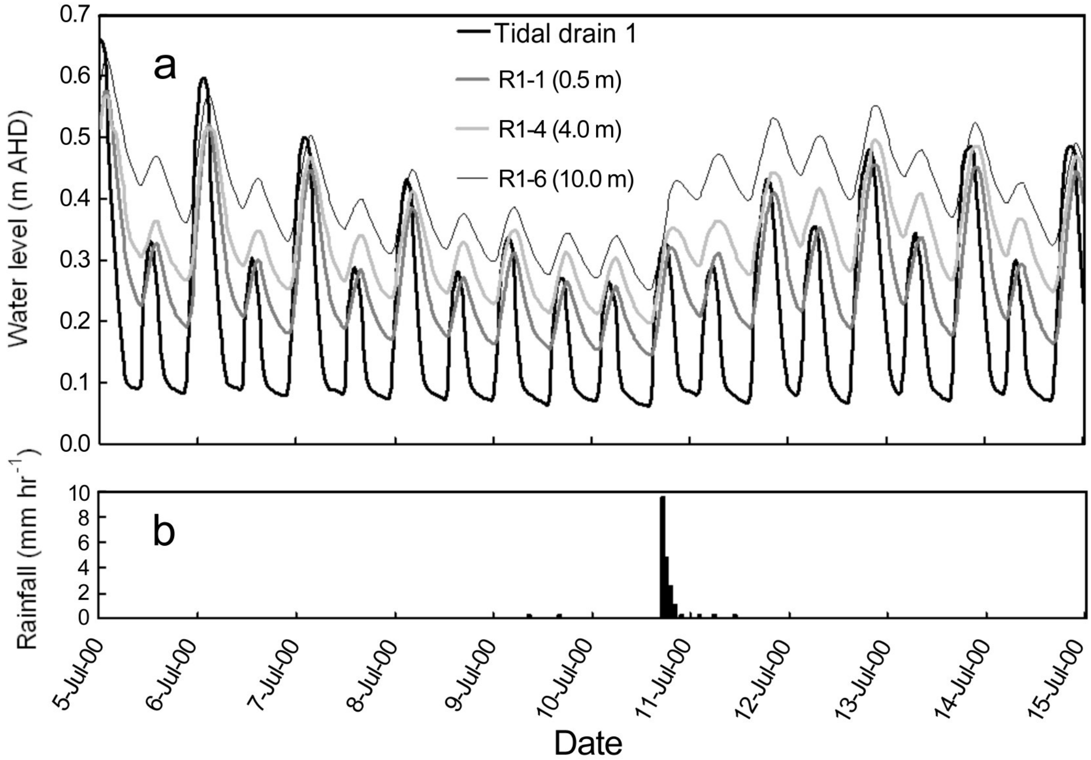

Fig.3. a) Tidal forcing in shallow groundwater over a 10 day period at transect R1 and b) hourly rainfall.

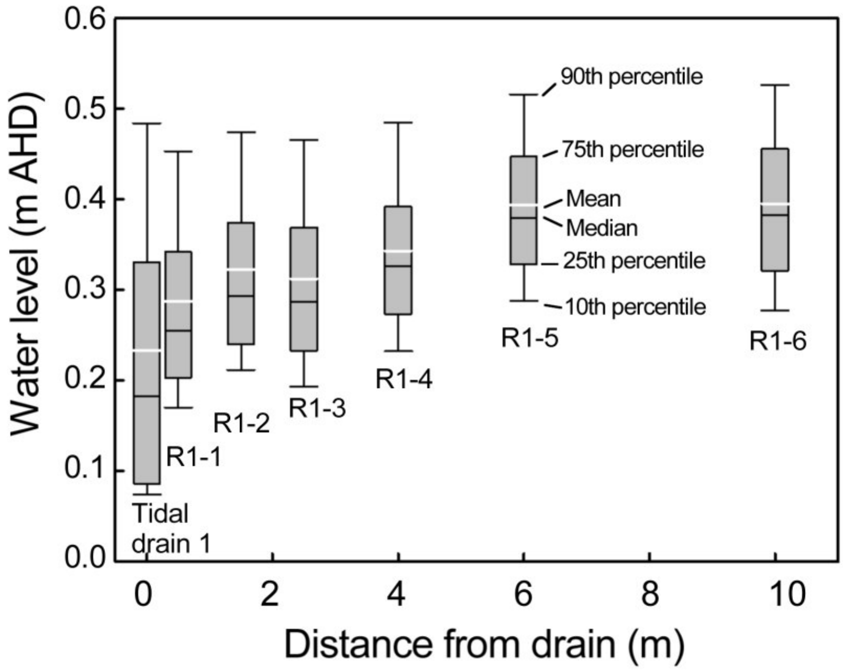

Fig. 4. Water level dynamics in Tidal drain 1 and piezometers at transect R1 over a 30 day period from 1 to 30 June 2000.

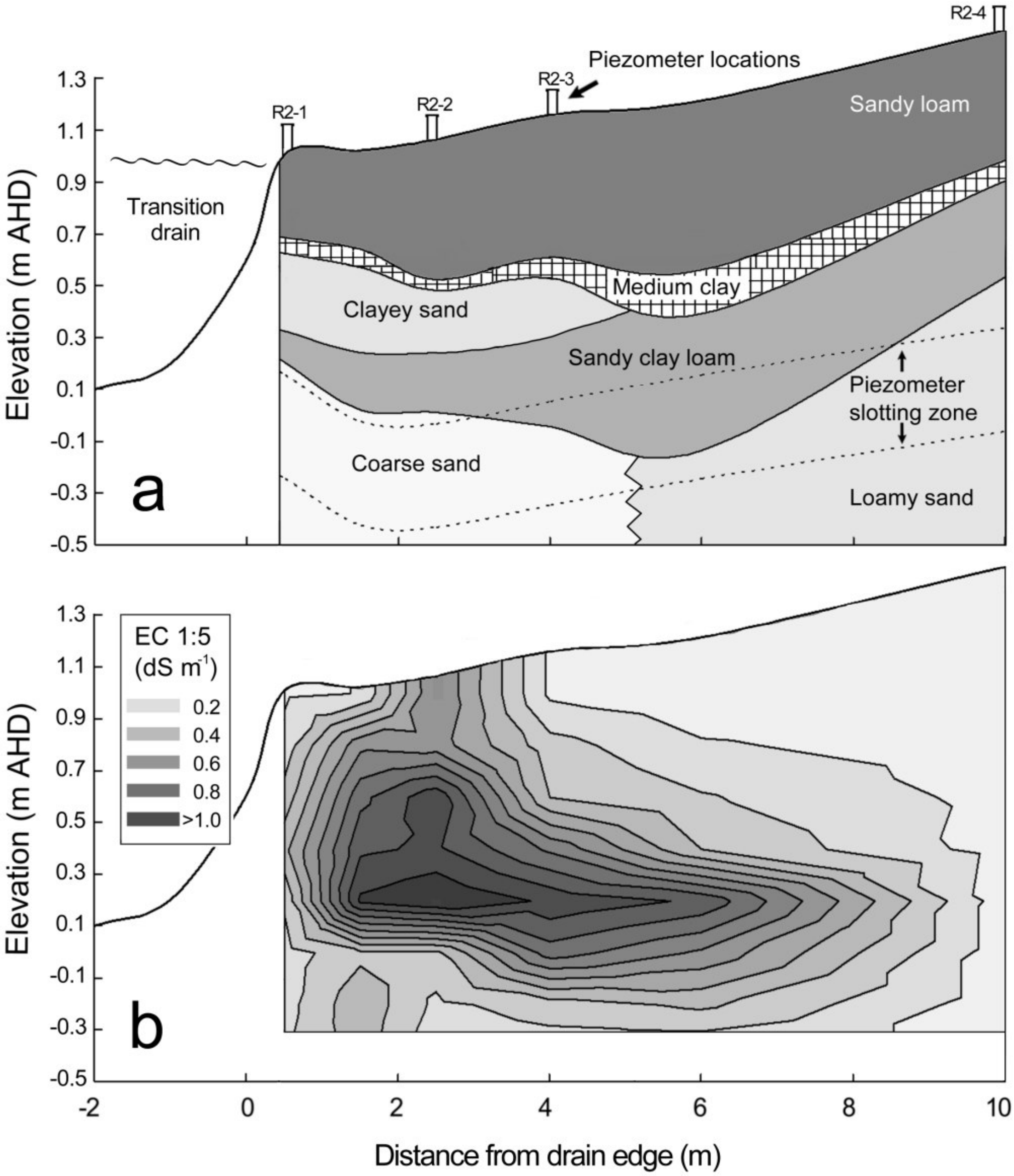

Fig. 5. Romiaka transect R2 a) Stratigraphy, piezometer well locations and piezometer slotting zone and b) soil EC (1:5 extract) in relation to distance from the drain. Soil EC contours based on linear interpolation (n = 48) of sampling undertaken before floodgate opening.

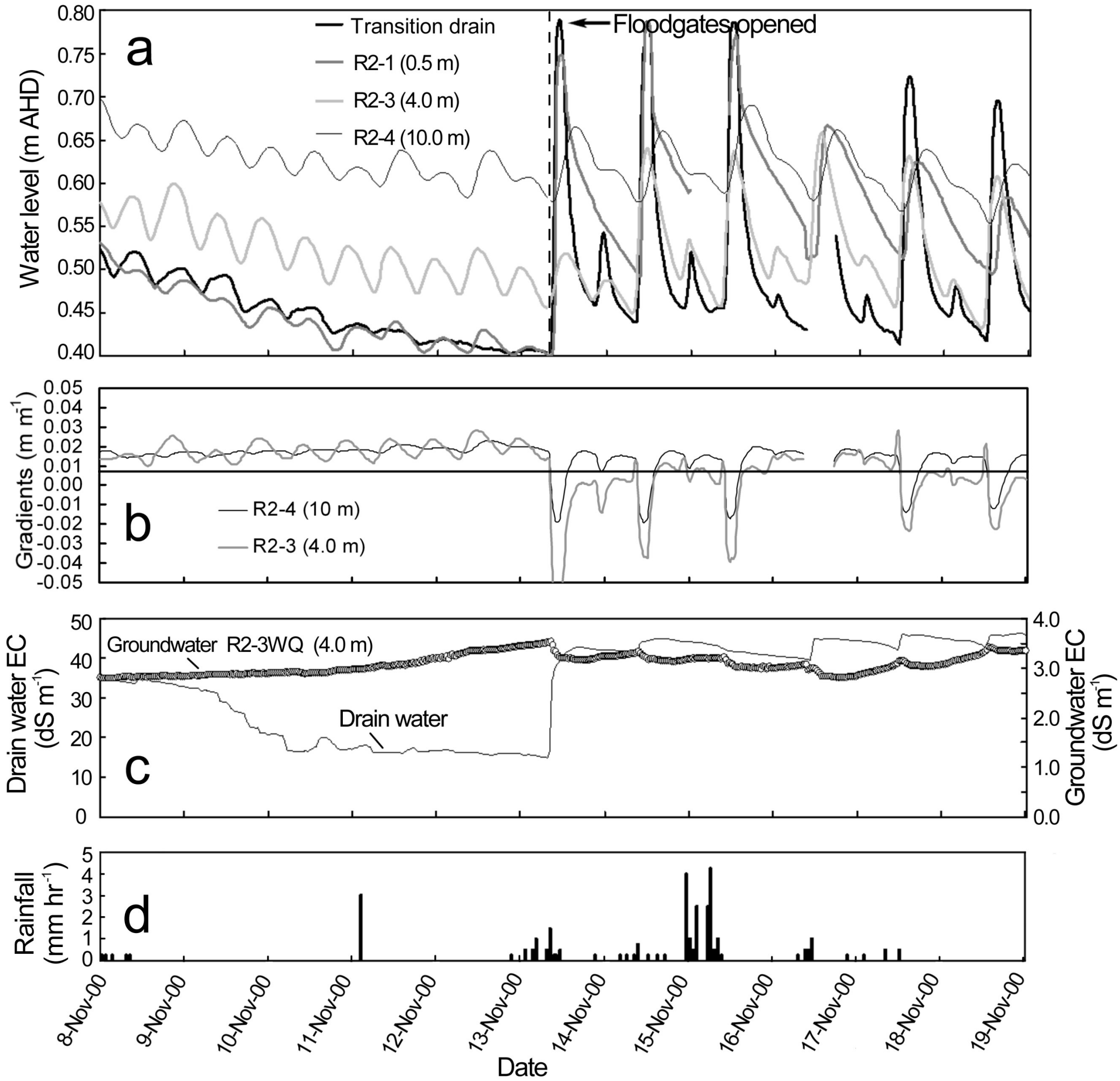

Fig. 6. a) Tidal forcing in shallow groundwater over an 11 day period at transect R2 immediately before and during floodgate opening, b) changes in groundwater gradients at 4 and 10 m from the drain, c) changes in drain water groundwater EC and d) rainfall.

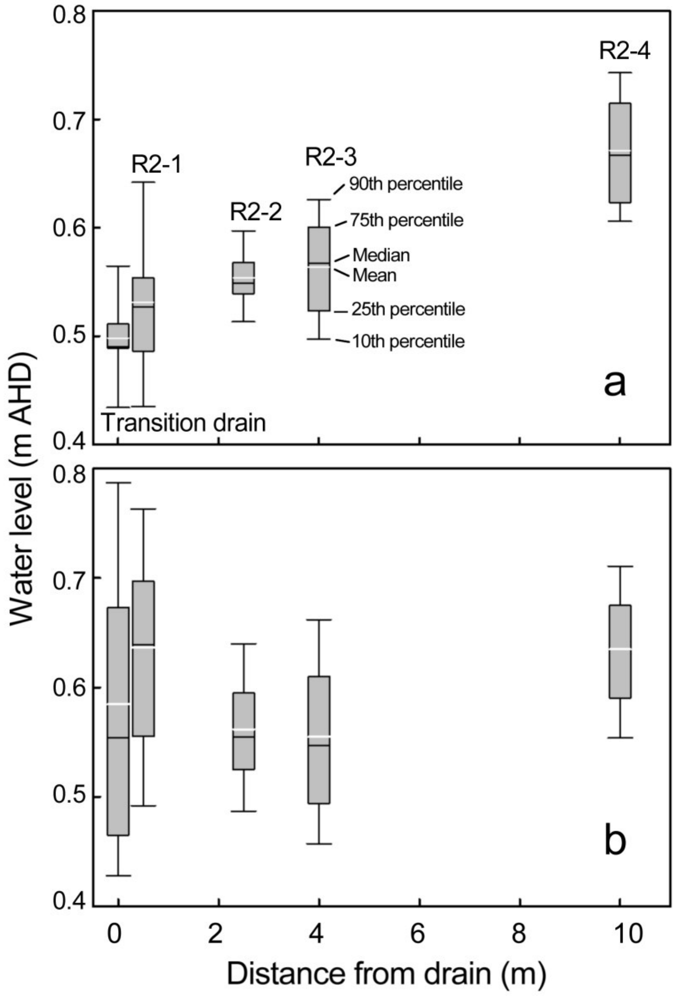

Fig.7. Water level dynamics in the Transition drain and transect R2 piezometers during a) periods of floodgate closure (n = 22 days) and b) periods of floodgate opening (n = 57 days).

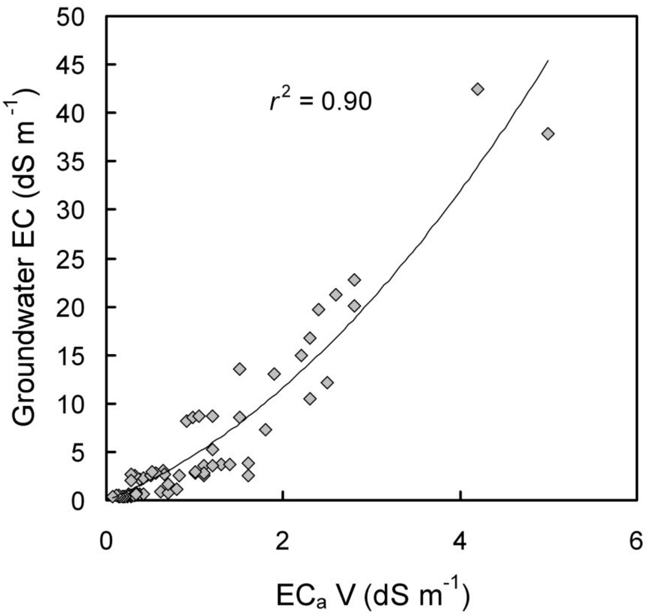

Fig. 8. Correlation between EC_a V and groundwater EC, before and during floodgate opening adjacent the Transition drain.

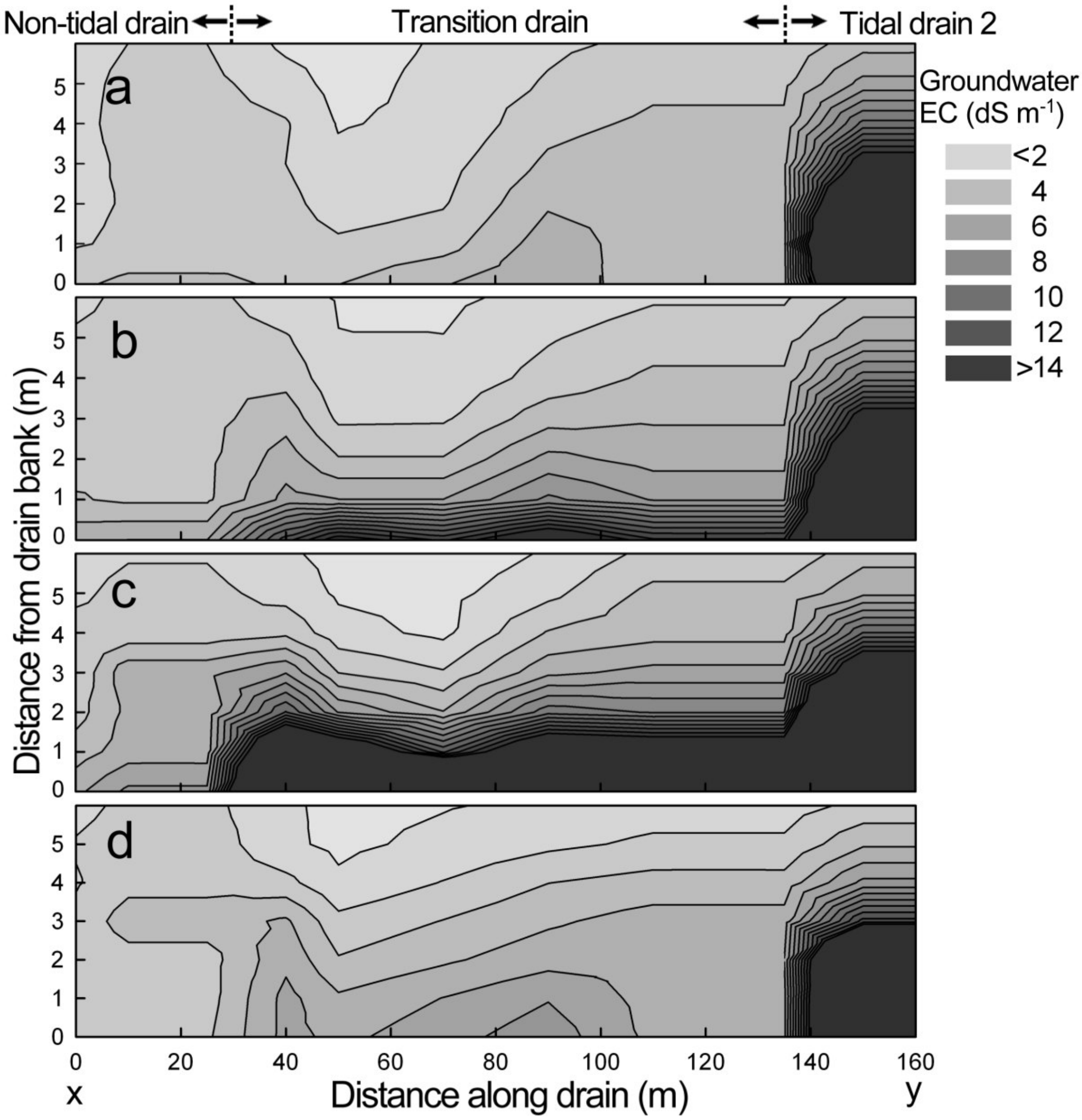

Fig. 9. Changes in groundwater EC adjacent Romiaka Non-tidal drain, Transition drain and Tidal drain 2 a) before floodgate opening, b) after 16 days of floodgate opening, c) after 57 days of floodgate opening and d) 60 days after floodgates were closed following flooding. The groundwater EC is inferred using EM38 measurements (see Fig. 8). Linear interpolation between points (n = 77). See Fig. 1c for location of x and y.

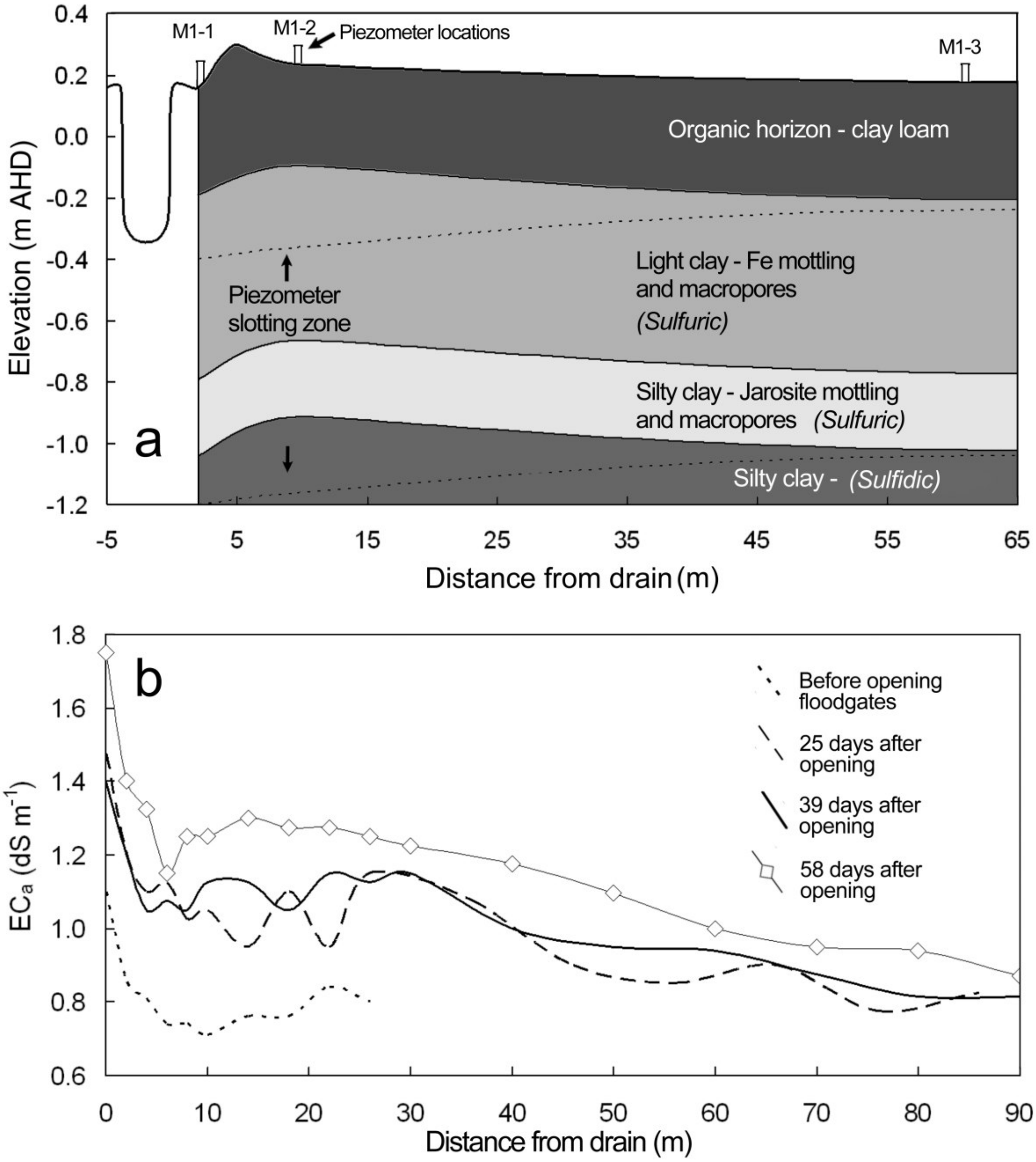

Fig. 10. a) Stratigraphy at Shark Creek transect M1 and b) mean EC_a at transect M3 before and after floodgate periods of opening, in relation to distance from the drain. The floodgate opening size was restricted to prevent any overtopping of the backswamp surface, thus the increases in EC_a are due to sub-surface flow of saline drain water into the aquifer (see Fig. 13).

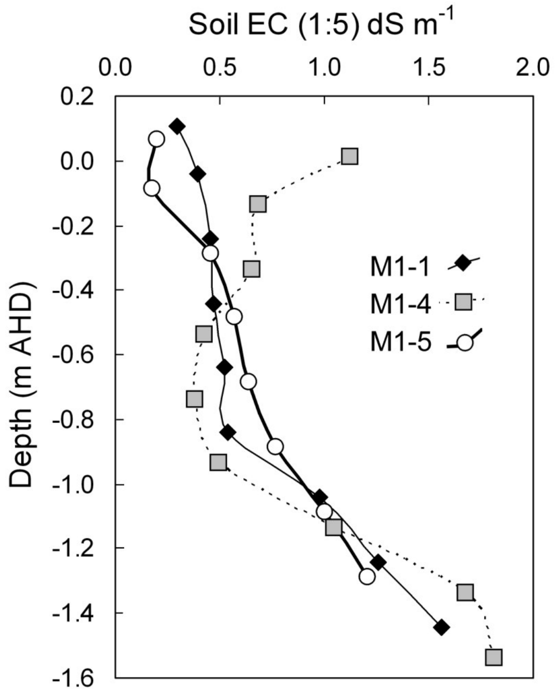

Fig. 11. Changes in soil EC (1:5 extract) with depth at profiles M1-1, M1-4 and M1-5. Sampled prior to floodgate opening.

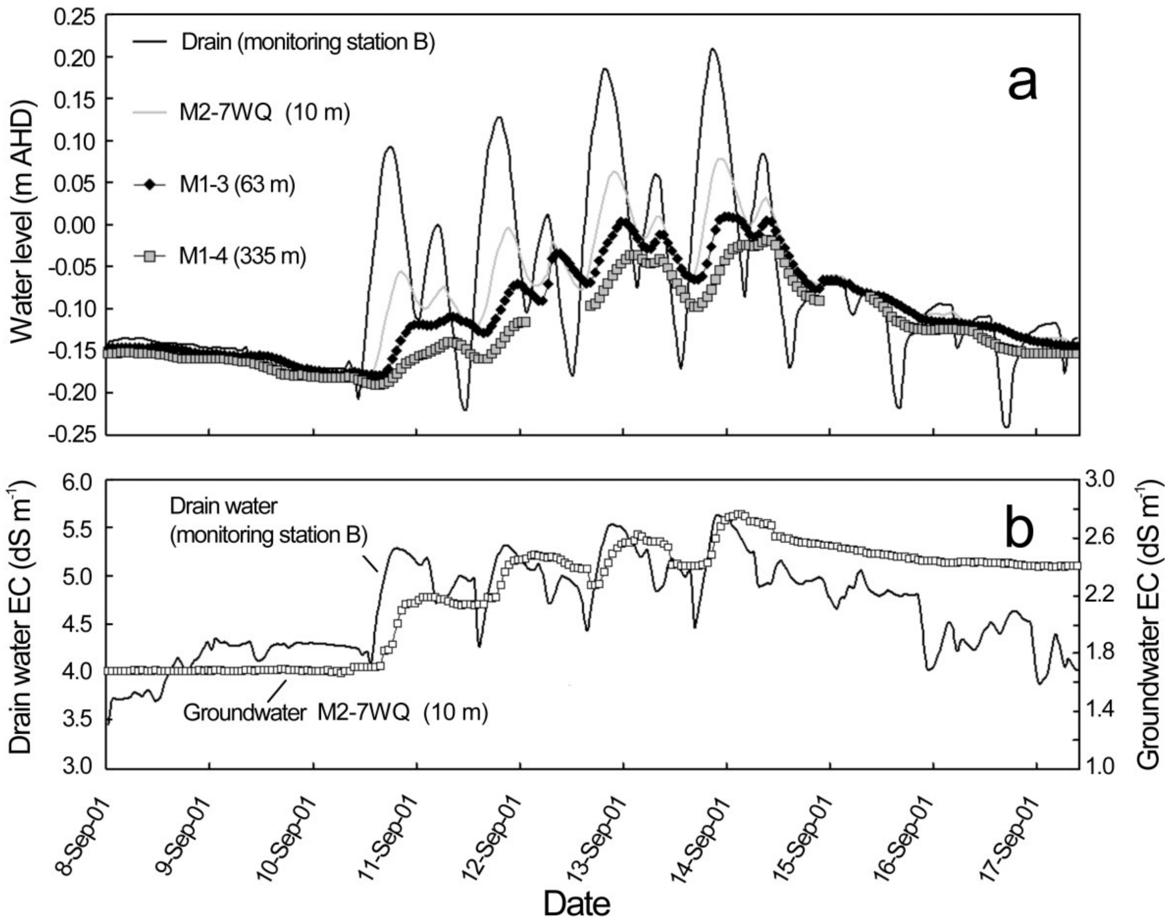

Fig. 12. a) Tidal forcing of shallow groundwater at Shark Creek during a four day floodgate opening event and b) tidally modulated changes in drain water and groundwater EC.

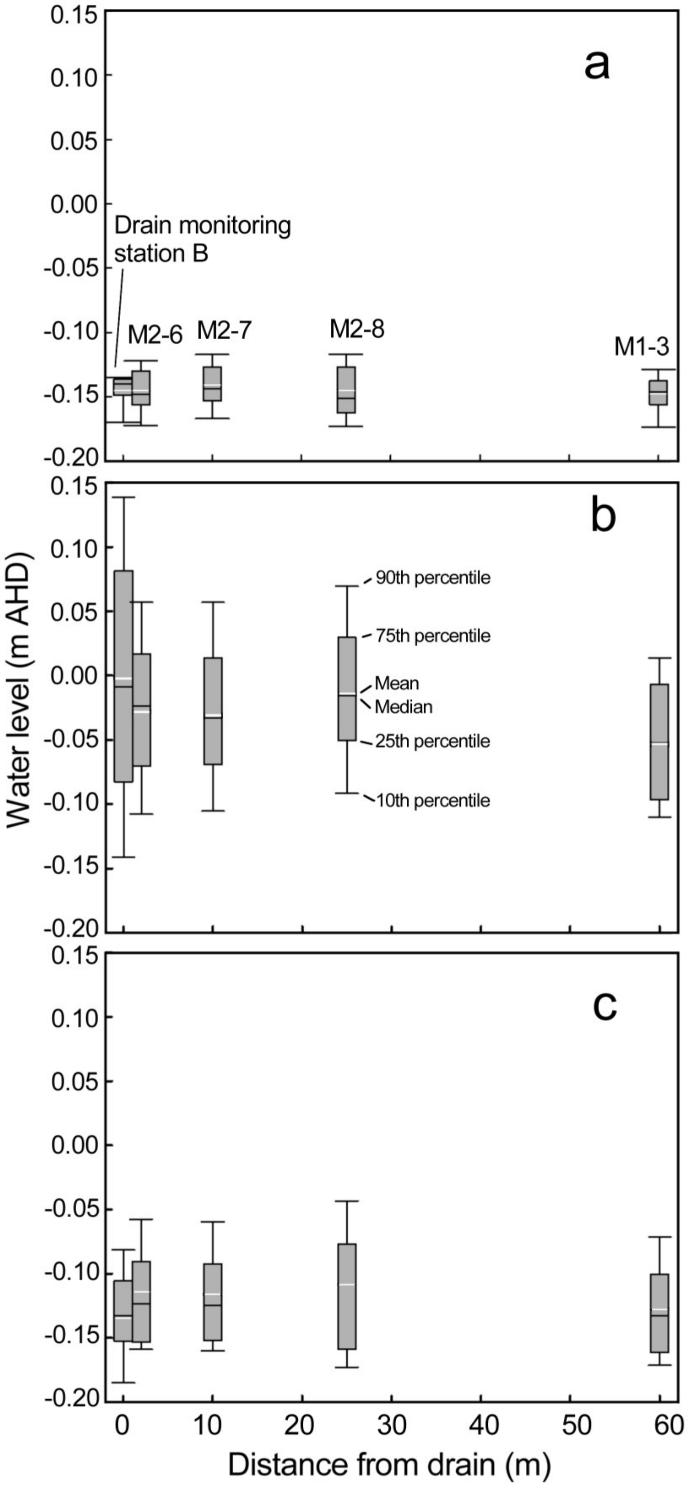

Fig. 13. Drain and groundwater level dynamics at Shark Creek a) four days before floodgate opening, b) during floodgate opening and c) four days immediately after floodgate opening. Based on the floodgate opening event shown in Fig. 11.

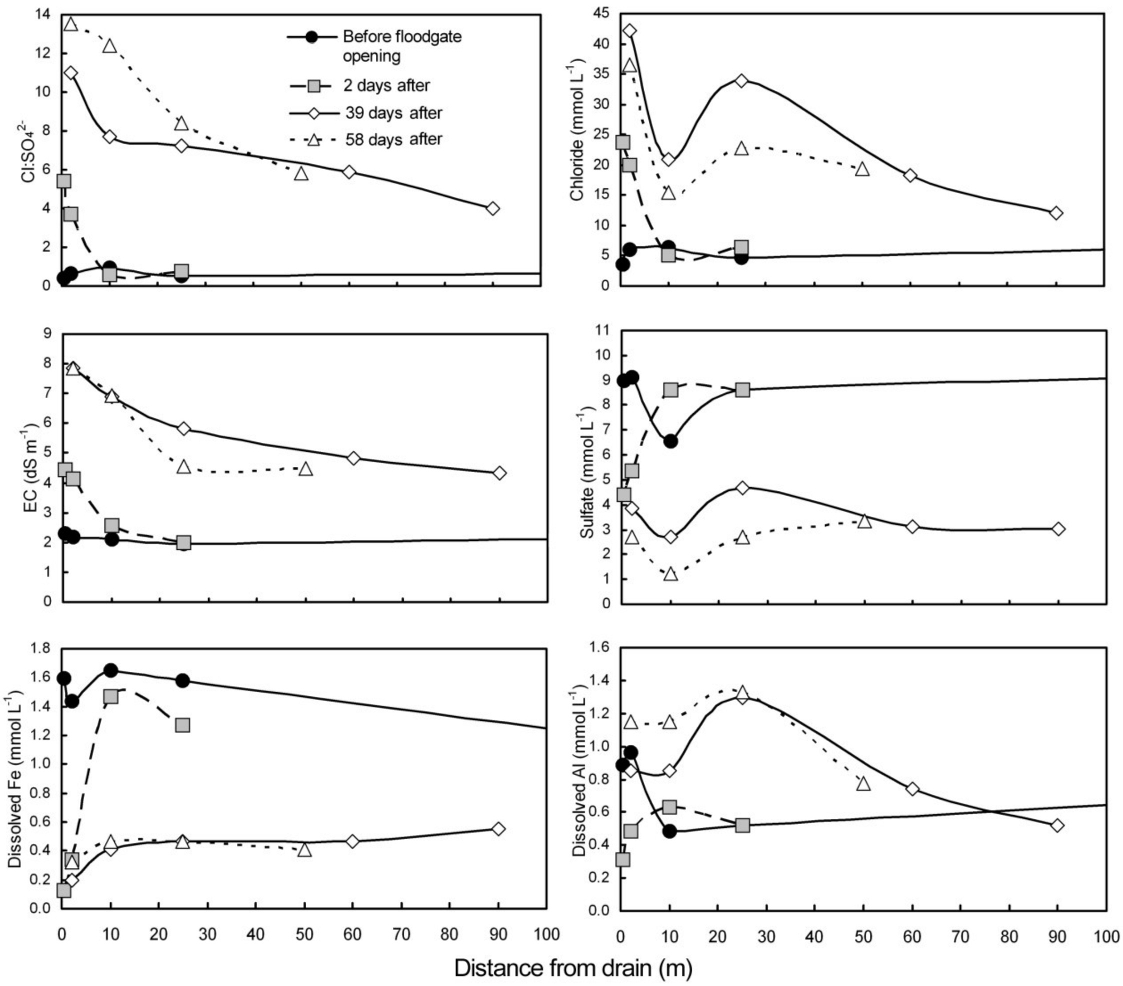

Fig. 14. Changes in the chemical composition of shallow groundwater at Shark Creek backswamp in relation to distance from the drain, before and after periods of floodgate opening. Ratios are based on molar concentrations. Note: the floodgate opening size was restricted and no overtopping of the backswamp surface occurred during the opening periods.

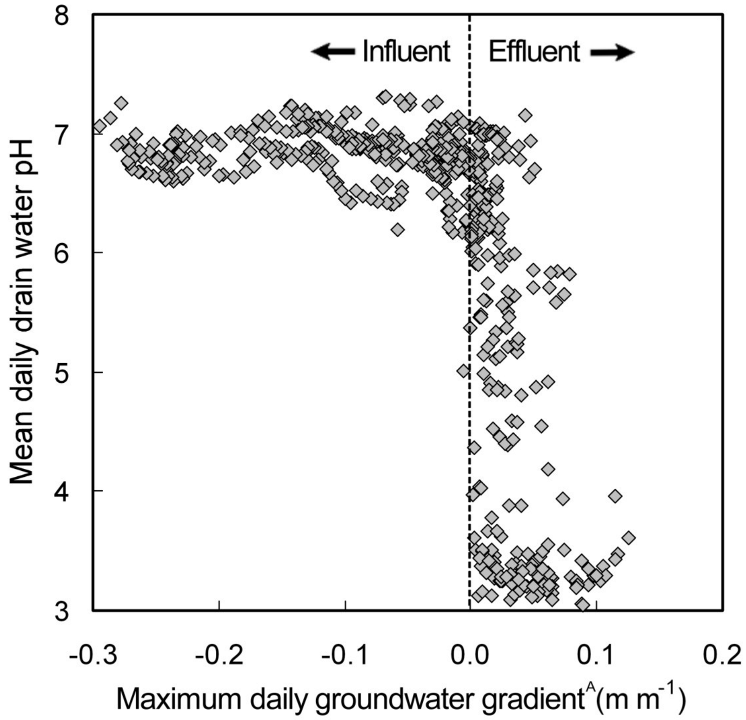

Fig. 15. Mean daily drain water pH values in relation to maximum daily groundwater gradients. pH values are the 24 hr mean from the SDL at monitoring station A. Data shown is from periods when the mean daily groundwater level (mean of M1-1 and M1-2) was below the ground surface, between December 2000 and March 2003. Influent groundwater gradients develop during dry periods. [A] = the difference between the mean daily groundwater level and the minimum daily water level at drain monitoring station B, assuming a horizontal distance of 2 m.