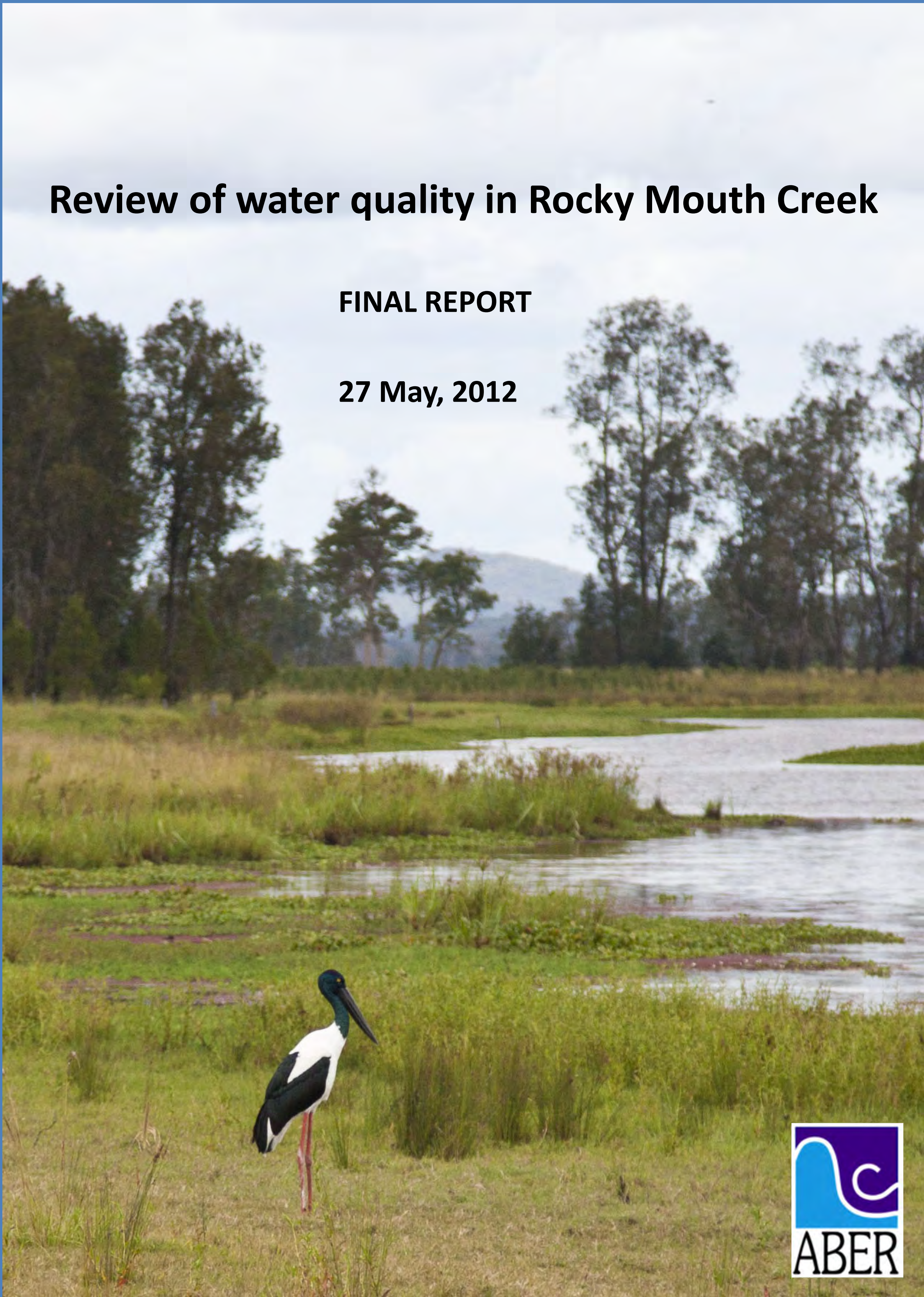
Review of water quality in Rocky Mouth Creek

FINAL REPORT

27 May, 2012



ABER

Review of water quality in Rocky Mouth Creek

To

Richmond River County Council

FINAL REPORT

27 May, 2012

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Aquatic Biogeochemical & Ecological Research

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Disclaimer

Executive summary

Rocky Mouth Creek drains a small backswamp sub-catchment of the Richmond River catchment and is impacted by severe seasonal acidification due to acid sulphate soil runoff and summer hypoxia due to blackwater and monosulphic black ooze (MBO) inputs. A tidal barrage situated approximately 3.8 km upstream of the confluence with the Richmond River is currently kept open outside of flooding times to promote tidal flushing of poor quality creek water, and only closed during floods to prevent flooding of the low lying Rocky Mouth Creek catchment due to ingress of floodwaters from the main river.

This report reviews water quality data collected between 2006 – 2012 at the sentinel monitoring site established immediately upstream of the tidal barrage in Rocky Mouth Creek. The aim of the report is to provide an analysis of water quality trends in relation to environmental forcing factors, with particular focus on the 2011 – 2012 year and closures of tidal barrage floodgates occurring during that year. The report also provides a discussion on the utility of long term water quality monitoring in the creek with regards to management and research objectives.

Overall, the data is of high quality and has yielded important insights into the nature of water quality variation in Rocky Mouth Creek which are of great value to ongoing research and management in this system. The collection of high quality data at a fixed sentinel site across successive years allows an in-depth analysis of the interaction between key environmental forcing factors responsible for observed water quality trends. The description of inter-annual variation in system response allows the development of more robust conceptual models of system function than those based on short term datasets (e.g. a single year).

Water quality in Rocky Mouth Creek varies over tidal, seasonal and inter-annual timescales due interactions between processes which cause water quality to decline (groundwater and blackwater inputs) and processes which promote recovery (seasonal

declines in temperature and rainfall, and tidal flushing). Seasonal and inter-annual variation in water quality arises due to variation in the timing, frequency and magnitude of rainfall events relative to seasonal variation in temperature and evapotranspiration. There is considerable variation over semi-diurnal and spring / neap tidal cycles which overlies and in some cases complicates trends associated with seasonal factors.

Acidification in the creek tends to be greatest during the late autumn – early spring period when hydraulic gradients between local groundwater and the creek are greatest. Once groundwater levels recede below the creek level, tidal flushing promotes an improvement of water quality over a timescale of months, however significant rainfall events during this recovery period can cause acute pulses of acid into the system.

Dissolved oxygen varies seasonally between anoxia during summer (due to large rainfall events which cause inputs of blackwater, and smaller events which can mobilise MBO sediments), and late winter when lower temperatures promote greater oxygen solubility and limit deoxygenating processes. As with pH, tidally flushing appears to play an important role in the recovery of tolerable dissolved oxygen conditions in the creek.

Tidal barrage floodgate closures during the 2011 – 2012 year occurred during Jan 2011, June 2011, and Jan 2012. A detailed analysis of water quality data spanning each event revealed little or no effect on any water quality parameters due to floodgate closure for two of the events, while for the Jan 2012 event there was a minimal decline in pH due to floodgate closure. However, the effect due to closure in this latter event was less than the background variation due to other factors. It can be concluded therefore that management of the tidal barrage floodgates for flood mitigation and fish passage has no real positive or negative impact on water quality in Rocky Mouth Creek. In contrast, the data show that keeping gates open outside of flooding times promotes large tidal excursions of good quality water into the creek. This enhances tidal flushing of the creek and greatly improves the aquatic habitat quality of Rocky Mouth Creek throughout the year.

Long term monitoring of water quality at the Rocky Mouth Creek sentinel site is vital to the effective management of this system. Major outcomes that benefit the environmental, social and economic bottom lines are:

1) The data is used to identify trends in temporal and spatial water quality variation in relation to environmental and anthropogenic forcing factors, on which meaningful and effective management actions are based.
2) Reduced fish kills.
3) Reduced flooding and associated costs in agricultural flood plains.

Important flow-on and other outcomes include:

4) Environmental
    a) Greater aquatic biodiversity
    b) Improved habitat for local and migratory bird populations
    c) The data is available and frequently accessed by researchers investigating hydrological and ecological dynamics of the Richmond valley catchment, the Richmond River, the Richmond River estuary and the near shore coastal zone.
5) Social and economic
    a) The viability of local fishery and agricultural industries is supported through greater yields and fewer costs.

Contents

1 Background

Richmond River County Council has overseen the deployment of a water quality logger at Rocky Mouth Creek barrage since 2000, with data providing critical information used in the management of the Rocky Mouth Creek and Tucombil Canal systems. The logger deployment is currently funded by Richmond River County Council and NSW OEH on a 2:1 basis. Aquatic Biogeochemical and Ecological Research (ABER) has been approached by Richmond River County Council to prepare a review of water quality data collected at Rocky Mouth Creek over the past 12 months.

2 Report scope and structure

2.1 Scope

This report aims to provide an analysis of water quality data collected in Rocky Mouth Creek between 2006 and 2012 in relation to environmental forcing factors. The report provides an overview of the primary factors responsible for the observed trends in water quality in Rocky Mouth Creek and the implications for management of the system. The utility of long term data collection to system management will be discussed with regards to flood mitigation initiatives, water quality, monitoring the effectiveness of environmental remediation initiatives, and research needs.

2.2 Structure

This report includes 5 main sections dealing with:

1) Analysis of long term water quality trends (2006 – 2012) in relation to annual and inter-annual variation in rainfall and temperature.
2) Detailed analysis of trends in water quality over the past 12 months and how these relate to longer inter-annual trends identified in section 1
3) An appraisal of water quality in relation to floodgate management
4) An appraisal of data quality issues arising from probe drift, poor calibration, probe fouling and installation
5) Discussion of management implications and recommendations for ongoing monitoring.

3 Site description

3.1 Setting

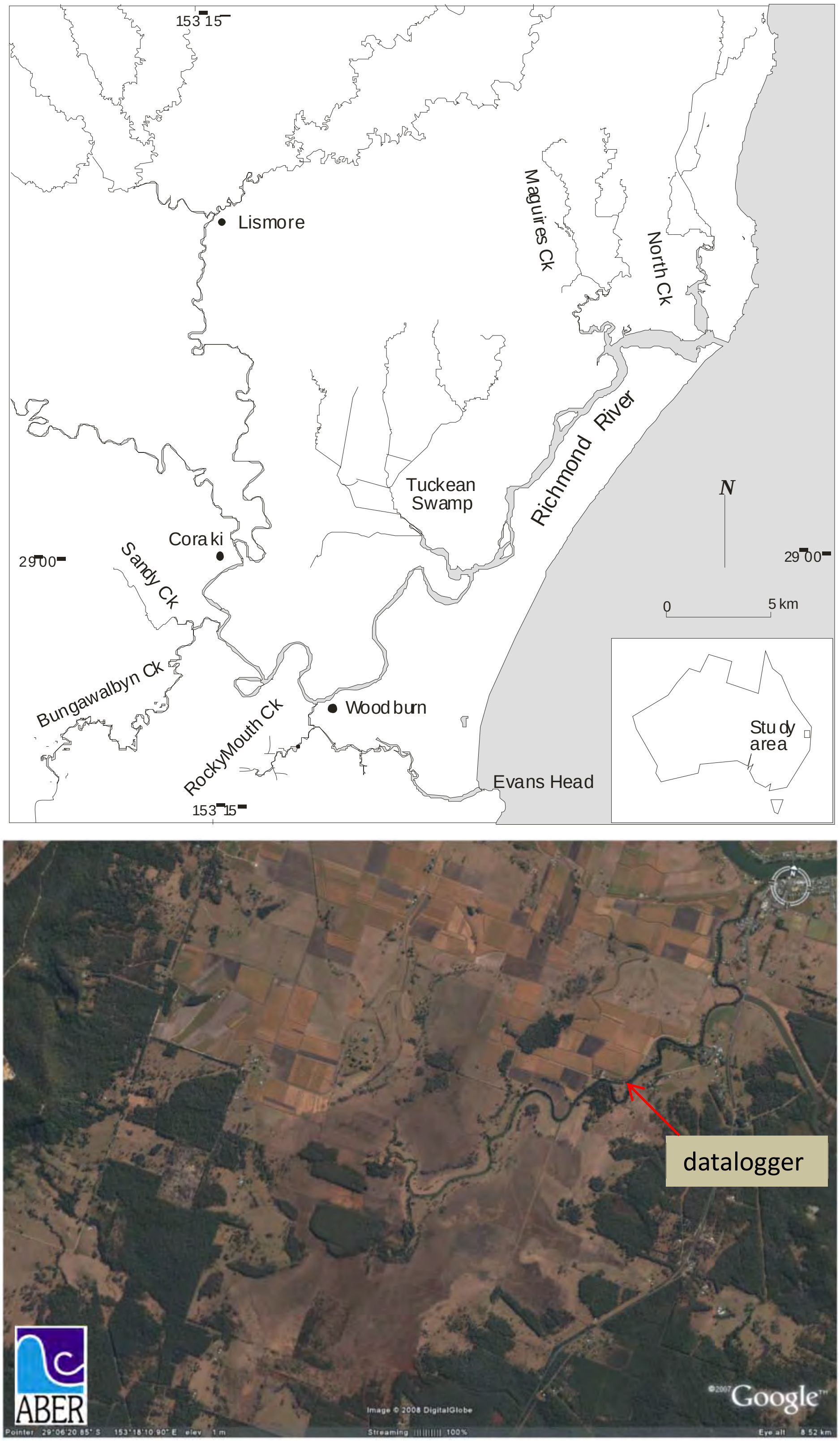
Rocky Mouth Creek is located within the floodplain of the Richmond River catchment, entering the Richmond River estuary at Woodburn (Map 1). The creek drains a small backswamp catchment containing significant areas of acid sulphate soils, and is impacted by severe acidification due to groundwater inputs for large parts of the year. The creek is also impacted by hypoxia due to inputs of blackwater (i.e. floodwaters deoxygenated during ponding over low lying pastures), and monosulphidic black ooze in drain and creek sediments.

3.2 Tidal barrage

A tidal barrage is located approximately 3.8km upstream of the confluence with the Richmond River (Map 1). The barrage consists of 5 tide gates that can be opened manually using a system of cables. Current management allows for the gates to be open outside of flooding times to promote tidal flushing of poor quality creek water. The gates are shut during flooding to prevent the ingress of floodwaters from the main Richmond River into backswamp land in the Rocky Mouth Creek catchment. In order to ensure maximum fish passage and avoid the trapping of fish behind the barrage during closure, the trigger for shutting the gates is when pH drops to 5.5 under the assumption that all fish will have left the creek by this time.

3.3 Water quality monitoring

Water quality in the creek (temperature, conductivity, dissolved oxygen and pH) is logged hourly by a telemetered *in situ* multi-probe logger housed on the upstream, western end of the tidal barrage. This sentinel water quality site has been maintained sporadically between 1994 – 2005 and constantly from 2005 – present.



Map 1 Rocky Mouth Creek catchment showing location of the datalogger site.

4 Long term trends 2006 - 2012

4.1 Rainfall and evaporation

Rainfall during the study period is summarised along with long term statistics for Woodburn in Figure 1. Rainfall tends to be greatest during the summer – autumn period, with peak rainfall events most likely between February and May. The dry season peaks in late winter to spring, giving way to the storm season during early summer when coastal thunderstorms can produce significant rainfall events. There was generally above average rainfall during the 2010 to 2012 study period, with the exception of the months of May and July 2011. Evaporation data were not available for this report, however daily measurements taken at Tuckean Swamp during the 2004 – 2006 period have been presented in Figure 2A to illustrate the seasonal trend of evaporation in the region. Figure 2A shows that evaporation is greatest during the peak of summer and least during mid winter, with very little inter-annual variation. Monthly variation in net daily water balance (precipitation minus evaporation) for the 2004 – 2006 period is presented in Figure 2B, showing that favourable conditions for groundwater recharge (i.e. positive values) occur primarily during the autumn – winter period.

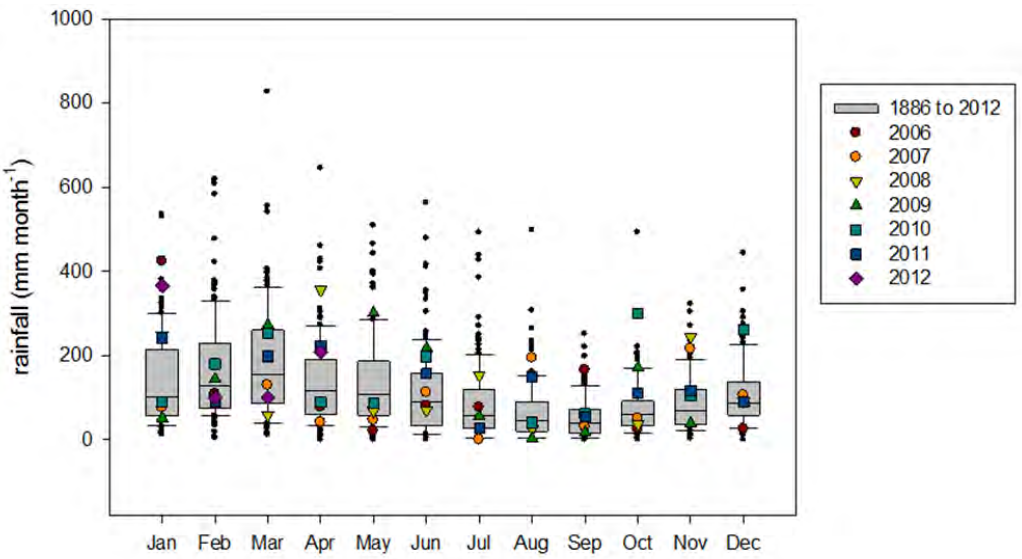


Figure 1 Rainfall at Woodburn during the study period compared to long term statistics (1886 to 2012).

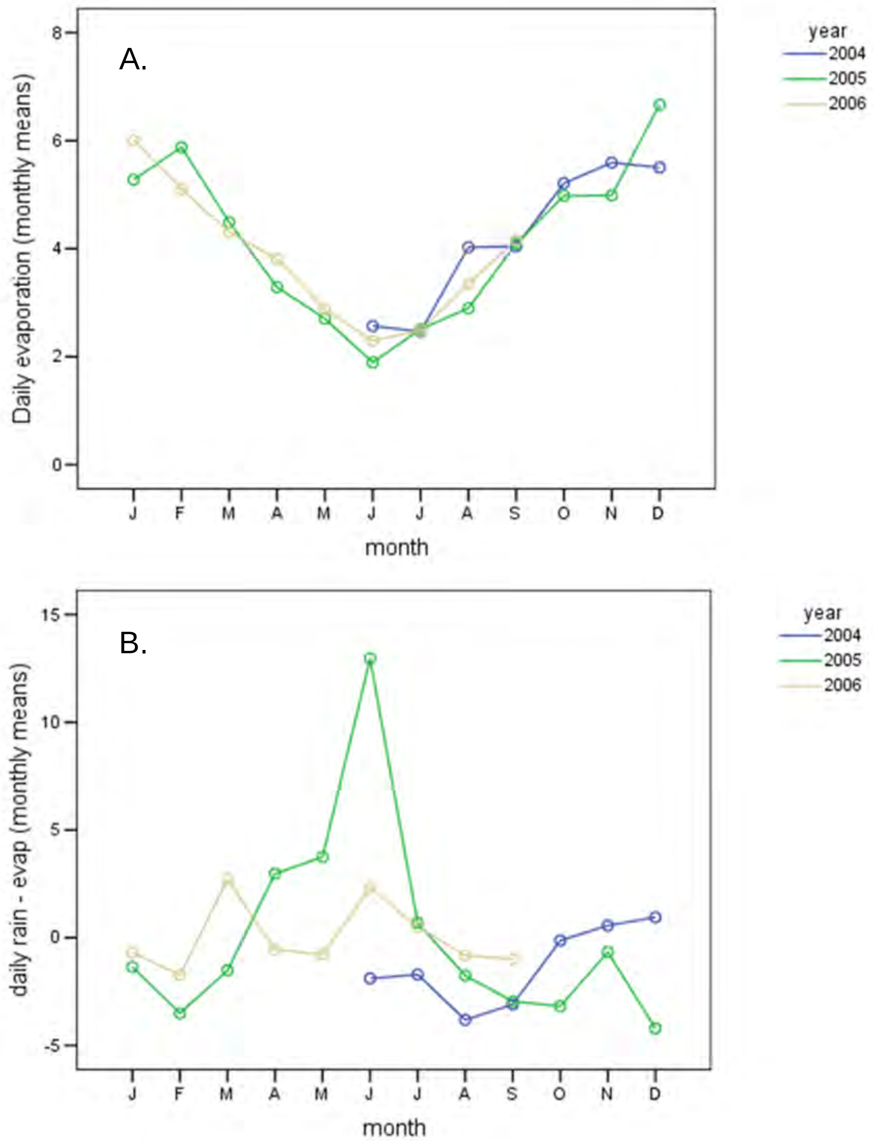


Figure 2 A. Daily evaporation (monthly means) at Tuckean Swamp. B. Net daily water budget (precipitation minus evaporation).

4.2 Cumulative rainfall statistics

Throughout this report, rainfall is discussed using the 1 day and 14 day cumulative deviation from the mean. This statistic is useful for differentiating between periods of above and below average rainfall graphically (Bell 1980)(Figure 3). Periods of above average rainfall correlate with an increasing trend in the cumulative deviation from the mean, while periods of below average rainfall correlate with the decreasing trend in cumulative deviation from the mean. This statistic is also useful in accounting for antecedent rainfall conditions that are important drivers of groundwater hydrology in floodplain areas (ABER 2008).

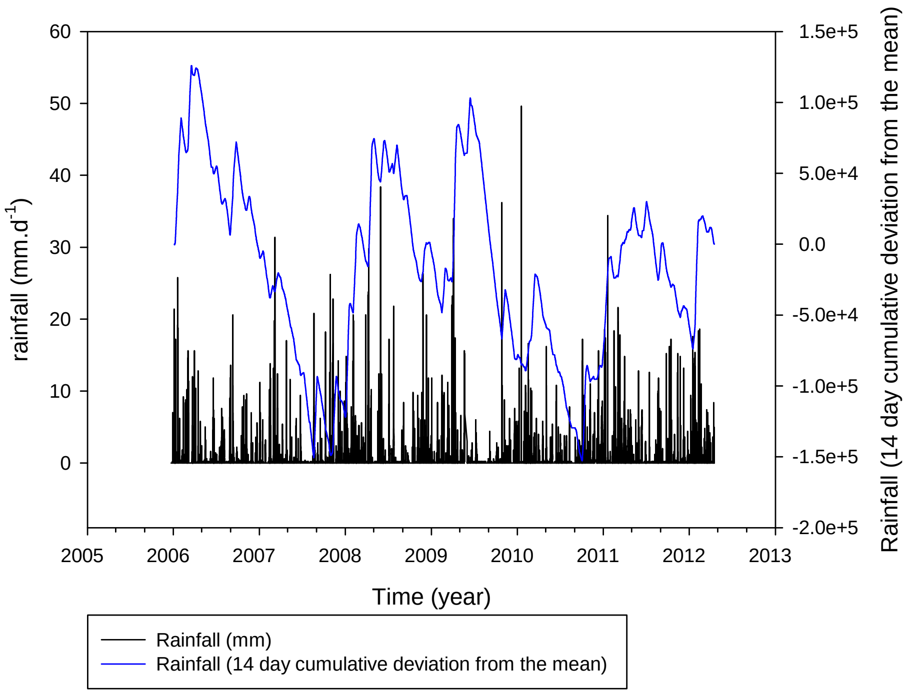


Figure 3 Rainfall at Rocky Mouth Creek between 2006 and 2012 showing the cumulative deviation from the mean for 14 day rainfall totals.

4.3 pH

4.3.1 Conceptual overview

For the purposes of this review, we propose a conceptual model of acidification in Rocky Mouth Creek based on generalised understanding of processes in acid sulfate soil areas of the Richmond River floodplain. pH variation in the creek is expected to be driven by interactions between inputs of acid groundwater and overland flow, and mixing with water from the Richmond River due to tidal action and / or the ingress of floodwaters. Acid groundwater inputs are determined by hydraulic gradients between local groundwater tables and the creek, and soil porosity (Santos and Eyre 2011). Acid groundwater discharge to the creek can occur when local groundwater levels are higher than water level in the creek (known as ‘gaining conditions’), while no discharge will occur when groundwater levels drop below creek water level (known as ‘losing conditions'). Hydraulic gradients themselves are primarily determined by the balance between rainfall and evapotranspiration, as well as variation in creek water levels due to tide and runoff events. Acidification in the creek can comprise chronic, seasonal decreases associated with long periods of above average rainfall when groundwater levels are raised and gaining conditions persist, or shorter lived acute acidification events, where discrete rainfall events during low rainfall periods cause temporary gaining conditions and a resultant pulse of acid groundwater inputs.

4.3.2 Data overview

The dataset shows that pH in Rocky Mouth Creek varies over inter-annual, seasonal and tidal timescales (Figure 4). ANOVA indicates that the main sources of variation in pH are on inter-annual and seasonal (month) timescales, with a much lesser (but still significant) effect due to above and below average rainfall periods (14 day cumulative deviation from the mean). There were significant interactions between all factors in the ANOVA model (Table 1), which can be best explained by the effects of inter-annual variation in the timing of seasonal rainfall patterns on the processes described above. The general pattern was for periods of chronic increases in acidification (e.g. mid 2007 to mid 2008), followed by relatively rapid recovery phases. Conductivity data indicate that the acidification phase was associated with a progressive increase in the relative proportion of groundwater in the creek. Both acidification and recovery phases were also influenced by acute pulses of acid water (e.g. late 2007).

4.3.3 Influence of above and below average rainfall periods

Rainfall is often a good predictor of general long and short term trends in pH in floodplain environments, however its predictive power is complicated by the fact that it is groundwater hydraulic gradients that ultimately control acid inputs to waterways (ref). We have utilised the 14 day rainfall cumulative deviation from the mean as a proxy for likely variation in groundwater hydraulic gradients, however this metric does not include the importance of evapotranspiration. . A more appropriate metric might be a net water balance calculated using rainfall and evapotranspiration rates, however this was not within the scope of this study.

During below average rainfall periods there is more likely to be losing conditions (i.e. groundwater hydraulic gradients directed away from the creek), with the result that pH is generally high in the creek (pH = 5-7). However, at these times any significant rainfall event can flush acid groundwater to the creek leading to rapid pH reduction (pH=3-4). It should be noted that while losing conditions are more likely to occur during below average rainfall periods, lag affects can occur during late autumn to winter where groundwater hydraulic gradients remain high and acid discharge to the creek continues for up to 3 – 4 months after the onset of below average rainfall. This affect means that the apparent correlation between above and below average rainfall periods and pH trends are reduced and that the variability described by the 14 day rainfall cumulative deviation from the mean in our ANOVA model is reduced.

Gaining conditions (i.e. groundwater hydraulic gradients directed toward the creek) are more likely to occur during above average rainfall periods, hence the significantly lower pH observed for these periods (Table 1 and Figure 4). However, acid groundwater may be diluted by floodwater from the Richmond River, and/or higher pH overland flow causing pH in the creek to rise. This causes added variation in pH trends that are not included in our model. The impact of these events will be discussed further on a case by case basis in other sections of the report.

Table 1 Analysis of variance (SPSS v 13.0) for pH in Rocky Mouth Creek during the period 2006 – 2012

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	52250.628(a)	125	418.005	1843.203	.000
Intercept	169677	1	169677	748197	.000
year	3567.294	5	713.459	3146.013	.000
month	8453.728	11	768.521	3388.810	.000
14 day rainfall	119.881	1	119.881	528.618	.000
year * month	9279.679	55	168.721	743.981	.000
year * risefall	122.258	5	24.452	107.820	.000
month * risefall	832.460	11	75.678	333.705	.000
year * month * risefall	1744.389	37	47.146	207.890	.000
Error	11454.300	50508	.227		

a R Squared = .820 (Adjusted R Squared = .820)

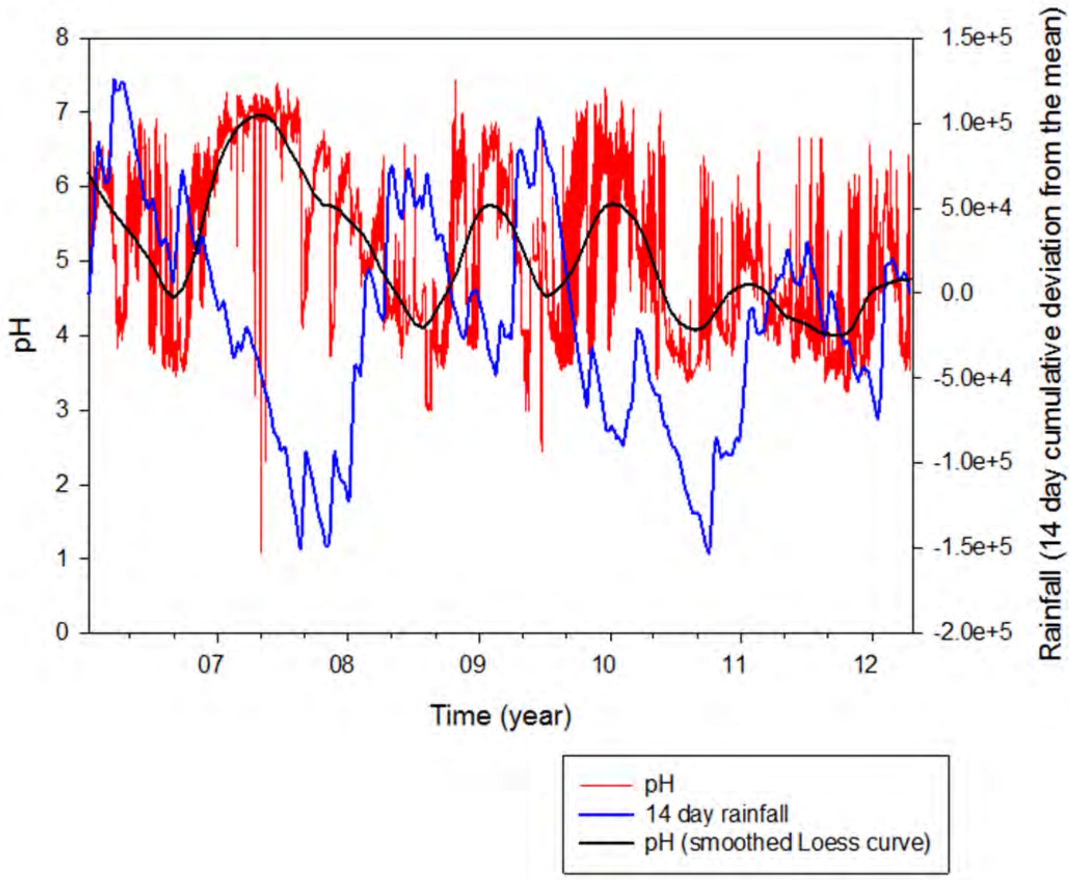


Figure 4 pH and 14day rainfall between 2006 and 2012

4.3.4 Seasonal variation

Seasonally, creek pH tends to be lowest during late winter, early spring and highest during mid to late summer (Figure 5). The strong trend in decreasing pH between summer and late winter is consistent with a seasonal increase in groundwater hydraulic gradients due to high rainfall in summer-autumn coupled with decreasing evapotranspiration rates post summer. The potential for increasing groundwater hydraulic gradient during this season is illustrated by the positive net daily water budget illustrated in Figure 2B. The rise in pH during the drier spring-early summer period can be attributed to 1) the lessening of hydraulic gradients as evapotranspiration rates increase in the absence of significant rainfalls; and 2) tidal mixing. The ANOVA clearly shows that while this trend holds generally for periods of above and below average rainfall, pH is generally lower during periods of above average rainfall. This is consistent with the maintenance of steeper hydraulic gradients by above average rainfall events, especially during the late Autumn – Spring period when evapotranspiration rates are low. The large difference between above and below average rainfall periods in early summer may reflect the impacts of relatively larger rainfall events that can occur during this season.

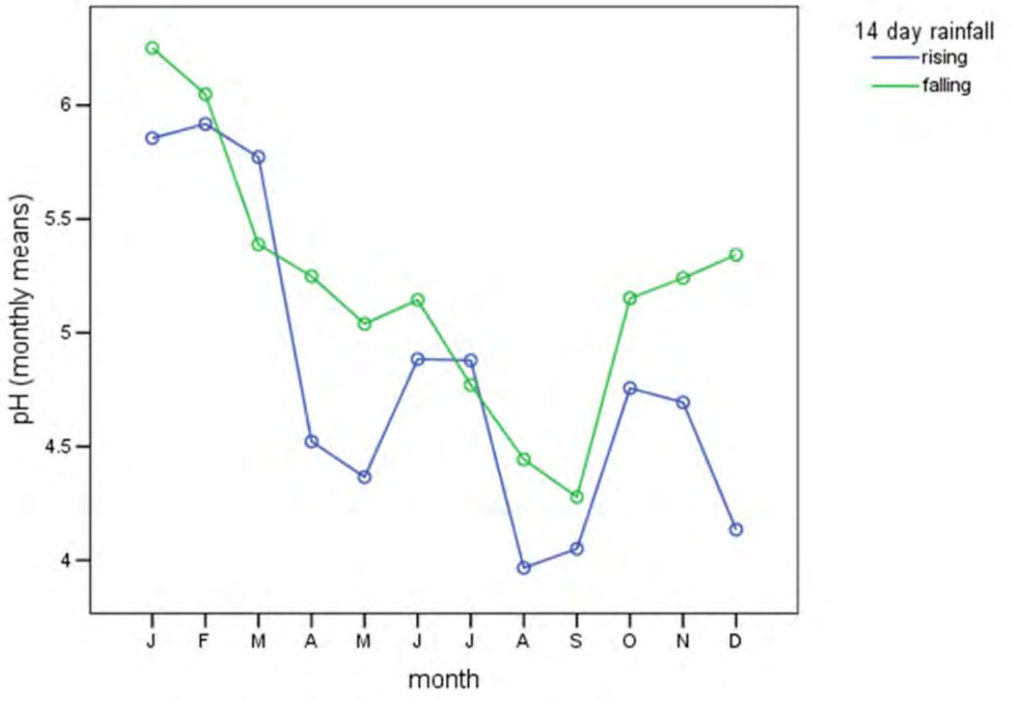


Figure 5 Seasonal variation in pH in Rocky Mouth Creek between 2006 and 2012. The blue and green lines indicate data that were collected during periods of above and below average 14 day rainfall.

4.3.5 Inter-annual variation

The ANOVA results show high inter-annual variation in pH, with an overall decrease between 2006 and 2011 (Figure 6), which can largely be explained by variation in the timing and magnitude of wet seasons. Early onset wet seasons will tend to cut short the recovery phase of pH, while extended dry seasons will tend to allow greater recovery (e.g. 2006 – 2007; Figure 4).

Acidification in the creek during the first part of 2006 occurred as a series of acute acid inputs in response to large rainfall events between January and mid March, followed by a series of rainfall events between June and August. pH values increased with the onset of an extended period of below average rainfall between late September 2006 and mid August 2007. Above average rainfall from this point till April 2008 saw steady decrease in pH, with 2 acute acidification events between August and November. The chronic acidification trend persisted until September 2008 when below average rainfall conditions set in and pH recovered. A rainfall event in mid November 2008 caused temporary acidification in the creek, with a general recovery in pH until the onset of the wet season in mid February 2009. Chronic acidification persisted in the creek until mid August 2009 when pH recovered, until a series of acute acidification events occurred in early November and late December 2009.

A period of chronic acidification began with the onset of the wet season in early February 2010 and lasted until mid August. This was despite a prolonged below average rainfall period between late March and early October 2010. Presumably during this period gaining groundwater conditions persisted causing a 4.5 month lag in pH recovery. Between early August and late September there was some increase in pH, interrupted by acute acidification due to a rainfall event. pH then rose in concert with a rainfall event in late December, probably due to overland flow. pH then began to fall with further rainfall events. The subsequent recovery was brief due to the onset of an early wet season with large rainfall events in early October and late December 2010, causing another chronic decline in pH which persisted until late October 2011. The subsequent recovery phase lasting until early February 2012 was punctuated by numerous acute acidification events caused by smaller rainfall events. A large series of rainfall events between mid January and early February saw another major input of acid to the creek.

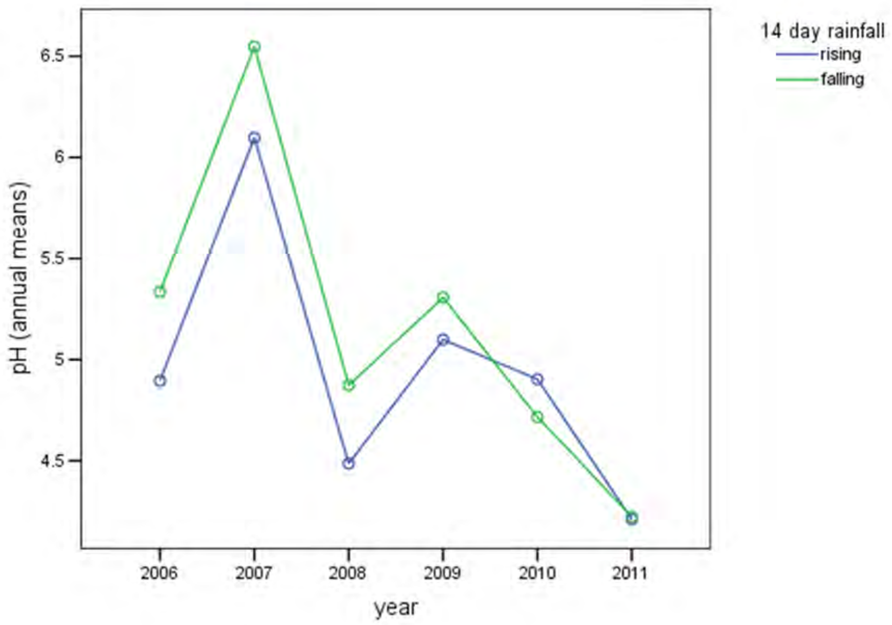


Figure 6 Inter-annual variation in pH between 2006 and 2011.

4.3.6 Tidal variation

Tidal influence on water quality in Rocky Mouth Creek is evident through the pattern of semi-diurnal variation in all water quality parameters, with greater variation associated with spring tides than neap tides (Figure 7). There is also oscillations in water quality evident over the spring / neap tidal cycle. Without contemporaneous water level data it is not possible to assess whether tidal variation in pH is associated with stratification (i.e. the probe being exposed to different water quality as a function of depth in the water column), or alternatively whether tidal variation causes the shunting of water bodies back and forth past the probe. The latter interpretation implies that there are strong water quality gradients along Rocky Mouth Creek and that tidal mixing is an important factor in the recovery of water quality. The semi-diurnal and spring / neap improvement of water quality in the creek also indicates that the benefits of tidal influence would therefore include increased utility as fish habitat and general biodiversity. Variation in pH associated with tidal cycles is not included in our ANOVA model, but will be discussed in association with the 2011 – 2012 year below.

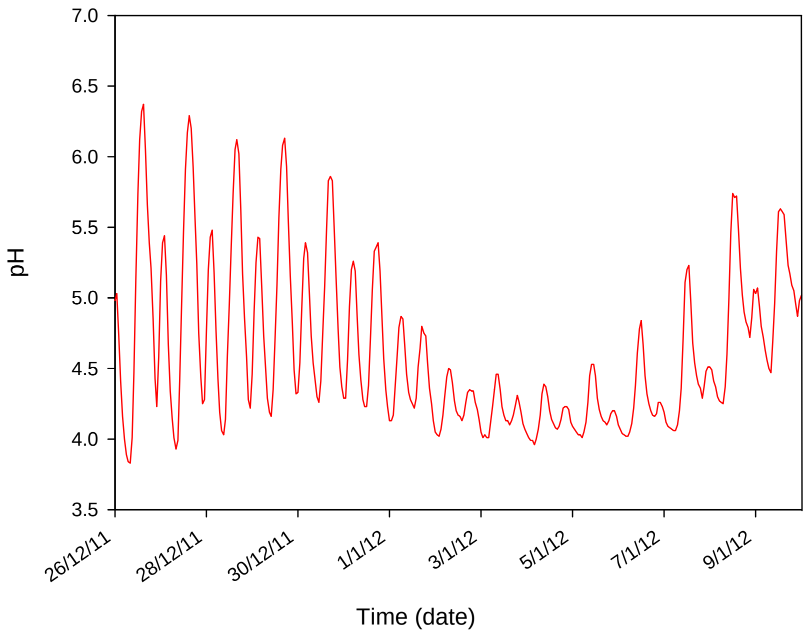


Figure 7 An example of semidiurnal variation in pH at Rocky Mouth Creek moving from spring tides to neap tides to spring tides again.

4.3.7 Relationships between pH and dissolved oxygen

Over shorter cycles of 6 months to 1 year within the 6 year period of 2006 to 2012, pH and DO appear to be either positively or negatively correlated (Figure 8). However the random direction of correlation seen over the 6 year data set indicates that these short term correlations are likely to be coincidental, rather than co-variance due to causative factors. These findings illustrate the danger in collecting environmental data over a short time period (less than several years) and then attempting to use them to inform management strategies. It also illustrates the value in collecting long term reliable datasets in a system, on which robust management decisions can be based.

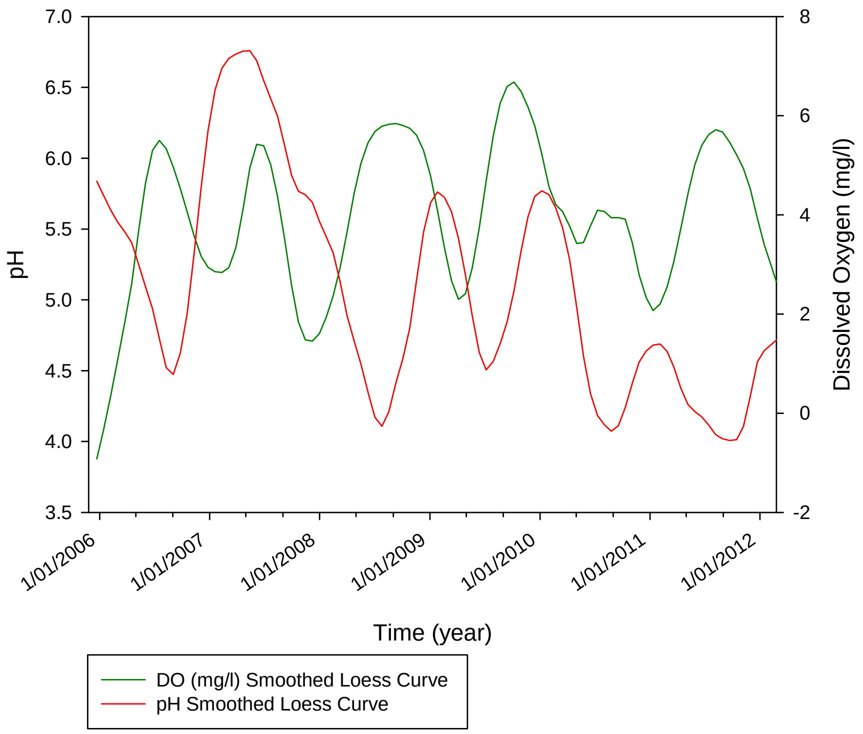


Figure 8 Inter-annual variation in pH and dissolved oxygen trends. Strong covariance or inverse correlation that applies during one year is unlikely to hold the next.

4.4 Dissolved oxygen

4.4.1 Conceptual overview

Dissolved oxygen (DO) in Rocky Mouth Creek is impacted by temperature dependent variation in saturation (high during winter and low during summer) and various temperature dependent biochemical processes that consume oxygen in overland runoff, acid groundwater and within the creek sediments. During flooding of low lying swamps and pastures oxygen is consumed due to the breakdown of organic matter (e.g. rotting pasture). The rate of breakdown and hence oxygen consumption is dependent on the depth and time of inundation, and the ambient temperature during inundation. In extreme cases during summer, this process results in the generation of ‘blackwater’ and can result in anoxic runoff overwhelming the creek. Another contributor to blackwater is chemical oxygen demand associated with the oxidation of reduced iron sulphides (monosulphic black ooze: MBO) accumulated in floodplain drains and creek sediments. MBOs can be resuspended during high flow events, thereby greatly enhancing the oxygen demand on overlying waters. Biochemical oxygen demand also occurs due to organic matter breakdown in creek sediments during low flow times, and is dependent on temperature and organic matter supply. As such, it can be seen that reductions in DO in the creek generally occur rapidly in response to runoff events. The degree of de-oxygenation depends on 1) the ambient temperature during the event; 2) the magnitude of event (e.g. large = blackwater + MBO mobilisation; moderate = MBO mobilisation); and 3) the frequency of rainfall events during the season. Obviously, large rainfall events and high temperatures tend to co-vary to some extent due to the periodic occurrence of summer onset wet seasons.

4.4.2 Data overview

As with pH, dissolved oxygen varied over inter-annual, seasonal and tidal timescales. The ANOVA model showed that the greatest variation occurred over seasonal (month) timescales (Figure 9; Table 2), followed by inter-annual variation and variation due to above and below average rainfall periods. Crashes in DO generally occurred in response to large runoff events during summer (refer to Figures XX in Floodgate opening section below), implicating ‘blackwater’ processes and mobilisation of MBOs in drain sediments as primary causes. Lesser reductions in DO occurred following smaller rainfall events during the winter – spring period suggesting mobilisation of MBOs in drain sediments as the primary cause. Recovery of DO saturation proceeded over seasonal timescales as temperatures decreased into winter. Tidal mixing also appears to aid in recovery.

Table 2 Analysis of variance (SPSS v 13.0) for dissolved oxygen in Rocky Mouth Creek during the period 2006 – 2012

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	238206.199(a)	125	1905.650	1504.126	.000
Intercept	102385.098	1	102385.098	80812.362	.000
month	40078.292	11	3643.481	2875.793	.000
risefall	380.422	1	380.422	300.267	.000
year	6103.662	5	1220.732	963.522	.000
month * risefall	3325.687	11	302.335	238.633	.000
month * year	85753.472	55	1559.154	1230.637	.000
risefall * year	149.338	5	29.868	23.574	.000
month * risefall * year	4025.790	37	108.805	85.880	.000
Error	64311.571	50761	1.267		

a R Squared = .787 (Adjusted R Squared = .787)

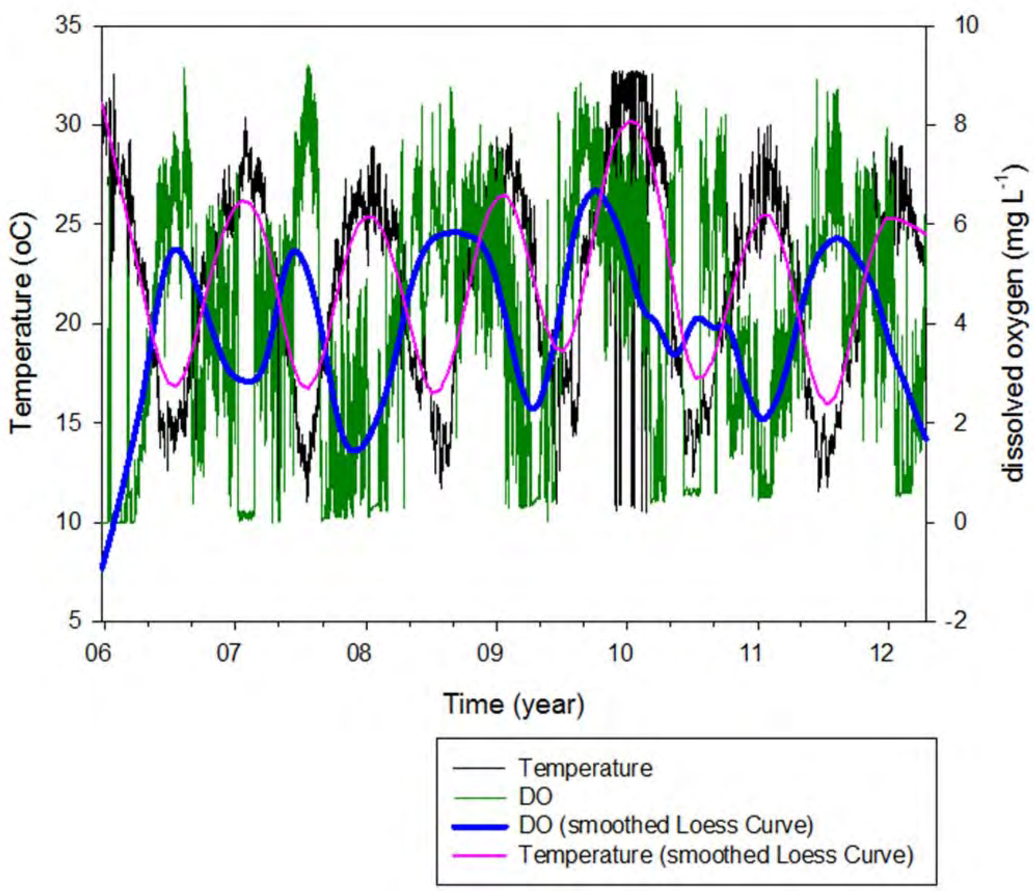


Figure 9 Dissolved oxygen and temperature between 2006 and 2012

4.4.3 Seasonal variation

Seasonal variation is characterised by an inverse relationship between DO and temperature over between 2006 and 2012, with DO highest during winter and lowest during summer (Figure 10). This is partially due to the inverse relationship between oxygen solubility and temperature, however DO saturation during summer was consistently hypoxic or anoxic indicating the influence of high biochemical oxygen demand over and above temperature dependent solubility (see above). The correlation between temperature and hypoxia may reflect either temperature dependent reactions and/or co-variation with high rainfall during summer (and hence runoff). There was a clear separation between above and below average rainfall periods from August to November, indicating the influence of hypoxic runoff events during the spring (e.g. 2010). The lack of separation between rainfall periods for the summer – autumn period most likely arises due to the persistence of hypoxic conditions in the creek for some time after above average rainfall (and hence inputs) ceases.

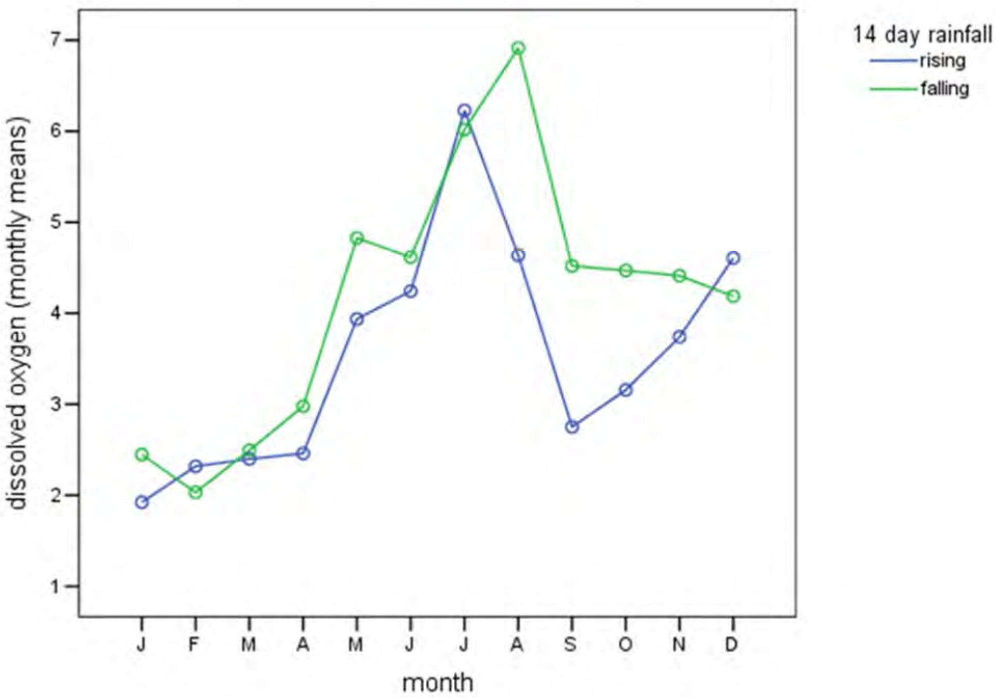


Figure 10 Seasonal variation in dissolved oxygen in Rocky Mouth Creek between 2006 and 2012. The blue lines indicate data that were collected during periods of above average rainfall and green lines during below average rainfall.

4.4.4 Inter-annual variation

Significant variation in dissolved oxygen over the inter-annual timescale was due largely to the timing and magnitude of the wet seasons, and the frequency of hypoxic pulses due to smaller rainfall events during the recovery phase. The influence of rainfall at this scale is supported by the clear separation between above and below average rainfall periods in Figure 11. In addition, some hypoxic events spanned two successive years, therefore dissolved oxygen was low before the onset of the wet season within that particular year (e.g. 2011). As such, it can be seen that while temperature imparts strong controls over dissolved oxygen saturation over seasonal timescales, variability in rainfall patterns is the primary control from year to year.

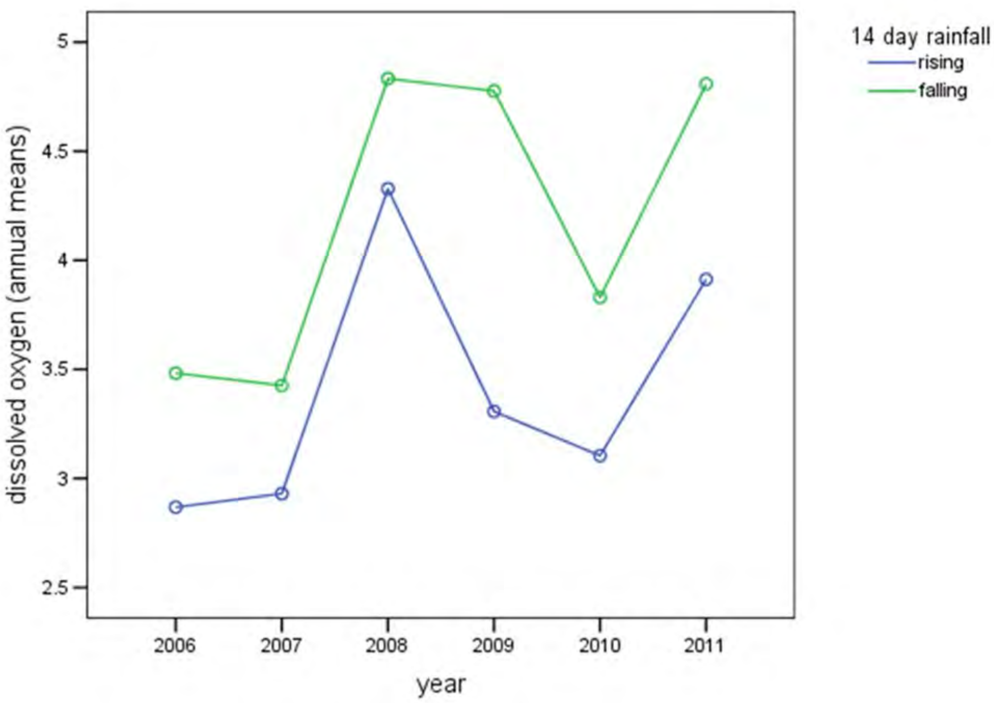


Figure 11 Inter-annual variability in dissolved oxygen concentrations (mg L-1) in Rocky Mouth Creek between 2006 and 2011 (note that 2012 has been excluded from this analysis since data was only available up to April). The blue lines indicate data that were collected during periods of above average rainfall and green lines during below average rainfall.

4.5 Conductivity

4.5.1 Conceptual overview

Rocky Mouth Creek is situated at the oligohaline (fresh – brackish) end of the Richmond River estuary, and is therefore only periodically influenced by brackish estuarine water during extended dry periods (ABER 2008). For the majority of the time Rocky Mouth Creek is dominated by freshwater and conductivity is generally less than 1 mS cm^{-1}, varying in response to the relative influence of overland flow (<0.3 mS cm^{-1}) and acid sulphate soil groundwater inputs (1 – 1.5 mS cm^{-1}), and the ingress of freshwater from the Richmond River estuary (<0.3 mS cm^{-1}) due to tidal flushing. As such conductivity provides a useful tracer of the inputs of ASS runoff and overland runoff to the system.

4.5.2 Data overview

Conductivity between 2006 and 2012 varied primarily as a function of season (month) reflecting the seasonal increases in acid groundwater dominance towards the spring as described for pH above (Figures 12, 13 and 14). There was a lesser effect due to above and below average rainfall reflecting the tendency of large rainfall events to flush the system with overland runoff. Inter-annual variability was large for the 2007 year when an extended dry period resulted in the ingress of brackish water from the Richmond River estuary causing conductivity to rise to 10 mS cm^{-1}. There was little inter-annual variability between other years in the dataset.

Table 3 Analysis of variance (SPSS v 13.0) for conductivity in Rocky Mouth Creek during the period 2006 – 2012

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	73951.229(a)	125	591.610	6526	.000
Intercept	6701.946	1	6701.946	73933	.000
month	2352.857	11	213.896	2359	.000
risefall	98.241	1	98.241	1083	.000
year	2963.621	5	592.724	6538	.000
month * risefall	1616.170	11	146.925	1620	.000
month * year	23533.293	55	427.878	4720	.000
risefall * year	139.657	5	27.931	308	.000
month * risefall * year	4657.204	37	125.870	1388	.000
Error	4601.413	50761	.091		

a R Squared = .941 (Adjusted R Squared = .941)

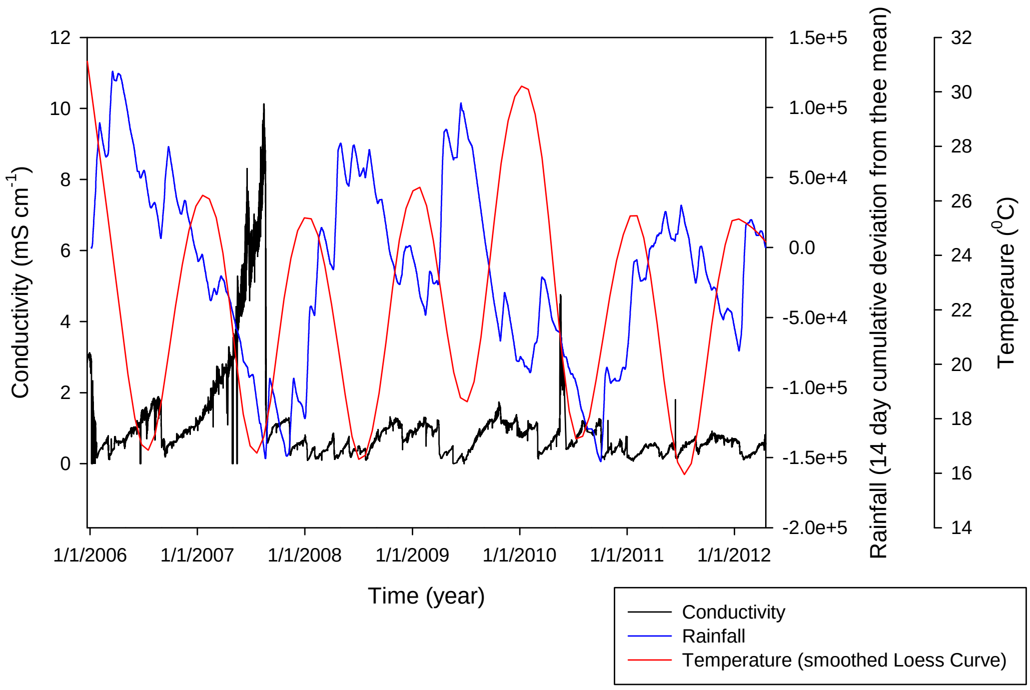


Figure 12 Conductivity, temperature and 14 day rainfall in Rocky Mouth Creek between 2006 and 2012.

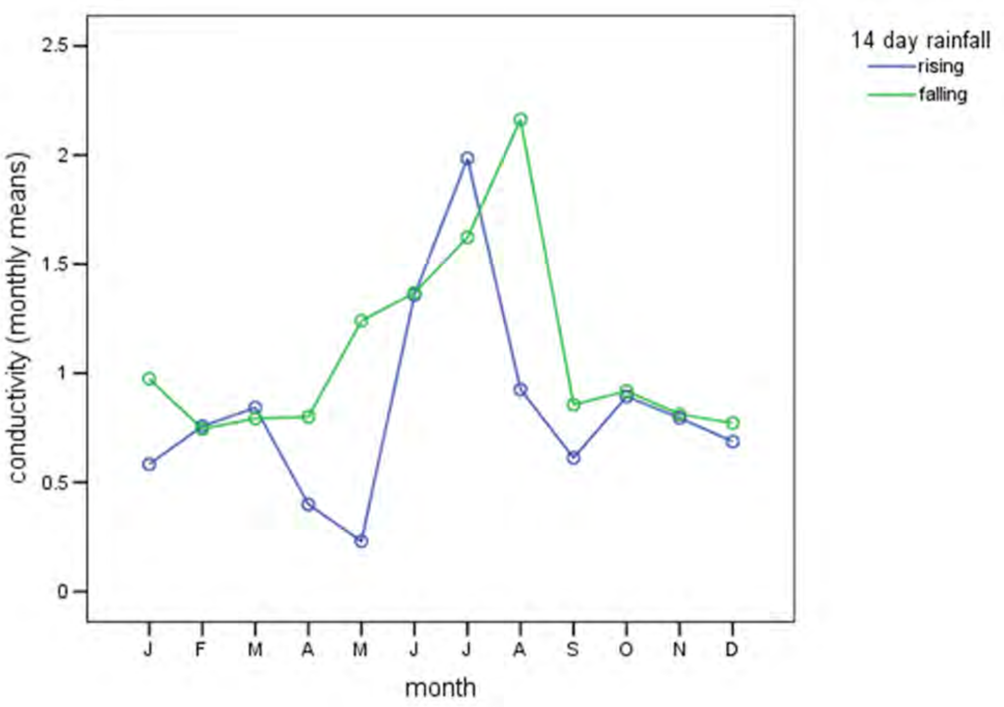


Figure 13 Seasonal variation in conducitivty in Rocky Mouth Creek between 2006 and 2012.

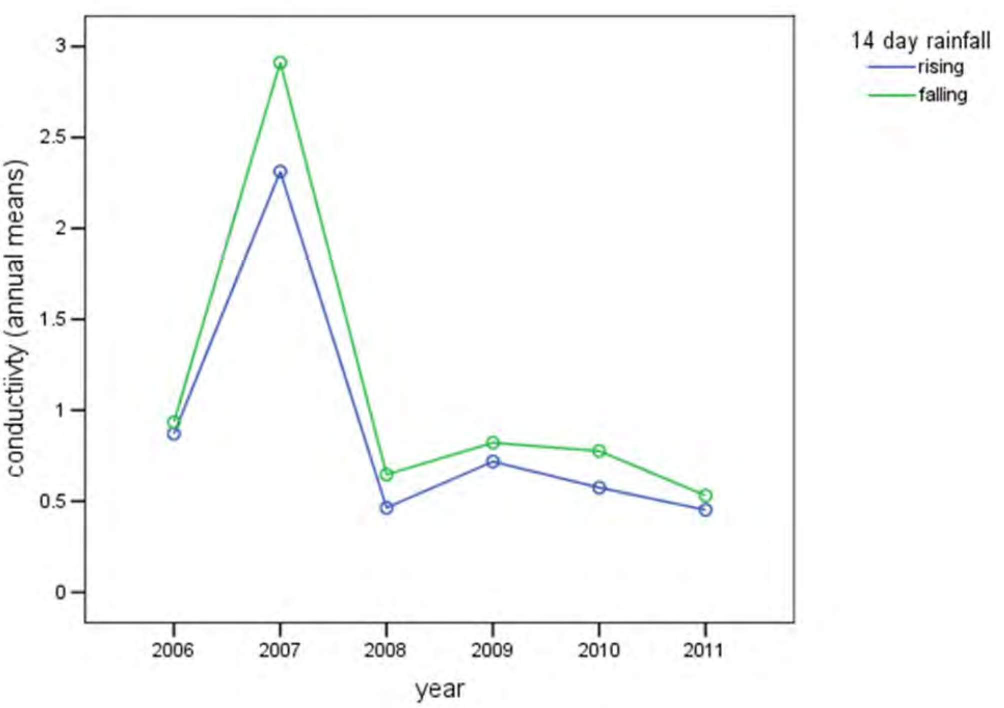


Figure 14 Inter-annual variability in conductivity in Rocky Mouth Creek between 2006 and 2011 (note that 2012 has been excluded from this analysis since data was only available up to April).

4.6 Temperature

4.6.1 Conceptual overview

Temperature varies in Rocky Mouth Creek in response to seasonal cycles in air temperature and solar radiation, tidal variation, and inputs of overland runoff. The seasonal cycle constitutes the strongest influence over water temperature and also influences the other factors. The temperature of overland water relative to creek water is likely to be strongly dependent on season: during summer runoff will tend to be warmer due to heating in shallow drains; during winter runoff will tend to be cooler due to heat loss in drains.

4.6.2 Data overview

The greatest variation in temperature occurred over seasonal (month) timescales, followed by inter-annual timescales (2009 and 2010 being significantly hotter than other years; Figures 15 and 16). There was small (but significant) difference between above and below average rainfall periods, however a significant interaction with year (Table 4) meant that this trend was cryptic. For the years 2006 to 2008 above average rainfall was associated with cooler temperatures while the opposite was true for 2009 to 2012. The reasons for this result are unclear, but suggest a higher proportion of overland runoff events during summer in the latter years.

Table 4 Analysis of variance (SPSS v 13.0) for temperature in Rocky Mouth Creek during the period 2006 – 2012

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1222920(a)	132	9264.549	5596.267	.000
Intercept	3332440.148	1	3332440.148	2012966	.000
month	568121.828	11	51647.439	31197	.000
risefall	34.690	1	34.690	20.955	.000
year	15495.469	6	2582.578	1560	.000
month * risefall	1786.929	11	162.448	98	.000
month * year	70263.322	58	1211.437	731	.000
risefall * year	406.332	6	67.722	40	.000
month * risefall * year	8109.638	39	207.939	125	.000
Error	87101.799	52614	1.655		

a R Squared = .934 (Adjusted R Squared = .933)

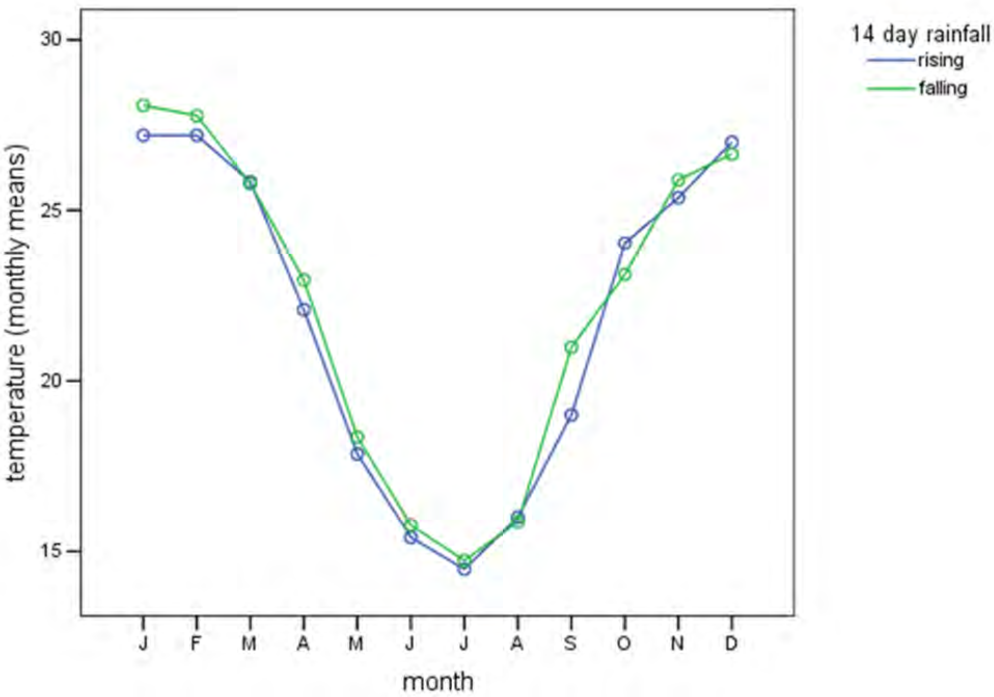


Figure 15 Seasonal variation in temperature in Rocky Mouth Creek between 2006 and 2012.

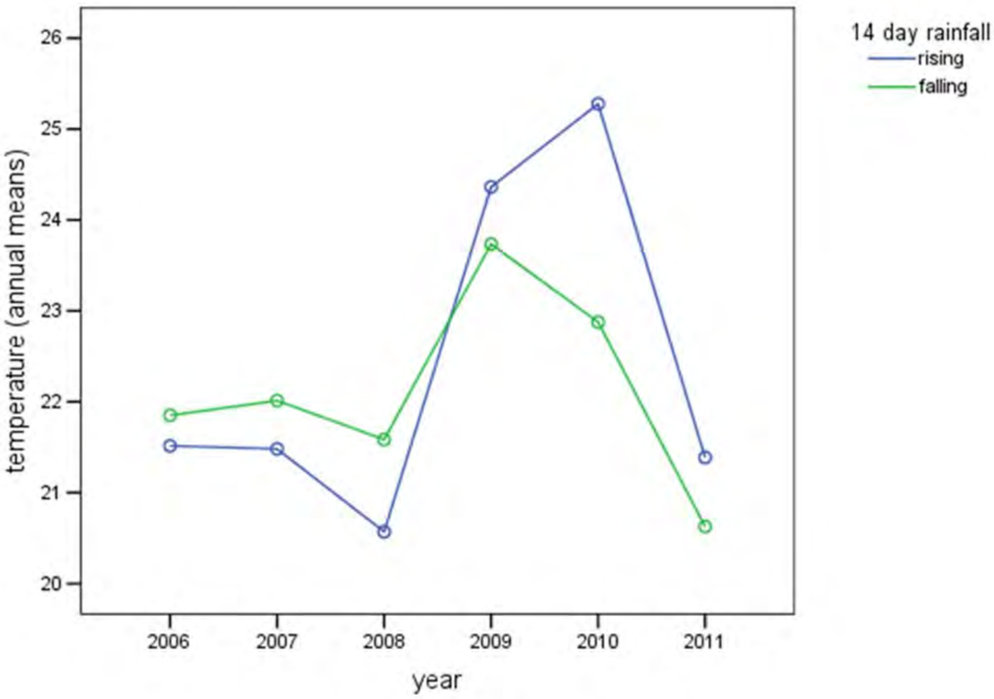


Figure 16 Inter-annual variability in temperature in Rocky Mouth Creek between 2006 and 2011 (note that 2012 has been excluded from this analysis since data was only available up to April).

5 Water Quality from 1/11/2010 to 16/4/2012

5.1 pH

5.1.1 Overview

The beginning of the period was marked by a chronic acidification phase which occurred in response to a large rainfall event in early October 2010, hence pH levels in the creek were relatively low for this time of year but consistent with above average rainfall and gaining conditions (see Figure 2B). A series of flooding rains occurring between late December 2010 and late January 2011 may have resulted in increased influence of overland runoff in the creek causing a small overall increase in pH during this period. A period of chronic acidification commenced in early January 2011 and persisted until late October 2011 when a recovery phase began. This recovery was interrupted by a number of acute acid pulses (e.g. late November 2011) but lasted until mid January 2012, flooding rains heralded the onset of the wet season. As occurred in early 2011, pH in the creek appeared to be influenced by overland flows until mid February when gaining conditions re-established and a phase of chronic acidification commenced. There was considerable variation in pH due to tidal variation.

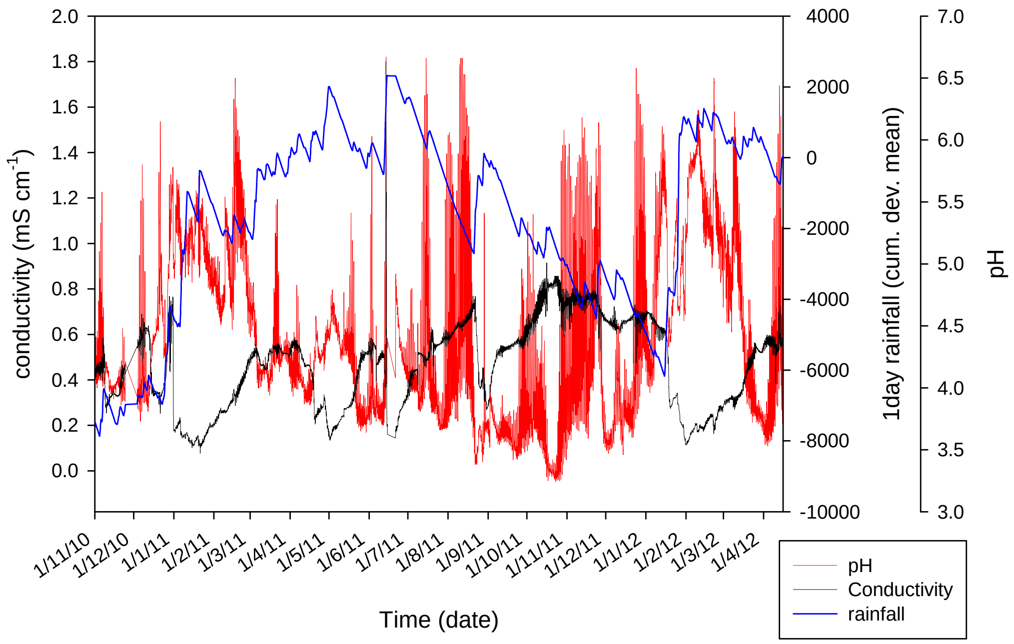


Figure 17 pH, conductivity and rainfall from Nov 2010 to April 2012.

5.1.2 Short period variation

In order to look more closely at how the trends in pH vary with rainfall and tidal influence, we have looked at the year of data in terms of baseline pH trends. These allow us to separate the direction of baseline pH trends from the large scale daily variation associated with tidal influence. Summarising this assessment of baseline pH variation with regard to rainfall and tidal influence, we find that throughout the study period:

1) Above average rainfall was associated with 5 periods of decreasing baseline pH, 7 periods of increasing pH baseline (1 with tidal influence), and 1 period of stable pH baseline.
2) Below average rainfall was associated with 8 periods of decreasing baseline pH (3 with no tidal influence despite high tidal pH values), and 7 periods of increasing pH (4 with tidal influence) and 1 period of stable pH baseline
3) Average rainfall was associated with 1 period of decreasing pH baseline and one period of increasing pH baseline.
4) Although changes in direction of the baseline pH value trends do concur with changes in rainfall and tidal regimes, they seem to be directionally random at worst and unreliable at best.

The inconsistency of directional relationships between trends in water quality parameters adds complexity to the analysis of causative processes. Without a conceptual model of how groundwater gaining and losing conditions interact with rainfall, acidification, groundwater flow and overland flow, the results would be impossible to interpret. The formation of conceptual models for these complex environmental systems is dependent upon the availability of reliable long term data sets.

5.2 Dissolved Oxygen

5.2.1 Overview

Coupling between dissolved oxygen and temperature was strong during this period. Aside from the impacts of blackwater runoff events, the majority of the large scale variation in DO appears to correlate inversely to seasonal trends in temperature, while the majority of small scale variation in DO appears to correlate inversely with tidal and weather related variation in temperature (Figure 18). The beginning of the period was characterised by low DO saturation resulting from a large rainfall event in early October 2010 (see Figure 9). There appeared to be little recovery of DO saturation after this event, with variation in DO associated with temperature variation over spring / neap tidal cycles. A large rainfall event between the 23rd and the 28th December 2010 resulted in an initial influx of low oxygen water at the cessation of rainfall, followed by another influx of anoxic water 2 days later (Figure 19A). This second influx was associated with an abrupt increase in temperature suggesting the drainage of blackwater impounded in drainage channels during high water levels in the main creek.

Anoxia persisted in the creek for 1 month until a recovery phase began with the seasonal decline in temperature from early February 2011. The recovery phase continued until mid August 2011 when a large rainfall event caused a hypoxic runoff event which lowered DO in the creek to approximately 3mg L-1 (Figure 19B). DO saturation improved marginally in the creek over the next four months following this event in association with tidal mixing and temperature fluctuations, however the recovery was interrupted by a series of smaller rainfall events which cause pulse inputs of hypoxic water. These smaller hypoxic inputs suggest biochemical oxygen demand due to disturbance of MBOs in drainage channels and creek sediments. Flooding rains in mid January 2012 caused another blackwater event resulting a two month period of anoxia in the creek (Figure 19C). Recovery from this period was initiated abruptly by a small rainfall event in early March 2012 which caused an increase in DO to approximately 2.5 mg L-1. The reasons for this improvement in DO are unclear. Recovery continued until a rainfall event in mid April caused another input of hypoxic water to the creek.

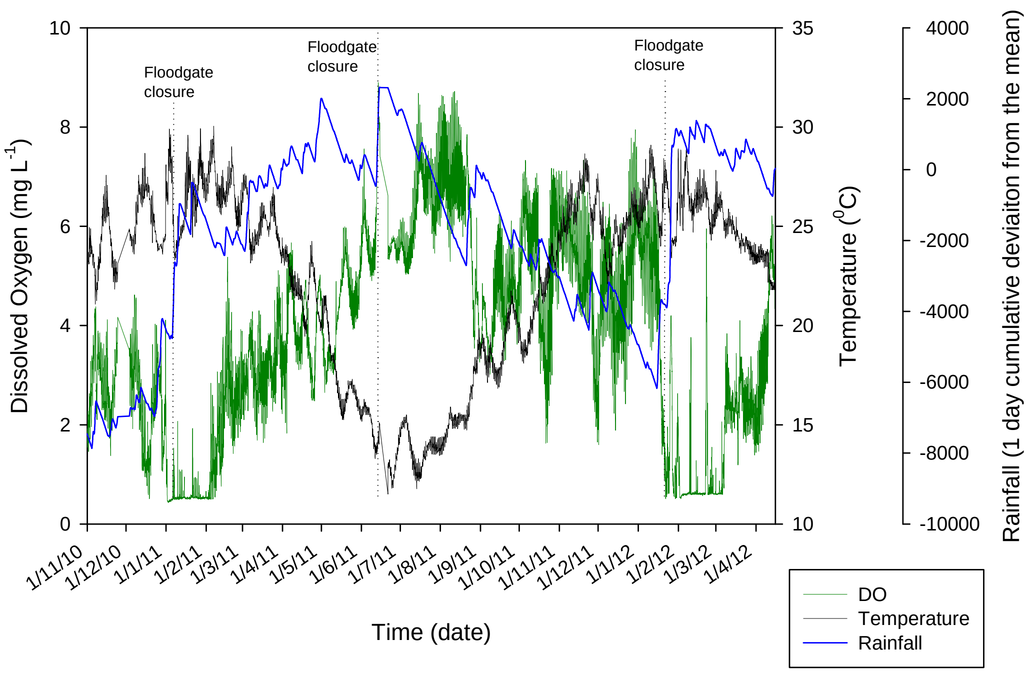


Figure 18 Dissolved oxygen, temperature and rainfall in Rocky Mouth Creek between Nov 2010 and April 2012

5.2.2 Tidal and short period variation

Dissolved oxygen in Rocky Mouth Creek varied widely over semi-diurnal and spring / neap tidal cycles (Figures 18). It is likely that both processes occur to varying degrees throughout the year. Tidal variation during recovery phases suggested that tidally induced flushing may be an important process in system recovery.

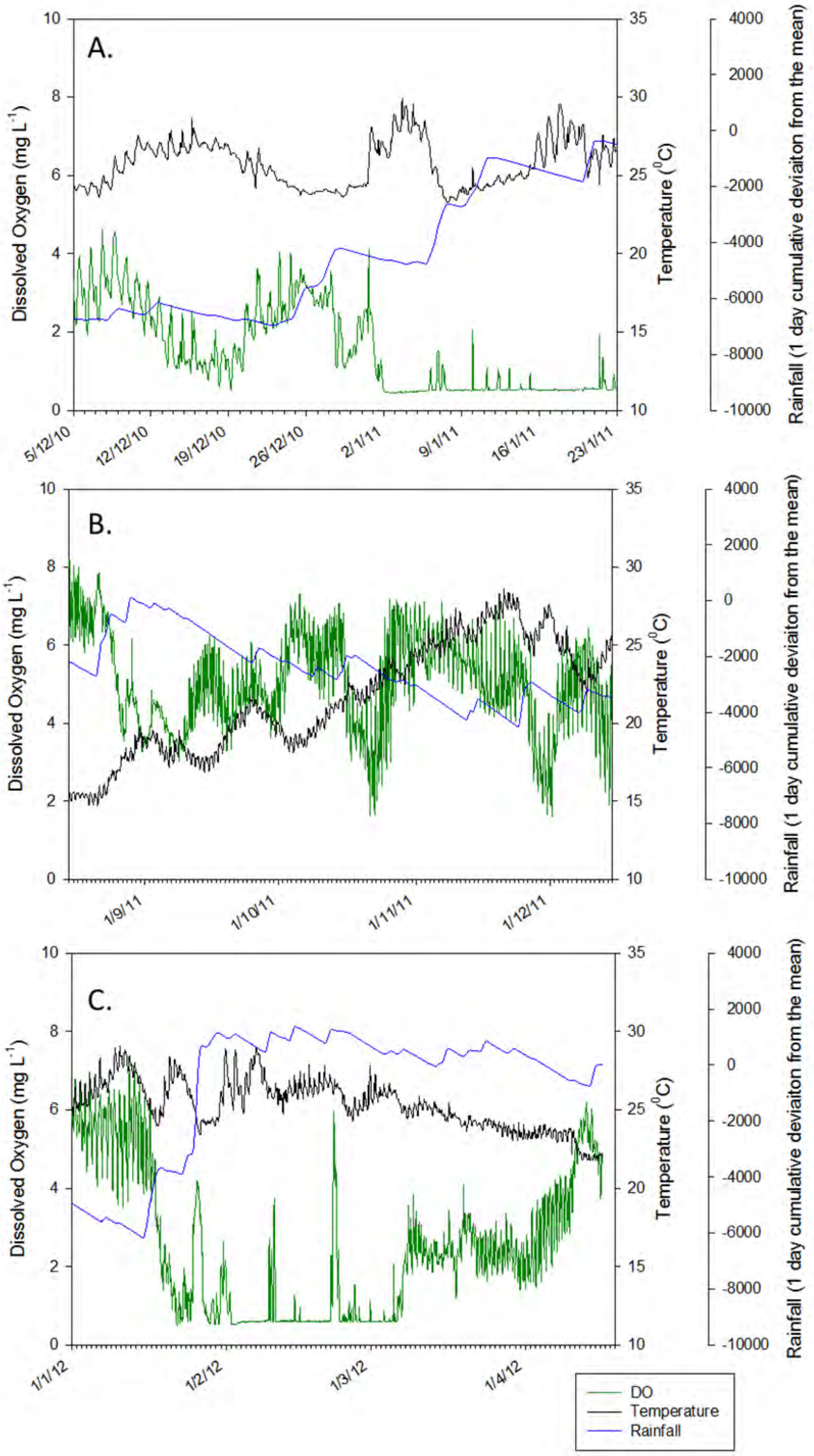


Figure 19 Detail of dissolved oxygen and temperature variation.

6 Influence of floodgate management over water quality

6.1 January 2011 floodgate closure

6.1.1 Pre-existing conditions

During the months prior to the January 2011 floodgate closure, baseline pH was on a generally upward trend, as the system appears to have entered a groundwater losing phase after a mostly dry autumn and winter (Figure 20). A wet period in October 2010resulted in a decreasing pH trend during November and early December, as acid groundwater drained into the creek. The pH rose during most of December, with a small acid pulse around the 12th and a larger one from the 23rd to the 26th associated with above average rainfall at these times. DO and conductivity both fell whilst pH was rising in mid-December, indicating that there was a shift at this time from low pH groundwater to low DO surface water. DO was recovering in late December when a new period of above average rainfall (23rd to 29th) caused a flush of acidified ground water into the system, baseline pH dropped back to 4.2- 4.3, and baseline DO peaked at 5.5 mg L^{-1} . Conductivity steadily increased at this time further indicating there had been an influx of sulphate-rich acid groundwater. As the rainfall declined on the 29th of December, the conductivity remained high, while pH continued to rise to 5.7 and DO dropped to 1 mg L^{-1}. This pattern is consistent with MBOs being flushed into the creek from wetland drains, as the oxidation of reduced sulphides consumes oxygen and elevates sulphate concentrations in the overlying water. As the catchment continued to drain, DO recovered to 5 mg L^{-1}, with a tidal peak up to nearly 6 mg L^{-1}. Then on the 31st of January a new body of water entered the creek, with a sudden 4 ^{o}C increase in temperature to 26-30^{o}C, a 0.45 mS cm^{-1} drop in conductivity, a drop in DO to 0.8 – 1.2 mg L^{-1}, and a drop in pH from 5.7 to 5. This pattern is indicative of deoxygenated surface swamp water moving into the creek. The lower pH is probably associated with spatial variation of water quality from different areas of the catchment. The pH rose again to 5.5 on the 2nd of January, probably when a different area of swap drained into the creek, with water quality that was anoxic (DO = 0.5 mg L^{-1}), and slightly higher temperature and pH.

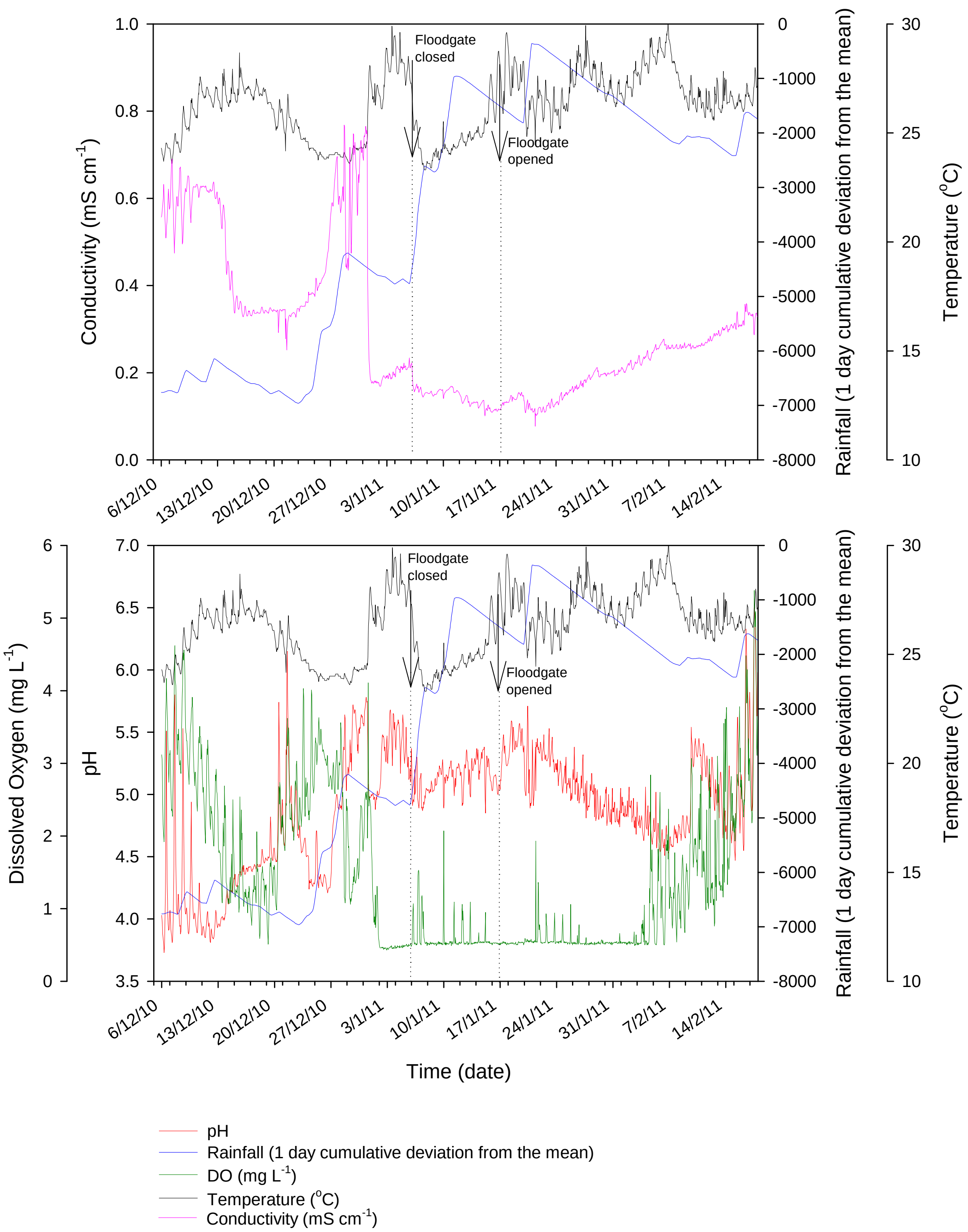


Figure 20 Water quality variation and rainfall over the summer floodgate closure from 6/1/2011.

6.1.2 The floodgate closure

The floodgates were closed on the 6^{th} of January, and another average rainfall event followed. During the first two days of rainfall following the floodgate closure, the water temperature dropped back down to $23^{o}C$, pH decreased to 5, and conductivity fell slightly, indicating some movement of water into the creek, possibly from a mix of drain water and overland flow. As these were flooding rains, we consider the movement of groundwater into the creek after the floodgates have closed to be unlikely, as water levels in the creek would have been too high to permit gaining conditions to occur. Despite inputs of lower temperature water, the DO remained anoxic throughout the floodgate closure and for just over 2 weeks after they were opened. The pH and temperature rose slightly while conductivity declined slightly during the remaining above average rainfall period and throughout the below average rainfall that followed within the closure period.

There are 9 peaks in DO, temperature and conductivity that coincide temporally with each other, and with 9 troughs in pH during the floodgate closure. The peaks look similar to tidal peaks in their timing and duration, but are difficult to pin down to a process during the floodgate closure. Clearly there are two separate water bodies with slightly different water quality characteristics, one of them dominating the other, and tidal influence was a factor in the presence of the minor contributor. Tidal influence could come about during this time through a number of mechanisms. Leakage of the floodgates due to debris jamming them slightly open is known to occur (Michael Wood, pers. com.). In this case, water body movement up and downstream could cause the tidal signatures. Alternatively if the water body behind the floodgates is stratified, movement up and down of water depth relative to the probe could cause a tidal signature. Finally gaining conditions during tidally induced lowered water levels could allow pulses of ground water into the creek. We have discounted the second 2 possibilities in this case for the following reasons: the temperature and conductivity differences of the 2 water bodies are too similar to cause stratification; groundwater inputs would not result in the spiked pattern in water quality variation, and as the tide rose and groundwater inputs mixed, pH would drop and conductivity rise, rather than the other way around. We conclude that it is most likely that a small plume of Richmond River water entered Rocky Mouth Creek during spring tide peaks during the flood, and drained out again after high tide. The data logger probe is very close to the floodgate opening, so it would be likely to pick up small tidal movements when they occurred.

After the floodgates were opened on the 17th of January, the full tidal signature is visible again in temperature data, the timing of which indicates that the gates may have been opened 2 days earlier than reported, on the 15th of January. Another above average rainfall event occurred on the 20th of January following which pH declined and conductivity increased steadily due to chronic acidification from post flood groundwater inputs. DO began to recover from anoxia on the 4th of February with the assistance of tidal influence. There were several pulses of warmer water into the creek between the floodgate opening and the recovery of DO, which may have been surface swap water input that contributed to the ongoing anoxia.

6.1.3 Management

The floodgate closure did not appear to impact on pH or DO trends, as such there does not appear to be any management issues for water quality associated with the floodgate operations. Tidal movements into Rocky Mouth Creek were minimised during floodgate closure, but the short time period of 9 to 10 days is unlikely to cause ecologically significant disruption, unless ingress of flood waters has ecological significance through processes that have not yet been identified. The anomaly of the return in the temperature data of the full tidal cycle signature prior to the reported opening of the floodgates indicates that the time of the floodgate opening and closing operations may need to be more exactly noted. However the presence of tidal peaks during the closure also requires further investigation.

6.2 June 2011 floodgate closure

6.2.1 Pre-existing conditions

In the months prior to the floodgate closure in June 2011 the baseline pH had been generally declining and the conductivity rising after the flooding rains in January (Figure 21). Throughout this period pH baseline had increased several times due to minor above average rainfall periods, but pH had decreased to lower values after each. Conductivity had generally decreased during rainfall events and increased after them. These trends were generally in line with overland flow and ingress from the Richmond River dominating during above average rainfall, and acidified groundwater entering the creek in the periods after above average rainfall. Prior to the June above average rainfall event, which caused the winter floodgate closure, baseline pH was 3.4 and conductivity was 0.5 mS cm^{-1}.

During this same period the DO baseline had been rising, in recovery from anoxia in January and high summer water temperatures. There was a strong semi-diurnal pattern in DO variation over this time, combined with longer period oscillations where the baseline varied by up to 3.5 mg L^{-1} coinciding with the spring / neap tidal cycle (Figure 22). These patterns suggest that water level increases in the creek over the spring / neap cycle tend shunt higher quality water up into the upper reaches of Rocky Mouth Creek, thereby shifting the axial water quality gradient upstream. As such, the relative position of the probes in the water quality gradient shifts and measures higher DO during spring tides. This mechanism would interact with rainfalls occurring during the spring / neap cycle which would impact on the water quality gradients in the creek.

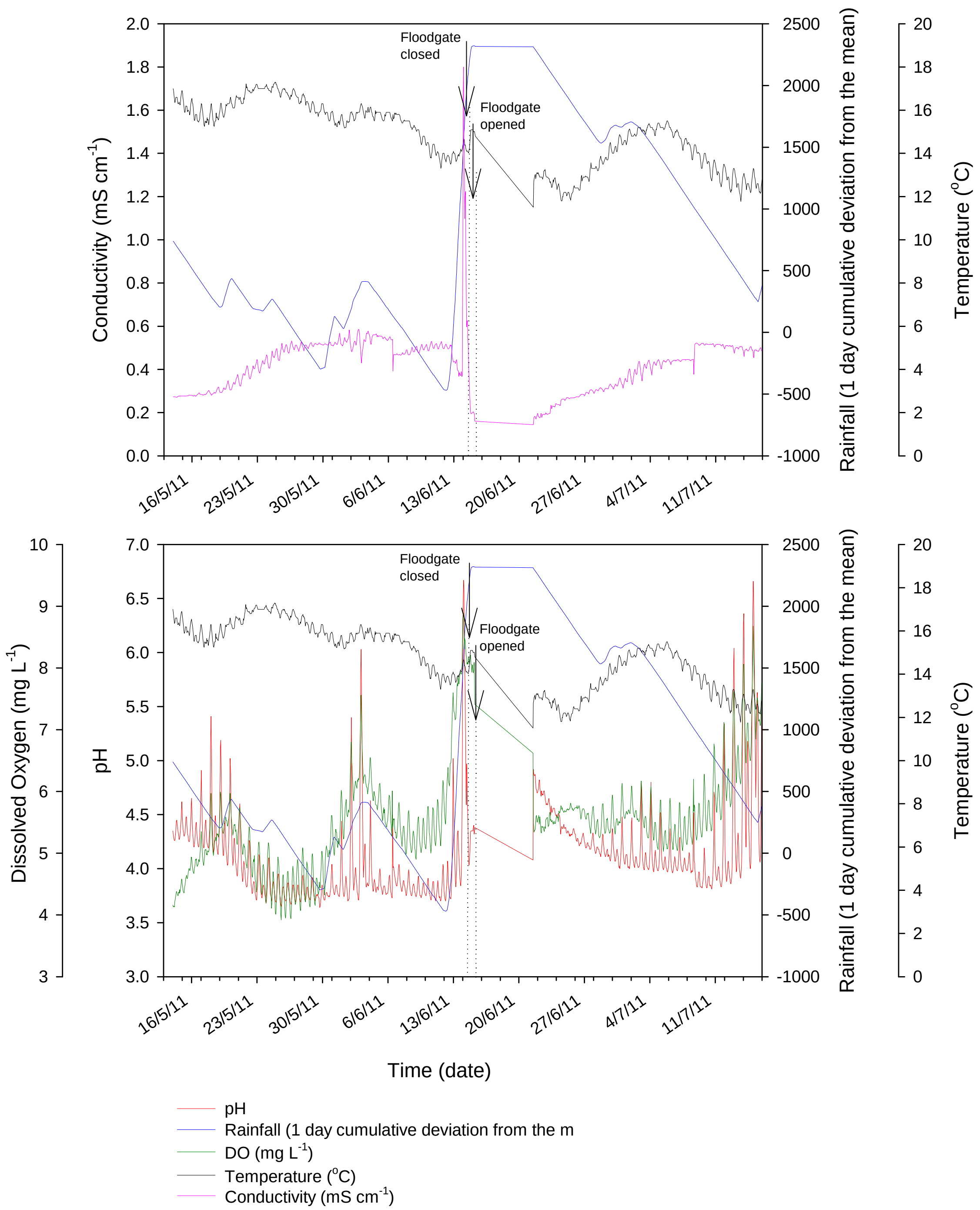


Figure 21 Water quality variation and rainfall over the winter floodgate closure from 16/5/2011.

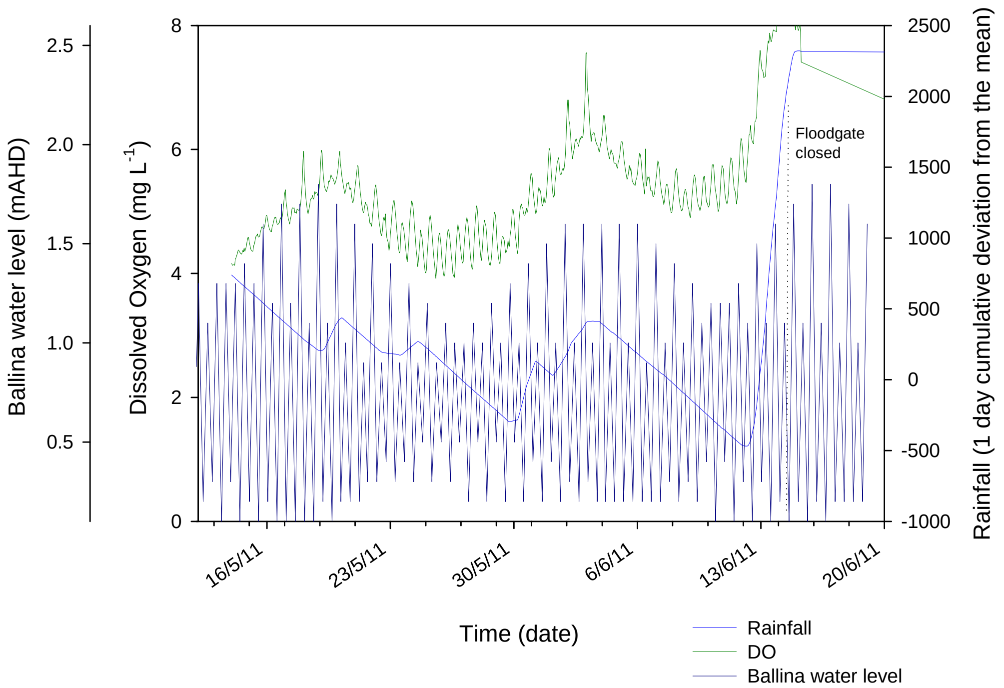


Figure 22 Variation in DO in the period leading up to the June 2011 floodgate closure, showing the influence of semi-diurnal and spring / neap tidal cycles.

6.2.2 The floodgate closure

Baseline pH rose to around 4, baseline DO to 7.9 mg L^{-1} and conductivity fell to 0.38 mS cm^{-1} with the onset of the June above average rainfall event. These trends are consistent with overland flow from rainfall and/or low salinity water from the Richmond River moving into the creek. The day prior to the floodgate closure there was what looks like a tidal peak that saw pH rise to 6.7, DO to 8.9 mg L^{-1} and conductivity rose to 1.8 mS cm^{-1}. These peaks are unusual because at this stage of a large runoff event we would expect floodwaters to be dominating the hydrological flows rather than tide. The conductivity peak is particularly unexpected because it is shaped like a tidal peak, and occurs with a tidally shaped peak to almost neutral pH, and very high DO conditions. Conductivity peaks during rainfall events can be associated with MBO inputs from the drains, however as these inputs also cause hypoxia and some acidification, this scenario is not supported. An unlikely alternative mechanism, particularly during a period of high freshwater flow in the River, is the ingress of brackish water with the high tide into Rocky Mouth Creek.

This is known to happen during very dry periods with conductivity building gradually over weeks. Finally the peak could have been associated with temporary fouling of the probes followed by a gradual clearing of the fouling material over the subsequent 20 hours. Assuming that the floodgates were closed in the middle of the day on the 14th of January, the water quality peaks dropped away to pH 4.1, DO 8.1 mg L^{-1} and conductivity 0.2 mS cm^{-1} just prior to the floodgates being closed. During this 1 day closure water quality did not change significantly. Unfortunately the next 6 days of data was lost, but it appears that pH remained quite high and was declining to 4.9 when the data base was restored, conductivity was 0.17 mS cm^{-1} and rising, DO was 5.5 mg L^{-1} and rising, and temperature was 14.2^{o}C.

6.2.3 Management

No discernible impact of the winter floodgate closure was made upon the water quality trends. The very large peak in conductivity is problematic enough to have invoked the possibility of probe fouling. Together with the sometimes substantial tidal signatures observed in the data when the floodgates are closed, this scenario raises uncertainties in the conceptual model, and indicate the need for further investigation into how tidal movements influence water quality in Rocky Mouth Creek during flood events.

6.3 January 2012 floodgate closure

6.3.1 Pre-existing conditions

The baseline pH values fell to a yearly low in late October with values down to 3.2 following a 6 month period of cumulatively below average rainfall which may have depleted the groundwater levels into losing conditions (Figure 23). The trend then switched to increasing pH values from the 30th of October, probably associated with a switch to predominately losing conditions in the creek. This is confirmed by the conductivity curve, which began to decline after a peak in late October. There were peaks and troughs associated with rainfall and tidal influences in pH and conductivity values within the overall rising pH and falling conductivity trends until the 15th of January.

The baseline DO values failed to follow a predictable temperature related decline from winter, through spring and into summer this year. There was a sharp decline in DO in late August following a moderately large above average rainfall event. However instead of continuing to decline, the baseline DO rose throughout September, and then effectively stabilised, despite large fluctuations, until early January. Temperature did follow the usual seasonal trend up during this period, aside from a dip between the 20^{th} of November and the 11^{th} of January.

Prior to the rainfall event that lead to the closing of the floodgates in January 2012, baseline pH had risen to 5.6, conductivity had fallen to 0.6 $ms.cm^{-1}$, baseline DO was 4.5-5.0 $mg.L^{-1}$, and temperature was $27^{o}C$.

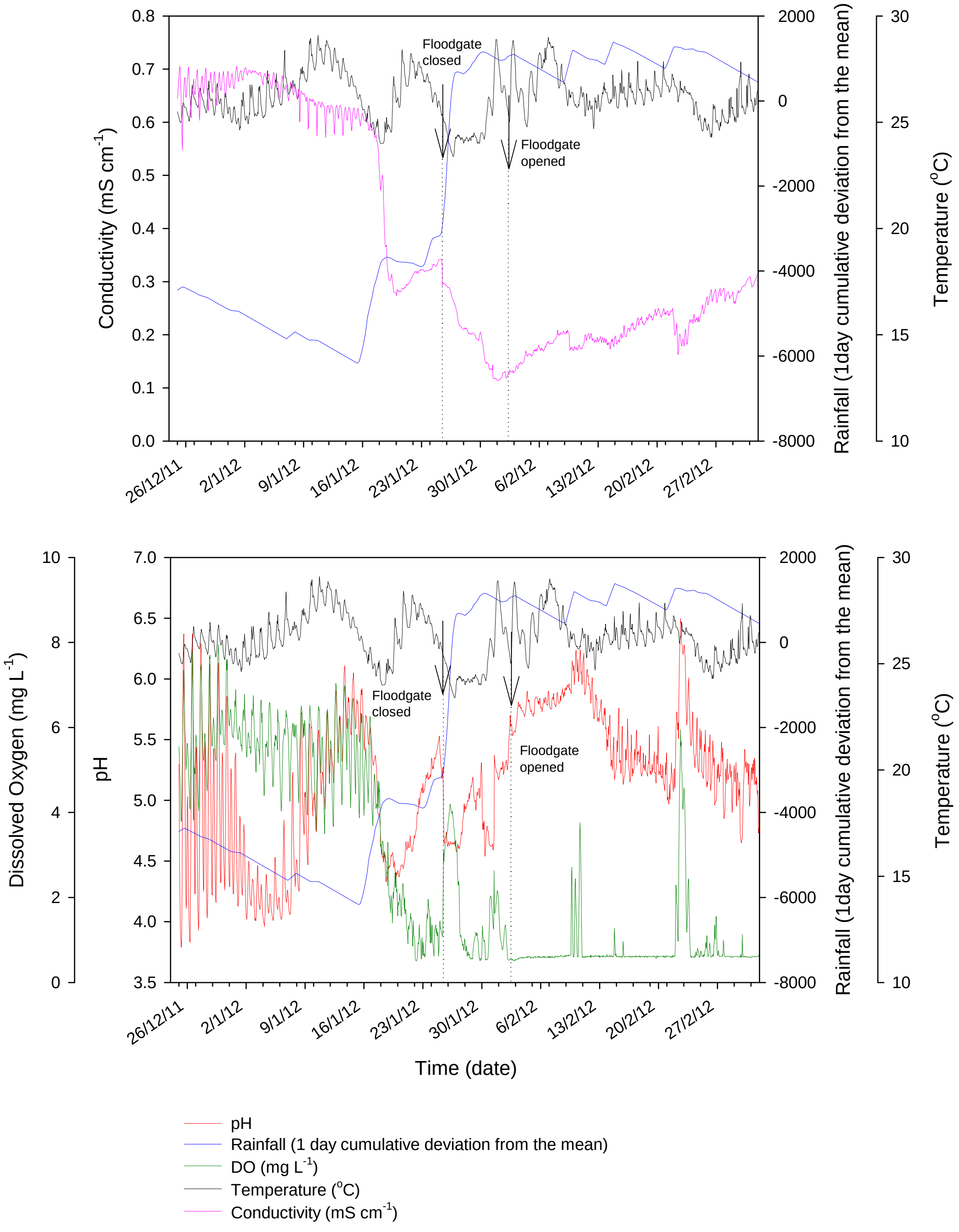


Figure 23 Water quality variation and rainfall over the summer floodgate closure from 14/1/2012.

6.3.2 The floodgate closure

The rainfall event leading to the closing of the floodgates began on the 15^{th} of January, and by the 17^{th} of January pH, DO and conductivity had all begun to decline rapidly. Temperature began to rise on the following day when the rainfall eased. The pH dropped to 4.4 and conductivity to 0.28 mS cm^{-1} on the 20^{th} of January and then both began to rise again, indicating a flush of acid groundwater to the creek, but with cryptic water chemistry causing a drop rather than a rise in conductivity. This is likely to be associated with several inputs to the creek simultaneously during and immediately following wet weather. The pH continued to rise to 5.5, and conductivity to 0.33 $ms.cm^{-1}$ on the 24^{th} of January, possibly due to continued losing conditions. Temperature peaked at $28^{o}C$ as DO decreased to 0.5-2.0 $mg.L^{-1}$ on the 22^{nd} of January. The low conductivity, rapid decline of DO to anoxia and temperature peak indicate that deoxygenated swamp water, rather than MBO rich drain water, entered the creek at this time, as MBO's are associated with higher conductivity due to the presence of sulphates. The floodgates were closed on the 25^{th} of January, as a new and larger above average rainfall event commenced. The pH had begun to drop prior to the floodgates being closed. When the floodgates were closed pH fell 1 point in 3 hours to 4.6 mg L^{-1}, conductivity dropped sharply but only slightly from 0.33 $ms.cm^{-1}$ to 0.3 $ms.cm^{-1}$, and DO rose sharply within 3 hours from 3.8 to 4.6 $mg.L^{-1}$. Temperature was falling when the floodgates were closed, and continued to drop another $4^{o}C$ after they were closed, but not as steeply as the changes described in the other water quality parameters. The rapid nature of these variations and their timing indicate that the floodgate closure was very likely to be causative. During the 8 day closure period pH had an overall rising trend with two sharply defined troughs, and conductivity had a falling trend with 2 periods of more rapid reduction which correlate with the low pH troughs. Causes for these variations in pH are difficult to define. There may have been eddies of poorly mixed water bodies with varying water quality values behind the gate. DO had a broad peak to 4.2 $mg.L^{-1}$ immediately after the closure but then dropped sharply again to anoxia. There were then several smaller DO peaks that broke through the anoxia over the remainder of the closure. These correlate with peaks in temperature and appear to be associated with a semi-diurnal tidal signature. The troughs in pH broadly correlate with the peaks in pH, but without the clear tidal signature, indicating that the pH troughs may also be due to tidal influence. The temperature semi-diurnal signature appeared to be suppressed during the first several days of the closure, but then seemed to be unaffected for the last 3 days of the closure, when the semi-diurnal pattern became strongly visible again with variations of up to 4^{o}C.

The floodgates were reopened on the 2nd of February. The pH rose sharply on the day that the gates were opened, but as this rise commenced at 4:45 am it is likely that the gate opening occurred later in the day and was not causative. pH and conductivity remained poorly correlated as both continued to rise over the week following the floodgate opening, indicating that a confounding factor was impacting on conductivity throughout this period. They become coupled again on the 11th of February when pH entered a chronic decline phase and conductivity continued to climb. The creek remained anoxic for several weeks after the floodgate opening, with occasional tidally induced peaks, while temperature oscillated between 24 and 29^{o}C with no overall directional trend.

6.3.3 Management

There appears to have been some impact on water quality parameters due to the floodgate closure on the 25th of January 2012. We have assumed that the closure occurred between 10am and 12noon when the rapid changes in pH, DO and conductivity occurred because we estimate that this would be the time of day that these works would most likely be carried out. If this is the case, it shows that the floodgate operations can, under some circumstances, cause shifts in water quality in Rocky Mouth Creek. However the changes seen are quite minor compared to temporal variation due to tidal influence, seasonal variation and rainfall patterns. As potential shifts in water quality due to floodgate closure, such as those illustrated by this event, occur over very short periods throughout the year, they do not present a risk to the ecological health of Rocky Mouth Creek. This floodgate closure illustrates the need for more exact information on the times of floodgates closures and openings to facilitate analysis of how these operations interact with water quality parameters.

There are factors influencing the conductivity in Rocky Mouth Creeks that have not been constrained within the conceptual model adopted to analyse data within this report. Further investigation into water quality dynamics and chemistry, particularly around above average rainfall events, would be useful to improve our understanding of the system.

7 Data quality

7.1 Overview

The data set is relatively complete and is of high quality compared to older Richmond water quality data sets that have been analysed (ABER 2008). There is little evidence of probe drift, poor calibration or probe fouling.

There are two periods where there was no data collected in 2010 – 2011. The first of these was for 9 days from the 25/11/10 to the 2/12/10. The second was for 5 days immediately after the floodgate was reopened on 14/6/2011. The timing of the second period without data is especially unfortunate as it undermines any possibility of assessing management impacts of the floodgate being closed, and responses of the system to high rainfall events at this time of the year. There are other periods of lost data throughout the 2006 to 2010 dataset, some of which are also associated with periods of high rainfall (e.g. May 2009). As such these data gaps represent a substantial loss in potential understanding and management of the system. These data losses may be to be associated with overflow of data, which occurs when loggers are not downloaded and reset before the memory is full (Pers. Com, Col Peake). Wet weather may hinder access to the logger when it is due to be downloaded, making this an ongoing systemic problem. The June 2011 data gap begins on the same day that the floodgates were reopened, so in this case it seems likely that the logger was accidently left off after it was down loaded.

There were numerous small scale variations apparent in the dataset that were not adequately explained by our conceptual model of water quality processes in the creek. The possibility that some of these variations may be due to problems with probes, loggers and any other quality assurance issues was investigated, however we were unable to identify any obvious major artefacts. The equipment is cleaned and calibrated on average, every 2 weeks, sometimes at 1 or 3 week intervals. When an instrument cannot be calibrated properly, it is replaced within 1 or 2 weeks (Pers, com, Col Peake). It appears, therefore, that current maintenance protocols are sufficient to minimise technical artefacts in the data. However, we recommend in addition to probe maintenance, that the quality of the probe installation housing be regularly checked for fouling by debris and sediment. It would also be useful to make regular observations of water circulation around the housing to ensure that its location is optimised to provide a representative sample of the bulk creek water (i.e. there are no backwater issues).

7.2 Data faults

There are data points where pH=0 throughout the data set. This is reportedly due to removal of the probe from the water for cleaning and calibration without switching the logger off first. This practice, whilst ensuring that the logger is not accidently left off for the following week or two, reduces the quality of the data set, and should therefore be avoided if possible.

Temperature was measured as -35 °C in early 2006 and in a cluster during late 2009 to early 2010. There were also 0 °C measurements on occasions in 2006, 2007, 2009 and 2010. There have been none of these spurious measurements since then, hopefully indicating that there has been an improvement in the way that the data has been collected.
Recommendations

1) Independent measurement of all parameters should be made at the logger site using a freshly calibrated hand held sonde upon retrieval and deployment of multiprobe loggers. This information should be entered as metadata attached to data files, with a brief analysis of the observed drift during each time period.
2) Avoid periods of data loss, particularly around flood events and floodgate opening and closing operations. This may require investigations into why the data is being lost. If it is due to delays in downloading logger data, especially during wet weather, solutions to this problem need to be examined. One possible solution is

downloading data early during wet weather in case flood waters rise, another may be remote download technologies. If the loggers are occasionally left off after data has been downloaded, a systems check routine may be useful. For example, a red tag could be attached to the logger on arrival at the site and not removed until all systems have been checked and are running just prior to leaving.

3) Switch the logger off prior to cleaning and calibration, perhaps using a similar systems check routine as described above.
4) Observations and comments should be recorded by field staff during probe deployment and retrieval and entered as metadata attached to data files.
5) Regular maintenance of probe housing should be carried out to ensure no fouling occurs.
6) Location of probe housing should be reviewed to ensure it is optimised for collecting representative samples of creek water.

8 Implications for management and research

8.1 Utility of long term monitoring

8.1.1 Understanding system function

The dataset analysed in this report has yielded important insights into the nature of water quality variation in Rocky Mouth Creek which are of great value to ongoing research and management in this system. The collection of high quality data at a fixed sentinel site across successive years allows an in-depth analysis of the interaction between key environmental forcing factors responsible for observed water quality trends. The description of inter-annual variation in system response allows the development of more robust conceptual models of system function than those based on short term datasets (e.g. a single year).

8.1.2 Baseline datasets

Understanding current background variation in water quality due to inter-annual variation in forcing factors such as rainfall is vital for detecting any responses to changes in pressures. The maintenance of ongoing monitoring at the Rocky Mouth Creek sentinel site provides an important baseline dataset which will allow the tracking of system responses to any future management initiatives (e.g. catchment rehabilitation and drain reshaping) and climate change impacts. The baseline dataset will allow a before – after impact assessment for any discrete changes to conditions in the catchment, thereby providing a useful feedback tool for honing rehabilitation efforts. Further, the conceptual understanding of system function (as described above) to will allow separation of effects due to natural variation in environmental forcing factors and those due to rehabilitation efforts.

8.1.3 Supporting research

The data from the Rocky Mouth Creek sentinel site provides an invaluable resource for research aimed at better understanding the nature of floodplain hydrology, acid sulphate soils, water quality issues, and their solutions. The data provide vital ancillary information for research efforts targeted at particular mechanisms (e.g. groundwater dynamics) in the Rocky Mouth Creek catchment. Developing cause and effect models for the linkages between processes and water quality will not only be useful for localised applications but also for the wider Richmond River floodplain and other NSW floodplains.

The conceptual understandings developed as part of this report provide the basis for hypotheses which should be tested more rigorously with targeted research efforts. Conversely, while we have been able to develop plausible explanations for many of the major trends in the data, there is still much small scale variation in the data which remains unexplained and warrants closer investigation. Research into understanding issues such as the mechanisms of tidal mixing in the recovery of water quality in the creek would greatly benefit interpretation of the data and help inform management strategies.

8.1.4 Supporting real time management initiatives

The current use of telemetered data alerts by Richmond River County Council to aid in floodgate management represents innovative best practice management. This approach has allowed the successful resolution of conflicts between two important management considerations (flood mitigation and fish passage) and should therefore be supported into the future. The data also has potential applications for other drainage management initiatives that require feedback for fine tuning (e.g. placement and level adjustment of drain sills).

8.1.5 Management of water quality recovery through tidal flushing

There is evidence from the data to suggest that tidal flushing may aid and speed up the recovery of water quality in Rocky Mouth Creek following hypoxia and acidification. Options for enhancing tidal exchange through floodgate management and channel alterations could be investigated using detailed hydrodynamic modelling. Water quality data collected at the sentinel site would be useful in this modelling and assessment exercise, and also in monitoring any future works in this direction.

8.2 Quality assurance

The 2006 – 2012 dataset is of high quality with relatively few artefacts associated with calibration and probe maintenance issues. It is vital that the servicing of data collection in Rocky Mouth Creek receive adequate resources to ensure the ongoing quality of data.

9 Conclusion

Long term monitoring of water quality at the Rocky Mouth Creek sentinel site is vital to the effective management of this system. Major outcomes that benefit the environmental, social and economic bottom lines are:

1) The data is used to identify trends in temporal and spatial water quality variation in relation to environmental and anthropogenic forcing factors, on which meaningful and effective management actions are based.
2) Reduced fish kills.
3) Reduced flooding and associated costs in agricultural flood plains.
4) Important flow-on and other outcomes include:
5) Environmental
    a. Greater aquatic biodiversity
    b. Improved habitat for local and migratory bird populations

c. The data is available and frequently accessed by researchers investigating hydrological and ecological dynamics of the Richmond valley catchment, the Richmond River, the Richmond River estuary and the near shore coastal zone.

6) Social and economic

a. The viability of local fishery and agricultural industries is supported through greater yields and fewer costs.

10 References

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