Monitoring Report: February 2011

Lower Lakes Groundwater Acidification Risk Monitoring Project

Monitoring Report February 2011

Government of South Australia
Department of Environment and Natural Resources

EPA
South Australia

Environment Protection Authority

Contents

Executive Summary **3**

1.0 Background **5**

2.0 Methodology **6**

3.0 Results **10**

3.1 Sediment moisture **10**

3.2 Groundwater (Piezometric levels) **14**

Campbell Park **14**

Windmill **19**

Point Sturt **24**

Currency Creek **28**

3.3 Groundwater Quality: **31**

Campbell Park **31**

Windmill **32**

Point Sturt **32**

Currency Creek **49**

4.0 Discussion **52**

4.1 Sediment Moisture and potential for acid generation **52**

4.2 Presence of acidity in groundwater **53**

4.3 Potential for Groundwater Flux to the Lake **53**

4.4 Risk of Groundwater Acidity flux to Lake Surface Water

5.0 Conclusion **53**

6.0 Recommendations **54**

7.0 Acknowledgments **54**

8.0 References **55**

Appendix 1 **56**

Executive Summary

This project is part of the South Australian Government's Murray Futures program funded by the Australian Government's Water for the Future program.

In 2009 the Department of Environment and Natural Resources (DENR) commissioned Earth Systems Consulting Pty Ltd to qualify acidity flux rates from Acid Sulfate Soils (ASS) into the surface waters of Lake Alexandrina and Lake Albert. The key objectives of the study were to (i) develop an improved understanding of acidity generation, neutralisation and groundwater transport processes within the lake sediments, (ii) quantify acidity flux rates during wetting events by assessing the hydrogeology and hydrogeochemistry of lake sediments, and (iii) provide recommendations for future management of the Lower Murray Lakes (Earth Systems 2009).

In December 2009, Earth Systems prepared the report, Quantification of Acidity Flux Rates to the Lower Murray Lakes: Final Report December 2009, detailing the Scope, Methodology and Results from the first six months of the study. A second report, Acidity Flux Rates to the Lower Murray Lakes: Supplementary Report June 2010, detailed the results from January to April. Please refer to these reports for a detailed background and methodology of the project as well as result interpretation from April 2009 to April 2010, discussion and acidity generation and flux rate modelling.

Since May 2010, the monitoring requirements for the project have been undertaken by the South Australian Environment Protection Authority (EPA) and DENR. Monitoring has been continued on an approximately monthly basis at the 4 piezometer locations, Currency Creek, Windmill, Campbell Park and Point Sturt. The aims of the EPA's component of the wider project to assess the risk that groundwater-related processes pose to lake acidification were:

- To monitor the groundwater levels, soil moisture and water quality at piezometer sites in the Lower Lakes region
- To provide data to assist in assessing risks of acidified groundwater flux to the main lake water body.

Sediment moisture levels, piezometric levels and groundwater quality (EC, pH, ORP, Acidity, Alkalinity, Dissolved metals (Al, Fe, Mn), Major Ions (Na, K, Mg, Ca, Cl, SO_4)) were measured at each location. This report contains data from all sites until the piezometers locations at Point Sturt, Windmill and Campbell Park were inundated following rising lake levels (from flooding in the upper Murray Darling Catchment). Sampling at Point Sturt ceased in August 2010 following a rise in the water level in Lake Alexandrina while sampling at Campbell Park and Windmill continued to late September 2010 due to the bund at Narrung keeping rising water levels from Lake Albert. After the removal of the bund on the 23rd September 2010 however, Lake Albert refilled rapidly, causing both Windmill and Campbell Park to be inundated and sampling to cease. Sampling at Currency Creek has continued into 2011 as the piezometers extend above the current water level.

As previously noted by Earth Systems data from sediment moisture probes, from January-April 2010 indicated that, despite surface water levels decreasing in both lakes (and corresponding decreases in piezometric levels in the lake sediments), effectively saturated conditions (moisture contents of around 40-50 vol% H_2O) were maintained below 0.4 – 0.5 m. Variability in soils moisture was seen above 0.4 m, with levels responding to both evaporation and rainfall.

Acidic groundwater was recorded at 3 of the 4 piezometer locations (all except Windmill). The acidic groundwater at these sites is likely to have originated from vertical transport of acid from the upper oxidised sediment layer. The sites posing the highest risk were Campbell Park and Currency Creek, with both locations illustrating acidic sites close to the lake water. High soluble (Fe, Al, Mn) metal levels were also recorded at acidic locations.

Although groundwater hydraulic head gradients were low, indicating there was limited potential for groundwater flux to the lake, gradients did increase towards the lake during high rainfall events, indicating a risk of acidity flux during such events. The hydraulic gradients at all locations were dynamic with complex relationships along the near shore environment. Hydraulic modelling would aid in better understand the shallow groundwater dynamics and calculate potential acidity fluxes under different water level scenarios.

It is recommended that monitoring continues in the Lower Lakes, by resampling the piezometers inundated at Campbell Park, Windmill and Point Sturt (by extending tubes above current water levels) and continuing sampling at Currency Creek. Continuous data on groundwater quality would allow the assessment of the potential for diffusion of acidity from the groundwater to the lake and/or neutralisation processes (e.g. sulfate reduction, carbonate dissolution) under longer term inundation.

1.0 BACKGROUND:

The regulation of the water level in the River Murray through the construction of locks, weirs and barrages over the 20th century has led to the loss of the natural wetting-drying cycles across the Murray Darling Basin. Regulation has enabled the maintenance of much more stable water levels over the last 50-100 years but has also created unanticipated environmental hazards. Principally, hydrological regulation has promoted the accumulation of sulfide minerals and sulfidic materials (predominantly iron pyrite) in the subaqueous sediments (Fitzpatrick and Shand 2008). These sulfide-containing sediments, known as Acid Sulfate Soils (ASS), pose little risk to the environment when inundated, but when uncovered, drained and exposed to atmospheric oxygen, the accumulated sulfide minerals (pyrite, FeS_2) in the upper layers of the soils profile oxidise and convert into sulfuric material ($pH<4$). The oxidation of one mole of pyrite produces 4 moles of acidity via the equation:

$$FeS_2 + 15/4O_2 + 7/2H_2O \leftrightarrow Fe(OH)_3 + 2SO_4 + 4H^+$$

The sediment moisture content is a key determinant to what degree of pyrite oxidation will occur, as oxygen diffusion is much slower in water than in air (Cook and Rassam 2002). The oxidation of pyrite not only produces acidity but also major cations and associated anions (Na^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2}, SiO_4^{4-}) and metal/metalloids including iron, manganese and aluminium (Fitzpatrick and Shand 2008, Simpson et al. 2010).

The Lower Lakes region in South Australia has received record low inflows from 2007–2009, due to a combination of the worst drought in the Murray Darling Basin, in 100 years of records, and over-allocation of water resources throughout the catchment. The lack water inflows into Lake Alexandrina and Lakes Albert caused the water level to recceed, exposing large areas of marginal shoreline environments for the first time in over 100 years. The exposure and drainage of these soils allowed large volumes of sulfidic material (pyrite) to be oxidised and converted to sulfuric material ($pH<4$)(Fitzpatrick et al. 2008, 2010). Following rewetting of many of these exposed areas during winter 2008 and 2009, localised areas of surface water acidification were noted at several locations, including Boggy Lake and Loveday Bay, on the northern and south eastern edge of Lake Alexandrina respectively, the western margin of Lake Albert and upper Currency Creek (EPA 2010). Experiments and field data also indicated release of metals and metalloids in these areas (Simpson 2010).

Based on concerns of the potential risks of larger-scale lake acidification, and uncertainty in the knowledge base for formulating management options, Earth Systems Pty Ltd undertook a project on behalf of the South Australian Government to assess the mechanisms of pyrite oxidation and potential acidity flux rates in groundwater underlying the exposed margins of the Lower Lakes. Results from this project on the acid generation, neutralisation, and groundwater flux processes can be found in Earth Systems (2009 and 2010). Since May 2010, the South Australia Environment Protection Authority (EPA) has continued the monitoring component of the wider project to assess the risk that groundwater-related processes pose to lake acidification.

The aims of the EPA's component of the wider project to assess the risk that groundwater-related processes pose to lake acidification were:

- To monitor the groundwater levels, soil moisture and water quality at piezometer sites in the Lower Lakes region
- To provide data to assist in assessing risks of acidified groundwater flux to the main lake water body.

This report details the monitoring findings from 2010, with comparison also to the previous findings of Earth Systems (2009 and 2010).

2.0 METHODOLOGY:

Previous project

Several management responses were investigated by Earth Systems Pty Ltd in response to the significant risk to the environment of the exposure and oxidation of ASS and associated generation of acidity and metals (Acid Metalliferous Drainage: AMD) in the Lower Lakes region. These included

1. Prevent AMD by managing lake water levels to ensure that ASS are permanently submerged and sulfide oxidation is therefore minimised.
2. Control AMD in-situ via neutralisation (addition of alkaline amendment to ASS) and/or reduction (addition of organic matter to ASS).
3. Treat AMD within the lake water bodies, either passively or actively, via neutralisation (alkalinity addition) and/or reduction (organic matter addition).

To inform these management responses it was considered necessary to further investigate the mechanisms of sulfidic material oxidation and potential acidity flux rates in the sediments of the Lower Lakes. Consequently, a project was developed to examine the groundwater characteristics, changes and movements within the shoreline sediments. The chief objectives were to

- Develop an understanding of the acidity generation, neutralisation and groundwater transport processes within the lake sediments of the Lower Murray Lakes.
- Quantify acidity flux rates to proximal water bodies during wetting events, by assessing the hydrogeology and hydrogeochemistry of lake sediments via a combination of laboratory and field testwork programs.
- Provide recommendations for future management of the Lower Murray Lakes.

To achieve these objectives Earth Systems Pty Ltd, under contract by DENR;

- Designed, established and implemented of a laboratory testwork program to measure sulfide oxidation rates of Lower Murray Lakes ASS as a function of sediment moisture content.
- Designed and established a field monitoring program to collect geological, geophysical, hydrogeological and hydrogeochemical data at selected high risk locations in the Lower Murray Lakes including:
    - Currency Creek (tributary of Lake Alexandrina).
    - Point Sturt (Lake Alexandrina).
    - Campbell Park (Lake Albert).
    - “Windmill” location (Lake Albert, north-eastern shoreline).
- Implemented a field monitoring program at the four sites listed above over a period of 7 months.
- Analysed Laboratory and field data, including modelling, to estimate acidity flux rates to the Lower Murray Lakes based on available data.
- Prepared of a final report incorporating laboratory and field monitoring results, modelling outputs, acidity flux rate estimates and management recommendations.

The above, including methodology, laboratory quantification of acidity flux rates, field monitoring program and results from the first 7 months of field monitoring are detailed in Earth Systems Reports: Quantification of Acidity Flux Rates to the Lower Murray Lakes: Final Report December 2009 and Acidity Flux Rates to the Lower Murray Lakes: Supplementary Report June 2010.

Sampling and analytical methods

Figure 1 illustrates the location of the piezometers on the shorelines of Lake Albert, Lake Alexandrina and Currency Creek. For a detailed description of the rationale for site selection, geology, geophysical surveys, piezometer installation, groundwater level sensor installation, rising head tests and hydraulic conductivity calculation please see Earth Systems (2009).

The EPA conducted monthly monitoring from June until September at the three lake sites Campbell Park, Windmill and Point Sturt (A total of 23 piezometers). During the monitoring period water levels in Lake Alexandrina, Lake Albert and Currency Creek rose significantly (from approximately -0.7 to +0.7 mAHD) as a result of winter rainfall in the area and increased flows from the Murray River (due to flooding in the north eastern region of the Murray Darling Basin). While the water level in Lake Alexandrina increased at a steady rate, the refill of Lake Albert was much more irregular. After initial increases over the winter period from -0.7 mAHD to -0.2 mAHD, Lake Albert experienced a rapid refill at the end of September 2010 (-0.2 mAHD to +0.7 mAHD) as a result of the removal of the artificial bund at Narrung which separated the two lakes. The water level in Currency Creek also increased from April to September from -0.1 mAHD to +0.8 mAHD, due regional rainfall, increased tributary flows and a rise in the pool level of the Goolwa channel behind the Clayton embankment. After the inundation of the piezometers at Point Sturt in August, and Campbell Park and Windmill in September 2010, monitoring at these locations ceased. Monitoring in Currency Creek, however, has continued as the piezometer pipes extended above the water level.

The EPA monitoring program was adapted from that of Earth Systems (2009 and 2010) and included:

1. Field measurements of the unperturbed (prior to piezometer purging/bailing) salinity, pH, Temperature and Oxidation-Reduction Potential in the groundwater profile using a calibrated YSI multi-meter. Increments of 25 cm were measured in shallow piezometers and increments of 50 cm in deep piezometers.

2. Purging of each piezometer using a Solonist peristaltic pump (suitable for areas where the water table is above 9m) connected to a 12V battery. In Currency Creek, 1 m bailers were used. Approximately 3 well volumes were pumped from each piezometer as per established groundwater sampling techniques (Appelo & Postma 2005). Groundwater was monitored during pump out with a YSI multi-meter and sampled were taken when fluid properties were stable.

3. Testing of fresh groundwater inflowing into the purged piezometer for general water quality parameters (pH, EC, temperature and ORP) and field acidity/alkalinity. pH, EC, temperature and ORP were measured using a calibrated YSI mulit-meter. Acidity was measured using a Hanna ® Acidity Testing kit using Phenolphthalein indicator and HI 3820-0 Solution. Alkalinity was tested using a HACH® Test Kit, using Bromcresol Green-Methyl Red indicator power and 1.6 M H_2SO_4 Titration Cartridge.

4. Sampling (both filtered and unfiltered) post purging for laboratory analysis of
   a. General water quality parameters (pH, EC)
   b. Alkalinity/acidity
   c. Major ions (Na, K, Mg, Ca, Cl, SO_4)
   d. Dissolved metals (Al, Fe, Mn)

   The samples were collected in new bottles which were washed and rinsed with deionised water. Analysis of above parameters was undertaken by the Australian Water Quality Centre (AWQC), a National Association of Testing Authorities (NATA) accredited laboratory. Following collection, the water samples were transported to the laboratory in ice-filled cooler boxes and then stored at 4ºC.

5. Manual measurements of water levels in both the shallow and deep piezometers were recorded for benchmarking with Australian Height Datum.

6. 15 minute interval groundwater (piezometric) level data from InSitu LevelTroll 500 sensors was downloaded from each shallow piezometer. 15 minute interval moisture data from Sentek EnviroSCAN moisture monitoring system sensors was downloaded from Campbell Park, Windmill and Point Sturt. This data was graphed alongside local rainfall data (Langhorne Creek Station for Point Sturt, Narrung Station for Campbell Park and Windmill and Currency Creek Station for Currency Creek), and surface water data from Department for Water (Previously DWLBC) lake level monitoring stations (Pt Mcleay for Point Sturt, near Waltowa Swamp and Warringee Point for Campbell Park and Windmill, and lower Currency Creek for Currency Creek). It is important to note that the surface water level stations were located some distance from the piezometer locations (Campbell Park and Windmill are located approximately 7.5km and 6km from the nearest water level station (Waltowa Swamp) respectively and Point Sturt is 7km nearest station (Point Mcleay)). Earth Systems 2010 proposed that survey errors may have been present in the level stations during the monitoring period, due to discrepancies between recorded piezometer levels and surface water level station readings. However, as discussed further below, when water levels rose during winter 2010, surface water levels and piezometric levels were closely related. Hence the observed difference in surface water and near shore piezometric levels is likely to be real and not a measurement error.

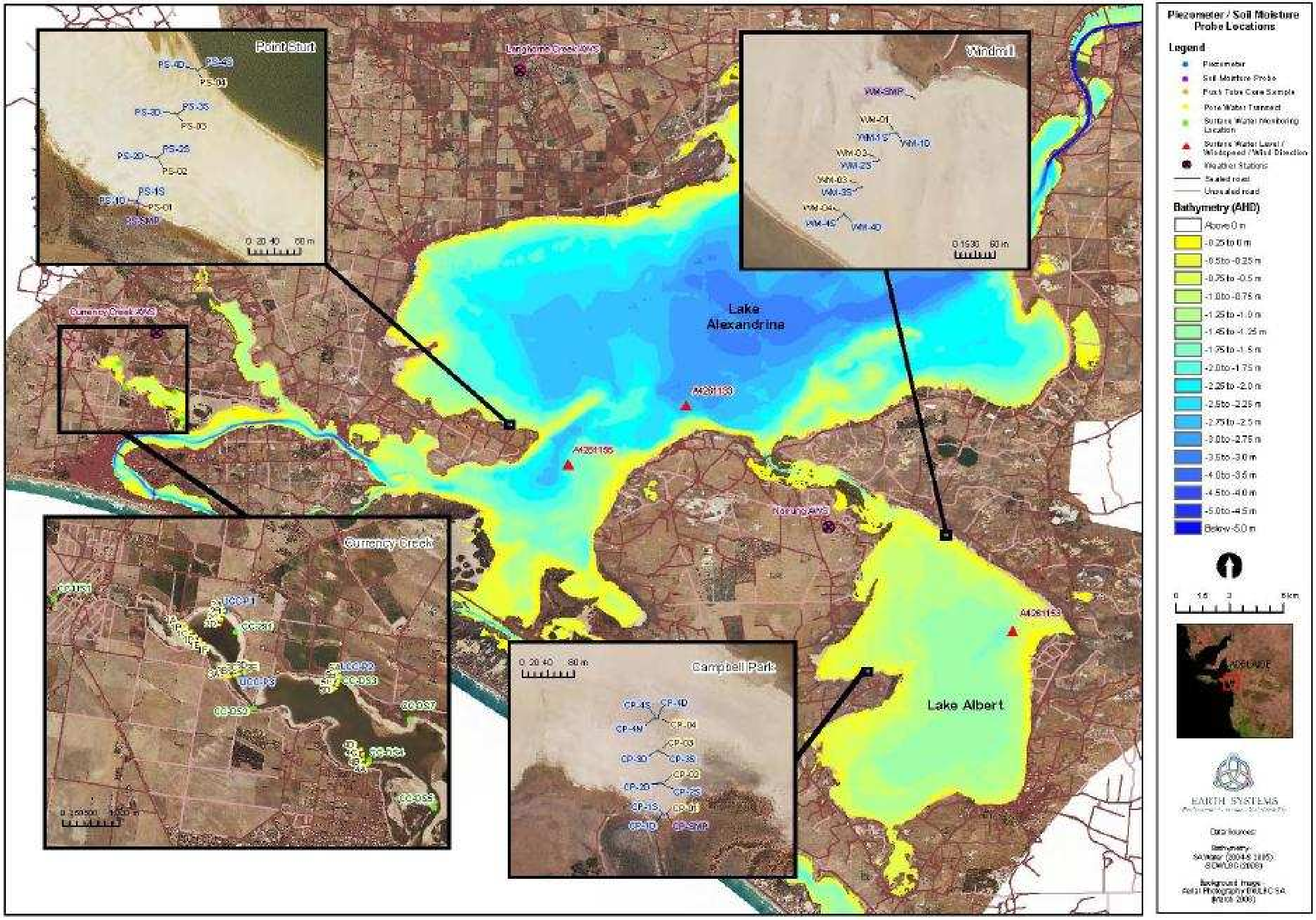


Figure 1: Piezometer location in Lake Albert, Lake Alexandrina and Currency Creek (map courtesy of Earth Systems Pty Ltd)

3.0 RESULTS

3.1 Sediment Moisture

The hourly moisture content from the sensors installed at Campbell Park, Windmill, and Point Sturt locations is graphed alongside rainfall in Figures 2-4 respectively.

- At all three locations, the moisture content increases with depth below ground, approaching saturation (40-50 %vol) at 30-40 cm. All three sites illustrate that the major variation of soil moisture content occurs between 0-30 cm with relatively constant levels at deeper depths. Following a progressive decrease in soil moisture contents observed at all sites from late August 09 to March 10 (Earth System, 2010), there was a progressive increase in soil moisture content from April to September 10 at all sites. The general trends of increasing soil moisture correlate with the period of higher winter rainfall and decreasing soil moisture with the period of higher summer evaporation.

- Campbell Park soil moisture contents (Figure 2) are most responsive to rainfall 0-30 cm below ground. Soil moisture remains relatively constant between 30-50 cm with moisture content near saturated (average 44.3 vol%). Despite the adjacent piezometer level reaching a minimum of 0.84 m below ground (piezometer effectively dry) between August 2009 and April 2010 (see below), the sediments remained saturated (average moisture content 39-45 vol%) at a depth of 30-50 cm throughout this period. Thus, approximately 30-50 cm of sediment was effectively saturated above the minimum piezometric level (Earth Systems 2010). Between April and September 2010, there a clear overall increase in soil moisture contents between 0 and 20 cm below ground, with a marked increase at the beginning of June 2010 (%vol moisture at 10 cm increased from 6.76 % (average) between Oct 2009 and Jan 2010, compared to 21.5 vol% (average) between May and September 2010). The most notable result from May to September is the highly variable nature of the moisture content between 0 and 10 cm below ground. Clear responses to rainfall can be seen with moisture contents rising from around 15 vol% to 30 vol% during significant rainfall events, with drainage and/or evaporation occurring to lower moisture levels over the following 5 to 7 days. Sustained periods of rainfall (like that seen at the beginning of August) kept moisture levels high (between 30 to 35 %vol) near the sediment surface. From the beginning of August the sediment below 20 cm reaches saturation (above 35 %vol) as the groundwater water levels increase.

- Soil moisture content at Windmill (Figure 3) saw variation in moisture content up to 40 cm, with clear responses to large rainfall events across all depths, although larger changes can be observed between 0-30 cm below ground than at 40 cm. Soil moisture at 40 cm increased only during major rainfall events. Overall, Windmill has a higher relative moisture content than the other sites, which has been attributed to higher porosity in the sediments (Earth Systems 2010). There was a sustained increase in overall soil moisture content volume from June to September 2010. Similar to Campbell Park, there are clear responses to rainfall events at Windmill, although Windmill shows responses to a deeper horizon than Campbell Park (to 30 cm below ground). The higher porosity of the sediments at Windmill likely means that drainage is quicker and hence rises in moisture level following rainfall events are lower in magnitude than at Campbell Park.

- The soil moisture content at Point Sturt (Figure 4) between 0-30 cm illustrated the clearest responses to rainfall events, while there was less variation in the soil moisture content at 40 cm. Overall there was an increase in soil moisture content from April to July 2010 at all levels compared with the summer period of November 2009 to March 2010.

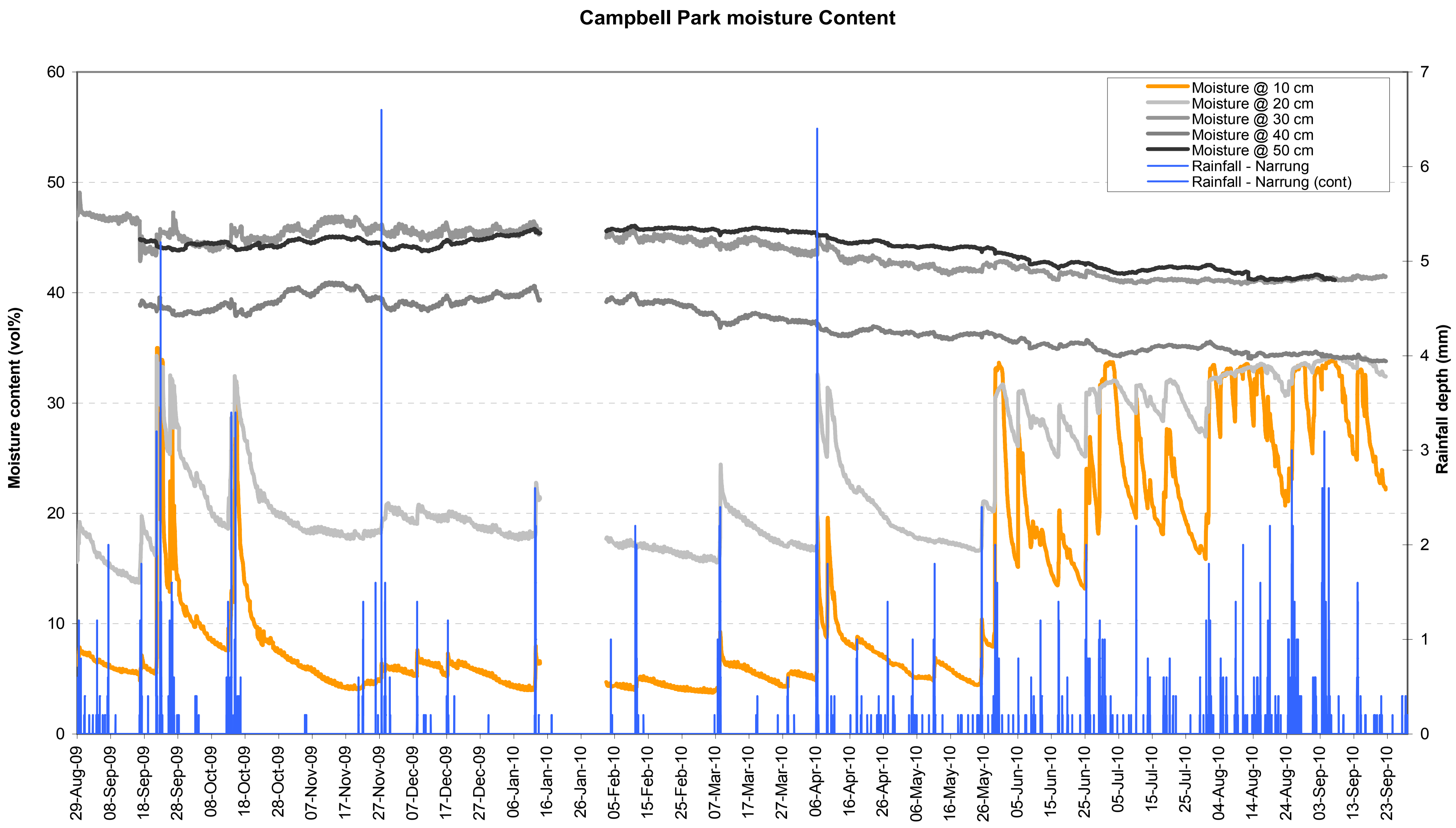


Figure 2: Temporal variation in sediment moisture contents at Campbell Park from the 29th of August 2009 to the 11th of September 2010.

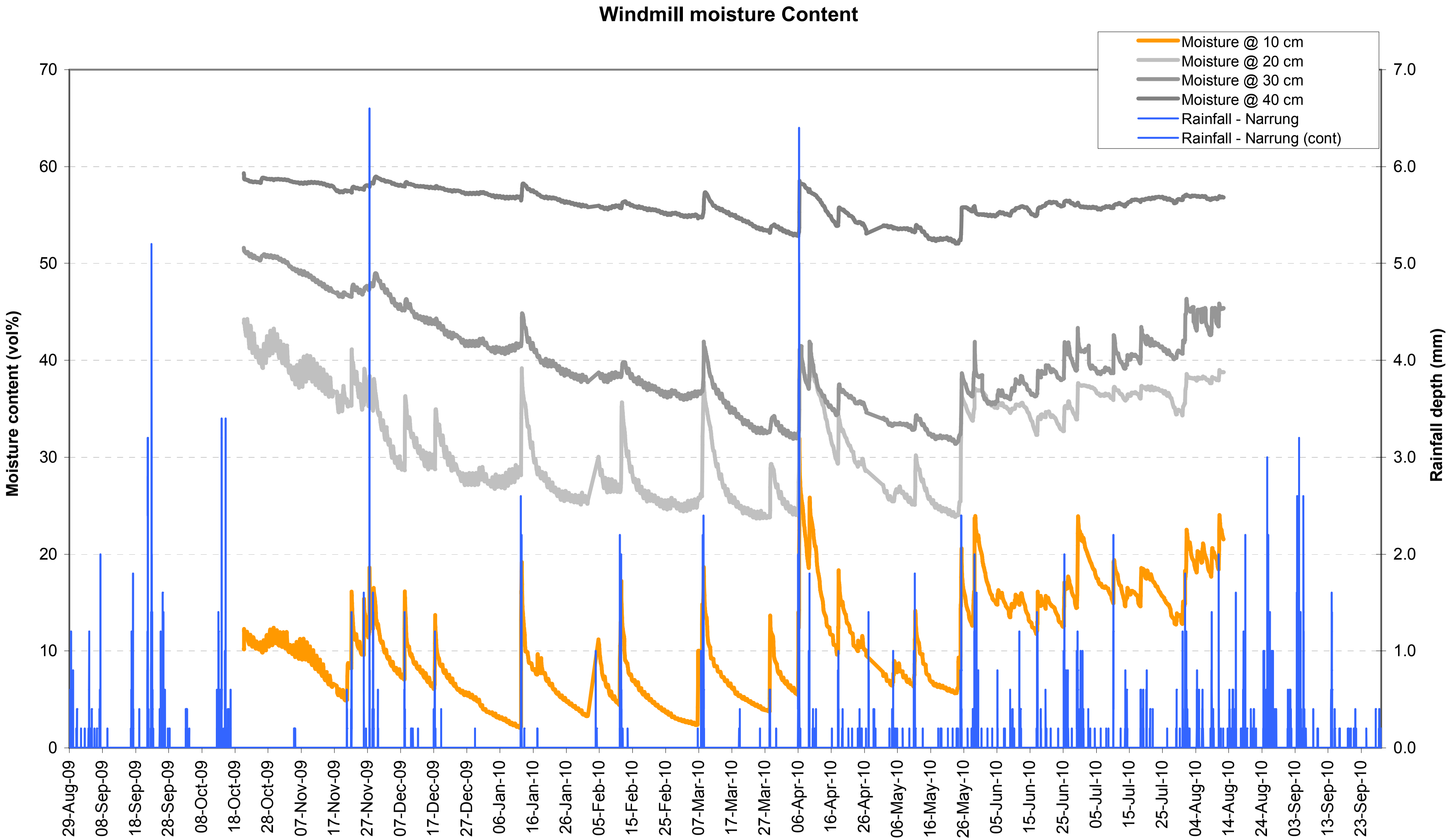


Figure 3: Temporal variation in sediment moisture contents at Windmill from the 29th of August 2009 to the 11th of September 2010

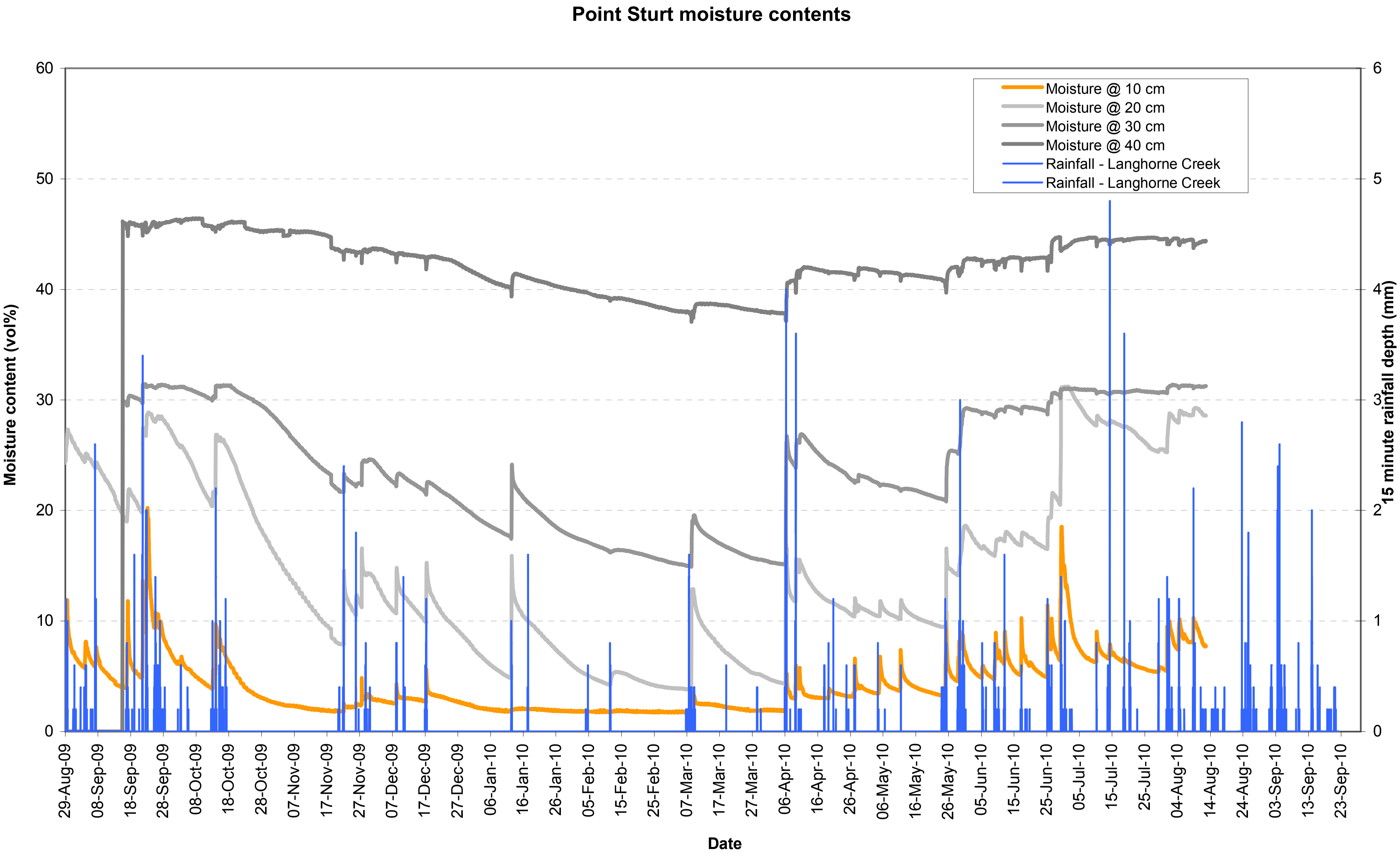


Figure 4: Temporal variation in sediment moisture contents at Point Sturt from the 29th of August 2009 to the 7th of August 2010.

3.2 Groundwater (piezometric) Levels

The piezometric levels at Campbell Park, Windmill and Point Sturt are illustrated in the Figures below. Each site has three graphs, demonstrating the entire monitoring period, the winter/high rainfall (May to September 2010) months and a rainfall event where precipitation was high for a period of time. Hydraulic gradients were also calculated from Site 1-2, Site 2-3 and Site 3-4 at each location.

Daily oscillations in piezometric levels are interpreted to be associated with the effects of Earth tides (Earth Systems 2010).

Campbell Park:

- After a decrease in the piezometric levels at Campbell Park of 0.5-1.0 m from late August 09 to February 10, piezometric levels at Campbell Park increased 0.5 – 1.0 m from June 2010 to October 2010 (Figure 5). The main increase in groundwater level began towards the end of May 2010 (with levels rising from -0.6 mAHD to -0.4 mAHD from 7th May to the 3rd of June 2010) due to higher rainfall and rising surface water levels.

- After sustained dry period in the upper sandy sediments of Site 1 from February to June, this piezometer contained water for the winter rainfall period from early June to October 2010.

- Piezometric levels increase after significant rainfall events at all sites. Figure 6 displays several occasions of high intensity high rainfall, including late May, late June, late July- early August and the most significant period of extended high rainfall, August 24 to the 5th of September. After these rainfall periods, the site with the greatest groundwater rise was Site 1 (nearest pre-drought shoreline), with increases of between 0.2 and 0.4 m. However, the piezometric level at this site also fell much more quickly than the other sites once rainfall ceased. The rapid decrease at this site may be result of a lateral hydraulic gradient towards the lake, as Site 1 is at 0.275 m above Site 2 and 0.443 m above Site 4 (nearest the current lake shoreline). These events illustrate that rainfall raises the groundwater level rapidly within a few hours, with decreases occuring over a period of 12-24 hours and then more slowly over a period of days.

- At the beginning of August (Figure 7), Campbell Park recorded a 2 week period of low intensity rainfall which rose the groundwater level at Site 2, 3 and 4 causing ponding above the surface (Site 1 was again more variable, responding and draining rapidly). From the 20th -24th of August, there was a period of little rainfall and the groundwater levels at site 1, 3 and 4 fell, however Site 2 remained high indicating ponding at this site. In addition, Site 4 (the closest piezometer to the lake) had a higher piezometric level than that at Site 3 and 1 during this time. These results indicate a very complex and dynamic hydrology at Campbell Park.

- At all sites at Campbell Park, the piezometric level in the lower layer of sediments are generally lower than the level in the upper layer of the sediments. As observed by Earth Systems 2010, this suggests that the layers are poorly hydraulically connected (consistent with a thick clay layer observed between the two sandy layers). Although poorly connected it should be noted that the groundwater level in the deep sediments rises over the winter months from -0.7 in May to -0.3 in September 2010, possibly indicating some deep drainage from the upper sandy profile through the semi-confining clay layer and/or increased recharge from the regional aquifer.

- Hydraulic gradients between piezometers at Campbell Park are shown in Figure 8. Hydraulic gradients are generally low but increase in response to rainfall. In general, positive and low hydraulic gradients are present at Campbell Park, indicating some potential for groundwater flow to the lake. Some flow reversals occur between Sites 2 and 3 during dry conditions, which is likely a result of Site 2 being lower topography, even though it is further up the shoreline.

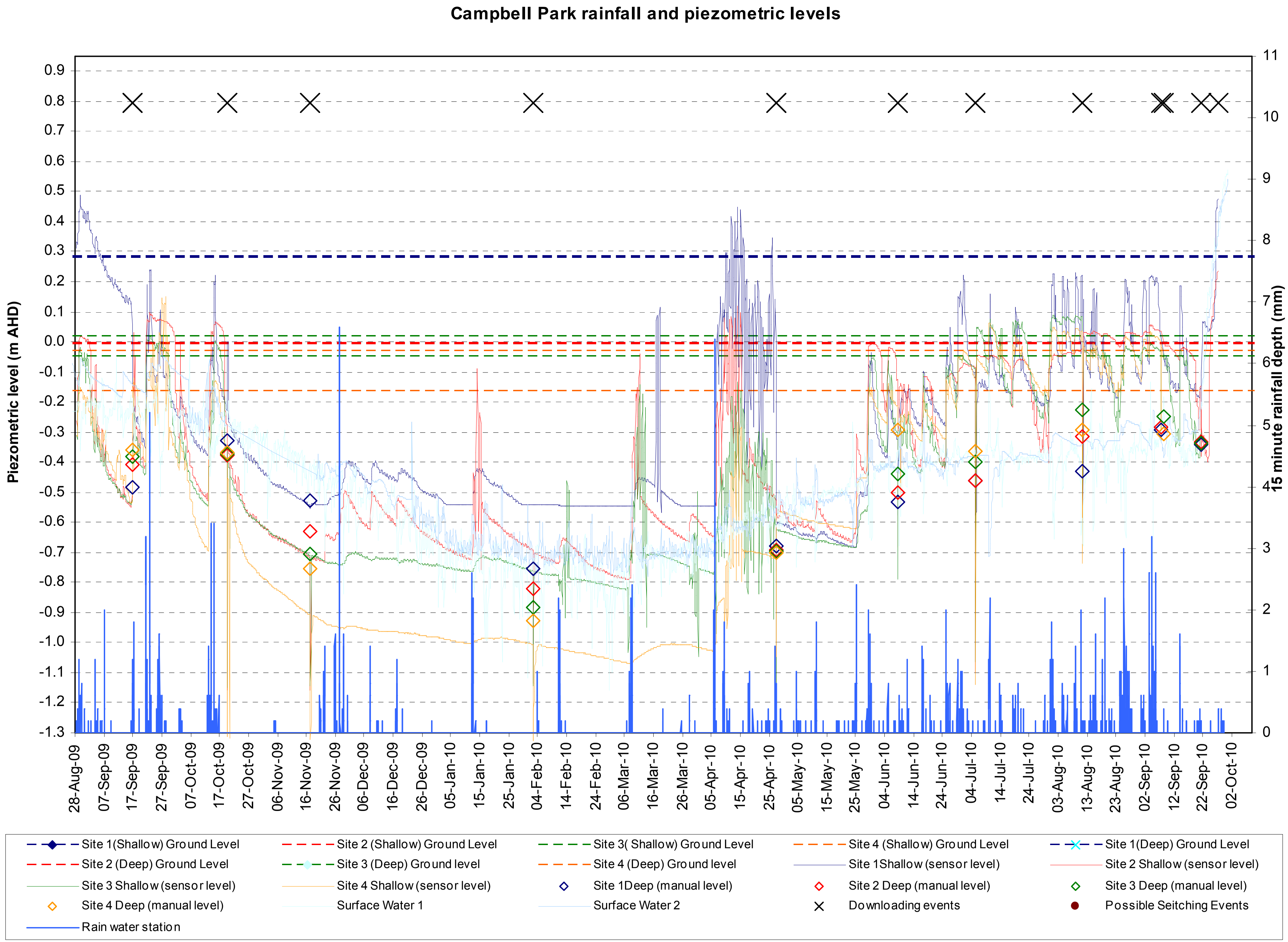


Figure 5: Campbell Park Rainfall and Piezometric Level from August 2009 until October 2010

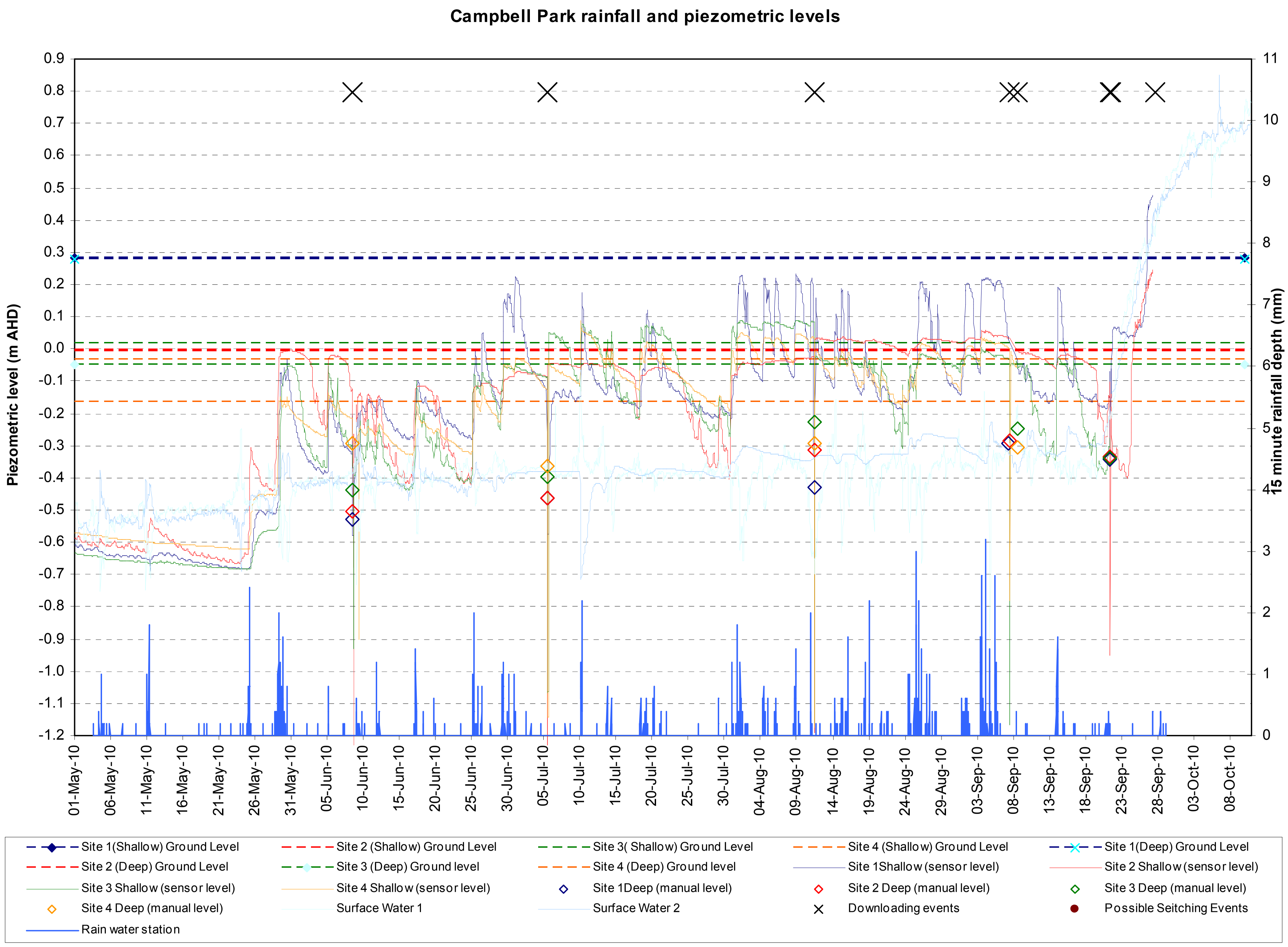


Figure 6: Campbell Park Rainfall and Piezometric Level during the winter/high rainfall months 2010

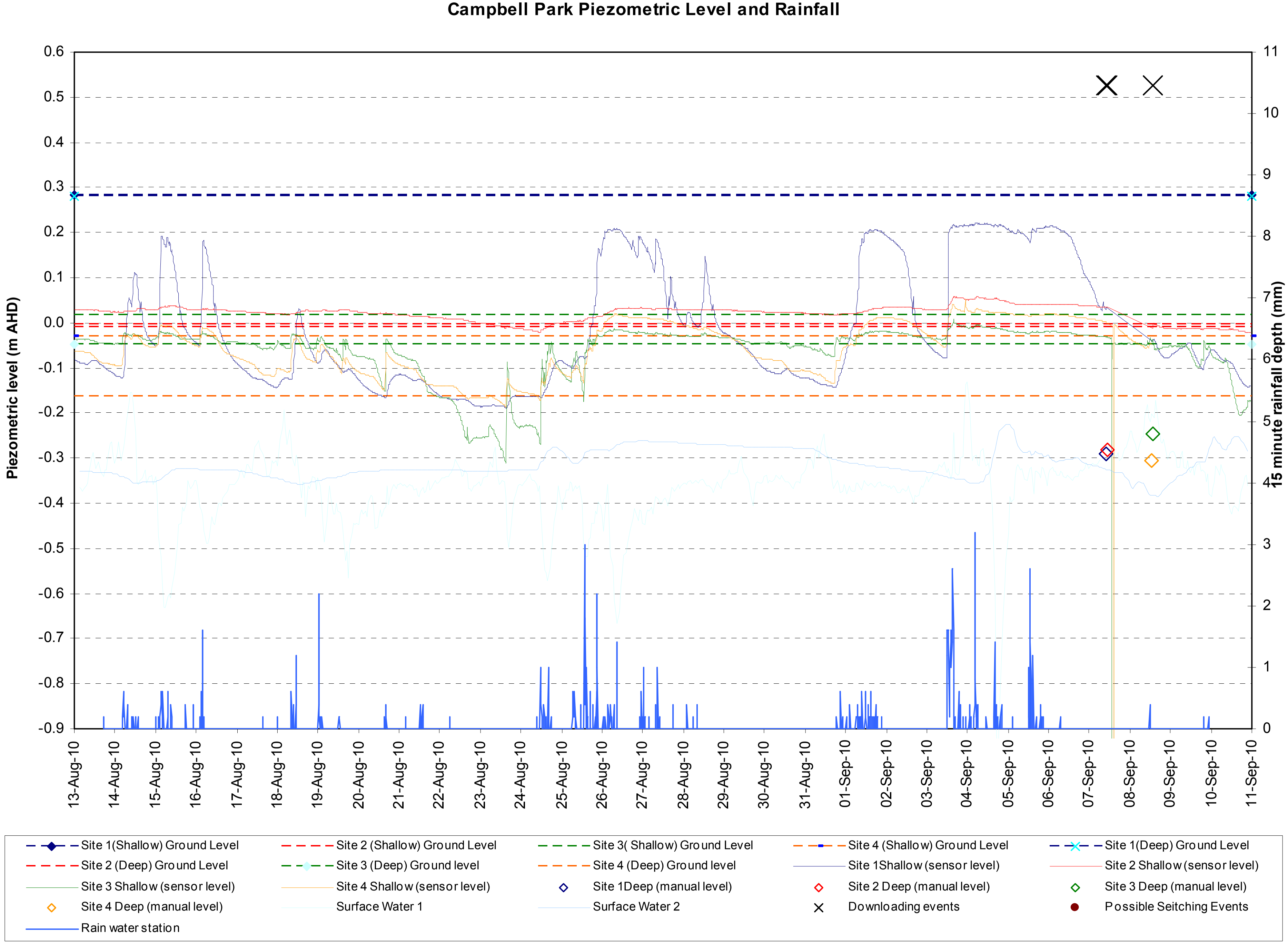


Figure 7: Campbell Park Rainfall and Piezometric Level during a significant rainfall event period (2010)

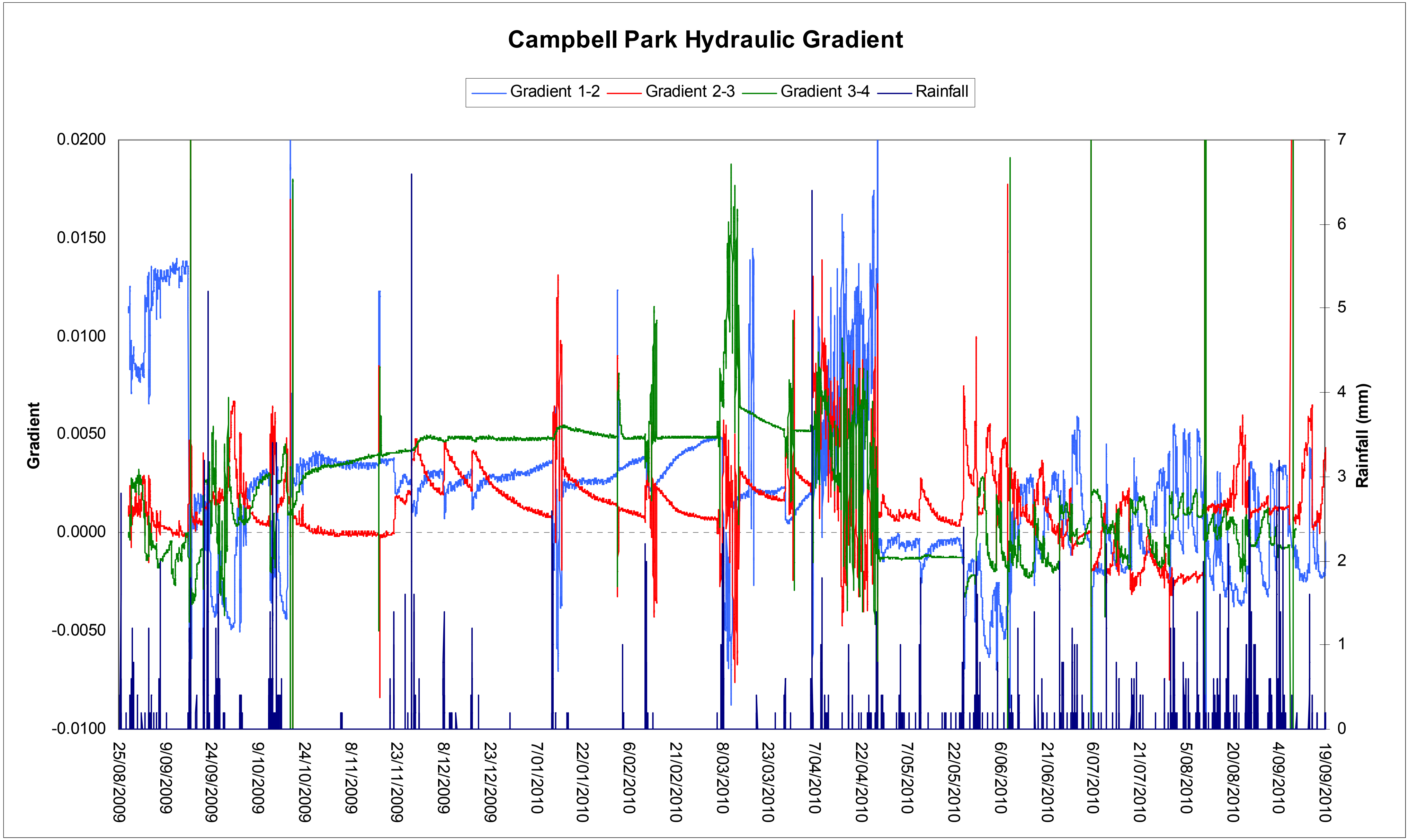


Figure 8: Hydraulic Gradient at Campbell Park between Site 1-2, Site 2-3 and Site 3-4

Windmill:

- After a decrease in the piezometric levels at Windmill of 0.5-0.6 m from late August 2009 to February 2010, piezometric levels at Windmill increased 0.3-0.6 m from June to October 2010 (Figure 9). The major increase in groundwater level began towards the end of May 2010 corresponding with the period of higher rainfall and rising surface water levels.

- Piezometer levels generally remain below ground level before May 2010, although, as noted by Earth Systems (2010), there are several times where the level increases above ground level, which is likely to be evidence of a seiching event, a period of significant rainfall or both. Earth Systems noted a seiching event on the 25 October 2009 and attributed other rises above ground level from November to April to periods of rainfall. A second seiching event on the 4th of September 2010 is noted (Figure 9).

- All sites at this location respond quickly to rainfall events (Figure 10) with increases in groundwater level within 1-2 hours. This is followed by a fall over a period of days to pre-rainfall event levels. From late May/early June 2010, there is a rise in groundwater level of around 0.3 m across all sites due to the lake level rise and frequent rainfall at the beginning of winter. During winter, groundwater levels remained high with variations from -0.3 up to 0 m AHD after rainfall periods. The frequency of rainfall appears important in sustaining high groundwater levels whereas sporadic high intensity events cause more temporary rises in groundwater levels. During the rainfall event at the beginning of August groundwater levels (especially at Site 1 and 2) are above ground level indicating areas of ponding.

- Throughout the winter period (Figure 10), the piezometric levels recorded in the shallow sediments were similar to those measured in deeper sediments, suggesting there is connection between the horizons. Earth Systems (2010) noted that during the summer period Site 4 was approx. 0.1 m higher in the deeper sands than in the shallow sands, meaning there was a possibility of a locally disconnected aquifer. This difference at Site 4 was not seen during the winter period.

- Figure 11 illustrates a period of high piezometric levels, as a result of intense rainfall at the beginning of September 2010, combined with a seiching event on the 4th of September. On this occasion, the piezometric level was above ground level at all sites, indicating complete inundation of the Windmill transect by lake water. The corresponding decrease in surface water level at the Warringee Point lake water level station (located in the southern end of the lake) further confirms the seiching event (the surface water is pushed in a northerly direction by a prevailing southerly wind).

- The piezometer levels at Windmill generally decrease with proximity to the lake surface water, indicating a small groundwater gradient towards the lake as found by Earth Systems (2010). Hydraulic gradients are low however as shown in Figure 12. After rainfall events hydraulic gradients increase, however these increases are relatively short lived with flow reversal occurring during drier periods. For example, the rainfall event during early March 2010 created a positive hydraulic head gradient, however, within a week this gradient reversed and a large gradient was present away from the lake. Similar to Campbell Park, the nature and occurrence of hydraulic gradients at this location is complex and requires further investigation.

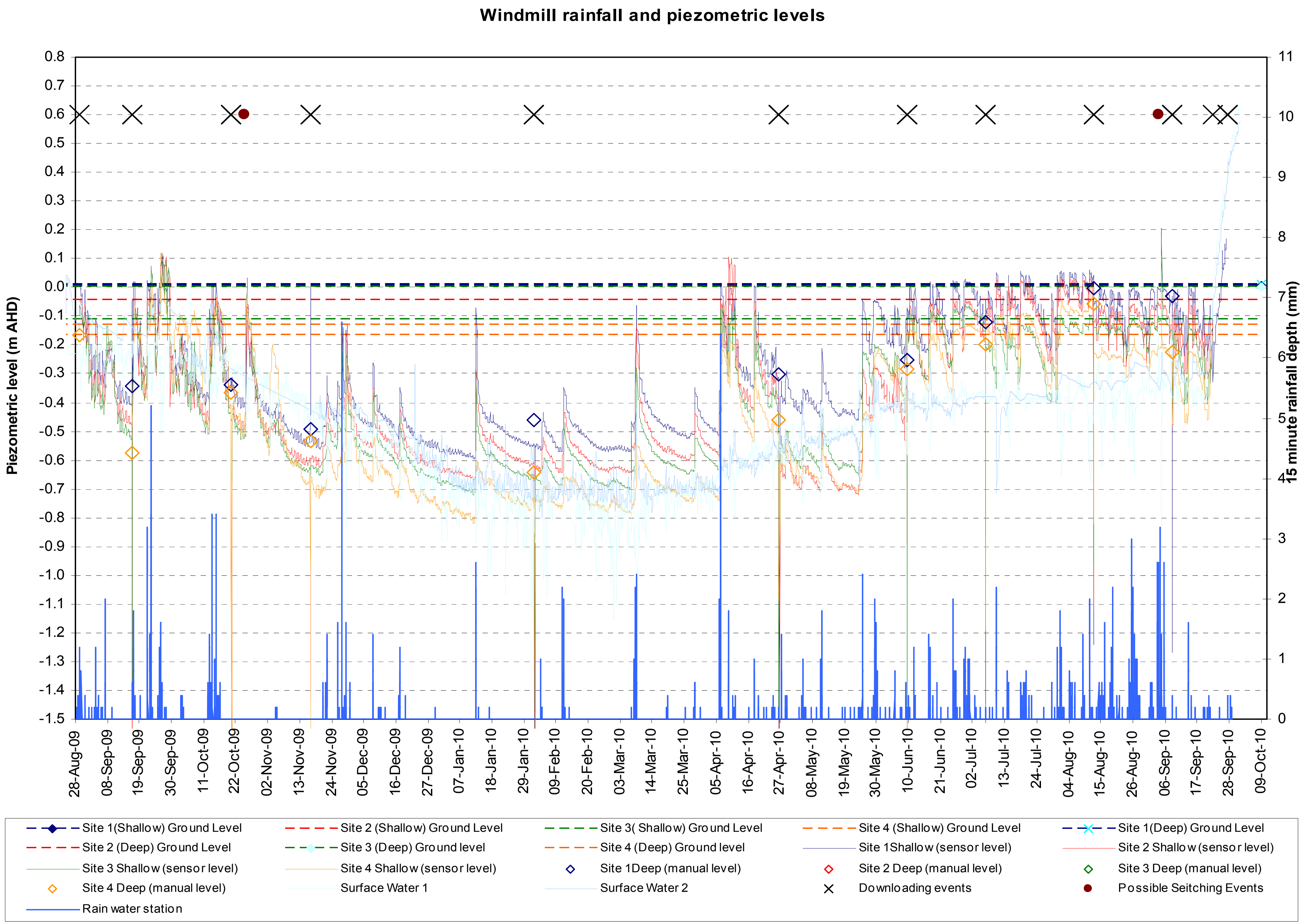


Figure 9: Windmill Rainfall and Piezometric Level from August 2009 to October 2010

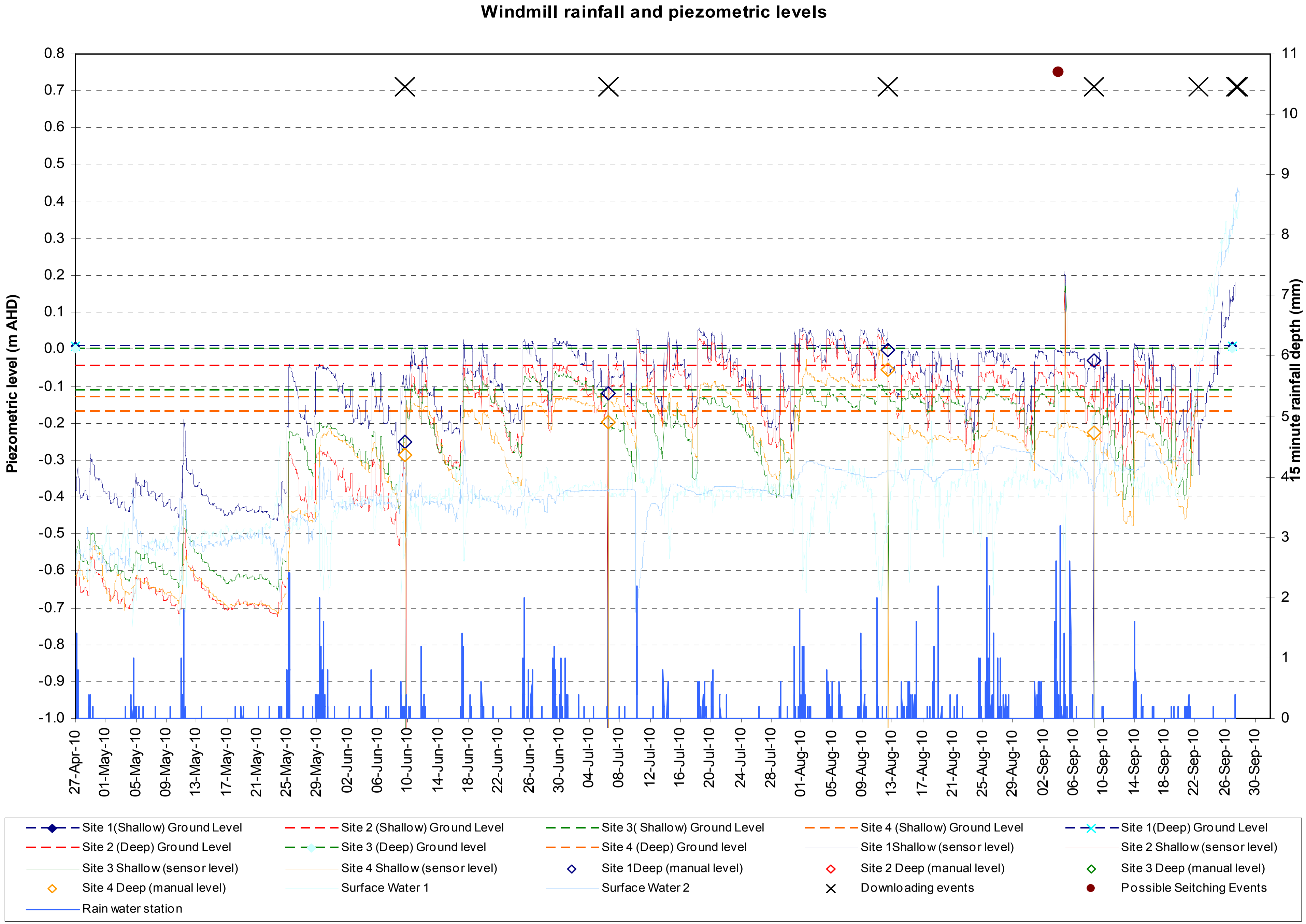


Figure 10: Windmill Rainfall and Piezometric Level during winter/high rainfall months (2010)

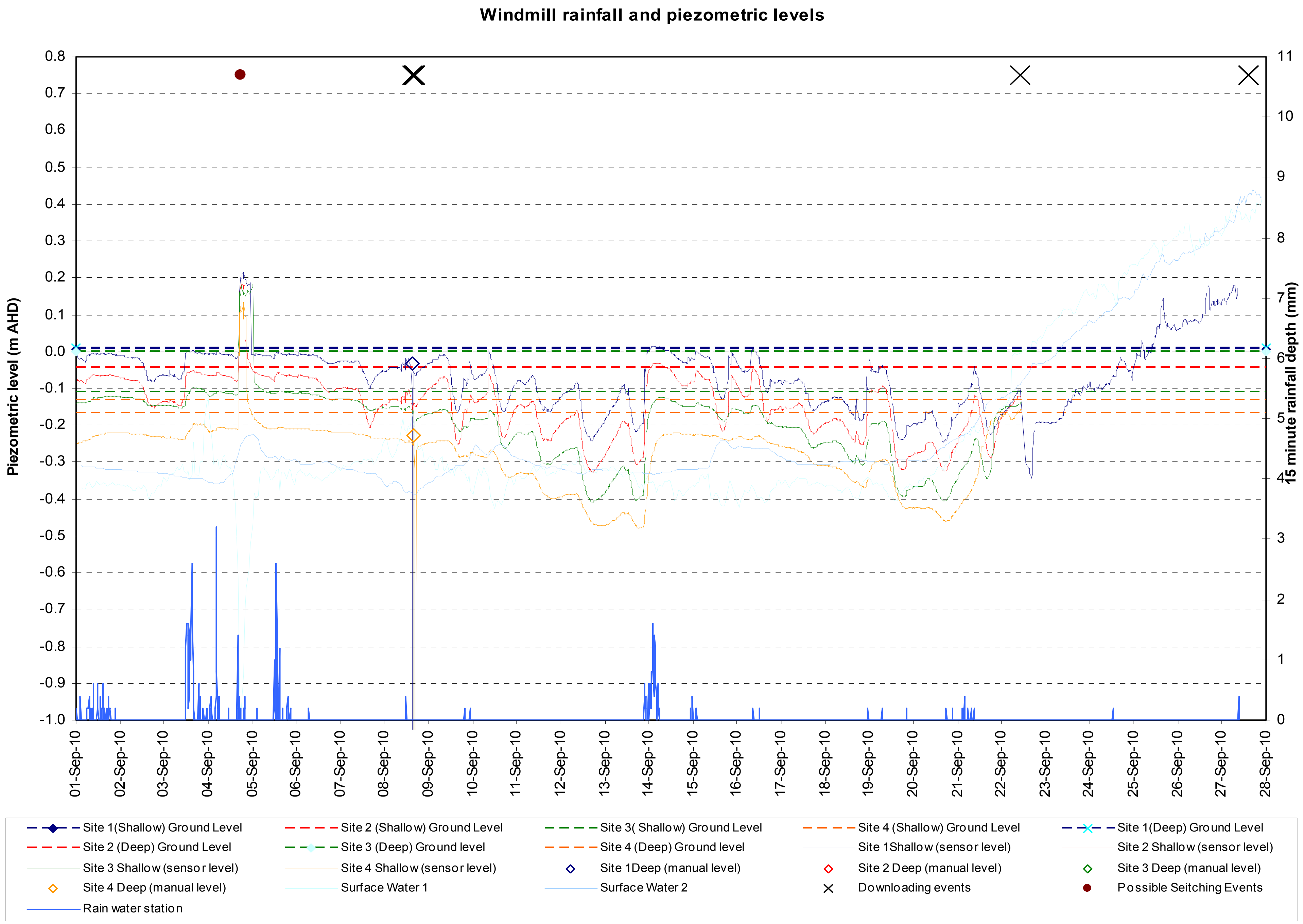


Figure 11: Windmill Rainfall and Piezometric Level during a significant rainfall event period (2010)

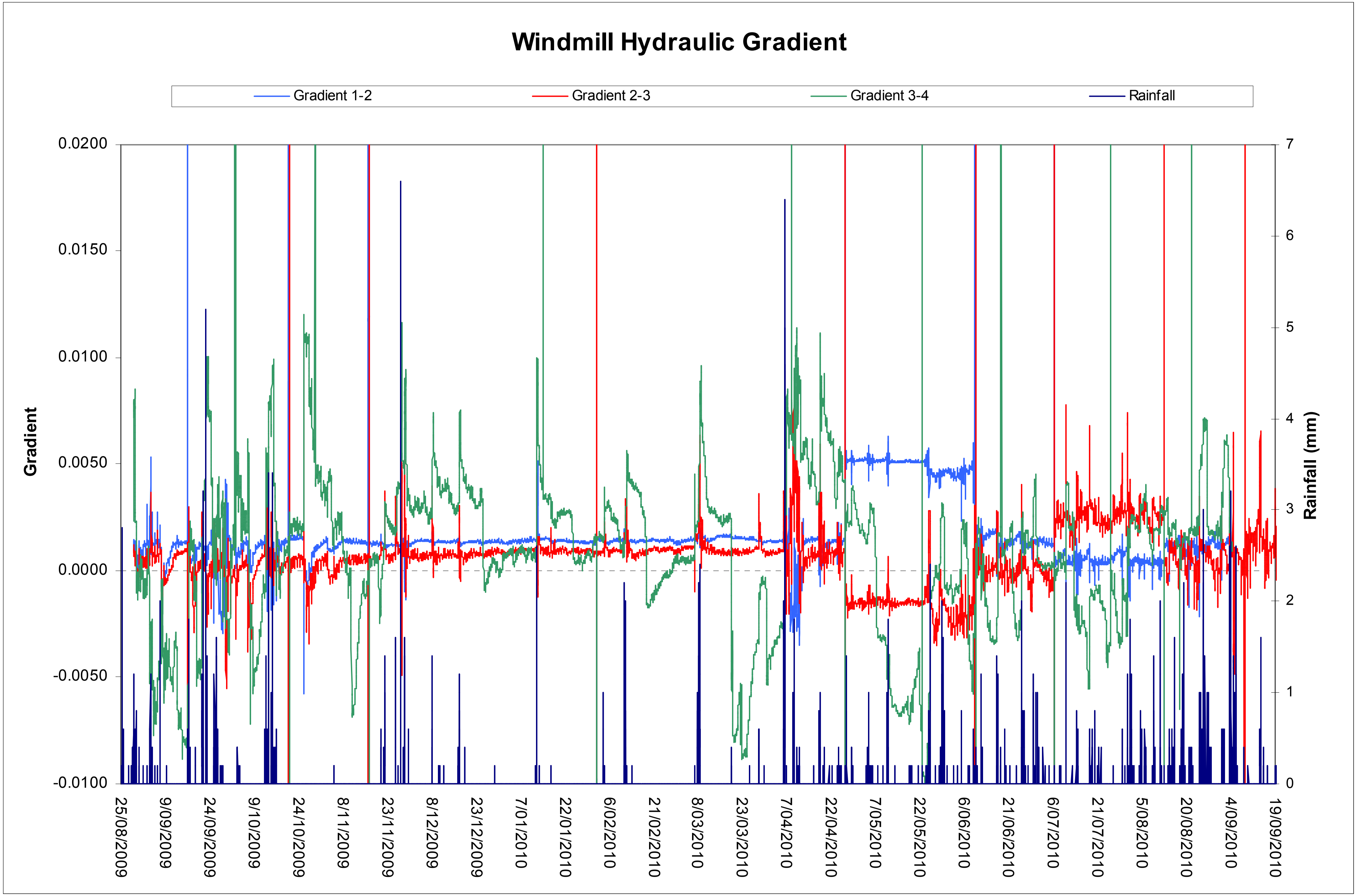


Figure 12: Hydraulic Gradient at Windmill between Site 1-2, Site 2-3 and Site 3-4

Point Sturt:

- The level cable from site 4 at Pt Sturt was removed on 11th June 2010 due to the complete inundation by rising lake water levels. The continued lake level rise over July and August progressively inundated both site 2 and 3 and the troll level cables were removed from these sites on the 12th of August 2010. At the beginning of September the last level cable from site 1 was removed. The piezometric level increase above ground level can be seen on Figure 11 in late May for site 4, mid June for site 3, mid July for site 2, and the beginning of September for site 1.

- From October 2009 to April 2010, the surface water levels at the nearest monitoring station (Pt McLeay) generally exceeded the piezometer levels at Point Sturt nearest the lake water (Site 4) by 0.1-0.2 m. This was proposed by Earth Systems (2010) to be a possible error in the data from water level station. However, as the lake water level rises during August, there is a clear agreement with the lake level data and the piezometric data (Figure 13). Earth Systems (2010) also noted that piezometric levels at Site 4 can exceed those at Site 3, and more recently over summer and autumn 2010 this has also been apparent between Site 3 and Site 2 during mid May and the beginning of June, and Site 1 and Site 2 at the beginning of August. These results suggest that there may often be a hydraulic gradient away from the lake at this location, particularly during drier periods.

- During winter 2010, the levels in all Point Sturt piezometers increased considerably (up to 0.7 m, Figure 14). This rise coincided with winter rainfall and the rapid refill of Lake Alexandrina as a result of flooding in the north-eastern Murray Darling Basin catchment area. From June 2010, the piezometric level at Sites 2 and 3 was often above ground level, indicating ponding at these sites. The surface water level was always above the piezometric level at Site 3 indicating a lack of a hydraulic gradient from the near shore region towards the lake. However, Site 1 and 2 had higher piezometric levels than Site 3 indicating a hydraulic gradient towards the lake in the first 150 m of the transect.

- The response of the piezometric level to significant rainfall events at Point Sturt is rapid with increases occurring on an hourly basis and returns to pre-event levels with 12 hours (Figure 14). The effect of rainfall at each site at this location is much more obvious during the summer months, than in the 2010 winter period.

- Hydraulic gradients between piezometers at Point Sturt are shown in Figure 15. As noted above a positive hydraulic head gradient is generally present between Sites 1-2 and 3-4. However, between Sites 3 and 4, a low or negative hydraulic gradient is present much of the time, indicating a low potential for significant groundwater flow towards the lake. The exception to this is following rainfall events when positive hydraulic gradients occur at all sites.

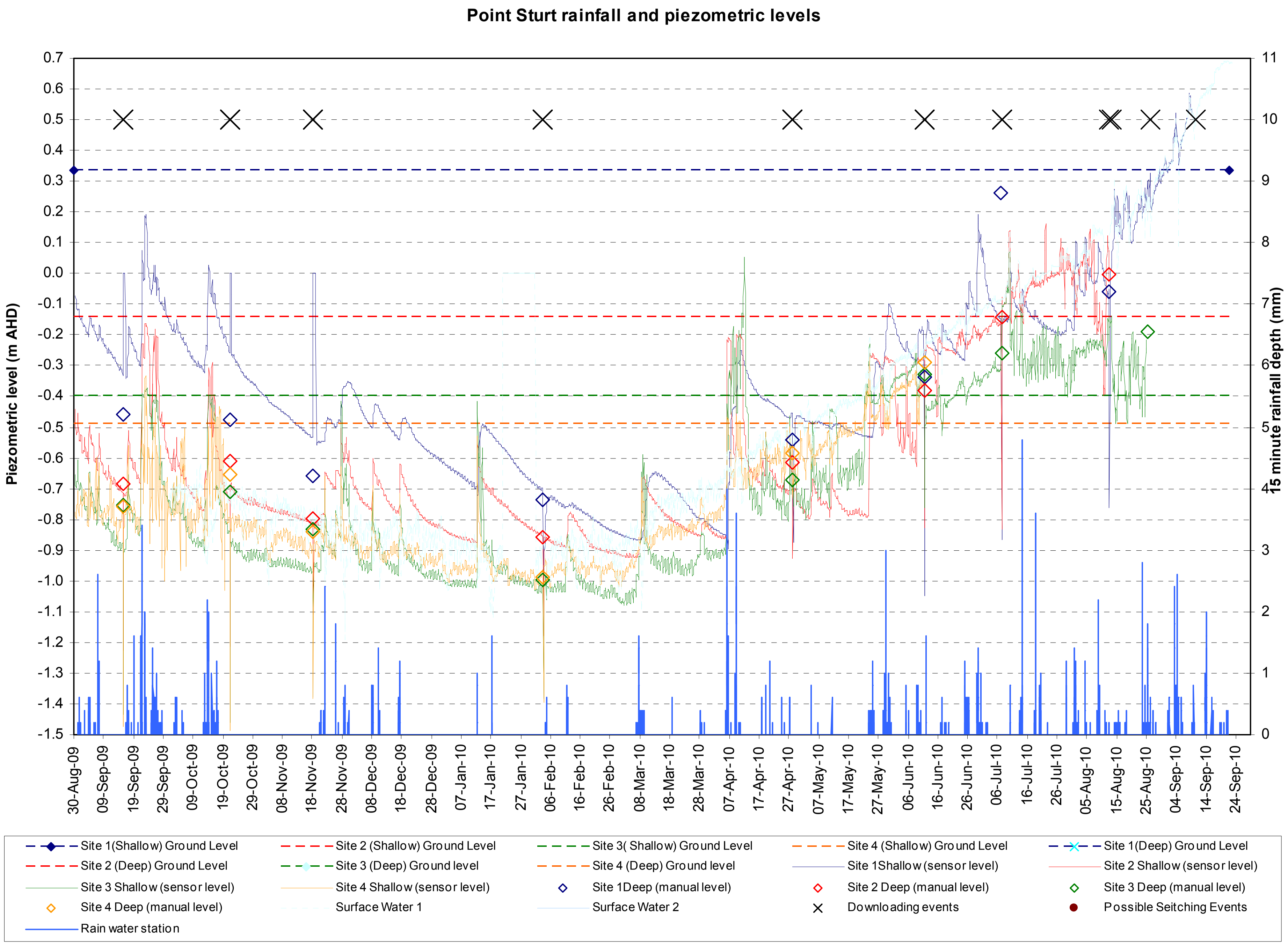


Figure 13: Point Sturt Rainfall and Piezometric Level from August 2009 until September 2010

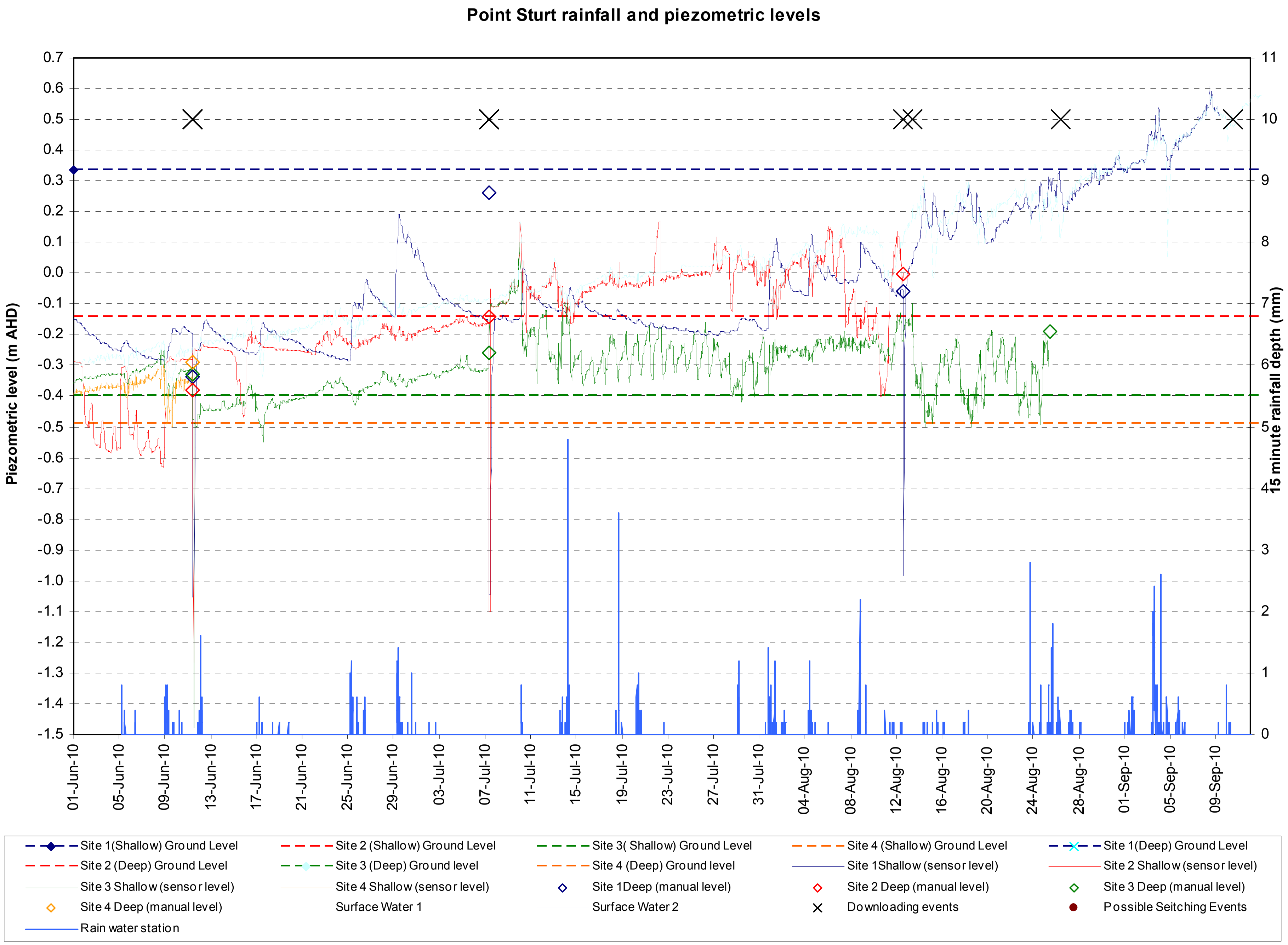


Figure 14: Point Sturt Rainfall and Piezometric Level from during winter/high rainfall months (2010)

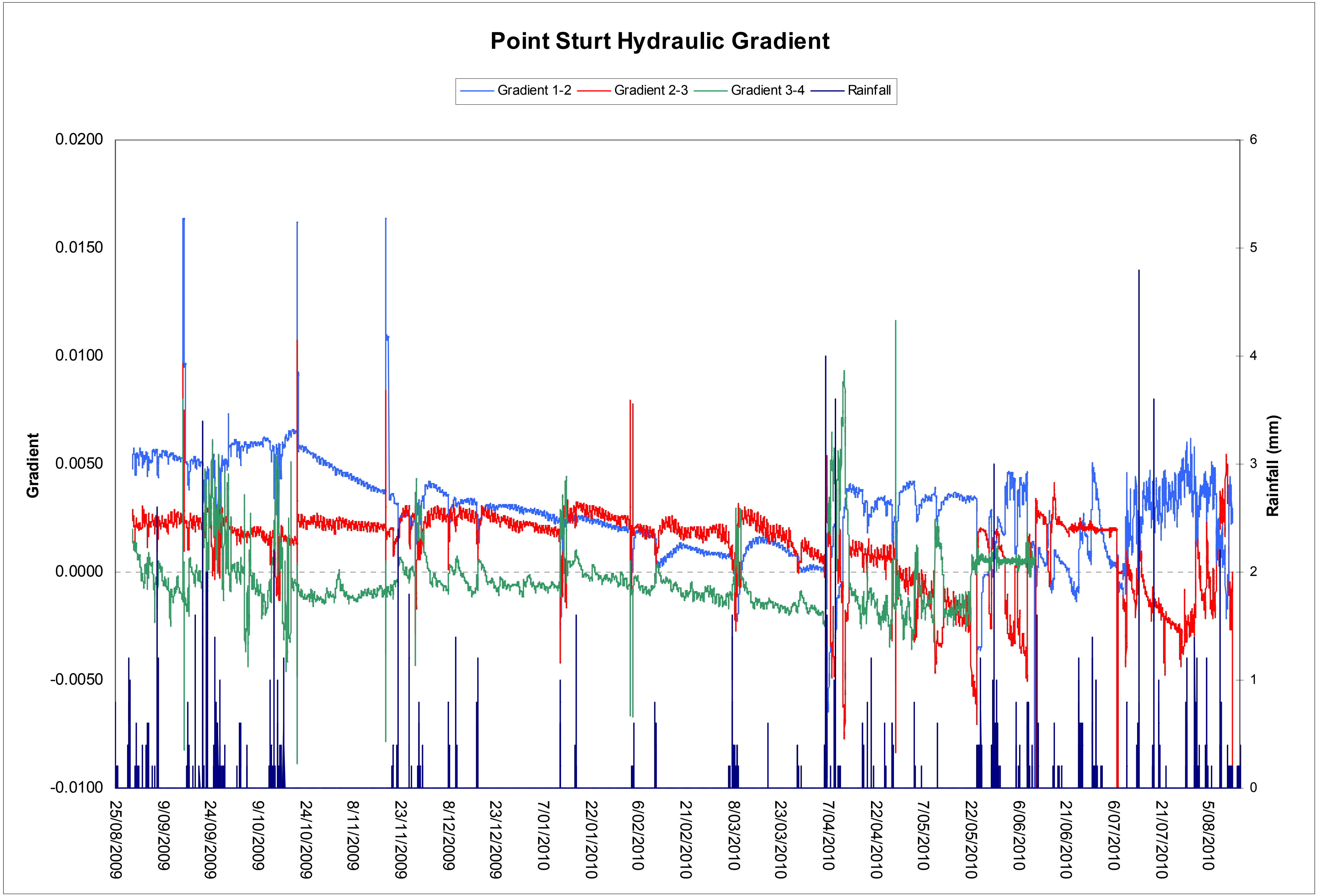


Figure 15: Hydraulic Gradient at Point Sturtt between Site 1-2, Site 2-3 and Site 3-4

Currency Creek:

- Currency Creek has single piezometers at three locations, unlike the other locations where a piezometer transect is present. From May 2009 until August 2010, piezometric levels decreased with location proximity to the Goolwa Channel. From mid-May to mid-September 2009, levels in UCC-P3 were approximately 0.2 m lower than in UCC-P1, while the levels at LCC-P2 were approximately 0.2-0.3 m below UCC-P1.

- As noted by Earth Systems (2010), piezometer levels in Currency Creek (Figure 16) increased by 1.0-1.2 m from mid-May to mid-November 2009 to a peak of 0.7 mAHD. This rise is attributed to increased rainfall over the winter months and surface water level rises following pumping from Lake Alexandrina into the Goolwa Channel after the regulator was built near Clayton. The following period was characterised by a decrease in piezometric and surface water levels at UCC-P1 and LCC-P2 (piezometric level fell to -0.4 m AHD at UCC-P1 and -0.6 m AHD at LCC-P2). The piezometric level at the beginning of April 2010 was comparable to when the monitoring commenced in May 2009. From late May 2010 levels in both piezometers began to rise with peaks corresponding with periods of high rainfall and surface water level rises.

- Superimposed on the general trend of rising piezometric levels in winter 2010, rainfall events increased the piezometric level (approximately 0.2 to 0.4 m) over a period of 24 hours which then decreased to pre-event levels over a period of days (Figure 17).

- From early August, the piezometers were overtopped and as expected surface water levels match piezometric levels. A similar result was found by Earth Systems, during the rapid surface water level rises from September to November 2009.

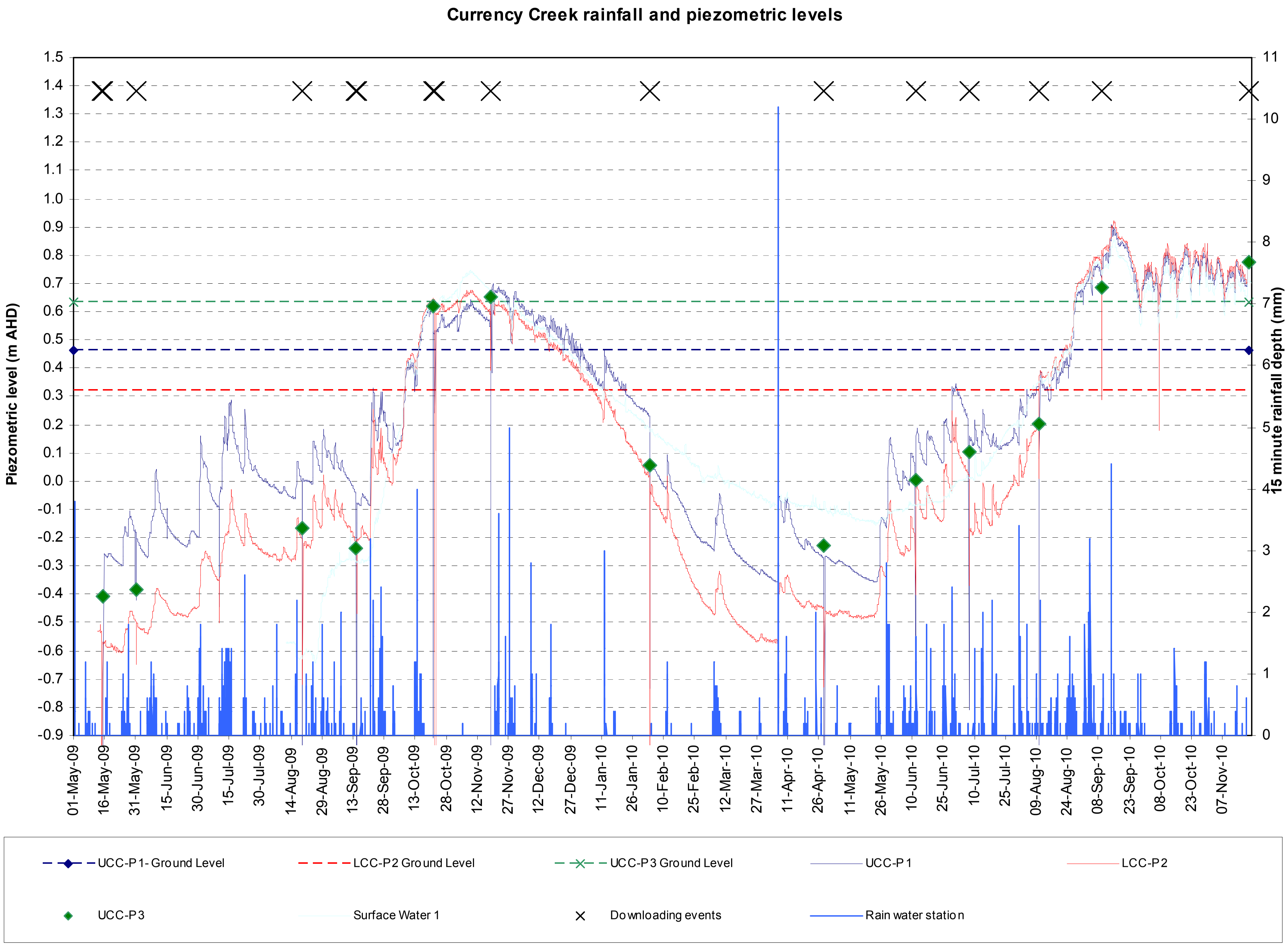


Figure 16: Currency Creek Rainfall and Piezometric Level from May 2009 to November 2010

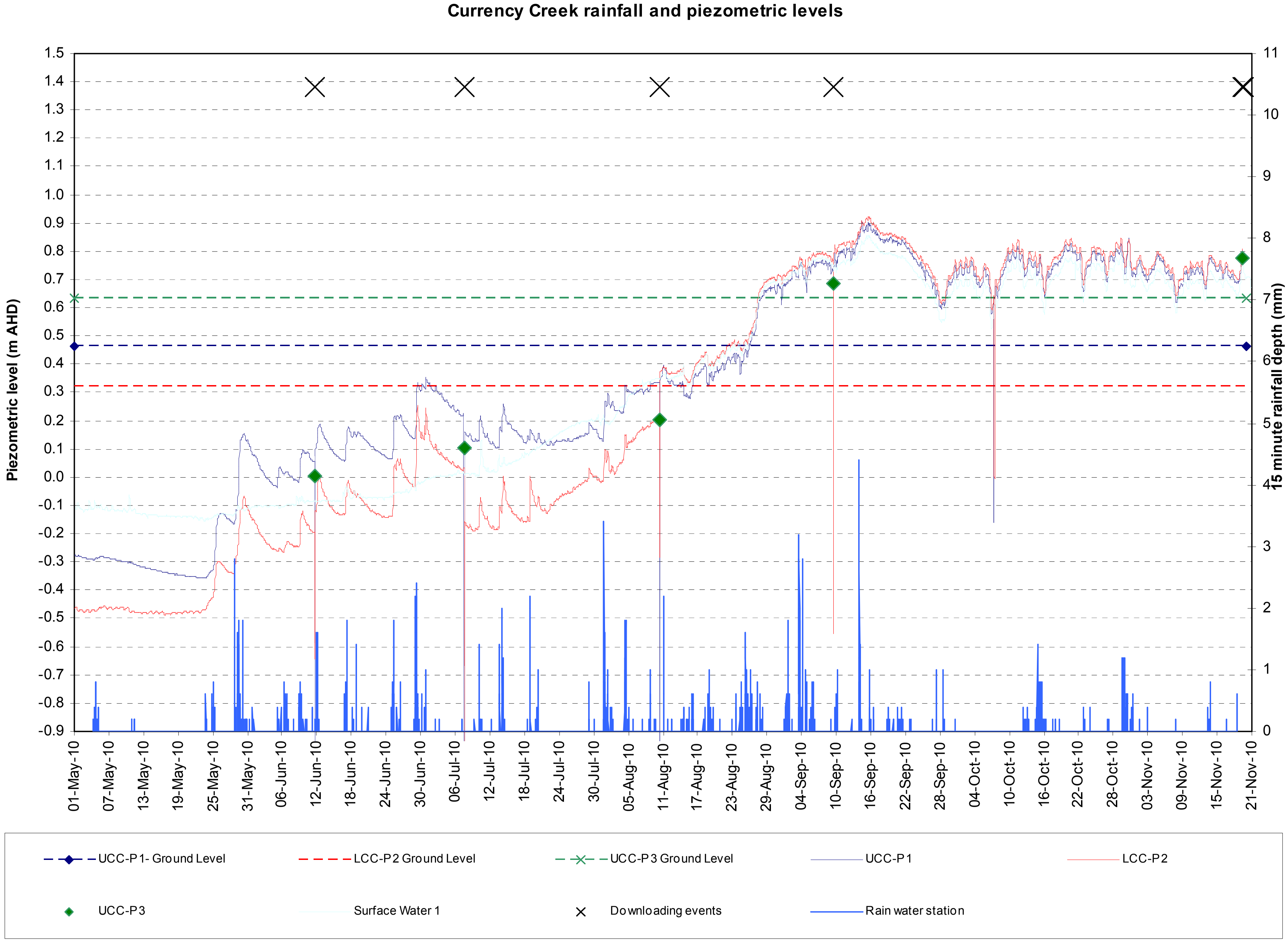


Figure 17: Currency Creek Rainfall and Piezometric Level during winter/high rainfall months (2010)

Note: Step change between 7th of July and 10th of August 2010 at LCC-P2 is currently being investigated.

3.3 Groundwater Quality

The trends in groundwater quality in the piezometers are shown in Figures 18. The data is presented for key parameters (pH, EC, ORP, alkalinity/acidity, sulfate:chloride ratio) in terms of distance along the piezometer transect for all sites combined (left - near shore to right - near lake) on various sampling dates (Figures 18-22) and individual site time series with the complete set of parameters (Figures 23-26). Surface water quality data, where available, is also shown for reference.

Campbell Park:

- The upper piezometers at Site 2, 3 and 4 of Campbell Park all show a pH<5 which is below the ANZECC (2000) guideline (pH 6.5-9.0) to protect aquatic ecosystems (Figure 18). Site 1 (when water present) was neutral (7-8 pH units) and the pH decreased along the transect towards the lake water. The groundwater in the upper piezometers of Site 1, 2, 3 and 4 all show acidity, with Sites 2, 3 and 4 showing the highest high levels (200-1800 mg/L as $CaCO_3$) (Figure 21). Acidity in the shallow piezometers of Site 2, 3 and 4 was highest when sampling occurred after sustained rainfall periods. The lowest acidity readings taken at the 3 acidic sites were in November 2009 and February 2010, after there was less than 1mm of rainfall in the proceeding 3 weeks before sampling (Figure 23 e). Large peaks in rainfall, however, did not necessarily increase acidity significantly at the site (i.e. sampling in early September after a large rainfall event did not encourage more acidity in the groundwater), rather maintained the high acidity reading found during the wetter months. The groundwater in the deeper piezometers also showed a slight decrease in pH during 2010, although values do not decrease below 6.5 (lower limit for ANZECC guidelines). Alkalinity in the deep piezometers is high (200-1200 mg/L) but there was a general trend of decline in the autumn months of 2010, with acidity present in higher qualities at Site 1 and 3 in June and Site 1 in July. Alkalinity recovered during the winter months of 2010 (Figure 23 (f)).

- More positive ORP values in the groundwater correlates with sites which have lower pH and are acidic (Figure 20).

- The acidity spikes in the upper groundwater of Campbell Park coincide with a sharp increases in soluble Al and slight increases in Mn concentrations (Figures 23 (i) and (j)). An example of increase was during monitoring on the 27th of April 2010, where a sharp increase in acidity at Site 2 (from 1242 mg/L to 1870 mg/L) corresponds with a sharp increase in Al from 35 mg/L to 105 mg/L and an increase in Mn from 12.9 to 15.9 mg/L. Similarly, at Site 4 in June, acidity rises sharply and is accompanied by a rise in Al and Mn and in Site 2, 3 and 4 at the beginning of August. These soluble metal ions comprise potential acidity that is subsequently released upon hydrolysis and precipitation. This is verified by the peaks Al and Mn (and associated acidity) occurring after periods of sustained rainfall in the area, and declining when rainfall decreases in frequency.

- Increases in Fe concentrations (Figure 23 h) do not seem to coincide with acidity increases in the upper groundwater, except on rare occasions like at Site 3 during monitoring in July (interestingly it was only Fe, not Al and Mn that responded with the acidity increase at Site 3 in July) and overall, the upper groundwater at Campbell Park has seen an overall decrease in soluble Fe concentrations from October 2009 to July 2010.

- Overall the electrical conductivity (EC, salinity) in the upper piezometers remained relative constant from November 2009 to April 2010 before decreased slightly from April to June 2010 (Figure 23 a). After an increase again during monitoring in July, the decreasing trend continued to September 2010. The EC was slightly lower in August 2010 than in August 2009. Decreasing EC over the winter months is most likely a result of increased infiltration through the upper sandy horizon after rainfall. From April to July 2010 there was a general decrease EC in the lower piezometers at Site 2 and 4, however Site 1 and site 3 are more variable with increases during August 2010 monitoring before decreasing during September.

- The decrease in EC in the upper sediments in winter corresponds with a decrease in the SO_4:Cl ratio (Figure 23 (b) and the key contributors to salinity are Cl, SO4, Na, Mg and Ca (Figure 23 k-p). In general, Site 2 had the highest major ion concentrations (Figure 23 k-p).

Windmill:

- Windmill, unlike Point Sturt and Campbell Park, shows pH neutral values (6.5-7.5) across all piezometers (Figures 18) and relatively reduced (low ORP) groundwater at all sites (Figure 20). Alkalinity at each site is quite high (200-1200 mg/L as $CaCO_3$). Overall, however, there has been a decline in alkalinity at most sites, especially at Site 2 and 3 during 2010 and since April 2010, acidity at all sites has increased and is comparable to the acidity increase from August to October 2009 (Figure 21).

- After quite high levels of Al between October and November 2009, Al at Windmill has been minimal (Figure 21 (i)). Fe has also decreased over time since October 2009 (Figure 24 (h)).

- Mn has been relatively steady over time, however, site 4 saw a sharp drop during monitoring in June, from 2.82 to 0.001 mg/L. Mn increased again at this site in July to 3.7 mg/L (Figure 24(j)).

- EC at Windmill ranges from 13.6 - 32.6 mS/cm, with the highest EC in the upper sediments in the sites closest to shoreline and the lowest closest to the lake. The lower sediments of Site 1 and 4 have the highest EC. There was an overall increase in EC up until April 2010, after which EC is much more variable depending on rainfall and/or dilution from rising surface water levels (Figure 16).

- There is a difference in the EC in the upper sandy lake sediments and lower underlying sands of the Bridgewater Formation at Site 4 (upper sediments 18.9 mS/cm, lower sediments 30.0 mS/cm). There has also been a decline in the key salinity contributors, Ca, Na and Mg since April 2010 (Figure 24k, l, n).

Point Sturt:

- In the upper piezometers at Point Sturt, only groundwater at Site 2 was acidic for the whole monitoring period with a low pH, declining from a pH of 5 in October 2009 to a pH of 3 in July 2010 (Figure 18). Acidity at this site increased since February 2010 from 198 mg/L as $CaCO_3$ to a peak of nearly 1500 mg/L as $CaCO_3$ in July (Figure 21). Acidity increases and pH drops directly after periods of high and sustained rainfall in the region. ORP values at this site show more oxidised conditions over time, consistent with the low pH and high acidity (Figures 20) .In winter 2010, Site 1 also went acidic and Sites 3 experienced a large drop in alkalinity. The deeper piezometer at Site 2 also went acidic but the other deeper piezometers maintained neutral pH and high alkalinity (Figure 21) and reducing conditions (negative ORP values – Figures 20).

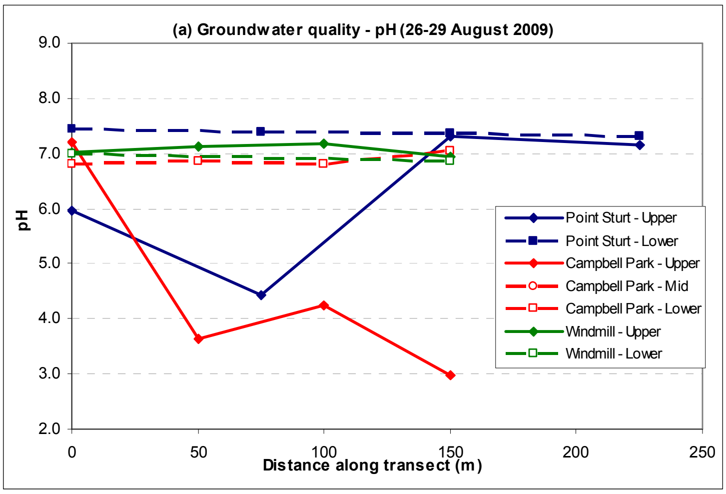
- Soluble Al also increased at Site 2 in conjunction with acidity increases, indicating a likely role of this metal in the acidity generation (Figure 25 (i)). Mn, remained more stable but decreased during winter 2010 decreased during this time (Figure 25 (j)), indicating a preference for the release of Al and Fe during acidity events at this location. Soluble Fe is generally higher at Point Sturt than the other locations, especially in the upper sediments.

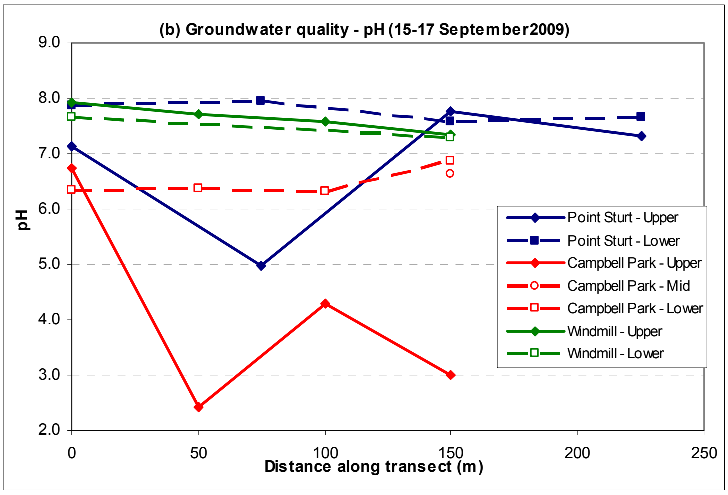
- EC at Point Sturt increases along the transect towards the lake (Figure 19) but has remained relatively constant over the monitoring period. After progressively increasing in EC during the summer months, the lower sediments of Site 2 and 3 have illustrated quite a marked decrease since the end of April to July (Figure 25 (a)). This is most likely a combination of rainfall and water levels increasing at the location. As of June 2010, site 4 was inundated by the Lake Alexandrina surface water, with progressive inundation of site 2 and 3 in August and Site 1 at the beginning of September.

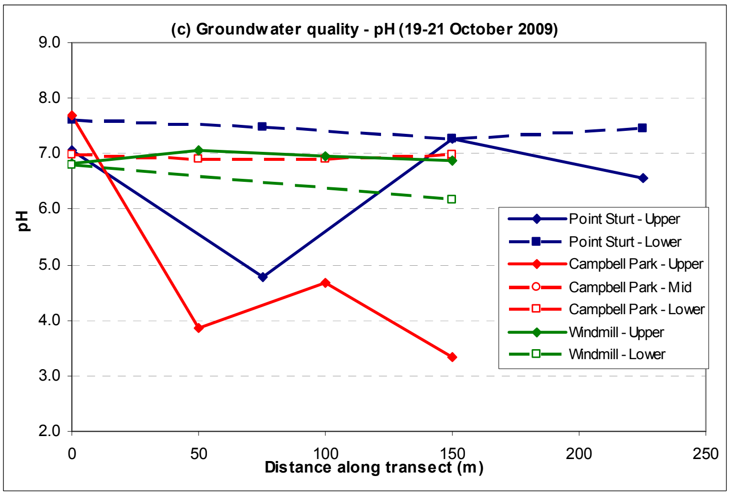
- There is a trend of increasing SO_4:Cl ratio in the shallow piezometers of Site 1 and 2 over summer 2010 (Feb-April). Sulfate concentrations in the upper sediments exceed those in the lower sediments (Figures 25 (b)).

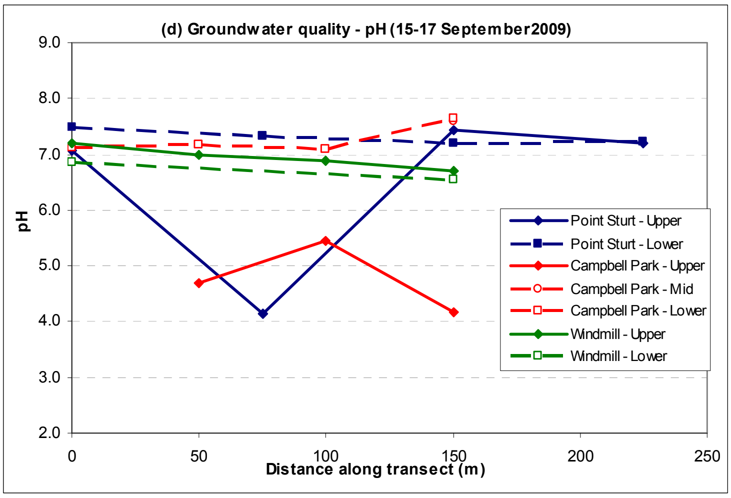
- The key contributors to salinity at Point Sturt are Cl, SO_4, Mg, Ca, and K (Figure 25 k-n).

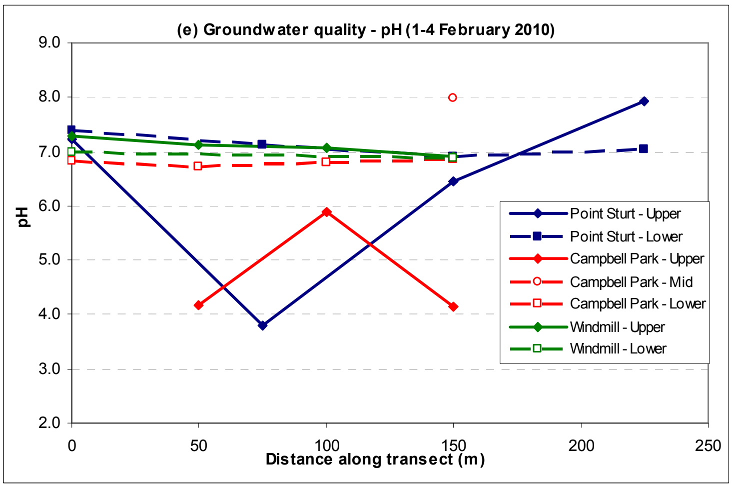
Figures 18 (a-k): Groundwater pH at Point Sturt, Campbell Park and Windmill (after purging) during each monitoring period from August 2009 and September 2010. Note that the distance along the transect is from Site 1 (closest to historical shoreline) to Site 4 (closest to the lake), left to right.

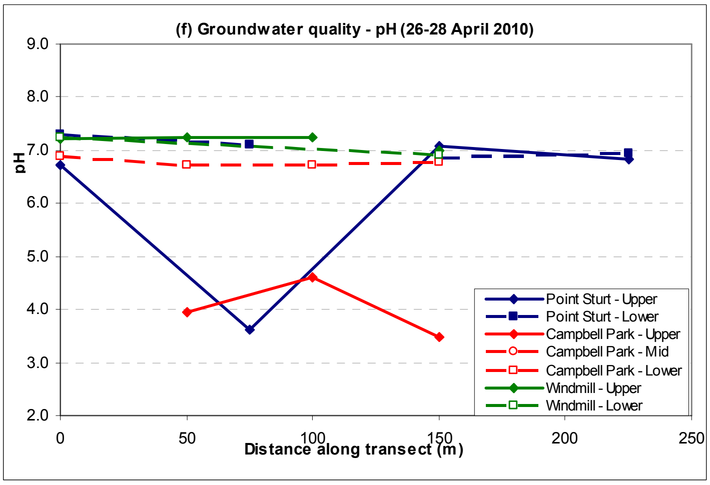


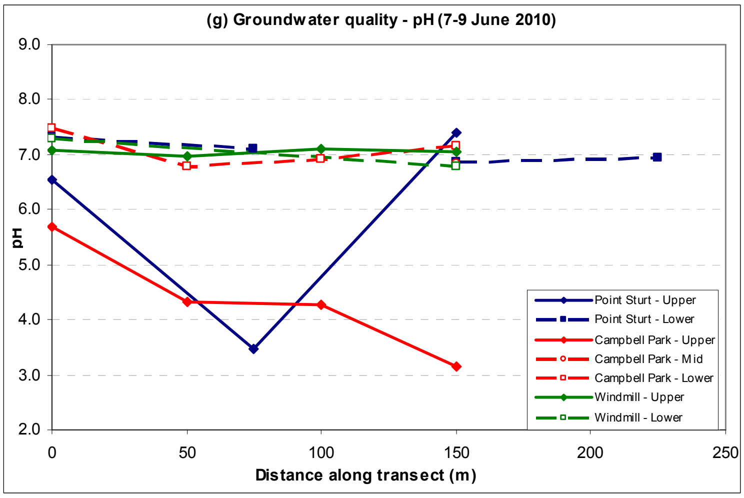


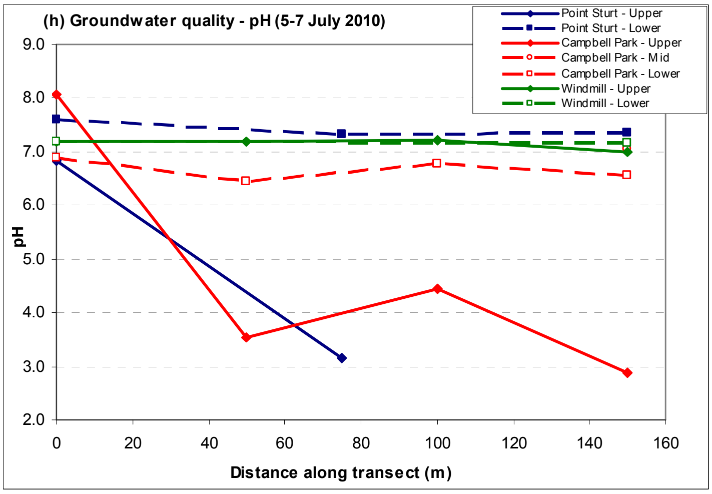


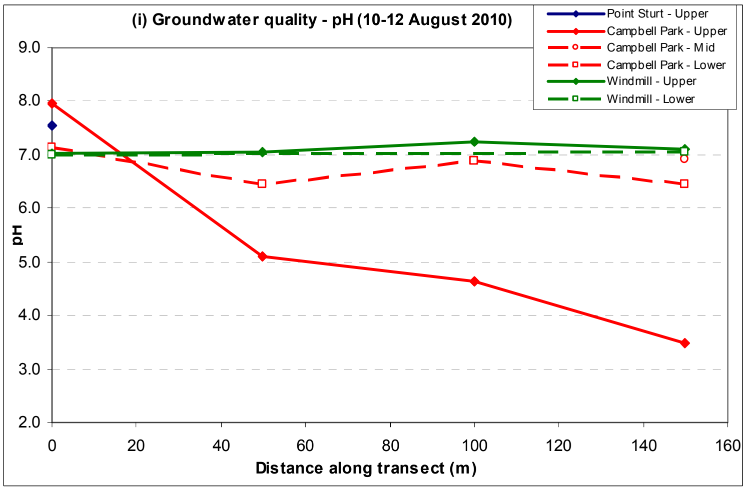


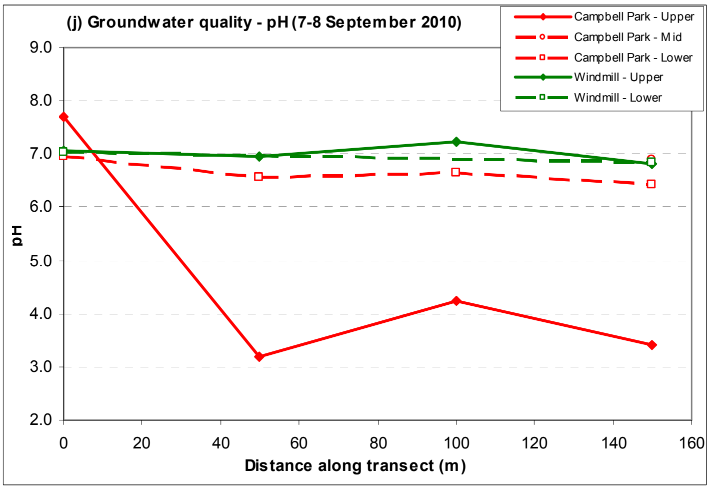


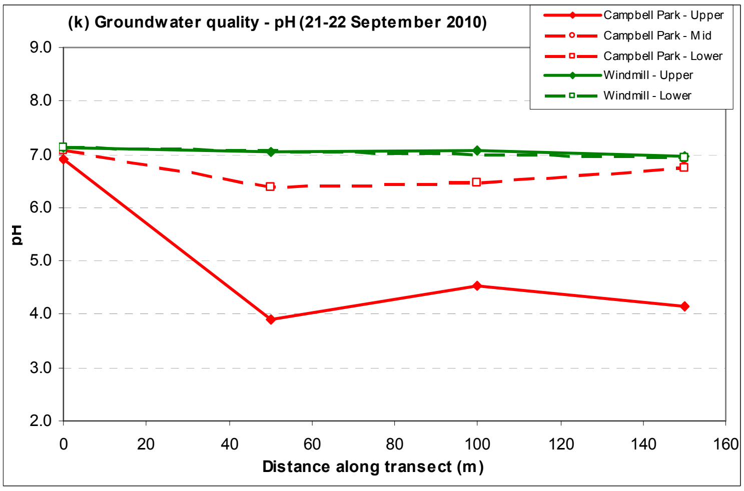



(g) Groundwater quality - pH (7-9 June 2010)

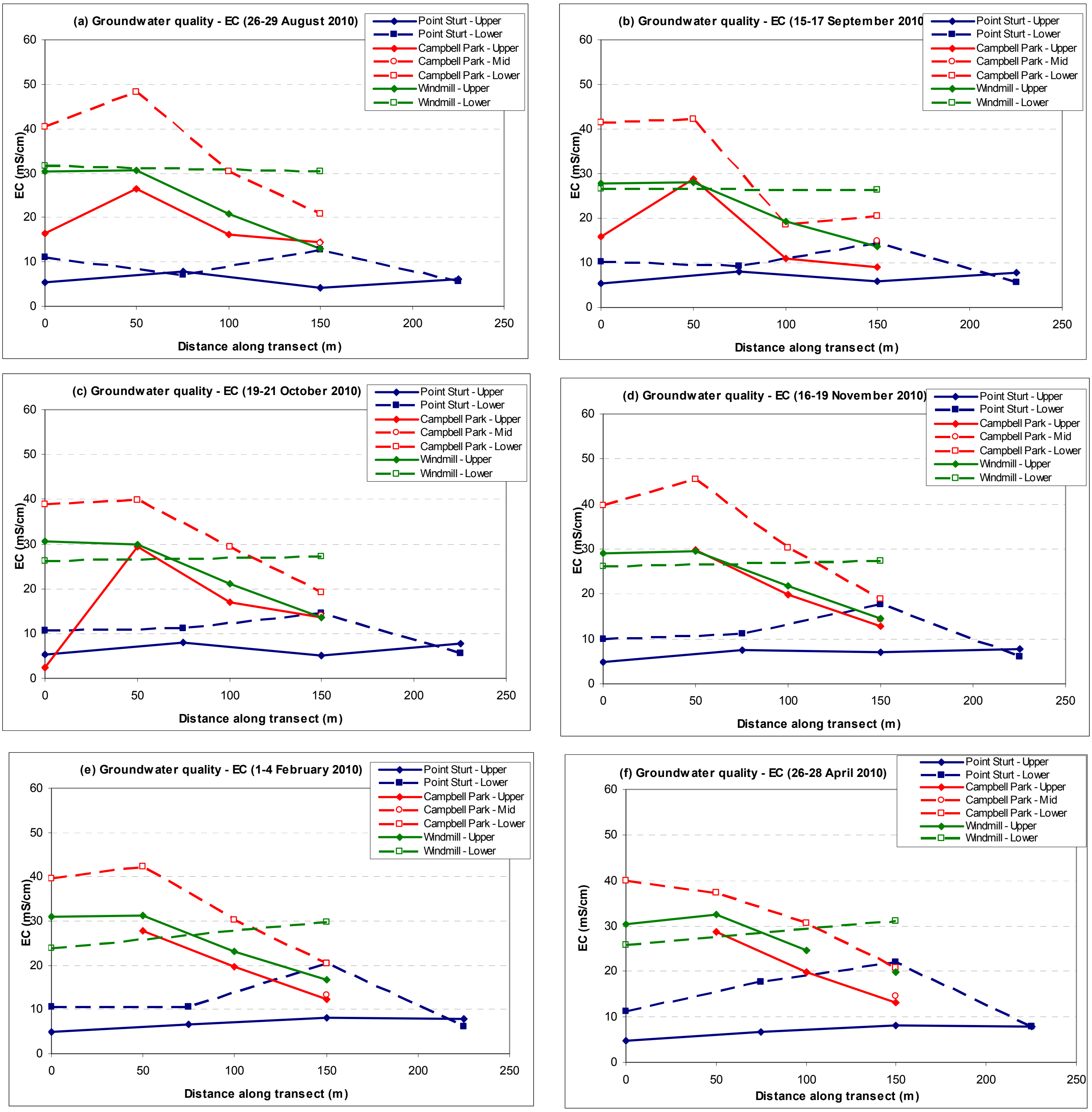

(h) Groundwater quality - pH (5-7 July 2010)

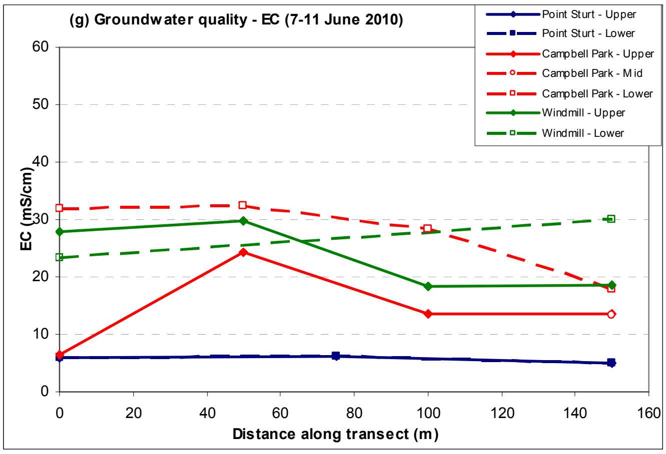

(i) Groundwater quality - pH (10-12 August 2010)

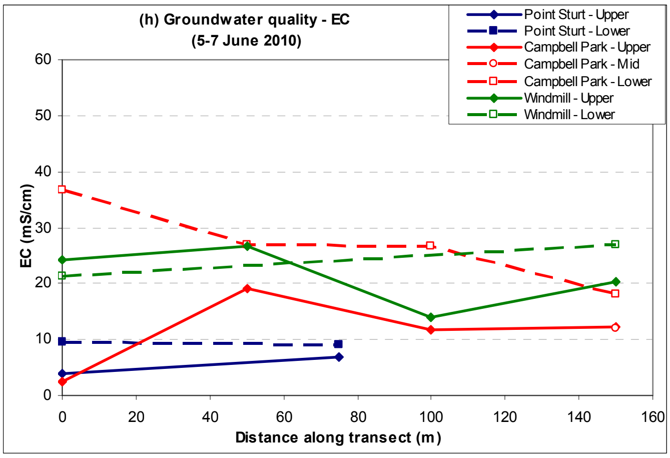

(j) Groundwater quality - pH (7-8 September 2010)

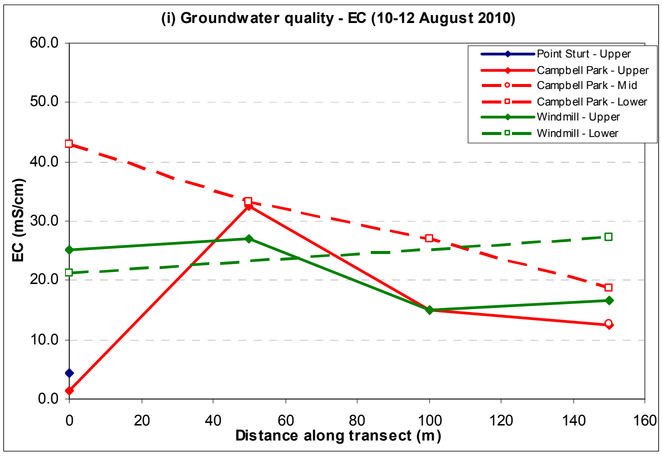

(k) Groundwater quality - pH (21-22 September 2010)

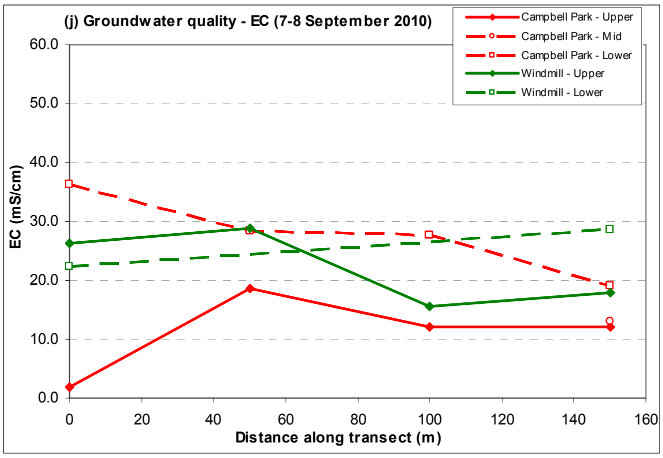
Figures 19 (a-k): Groundwater EC at Point Sturt, Campbell Park and Windmill (after purging) during each monitoring period from August 2009 and September 2010. Note that the distance along the transect is from Site 1 (closest to historical shoreline) to Site 4 (closest to the lake), left to right.

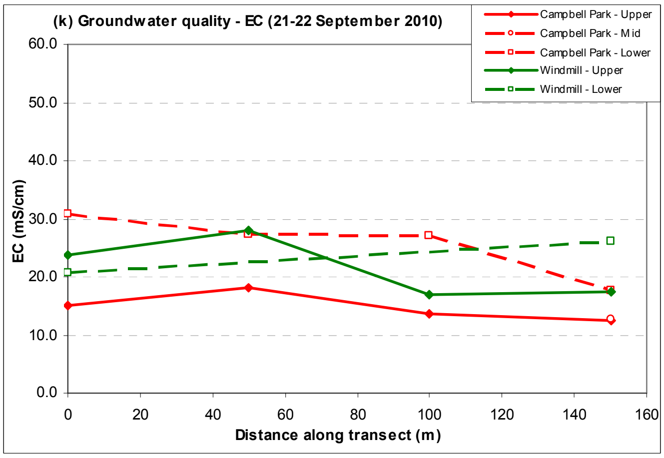



(g) Groundwater quality - EC (7-11 June 2010)
EC (mS/cm)
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
Distance along transect (m)
Point Sturt - Upper
Point Sturt - Lower
Campbell Park - Upper
Campbell Park - Mid
Campbell Park - Lower
Windmill - Upper
Windmill - Lower

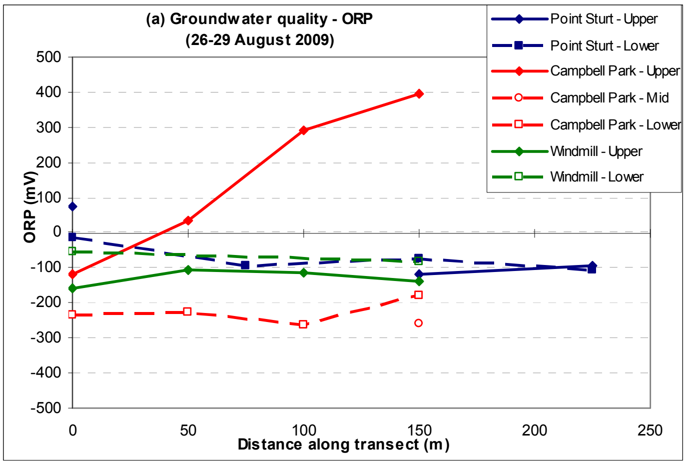

(h) Groundwater quality - EC
(5-7 June 2010)
EC (mS/cm)
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
Distance along transect (m)
Point Sturt - Upper
Point Sturt - Lower
Campbell Park - Upper
Campbell Park - Mid
Campbell Park - Lower
Windmill - Upper
Windmill - Lower

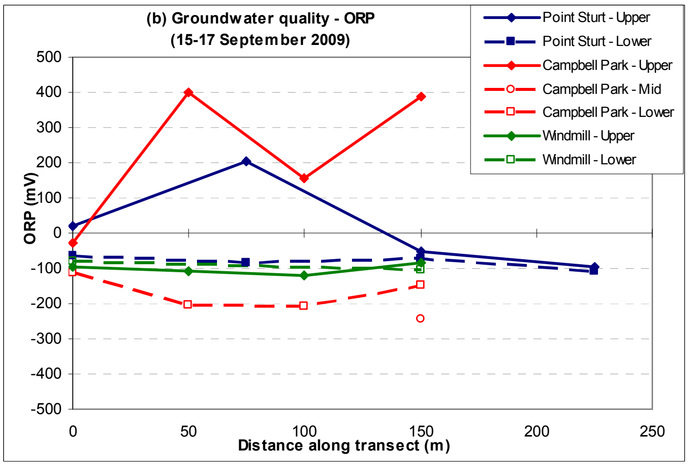

(i) Groundwater quality - EC (10-12 August 2010)
EC (mS/cm)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
20
40
60
80
100
120
140
160
Distance along transect (m)
Point Sturt - Upper
Campbell Park - Upper
Campbell Park - Mid
Campbell Park - Lower
Windmill - Upper
Windmill - Lower

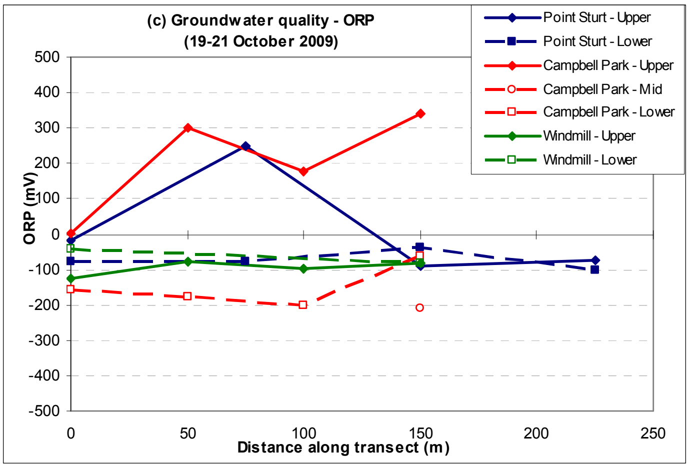

(j) Groundwater quality - EC (7-8 September 2010)
EC (mS/cm)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
20
40
60
80
100
120
140
160
Distance along transect (m)
Campbell Park - Upper
Campbell Park - Mid
Campbell Park - Lower
Windmill - Upper
Windmill - Lower

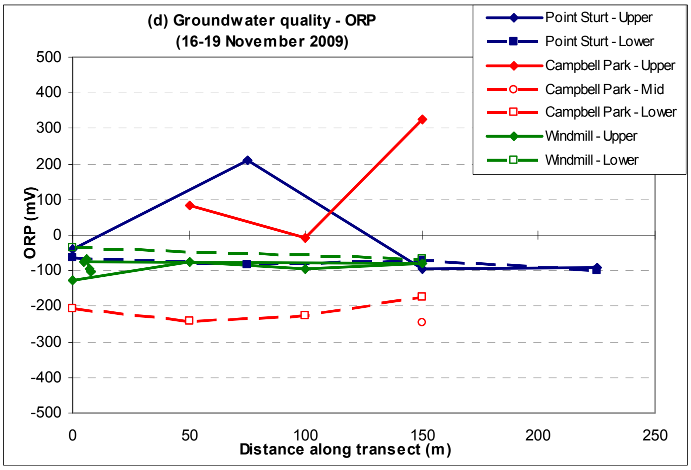

(k) Groundwater quality - EC (21-22 September 2010)
EC (mS/cm)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
20
40
60
80
100
120
140
160
Distance along transect (m)
Campbell Park - Upper
Campbell Park - Mid
Campbell Park - Lower
Windmill - Upper
Windmill - Lower

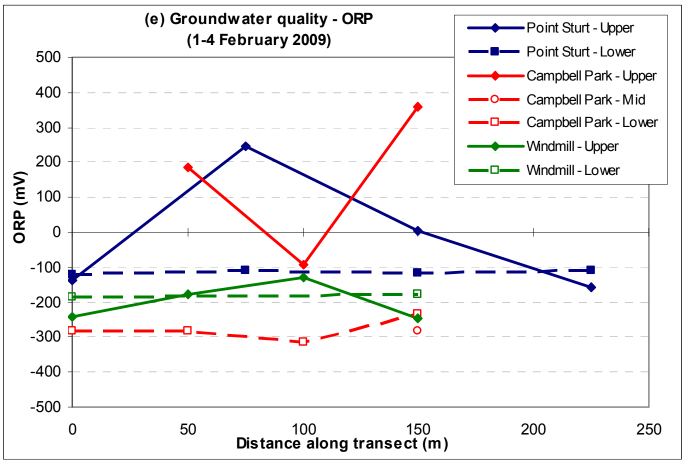
Figures 20 (a-k): Groundwater ORP at Point Sturt, Campbell Park and Windmill (after purging) during each monitoring period from August 2009 and September 2010. Note that the distance along the transect is from Site 1 (closest to historical shoreline) to Site 4 (closest to the lake), left to right.

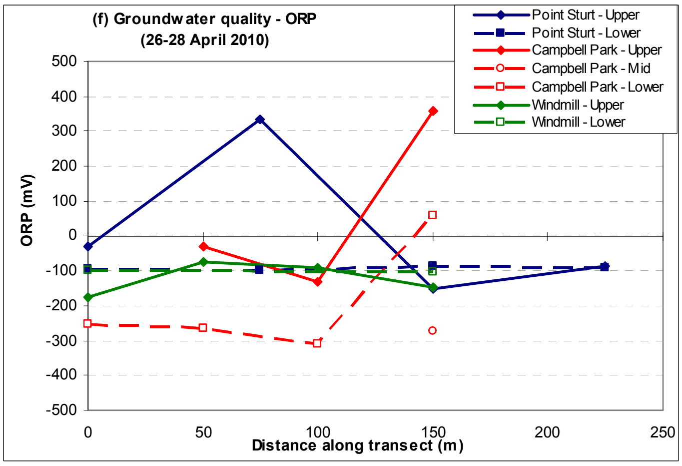


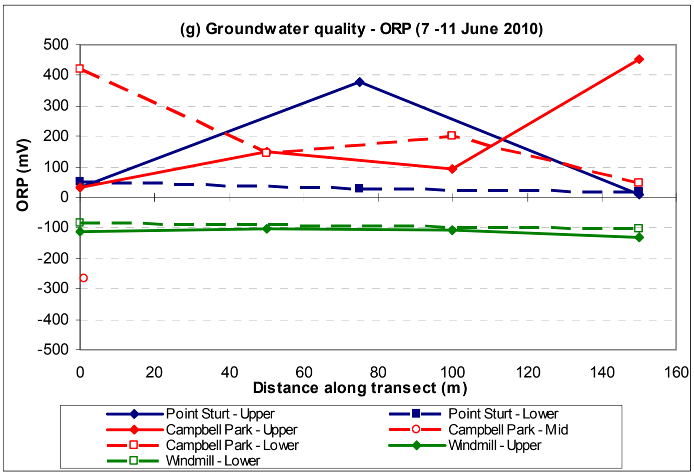


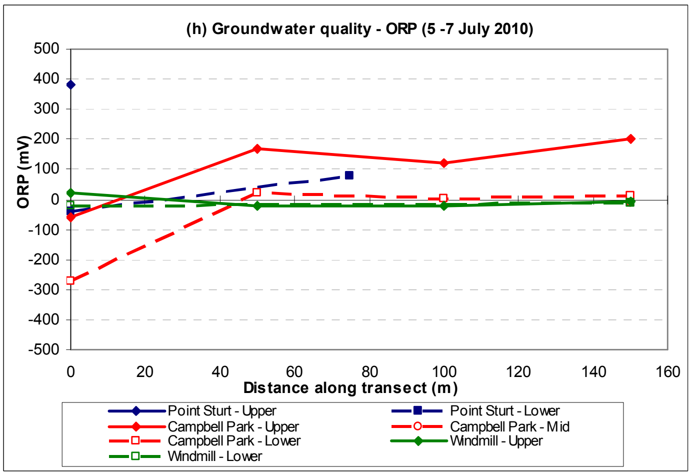


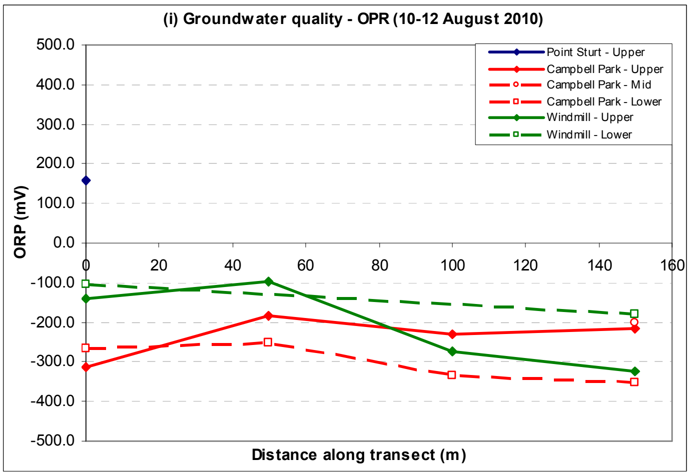


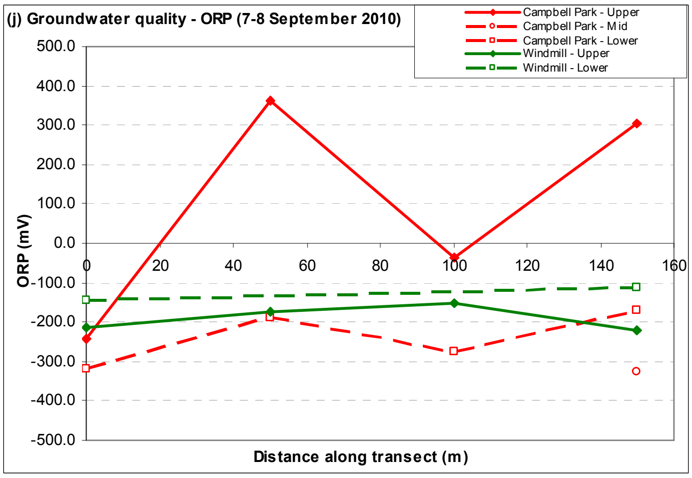





(g) Groundwater quality - ORP (7 -11 June 2010)


(h) Groundwater quality - ORP (5 -7 July 2010)


(i) Groundwater quality - OPR (10-12 August 2010)


(j) Groundwater quality - ORP (7-8 September 2010)

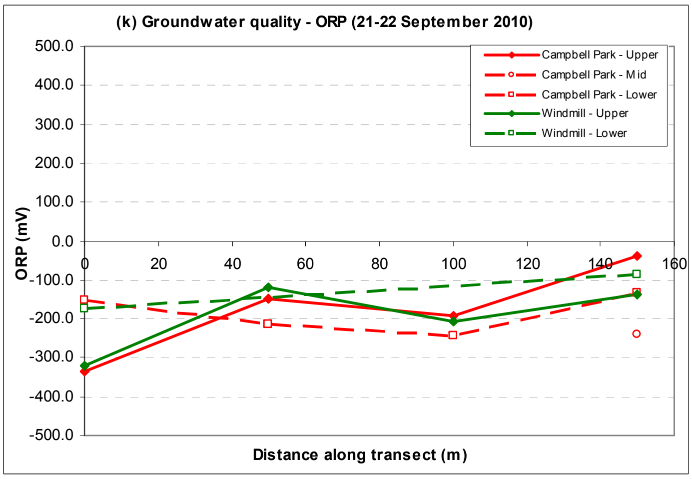
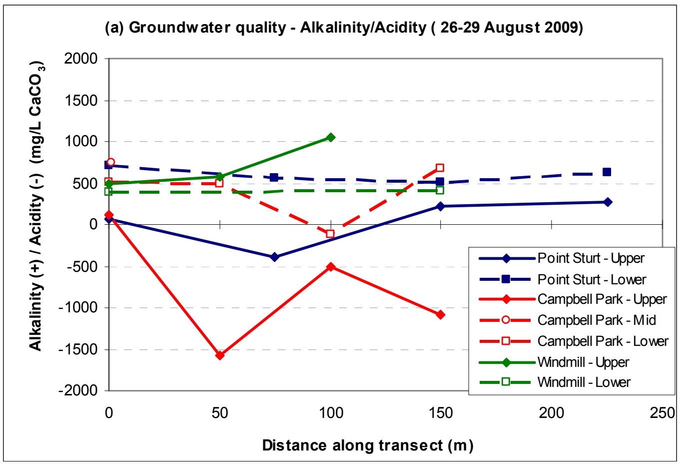
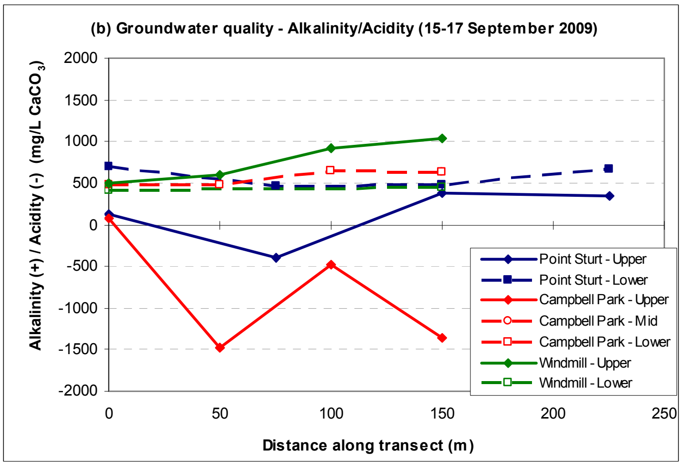
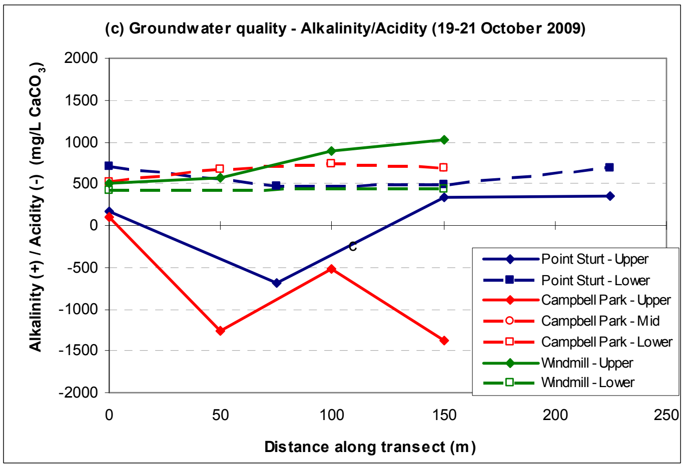
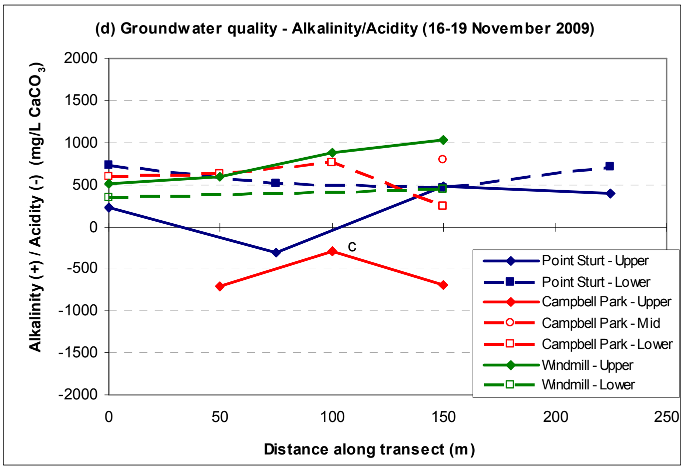

(k) Groundwater quality - ORP (21-22 September 2010)

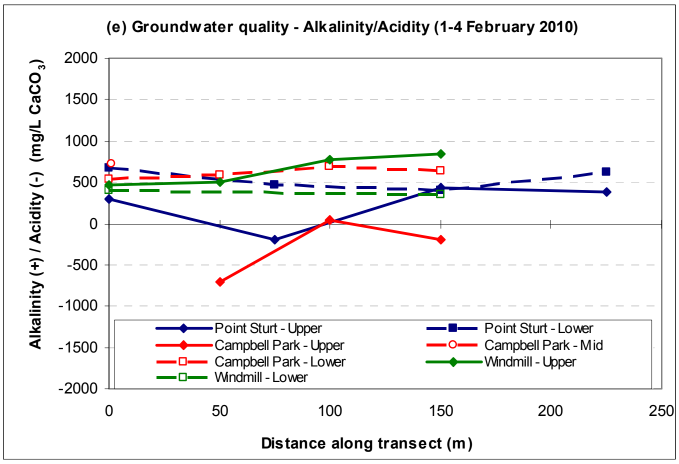
Figure 21(a-k): Groundwater alkalinity (positive values) and acidity (negative values) at Point Sturt, Campbell Park and Windmill (after purging) during each monitoring period from August 2009 and September 2010. Note that the distance along the transect is from Site 1 (closest to historical shoreline) to Site 4 (closest to the lake), left to right.

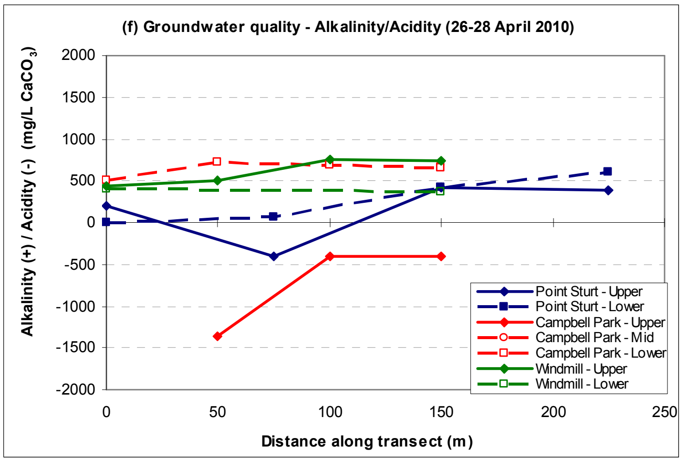


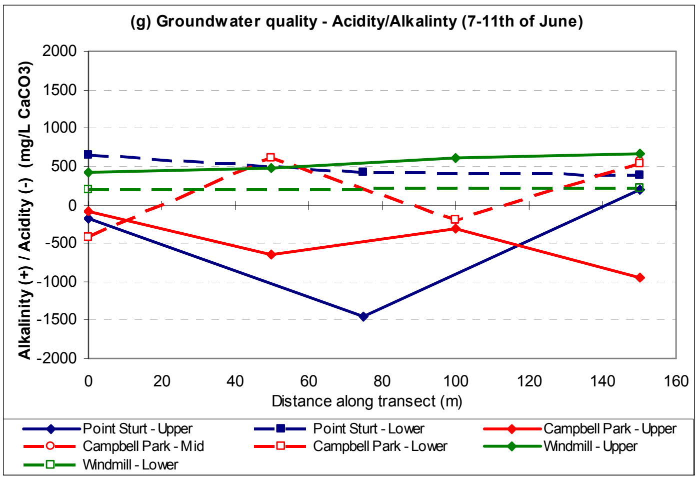


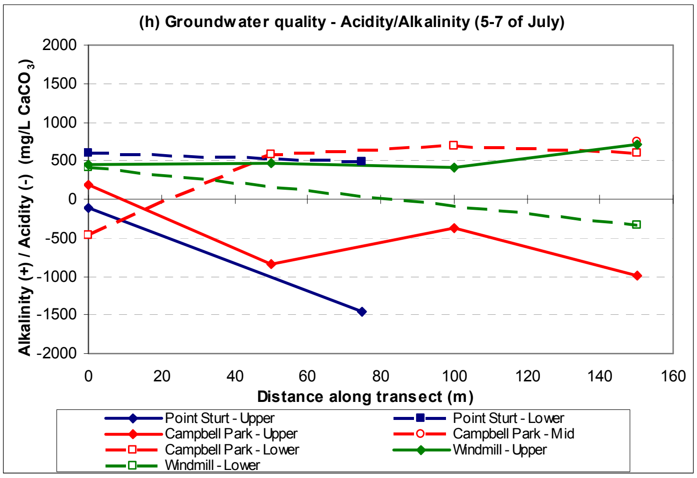


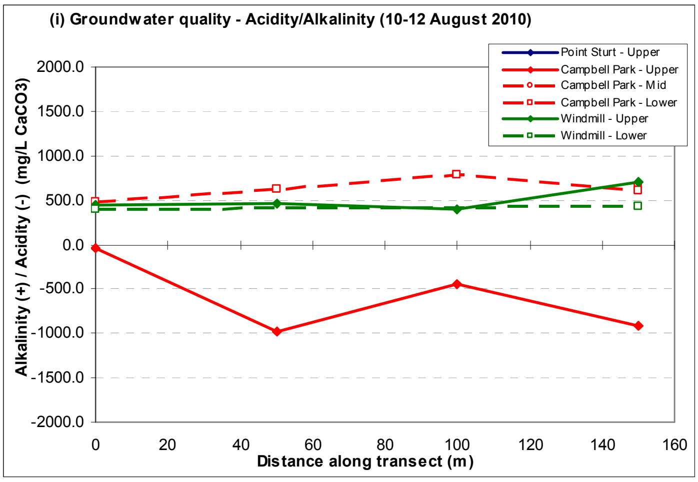


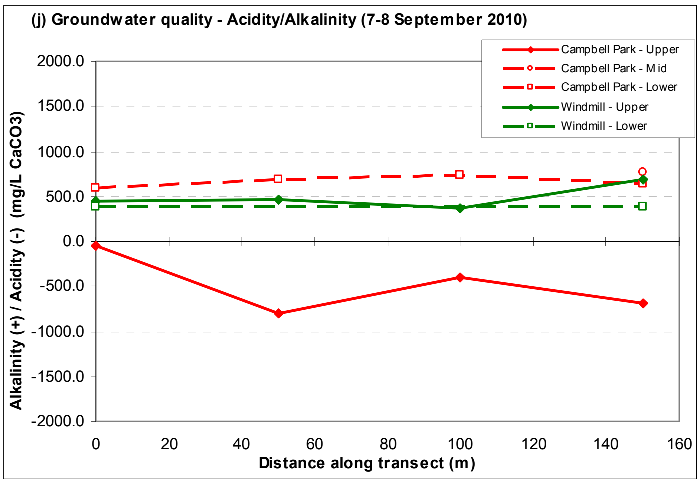


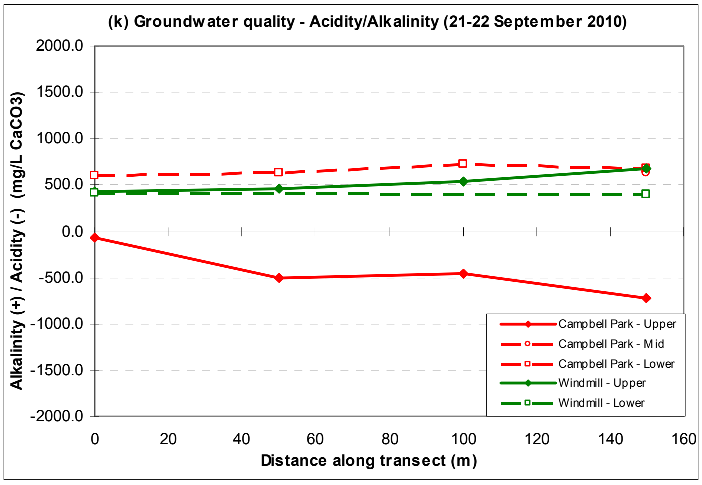



(g) Groundwater quality - Acidity/Alkalinty (7-11th of June)

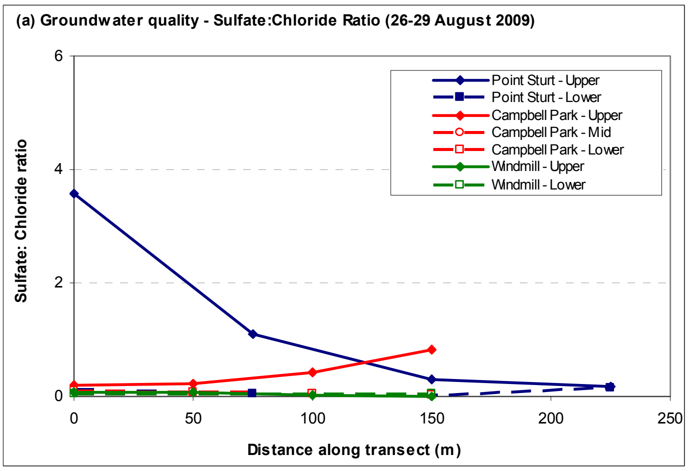

(h) Groundwater quality - Acidity/Alkalinity (5-7 of July)

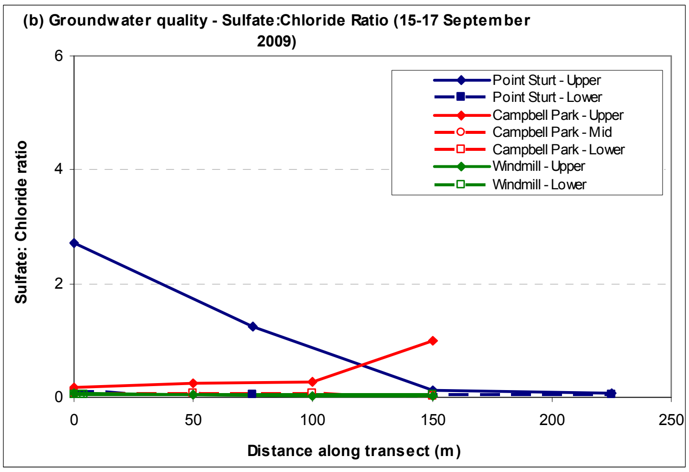

(i) Groundwater quality - Acidity/Alkalinity (10-12 August 2010)

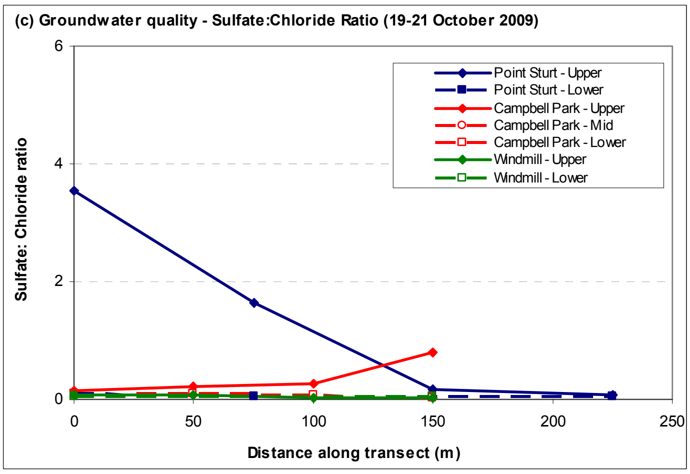

(j) Groundwater quality - Acidity/Alkalinity (7-8 September 2010)

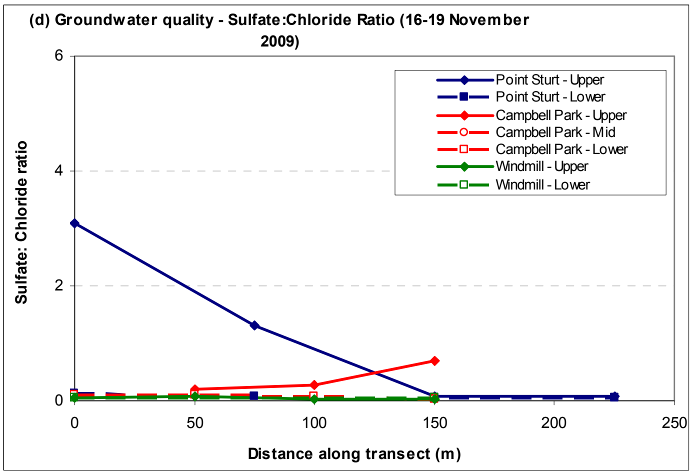

(k) Groundwater quality - Acidity/Alkalinity (21-22 September 2010)

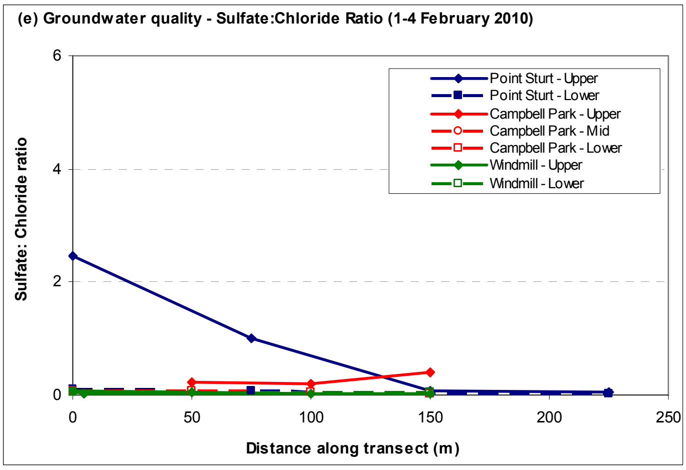
Figures 22 (a-k): Groundwater sulfate:chloride ratio at Point Sturt, Campbell Park and Windmill (after purging) during each monitoring period from August 2009 and September 2010. Note that the distance along the transect is from Site 1 (closest to historical shoreline) to Site 4 (closest to the lake), left to right.

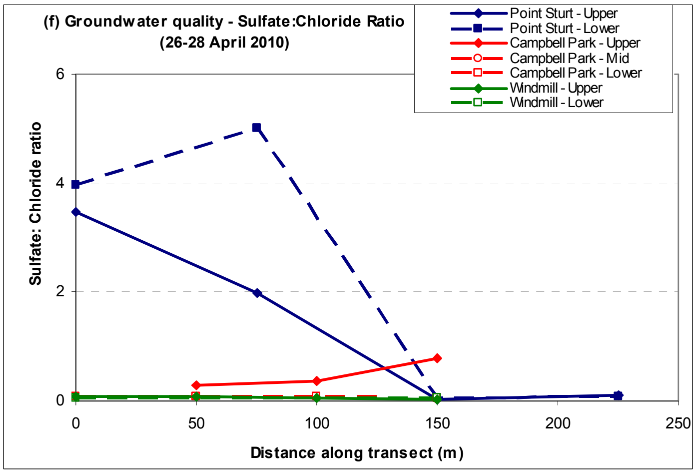


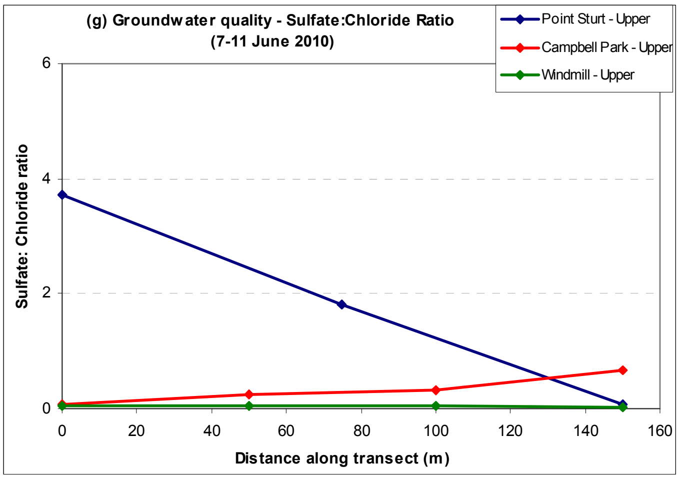


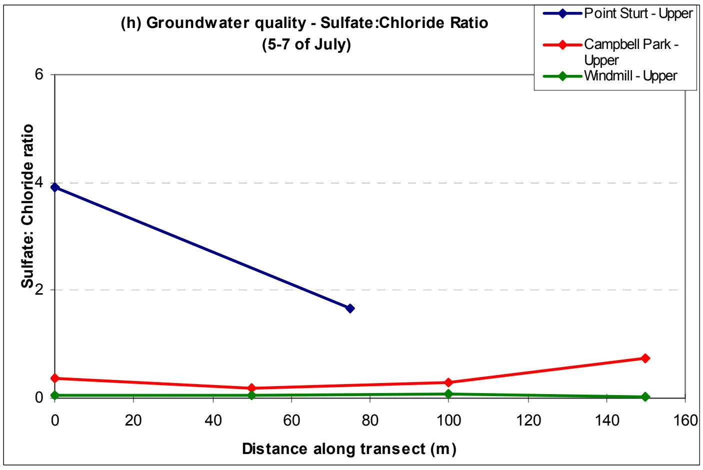


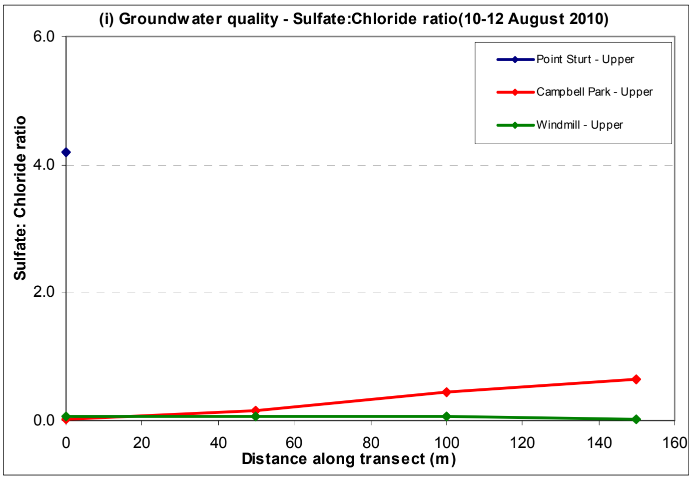


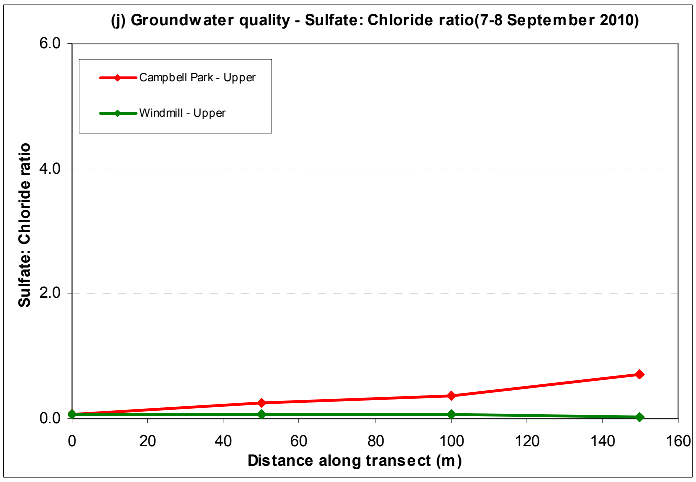


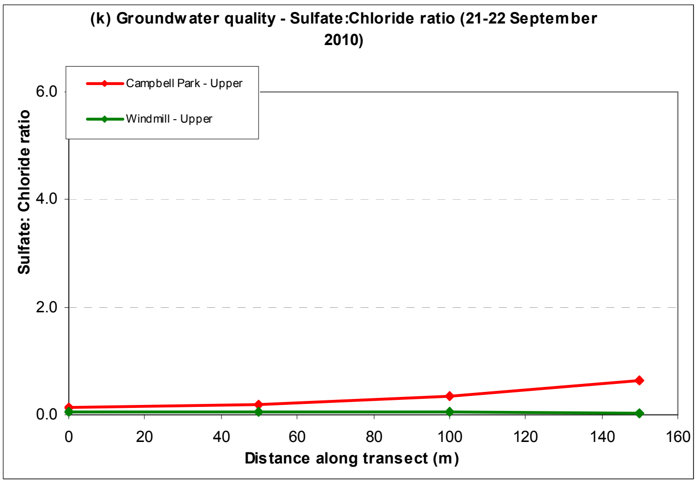



(g) Groundwater quality - Sulfate:Chloride Ratio (7-11 June 2010)

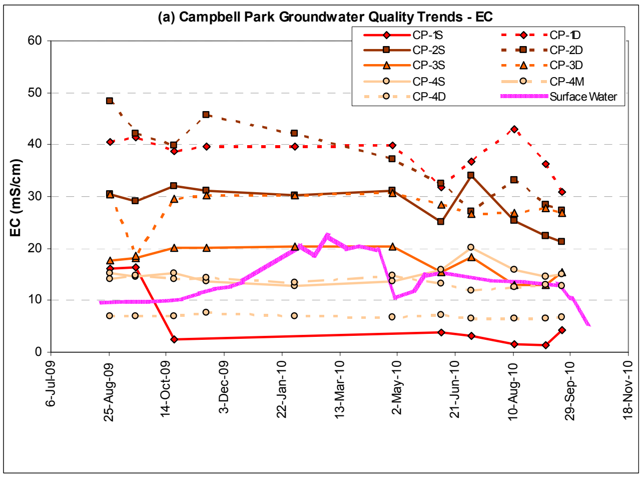

(h) Groundwater quality - Sulfate:Chloride Ratio (5-7 of July)

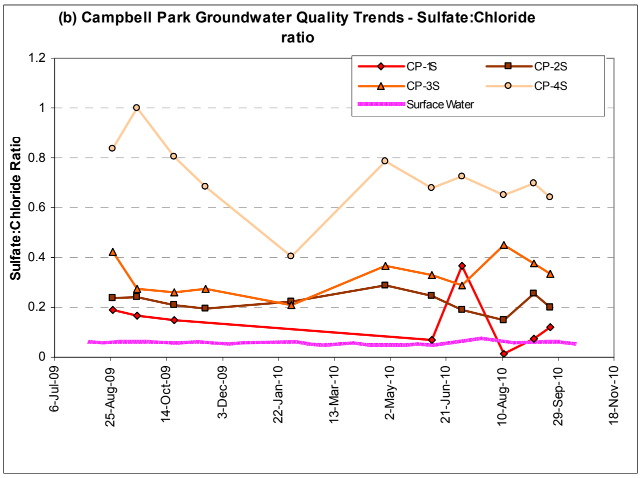

(i) Groundwater quality - Sulfate:Chloride ratio(10-12 August 2010)

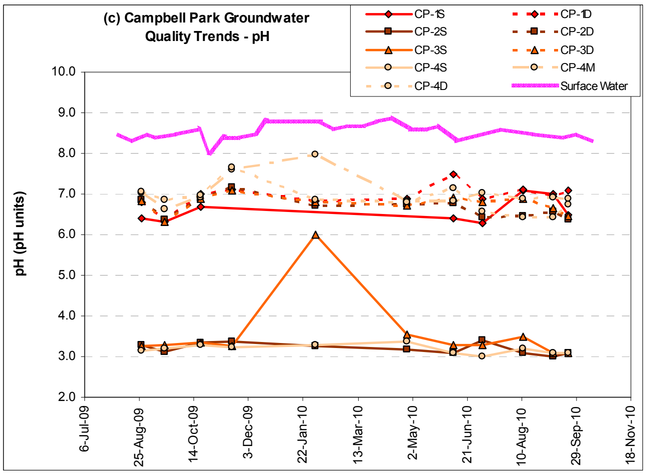

(j) Groundwater quality - Sulfate: Chloride ratio(7-8 September 2010)

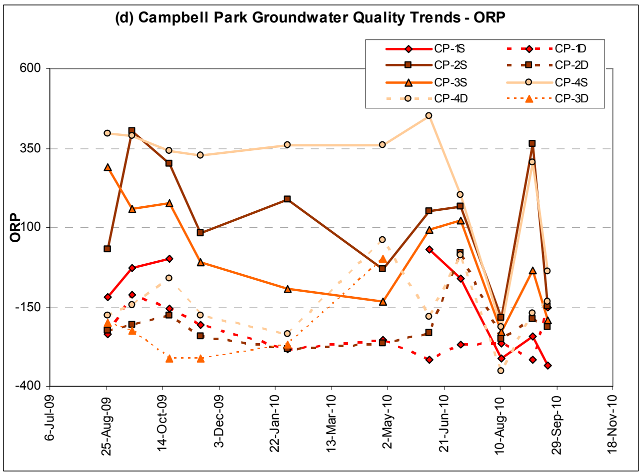

(k) Groundwater quality - Sulfate:Chloride ratio (21-22 September 2010)

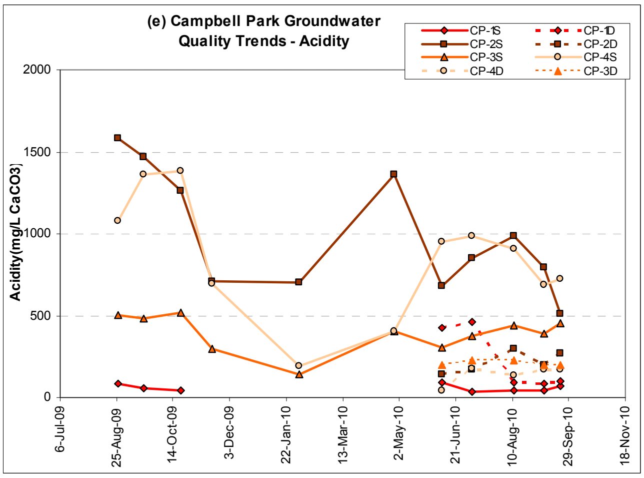
Figures 23 (a-p): Groundwater Quality trends at Campbell Park from August 2009 until September 2010.

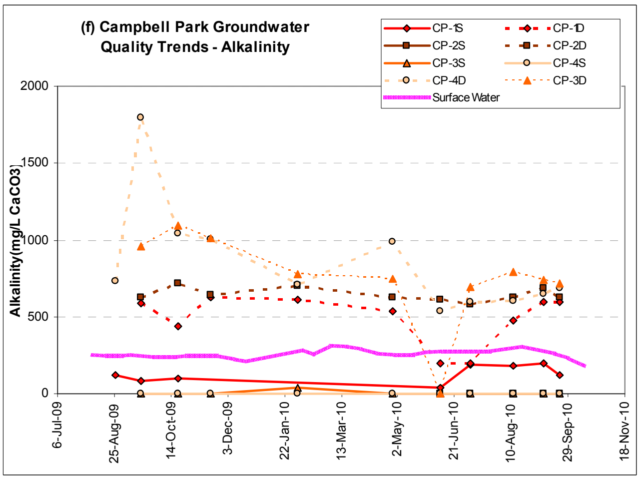

(a) Campbell Park Groundwater Quality Trends - EC

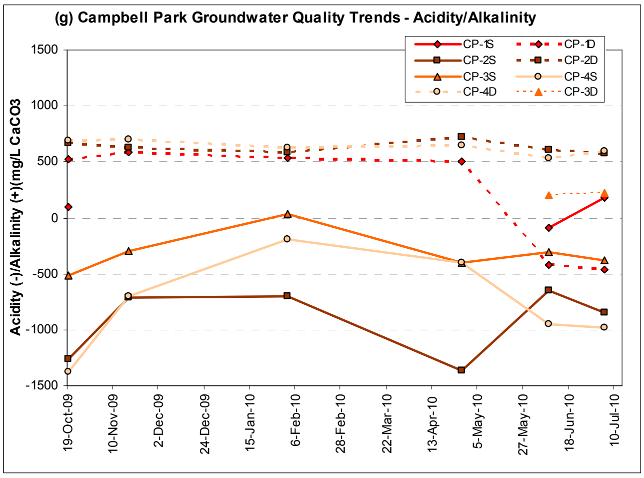

(b) Campbell Park Groundwater Quality Trends - Sulfate:Chloride ratio

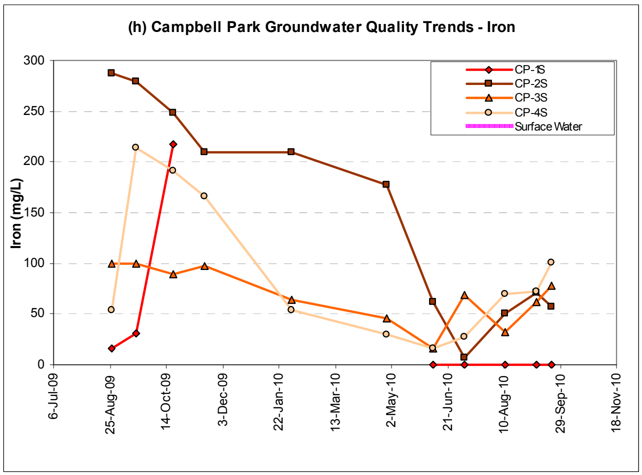

(c) Campbell Park Groundwater Quality Trends - pH

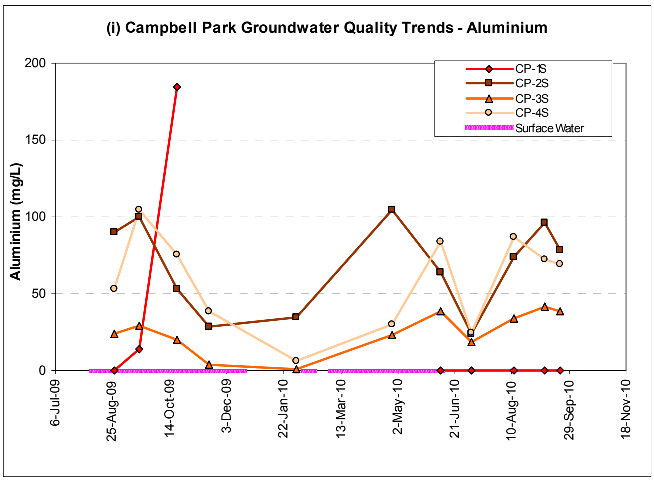

(d) Campbell Park Groundwater Quality Trends - ORP

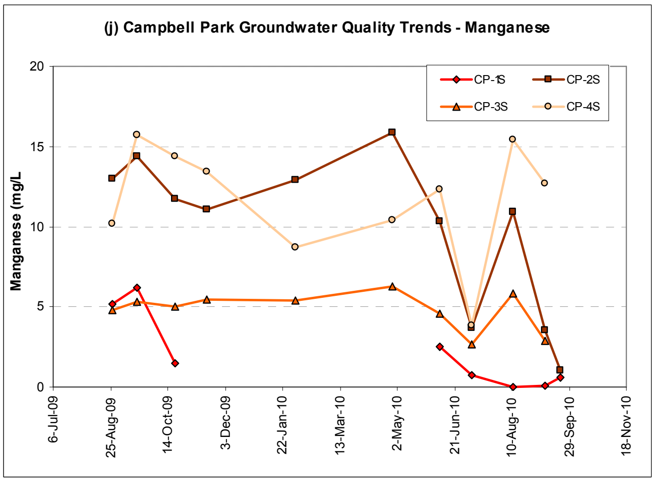

(e) Campbell Park Groundwater Quality Trends - Acidity

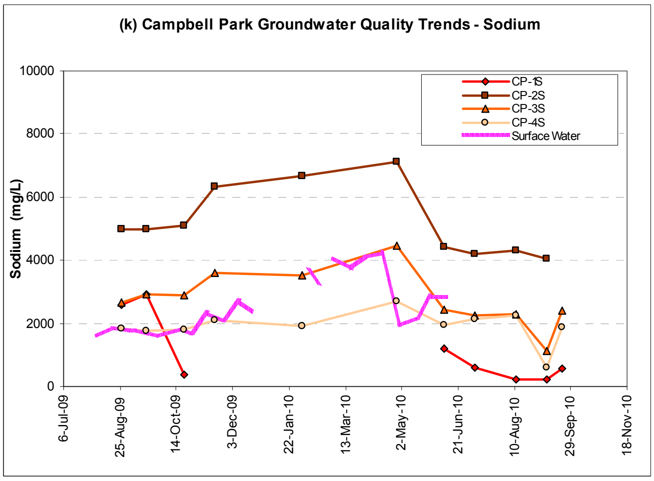

(f) Campbell Park Groundwater Quality Trends - Alkalinity

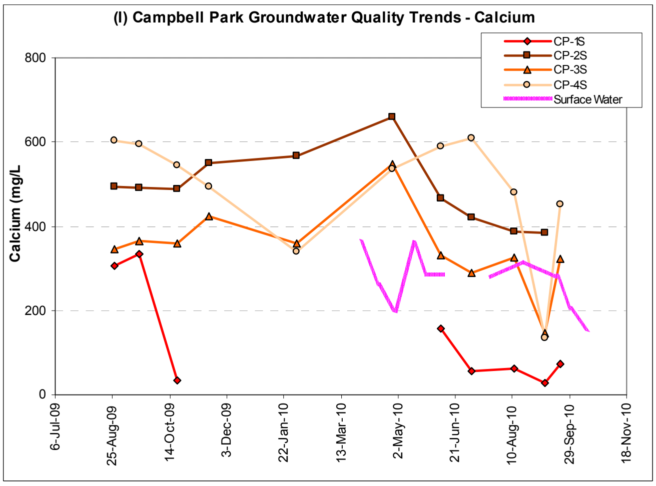

(g) Campbell Park Groundwater Quality Trends - Acidity/Alkalinity

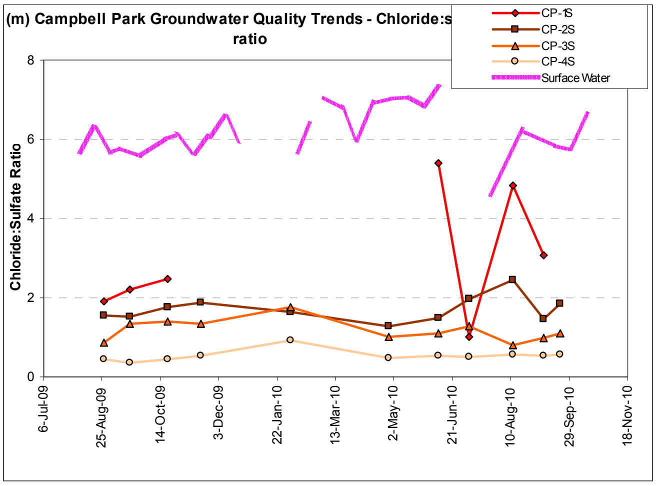

(h) Campbell Park Groundwater Quality Trends - Iron

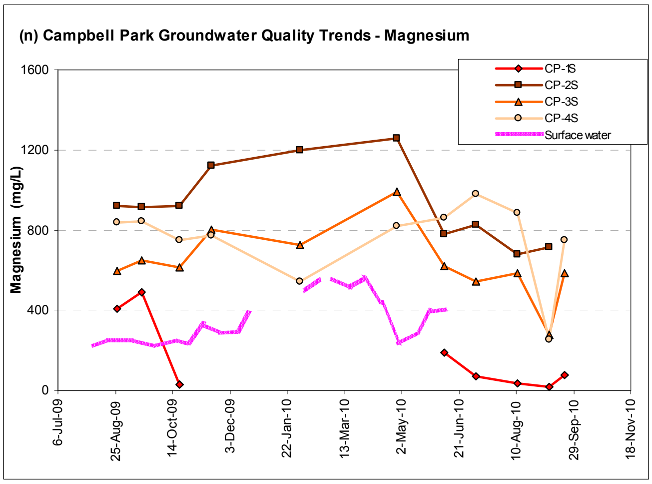

(i) Campbell Park Groundwater Quality Trends - Aluminium


(j) Campbell Park Groundwater Quality Trends - Manganese

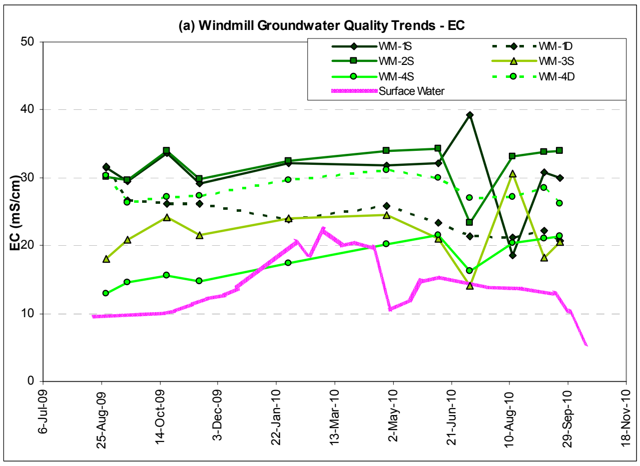

(k) Campbell Park Groundwater Quality Trends - Sodium

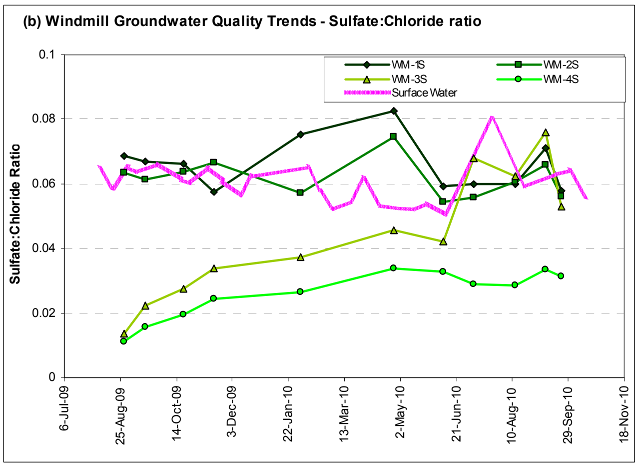

(l) Campbell Park Groundwater Quality Trends - Calcium

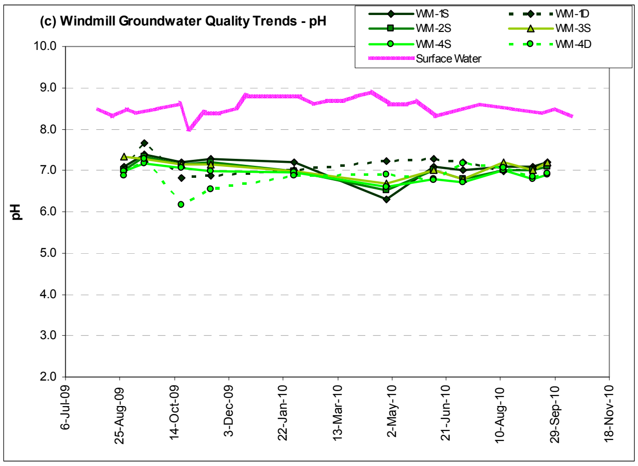

(m) Campbell Park Groundwater Quality Trends - Chloride:s ratio

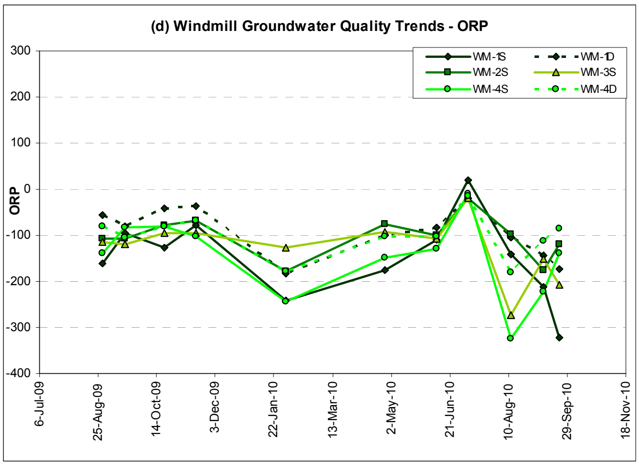

(n) Campbell Park Groundwater Quality Trends - Magnesium

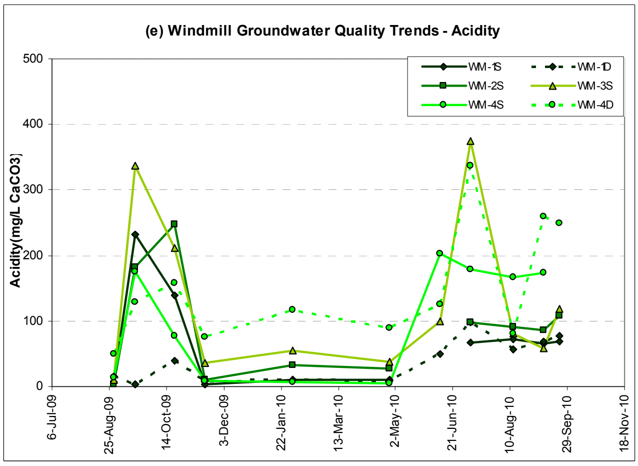
Figures 24 (a-n): Groundwater Quality trends at Windmill from August 2009 until September 2010.

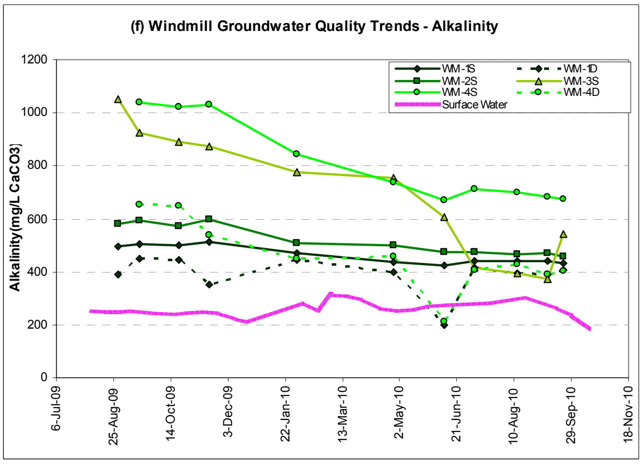

(a) Windmill Groundwater Quality Trends - EC

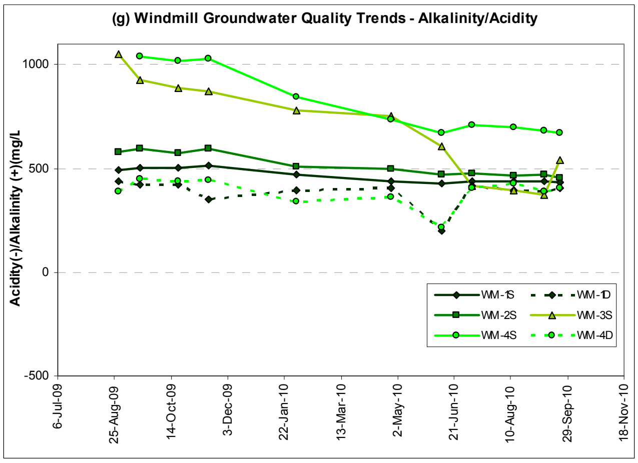

(b) Windmill Groundwater Quality Trends - Sulfate:Chloride ratio

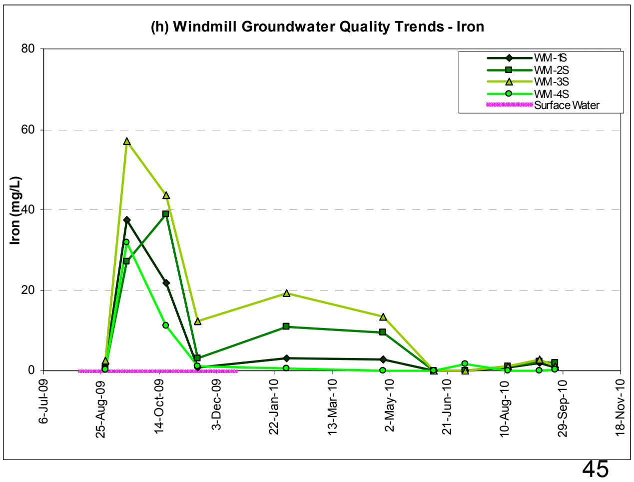

(c) Windmill Groundwater Quality Trends - pH

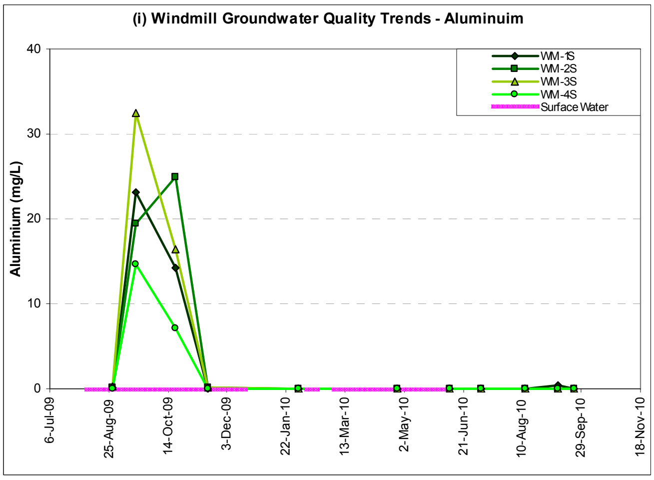

(d) Windmill Groundwater Quality Trends - ORP

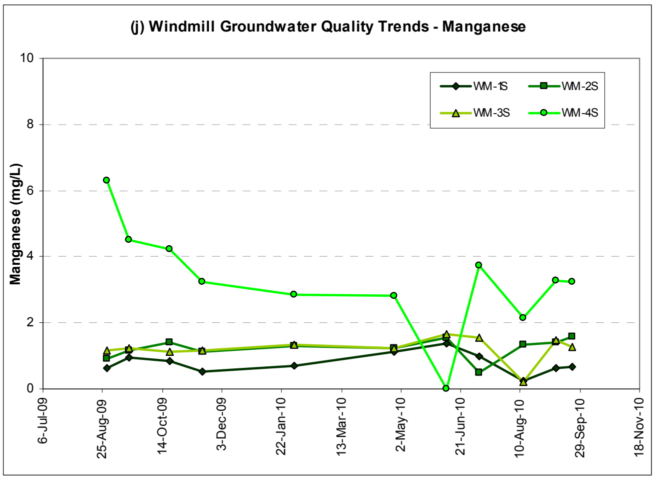

(e) Windmill Groundwater Quality Trends - Acidity

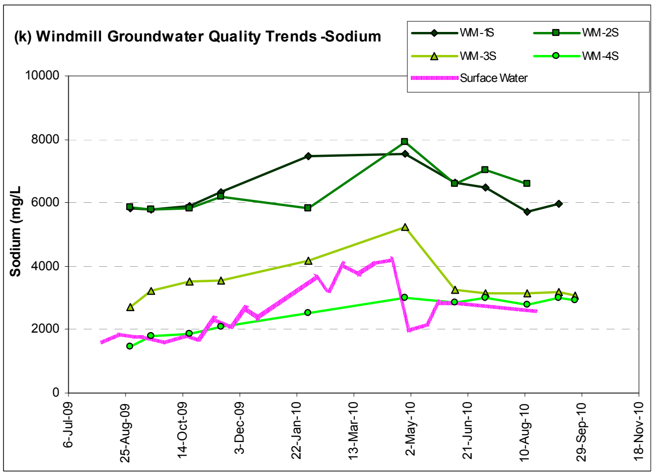

(f) Windmill Groundwater Quality Trends - Alkalinity

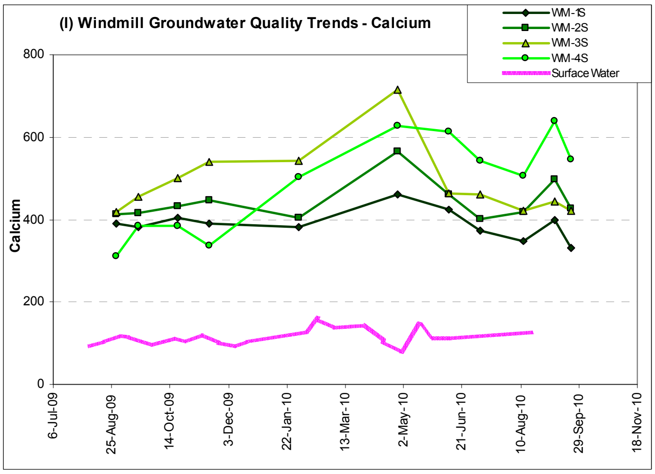

(g) Windmill Groundwater Quality Trends - Alkalinity/Acidity

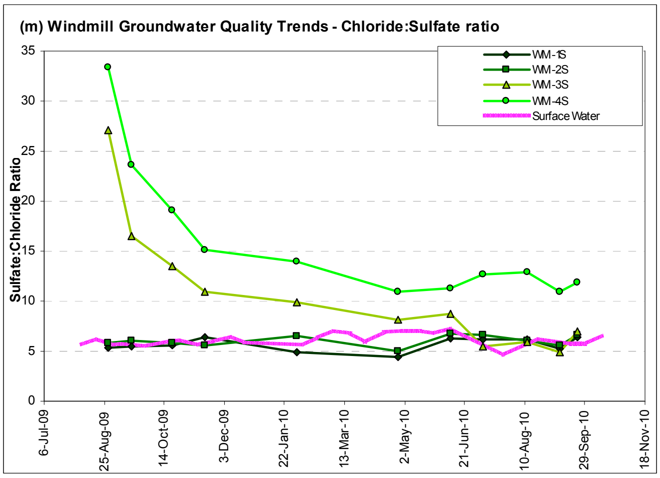

(h) Windmill Groundwater Quality Trends - Iron

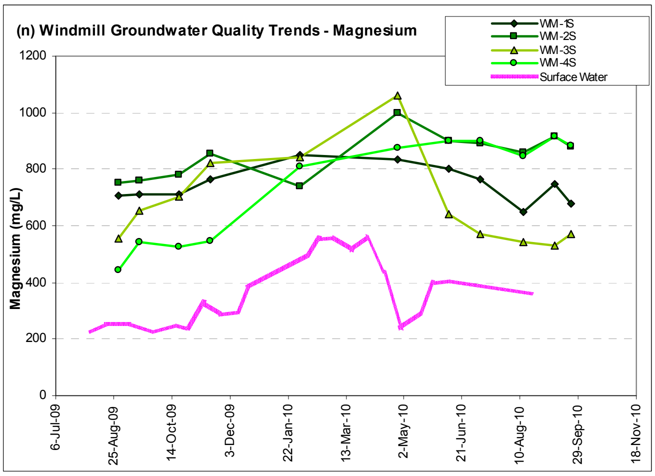

(i) Windmill Groundwater Quality Trends - Aluminuim
Aluminium (mg/L)
0
10
20
30
40
6-Jul-09
25-Aug-09
14-Oct-09
3-Dec-09
22-Jan-10
13-Mar-10
2-May-10
21-Jun-10
10-Aug-10
29-Sep-10
18-Nov-10
WM-1S
WM-2S
WM-3S
WM-4S
Surface Water


(j) Windmill Groundwater Quality Trends - Manganese
Manganese (mg/L)
0
2
4
6
8
10
6-Jul-09
25-Aug-09
14-Oct-09
3-Dec-09
22-Jan-10
13-Mar-10
2-May-10
21-Jun-10
10-Aug-10
29-Sep-10
18-Nov-10
WM-1S
WM-2S
WM-3S
WM-4S

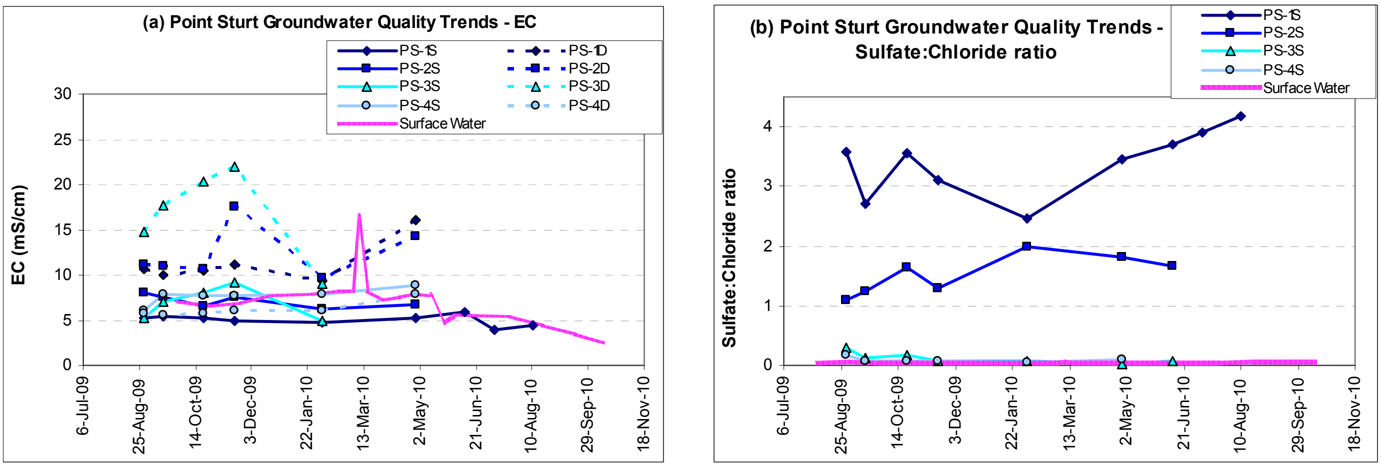

(k) Windmill Groundwater Quality Trends -Sodium
Sodium (mg/L
0
2000
4000
6000
8000
10000
6-Jul-09
25-Aug-09
14-Oct-09
3-Dec-09
22-Jan-10
13-Mar-10
2-May-10
21-Jun-10
10-Aug-10
29-Sep-10
18-Nov-10
WM-1S
WM-2S
WM-3S
WM-4S
Surface Water

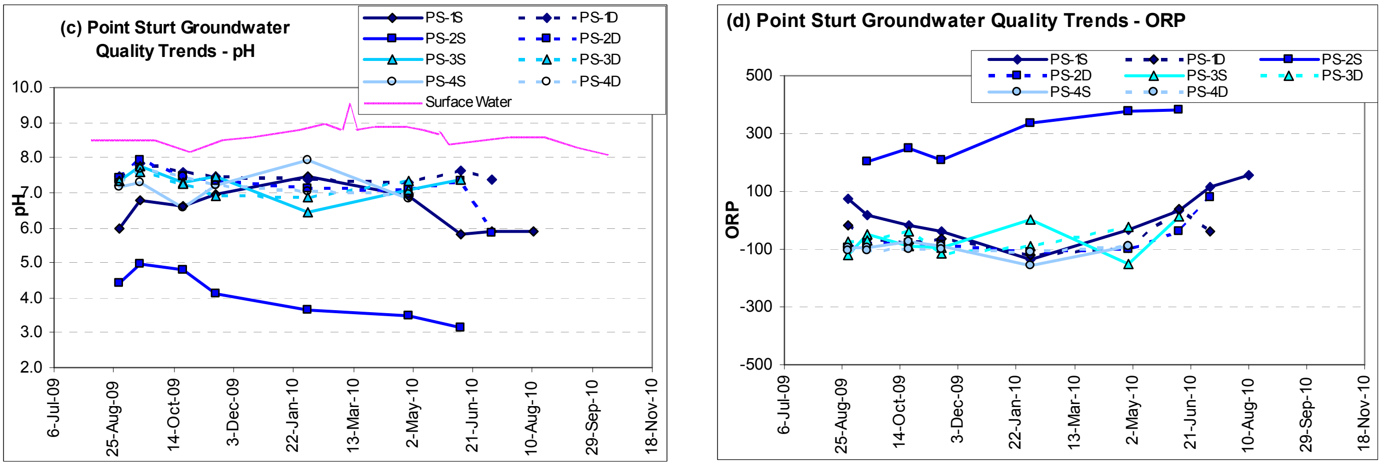

(l) Windmill Groundwater Quality Trends - Calcium
Calcium
0
200
400
600
800
6-Jul-09
25-Aug-09
14-Oct-09
3-Dec-09
22-Jan-10
13-Mar-10
2-May-10
21-Jun-10
10-Aug-10
29-Sep-10
18-Nov-10
WM-1S
WM-2S
WM-3S
WM-4S
Surface Water

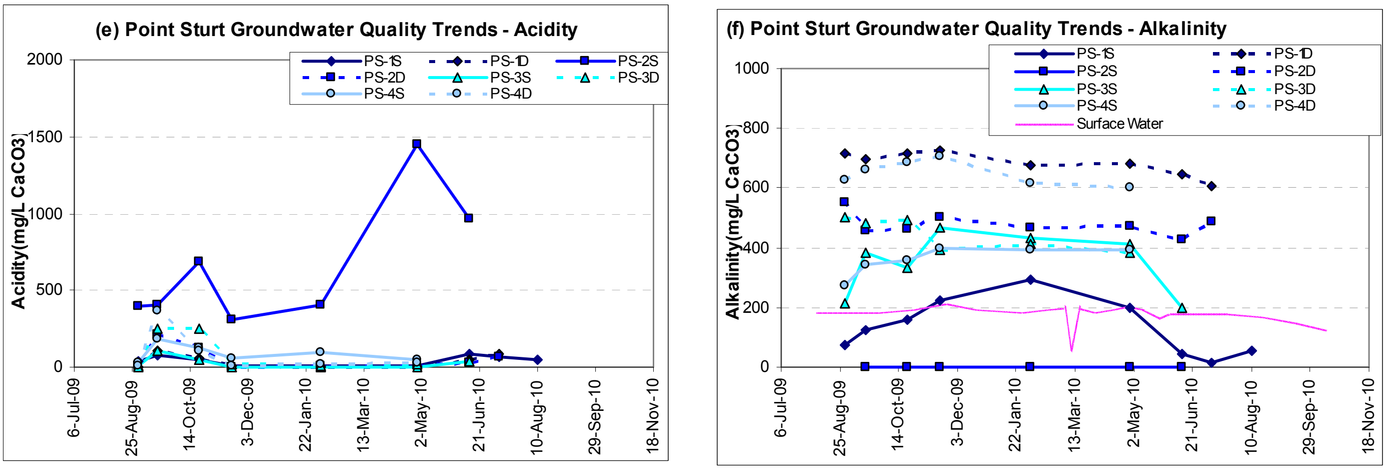

(m) Windmill Groundwater Quality Trends - Chloride:Sulfate ratio
Sulfate:Chloride Ratio
0
5
10
15
20
25
30
35
6-Jul-09
25-Aug-09
14-Oct-09
3-Dec-09
22-Jan-10
13-Mar-10
2-May-10
21-Jun-10
10-Aug-10
29-Sep-10
18-Nov-10
WM-1S
WM-2S
WM-3S
WM-4S
Surface Water

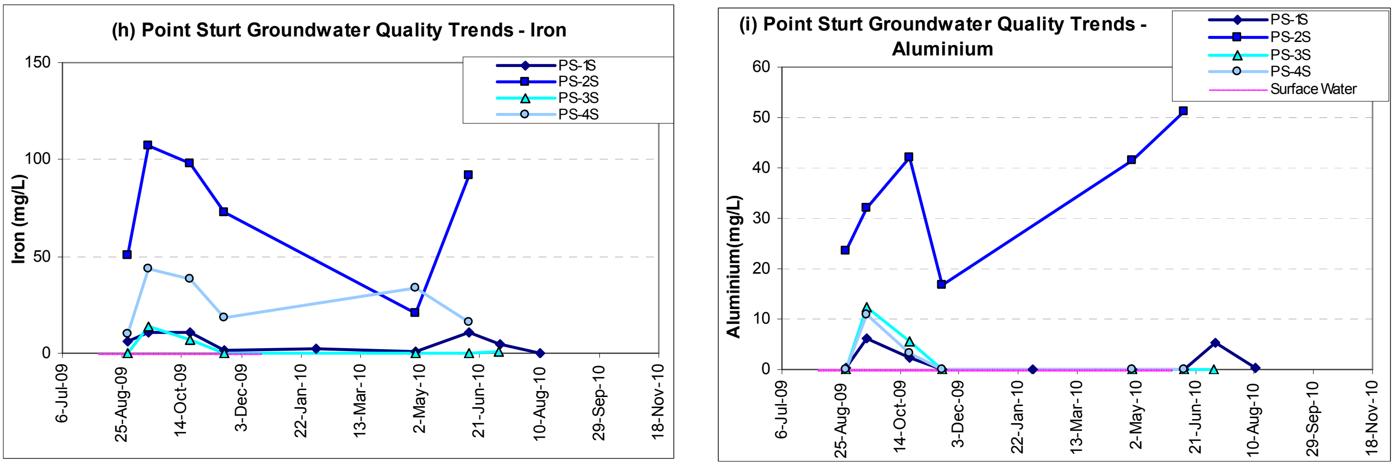

(n) Windmill Groundwater Quality Trends - Magnesium
Magnesium (mg/L)
0
200
400
600
800
1000
1200
6-Jul-09
25-Aug-09
14-Oct-09
3-Dec-09
22-Jan-10
13-Mar-10
2-May-10
21-Jun-10
10-Aug-10
29-Sep-10
18-Nov-10
WM-1S
WM-2S
WM-3S
WM-4S
Surface Water

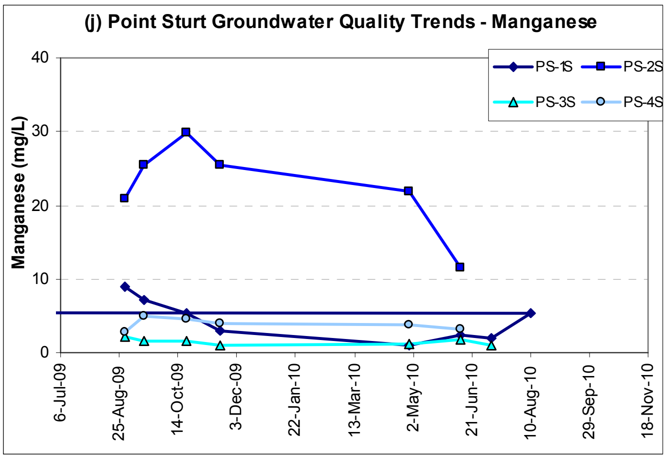
Figures 25 (a-n): Groundwater Quality trends at Point Sturt from August 2009 until August 2010.

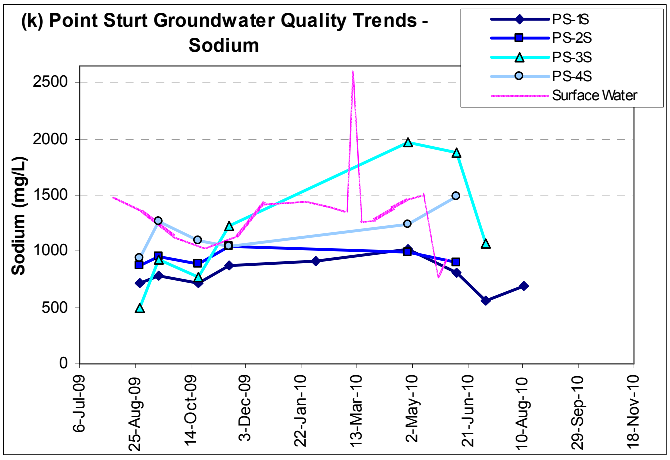


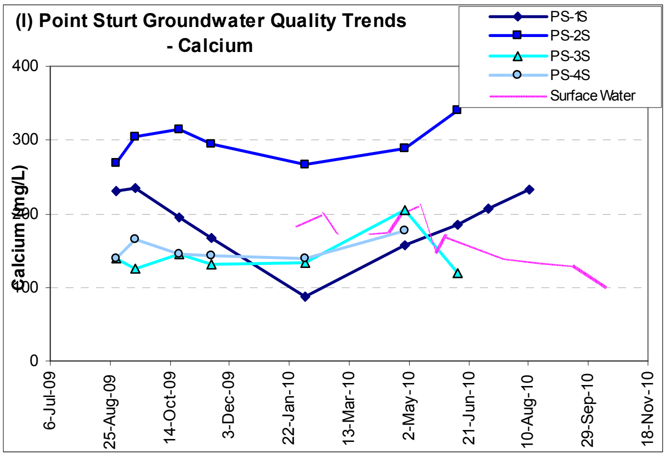


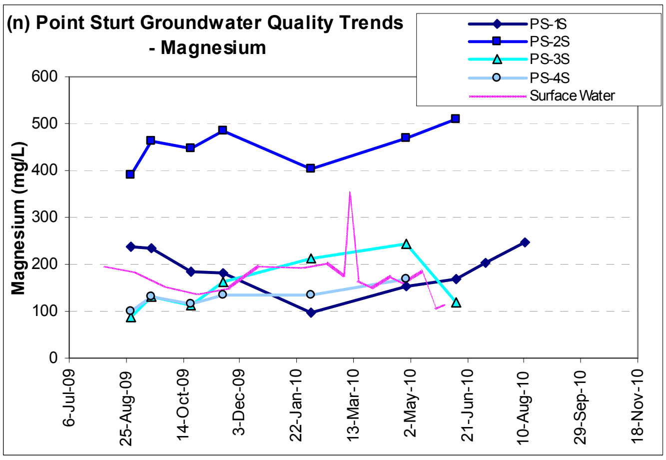





(j) Point Sturt Groundwater Quality Trends - Manganese


(k) Point Sturt Groundwater Quality Trends - Sodium


(l) Point Sturt Groundwater Quality Trends - Calcium

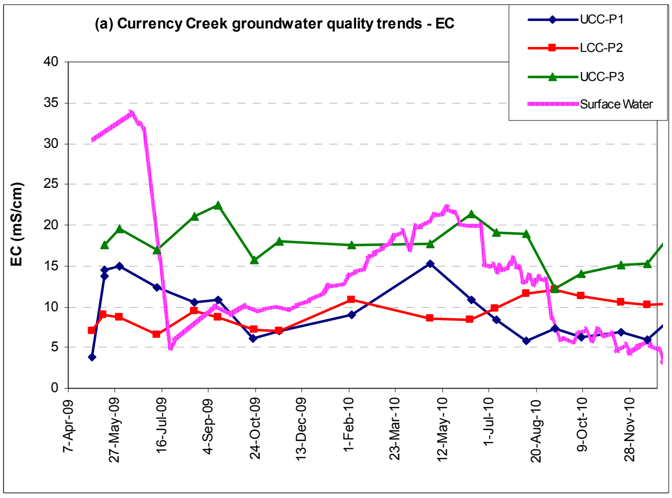

(n) Point Sturt Groundwater Quality Trends - Magnesium

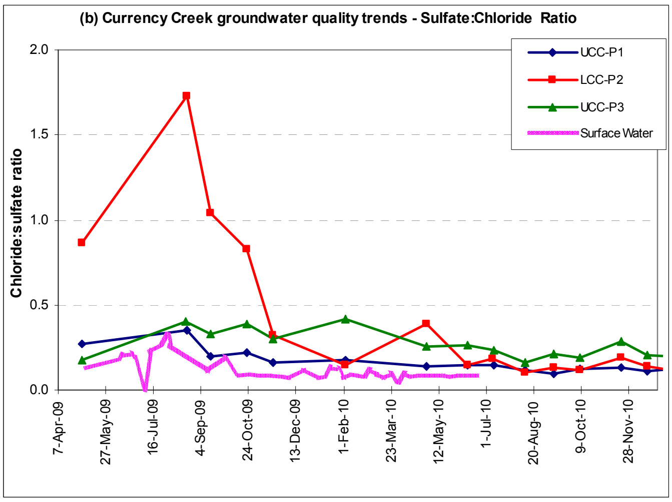
Currency Creek:

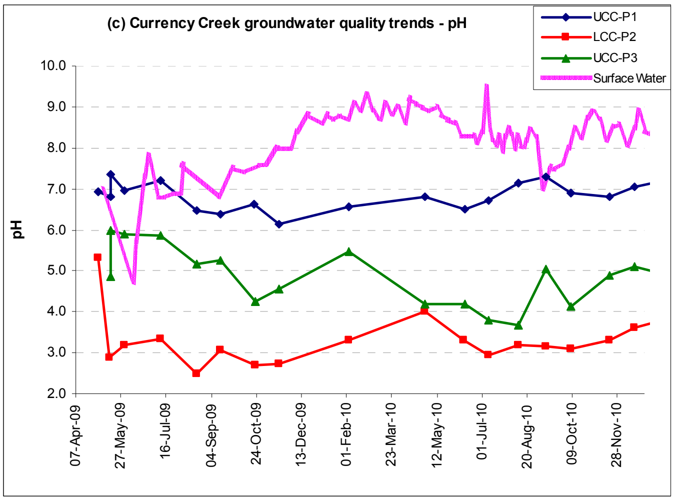
- UCCP1:
  - UCC-P1 had the highest pH of all the three Currency Creek piezometers, with pH 6.1-7.35 between April 2009 and November 2010 (Figure 26 (c)). Acidity was present, but in low concentrations and alkalinity was relatively high. Alkalinity in this piezometers tends to decrease during times of higher rainfall and surface water level rise, for example there was a large drop from September to October 2009 (297 mg/L $CaCO_3$ to 48 mg/L $CaCO_3$) and from April to June 2010 (418 mg/L $CaCO_3$ to 169 mg/L $CaCO_3$) (Figure 26 (f)) .
  - EC has been variable over time in UCC-P1, with rises over the summer months and declines during winter months (Figure 26 (a)). The key contributors to salinity (in order of magnitude) are Cl, SO_4, Na, Mg, Ca and K.
  - Soluble Fe, Al and Mn concentrations have been low and not changed significantly recently, in accordance with the lack of observable increases in acidity (Figure 26 (h), (i) (j)).
- LCC-P2:
  - pH in LCC-P2 is the lowest out of the 3 Currency Creek piezometers, with pH values below 4 throughout most of the monitoring period (Figure 26 (c)). After increasing slightly from November 2009 to April 2010 (a rise from 2.72 to 4.02), pH declined again to below pH 3 in July and remained between 3.0 and 3.3 until November 2010. Time of lower pH corresponds with times of higher rainfall in the region (increase from 2.72 to 4.02 in summer 2009–2010 declined to 2.94 in July 2010). Acidity has been very high at this site with acidity ranging from 746-1800 mg/L as $CaCO_3$ (Figure 26 (e)). There as a large peak in acidity in August 2009 but has been relatively steady at around 750-1000 mg/L from November 2009 to July 2010. There was a drop at the beginning of October to 300.7 mg/L $CaCO_3$, but then rise again to 700 mg/l $CaCO_3$ in November. ORP has ranged between 100-450 mV illustrating oxidising conditions since monitoring begun (Figure 26 (d)).
  - EC has been relatively stable over time, with a slight increase over summer and slight decrease after April (Figure 26 (a)). Unlike UCC-P1, this site increased in EC during the recent winter/rainfall months.
  - Al and Mn showed an increasing trend during April and November 2009 (Figure 26 (h) and (i)). Over the summer of 2009-10 levels decreased (corresponding with decreasing acidity) and were relatively stable. As rainfall increased there were increase Al (from 13.1 mg/L in April 2010 to 32.2 mg/L in July 2010), however, the Al results are still variable, with a decrease at the beginning of August and followed by an increase again in September to 35.5 mg/L. It appears that a sustained period of high rainfall increases Al in this piezometer.
  - Fe is much more variable at this site, with a large peak (476 mg/L) during monitoring in January (Figure 26 (h)). Since this time Fe decreased to between 156 mg/L to 189 mg/L from July until October 2010 (with a notable decrease in August 2010).
- UCC-P3:
  - UCC-P3 is located between UCC-P1 and LCC-P3. This piezometer illustrated a declining pH trend since February 2010 (pH 5.48) to July 2010 where it was at its lowest pH (pH 3.79) since monitoring began (Figure 26 (c)). However, pH increased in September and November 2010 varying between 4.89 and 5.02, with a slight dip in October to 4.14. The decline in pH in July was consistent with a rise in acidity, from 284 mg/L as $CaC0_3$ in February to 605 mg/L as $CaC0_3$ in July (Figure 26(e)), and a rise in ORP values indicating an increasingly oxidised environment (Figure 26 (d). Similarly, the increase in pH in September 2010 corresponded with a decrease in acidity.
  - EC in this piezometer is the highest out of the 3 Currency Creek piezometers, with values between 15 – 22 mS/cm). There was a decline in EC from June to September, which is consistent with increased winter rainfall and lake water level rises (Figure 26 (a)). During October and November EC began to rise again, consistent with less rainfall in the region in these months.

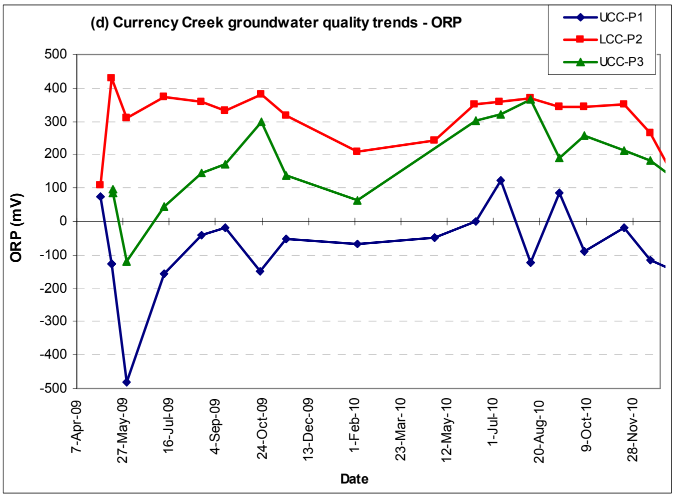
- Soluble metals at UCC-P3 all show quite different results. Fe has declined overall since November 2009 (Figure 121). Al increased from August to November 2009 before falling to nearly undetectable levels in February, and increasing again to its highest level in August 2010 (Figure 26 (i)). Al has fallen again from September to November.
- UCC-P3 recorded the highest Mn results of all 3 piezometers (Figure 26 (j)), with the results quite variable over time. A notable decline has occurred since August 2010.

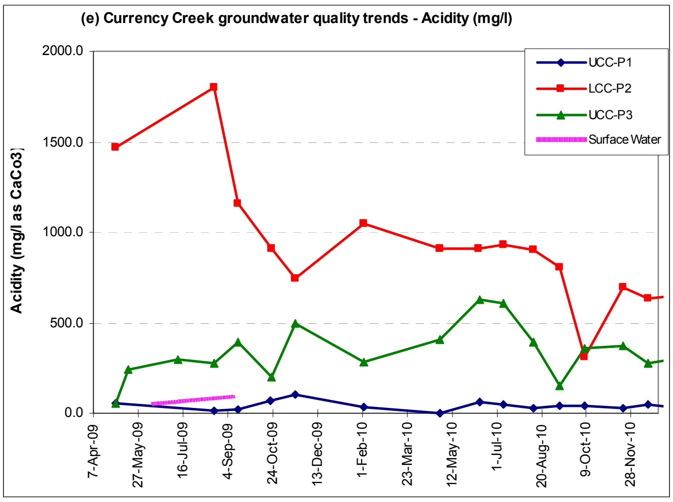
Figures 26 (a-n): Groundwater Quality trends at Currency Creek from April 2009 until November 2010

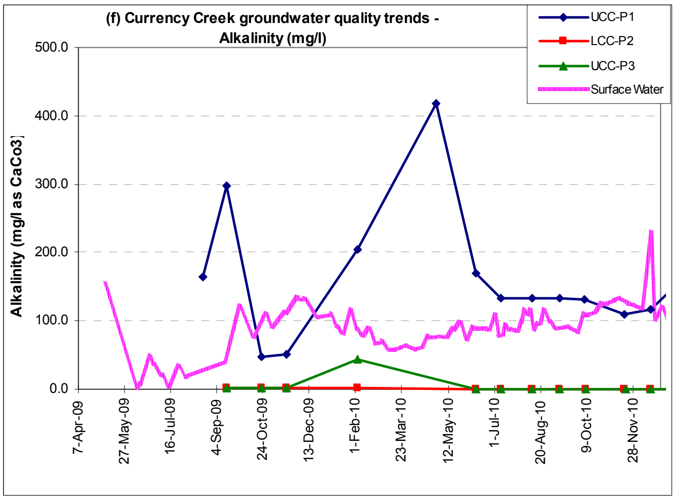


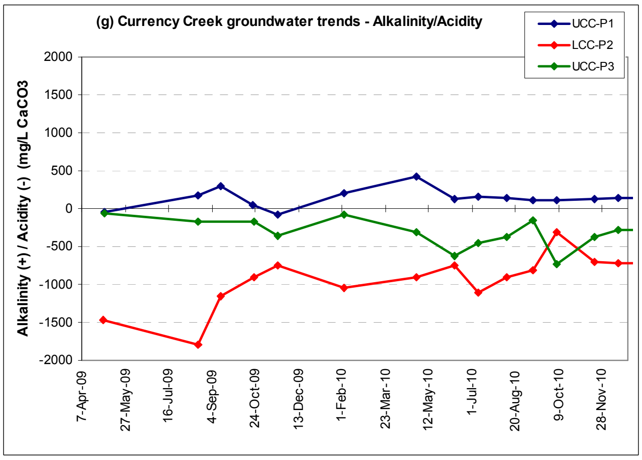


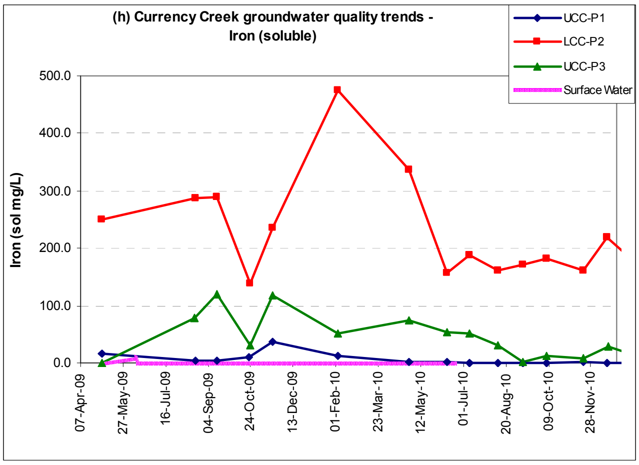


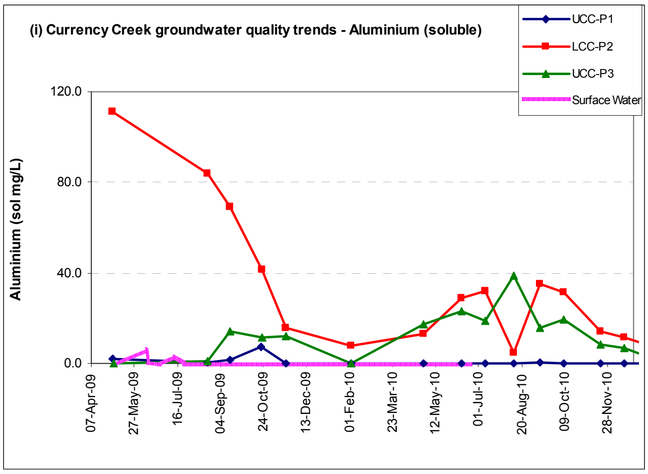


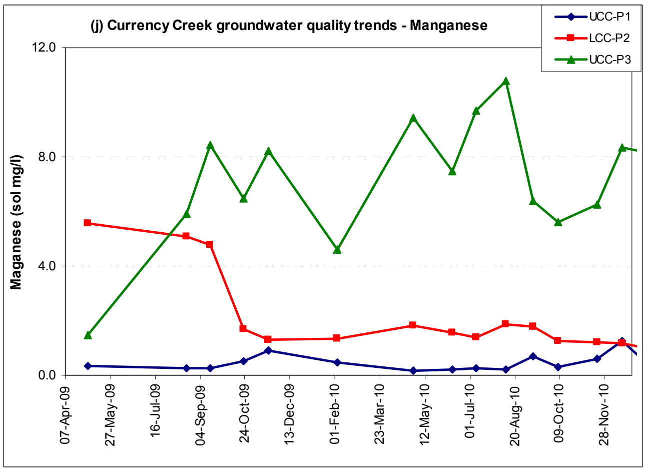


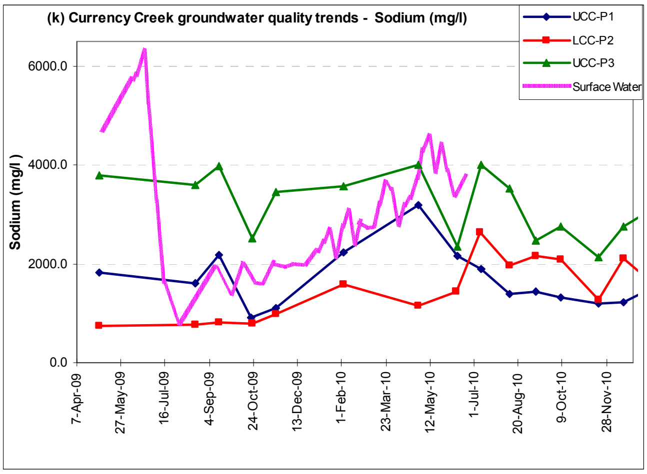


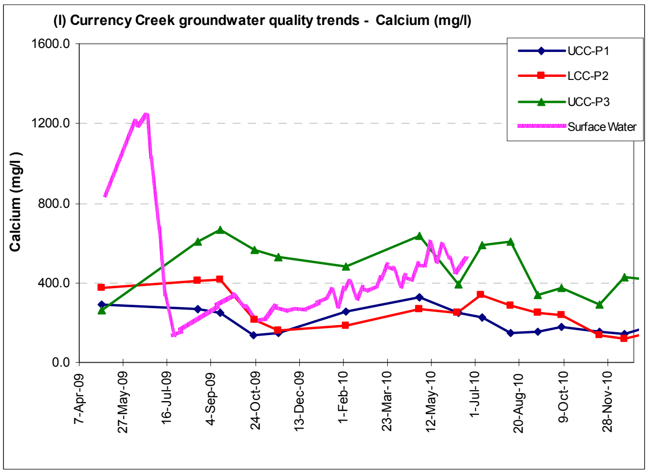

(g) Currency Creek groundwater trends - Alkalinity/Acidity

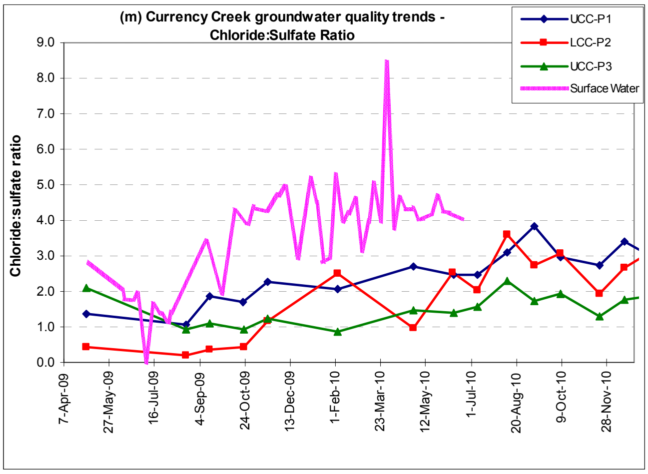

(h) Currency Creek groundwater quality trends - Iron (soluble)

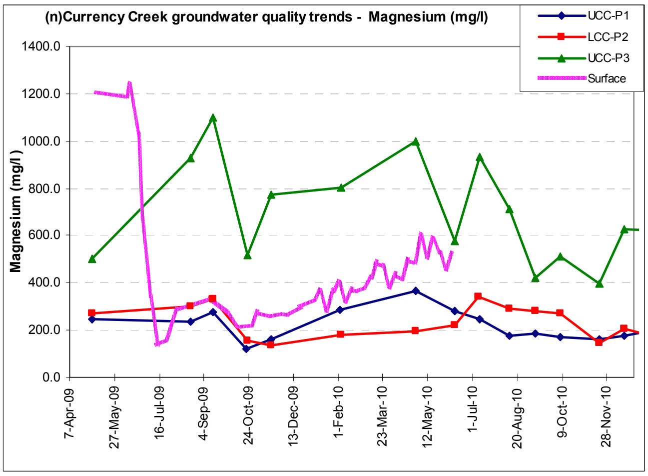

(i) Currency Creek groundwater quality trends - Aluminium (soluble)


(j) Currency Creek groundwater quality trends - Manganese


(k) Currency Creek groundwater quality trends - Sodium (mg/l)


(l) Currency Creek groundwater quality trends - Calcium (mg/l)


(m) Currency Creek groundwater quality trends - Chloride:Sulfate Ratio


(n)Currency Creek groundwater quality trends - Magnesium (mg/l)

4.0 DISCUSSION

There are several factors that determine the risk that acid sulfate soils pose in relation to groundwater and lake water quality (see Appendix for summary by Earth systems 2010). The potential and available acidity in the exposed sediment is a key factor determining the hazard level. Fitzpatrick et al. (2010) provide comprehensive information on this. The potential groundwater related mechanisms that could create risks of lake acidification are discussed below. Detailed hydraulic and geochemical modelling was outside the scope of this report. Such modelling would be required to better assess the complex and dynamic processes which are noted in this report.

4.1 Sediment Moisture and potential for acid generation

A complete year of data has been collected of the sediment moisture at three locations. These probes are located at Site 1 (closest to pre-drought shoreline) at each of the locations. Results show that despite groundwater levels nearest the original shoreline decreasing during the summer of 2009–2010, the moisture content remained relatively constant and saturated at depths below 40 cm. The relatively constant soil moisture below about 40 cm occurred despite the groundwater (piezometric) level being much lower (ca. 0.4-0.5 m) for the summer months of 2009/10. This saturation above the water table is likely due to capillary rise, which can be very large, particularly in clay soils (White et al 1987). Increasing soil moisture levels occur between 0 - 30 cm in response to rainfall intensity, with increases occurring within a couple of hours of a rainfall event and desaturation occurring over a period of 24-48 hours. The lowering soil moisture levels during the summer months could be due to three factors; deep drainage, down slope lateral flow, or evaporation (Cook and Rassam 2002). Rises in moisture levels are linked to rainfall and lake level rises.

Importantly these findings suggest that even with lake level decreases of 1.7m, there is not likely to be acid generation in much more than the 0.4m of the sediment profile. However, in sandy sediments such as Pt Sturt (higher drainage, less capillary rise) the oxidation front has been observed to be deeper (approximately 70 cm and ph > 4) (Baker et al. 2010).

4.2 Presence of acidity in groundwater

Acidic groundwater was found at Campbell Park (all shallow sites except Site 1), Point Sturt (Site 2) and at Currency Creek (Sites LCC-P2 and UCC-P3). Windmill recorded slight acidity but pH was maintained at satisfactory levels. The acidity in the groundwater at these sites has likely originated from vertical transport of acid from the upper oxidised sediment layer. A key driver for this transport is likely to be rainfall events when flushing of the upper sediment occurs and the piezometric levels rise into the normally unsaturated zone.

Campbell Park (Site 4) and Currency Creek (LCC-P2 and UCC-P3) were the only locations with acidic groundwater close to the lake water, hence these sites would appear to pose the most risk to lake water quality. Localised surface water acidification has been observed in both these regions which supports this hypothesis (EPA 2010).

Soluble metal acidity was present at all sites to some degree, with higher concentrations at the sites which illustrated acidity. Mobilisation of metals appears to be linked to early winter rainfall as prior to this the sediments have dried, and metals have presumably accumulated and not been mobilised, over the summer period. Levels of soluble metals at the acidic sites, particularly Al, are likely to be toxic to any benthic organisms present (ANZECC 2000).

The deeper sediments at all locations, including those below shallow acidic sites, recorded neutral pH, therefore it is likely that the upper and lower sediments had limited hydraulically connectivity as also proposed by Earth Systems (2010). There was some evidence of vertical transport of acidity to the deeper sediments at Point Sturt Site 2, as there was a lowering of pH and a small rise in acidity during August 2010. Salinity differences between the shallow and deep groundwater sediments were also observed. The lower salinities in the shallow groundwater is likely to be a result of dilution and mixing processes with fresher rain and lake water, whereas the lower piezometer are more saline as they are likely influenced more by the regional aquifer water.

4.3 Potential for Groundwater Flux to the Lake

In general, hydraulic head gradients were quite low at all sites, which limited the potential groundwater flux to the lake. Following rainfall events these gradients increased and a positive hydraulic head gradient towards the lake was established. The elevated piezometric levels following rainfall decreased over subsequent days indicating likely lateral drainage to the lake and perhaps some deep drainage.

As found by Earth Systems, hydraulic gradients often reversed indicating groundwater flow away from the lake, especially during dry periods. This is likely due to evaporation lowering the water table under the exposed sediment (Cook and Rassam 2002). This type of complex and dynamic behaviour in the near shore environment has been observed in other lake systems (Berkowitz et al 2004). Detailed hydraulic modelling is required to better understand the complex and dynamic fluxes of groundwater under different climatic conditions in the Lower Lakes.

4.4 Risk of Groundwater Acidity flux to Lake Surface Water

All locations, with the exception of Windmill (where no acidification present) showed some potential for acidity flux to the lakes. The highest risk locations appear to be Campbell Park and Currency Creek where acid water was found close to the surface water margin and positive hydraulic gradients were commonly present. This high risk level assessment in these locations is also supported by evidence of surface water acidification at nearby sites (EPA 2010). The risk of acidity flux was heightened during rainfall events where the hydraulic gradient increased. However, some of the large hydraulic head increases across the locations were very transient and water quality sampling did not often coincide with these. Hence, there may have been temporary pulsing of acidic water that was not monitored, possibly including at Point Sturt where acidity was found in the mid shore region. Hydraulic modelling and more event-based sampling would be beneficial to examine this potential issue in more detail. Such modelling is required to determine the magnitude of these acidity fluxes and the potential for these to influence lake alkalinity under varying water levels.

Lake levels recovered as a result of flooding in the north-eastern Murray Darling Basin catchment during September 2010. This has reduced the potential for acidification by removing hydraulic gradients between the surface water and groundwater (equal piezometric and lake levels) and providing substantial dilution water. However, acidic groundwater may still pose a risk to lake water quality (e.g. via diffusion) but this is unclear at present. The risk is believed to be low however as vertical diffusion rates are likely to be small through the sediment from the acidic groundwater to the surface water. Event-based monitoring post-inundation generally supports this assumption as, while some low levels of soluble metals (in particular Fe) have been observed, alkalinity has been maintained in the water body over previously acidified areas (e.g. Boggy Lake, Currency Creek, Boggy Creek, Hunters Creek). The inundated conditions are also conducive for sulfate reduction processes which could potential neutralise acidity. This could be examined with more detailed geochemical analysis of the data (outside scope of current project).

5.0 Conclusion

There has been groundwater acidification from the exposure and desaturation of Acid Sulfate Soils in the Lower Lakes of South Australia during the recent hydrological drought. Soil moisture measurements indicated saturated conditions are maintained from 40-50cm below ground level and this did not change significantly with the underlying water table fluctuations. Hence the upper 40-50cm of sediment is the zone of potential acid generation. Acidic groundwater was recorded at 3 of the 4 piezometer locations (all except Windmill). This was likely mobilised during early winter rainfall washing acidity down from the overlying oxidised sediment layer. The sites posing the highest risk were Campbell Park and Currency Creek and localised observations of surface water acidification are consistent with this. High soluble (Fe, Al, Mn) metal levels were recorded at acidic locations. The low hydraulic gradients present likely limit the amount of acid flux in these locations, and groundwater flow reversals were also common. While a detailed analysis of the complex and dynamic hydrology and geochemistry was beyond the scope of this report the results provide important information for the planned more detailed modelling of the groundwater-related acidification risks. A better understanding of these risks is particularly important if there is any subsequent major reduction in water level in the Lower Lakes. Ongoing monitoring is required to assess the timescale for the recovery of the groundwater quality at acidic sites following reinundation.

6.0 Recommendations

Based on the findings of this report the recommendations are:

- Undertaken 2 Dimensional modelling of the lake and shallow groundwater interactions to aid data interpretation better understand potential mechanisms and fluxes of acid delivery to the lakes.

- If possible, resample the piezometers (by extending tubes above current water levels) to determine whether groundwater is remaining acidic following refilling of the lakes. The water quality parameters being analyses should also be reviewed following this changing environmental context.

- Undertake further assessment of the potential for diffusion of acidity from the groundwater to the lake and/or neutralisation processes (e.g. sulfate reduction, carbonate dissolution) under reinundation

7.0 Acknowledgments

We wish to thank EPA field staff for groundwater sampling and data processing and analysis. The support of Earth Systems Pty Ltd. (in particular Jeff Taylor and Nic Bourgeot) and Department of Environment and Natural Resources (in particular Liz Barnett and Ann-Marie Jolley) are also kindly acknowledged. This work was conducted under funding from the Australian Government’s Murray Futures program.

8.0 References

ANZECC (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Australian and New Zealand Environment and Conservation Council

Appello, C.A.J., and Postma, D., (2005) Geochemistry, groundwater and pollution, Second Edition. Taylor and Francis Group CRC Press, Amsterdam, The Netherlands.

Baker, A.K.M., Fitzpatrick, R.W., Shand, P. Simpson, S.L., Merry R. H. and Thomas, M. (2010) Temporal variations in representative Acid Sulfate Soil environments around Lakes Alexandrina and Albert, South Australia. Murray-Darling Basin Authority/CSIRO, http://www.clw.csiro.au/publications/science/2010/SAF-Lakes-Alexandrina-Albert-sulfate-soils-temporal.pdf

Berkowtix, B., Silliman, S.E., Dunn, A.M. (2004) Impact of the Capillary Fringe on Local Flow, Chemical Migration, and Microbiology. Valdose Zone Journal, vol.3, pp.534-548

Cook, F.J., and Rassam, D.W. (2002) An analytical model for predicting water table dynamics during drainage and evaporation. Journal of Hydrology, vol. 263, pp.105-113

DFW (2010) Surface water level Lake Alexandrina Beacon 57 (Site A4261133), Lake Albert near Waltowa Swamp (Site A4261153) and Warringee Point (Site A4261155) and Currency Creek (A4261203), Data provided by P. Hansen, Department For Water South Australia

Earth Systems Pty Ltd (2009) Quantification of Acidity Flux Rates to the Lower Murray Lakes: Final Report. Consultants report prepared for the Department for Environment and Heritage, South Australia

Earth Systems Pty Ltd (2010) Quantification of Acidity Flux Rates to the Lower Murray Lakes: Supplementary Report Consultants report prepared for the Department for Environment and Heritage, South Australia. April 2010.

EPA (2010). Lower Lakes water quality reports – ambient and event-based monitoring. Environment Protection Authority South Australia. Available at http://www.epa.sa.gov.au/environmental_info/water_quality/monitoring_programs_and_assessments/lower_lakes

Fitzpatrick, R. W., Shand, P., Marvanek, S., Merry, R. H., Thomas, M., Raven, M., Simpson, S. L., and McClure, S. (2008) Acid sulfate soils in subaqueous, waterlogged and drained soil environments in Lake Albert, Lake Alexandrina and River Murray below Blanchetown (Lock 1): properties, distribution, genesis, risks and management. 183 pp. CSIRO Land and Water Science Report 46/08: Canberra, Australia. Available at http://www.clw.csiro.au/publications/science/2008/sr46-08.pdf

Fitzpatrick, R.W., Grealish G., Chappell A., Marvanek S. and Shand P. (2010) Spatial variability of subaqueous and terrestrial acid sulfate soils and their properties for the Lower Lakes South Australia, CSIRO Land and Water report.

SAMDNRMB (2010-11). Rainfall for Currency Creek, Langhorne Creek and Narrung, downloaded from: http://www.samdbnrm.sa.gov.au

Simpson, S.L., Fitzpatrick, R.W., Shand, P., Angel, B.M., Spadaro, D.A. and Mosley, L.M. (2010) Climate-driven mobilisation of acid and metals from acid sulfate soils, Marine and Freshwater Research, vol. 61, pp.129–138.

White, I., and Sully, M.J. (1987) Macroscopic and microscopic capillary length and time scales from field infiltration, Water Resources Research, vol.23, no.8, pp.1514-1522

APPENDIX 1

Key ASS risk factors (from Earth System 2010)

Primary risk factors

1. Elevation of outer lake margin sediments (bathymetry).
2. Sulfide content.
3. Desaturation rate:
    a. Low moisture retention capacity (high sand content relative to clays);
    b. Low potential for inundation during seich events;
    c. Presence of vegetation.
4. Potential for groundwater flux from sediments to lake:
    a. High hydraulic conductivity / permeability (high sand content relative to clays);
    b. High hydraulic gradient:
        i. Low relief upgradient of lake sediments;
        ii. High gradient of sediment bank (bathymetry);
        iii. High gradient of sand/clay contacts;
        iv. Low lake water level (current and predicted levels, relative to previous minimum lake levels).
5. Volume of unsaturated lake sediments:
    a. Depth to groundwater / saturated zone at outer lake margin;
    b. Surface area (length and width) of exposed lake sediments.
6. Geological distribution of Bridgewater Formation.

Secondary risk factors

7. Availability of organic matter / iron for bacterial pyrite precipitation.
8. ANC content in near-surface lake sediments (unsaturated zone and upper saturated zone).
9. Visible evidence of acid formation (metal precipitates and acid efflorescences).
10. Potential for acid ponds to develop on lake margins.
11. Potential to impact on populated areas (proximity).