MURRAY FUTURES
Lower Lakes & Coorong Recovery

Acid Sulfate Soils Research Program

Lower Lakes Hydro-Geochemical Model Development and Assessment of Acidification Risks

Report 6 | Part 4 of 4 | October 2010

Australian Government

Government of South Australia

WATER FOR GOOD

7.2 Lake Alexandrina: drawdown scenarios and analysis (Sep 2009 – Sep 2013)

Lake Alexandrina water quality forecast

The plots of water level and water quality for the period from Sept 2009 – Dec 2012 are shown in Figures 7.21-7.33. These plots show four simulations that represent the main simulations tested to date: the 'do nothing' (or drawdown, '*DDN*'), freshwater pulse ('*FWp*'), freshwater inundation (or freshwater stabilisation, '*FWs*') and seawater inundation (or seawater stabilisation, '*SWs*'). Clearly there are many permutations of how these different management approaches may ultimately be implemented, and these are presented as a guide for testing the lake response to drawdown and refilling from a lake acidification point of view.

As is seen in Figure 7.21, the water level of the simulations varies in response to the level of supplemental water provided. The do nothing (DDN) scenario indicates the lake will drop to -2.0m AHD by the end of summer 2011 (this assumes pumping to Lake Albert implemented to maintain it about -1.0m; Lake Alexandrina will go lower than 2.0m for higher Lake Albert pumping rates). The prescribed flows for the freshwater and seawater input raise the water level by approximately 1.0 m.

The temperature of the domain is largely unaffected by the different inflows (Figure 7.22). This is due to the fact that the seasonal temperature changes are driven by the surface thermodynamics, which are similar regardless of lake inflows. There is some divergence between simulations towards the end of the simulation period due to differences in the extinction coefficient, which impacts surface temperature and therefore evaporation. Salinity varies markedly between the simulations as expected based on the different inflow rates and water sources. In the 'do nothing' drawdown simulation, the salinity peaks at 14,500 $uScm^{-1}$ following the 2009-2010 summer, and then at 20,000 $uScm^{-1}$ after the 2010-2011 summer. For the freshwater supplementation scenario, the extra water enters in early 2010, and following the peak salinity in the centre of the water body it is rapidly diluted, and by the 2010-2011 peak it is back down top the initial value of ~7,500 $uScm^{-1}$, and continues to drop for the remainder of the simulations. The seawater supplementation scenario however, creates a peak of EC in the middle of Lake Alexandrina of around 50,000 by the 2010-2011 summer, and this is reduced during the winter but then increases more substantially in the 2011-2012 summer (not this is seawater supplementation to -1.0m AHD).

Dissolved oxygen concentrations do not differ significantly between the simulations (Figure 7.23), despite the difference in sediment-area to volume ratios of the different simulations (due to their different volumes). The DOC levels in the lake do evapo-concentrate considerably under the do-nothing scenario, but are diluted under the freshwater and seawater scenarios in line with the volume of water that is introduced since the boundary value concentrations are low compared to that in the lake.

Nutrient and chlorophyll-a values show some interesting changes (Figure 7.24-7.26), both in the speciation between nutrient components and in the total N and P concentrations. Seawater is most effective at reducing nutrients as would be expected given the low values within Coorong/Murray Mouth waters providing a dilution effect. Note also that seawater has potential to greatly reduce turbidity and change the primary producer community structure and abundance (e.g., as in Goolwa channel – macrophytes more abundant as turbidity is now low); these effects have not been modelled. The rise in nutrients is generally reflected in a rise in the total Chlorophyll-a concentration with levels reaching ~100 ugL^{-1} in the summer periods, except for the simulation where seawater was introduced.

Most of the major ions following the trends outlined for salinity, as would be expected given they are mostly conservative. The exception is for dissolved inorganic carbon (DIC) and Ca due to solubility equilibrium control with calcite/aragonite, and alkalinity consumption by the acid sulfate soil model (Figure 7.17). The alkalinity is generally stable (Figure 7.27) and noticeably lower for the seawater scenario, although not fully depleted. The alkalinity does get close to zero as the seawater flows in and along the southern lake margin towards Pt Sturt, and at these locations pH responds accordingly (Figure 7.28). The metals are also stable and dissolved phases are not present for the life of the simulation.

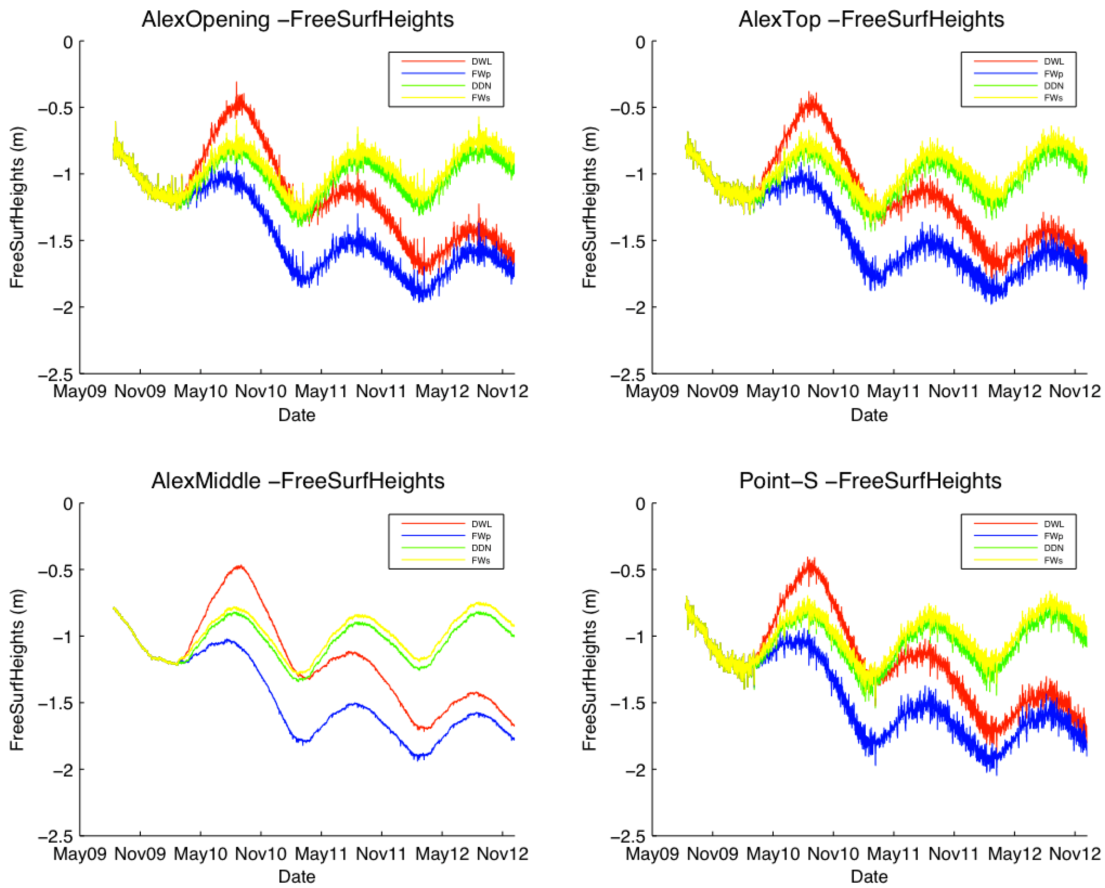

Figure 7.21: Forecast scenarios of modelled water level (m AHD) (DDN, FWp, FWs, SWs) for four stations within Lake Alexandrina.

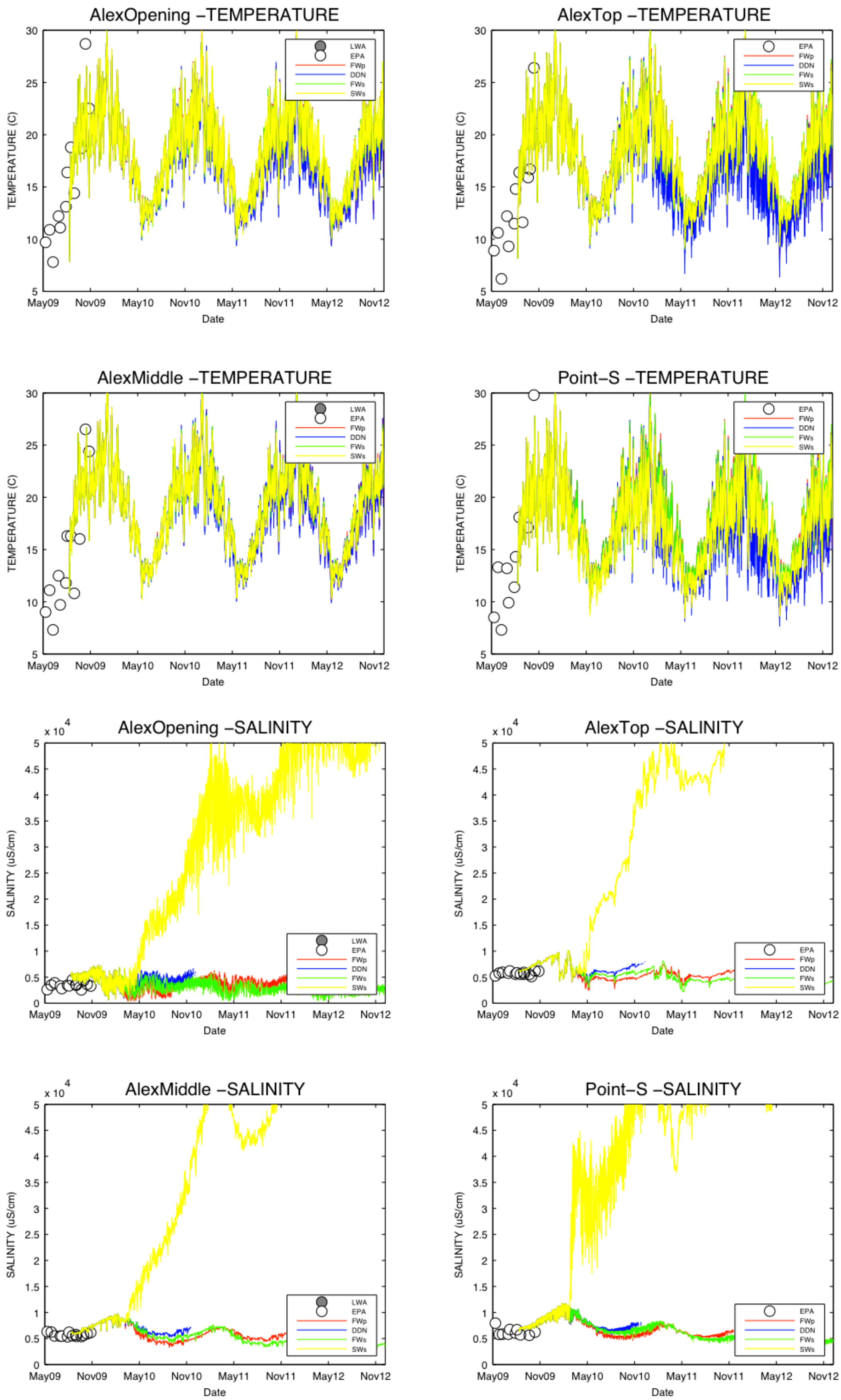

Figure 7.22: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) temperature (°C) and salinity (uS cm^{-1}) data for four stations within Lake Alex.

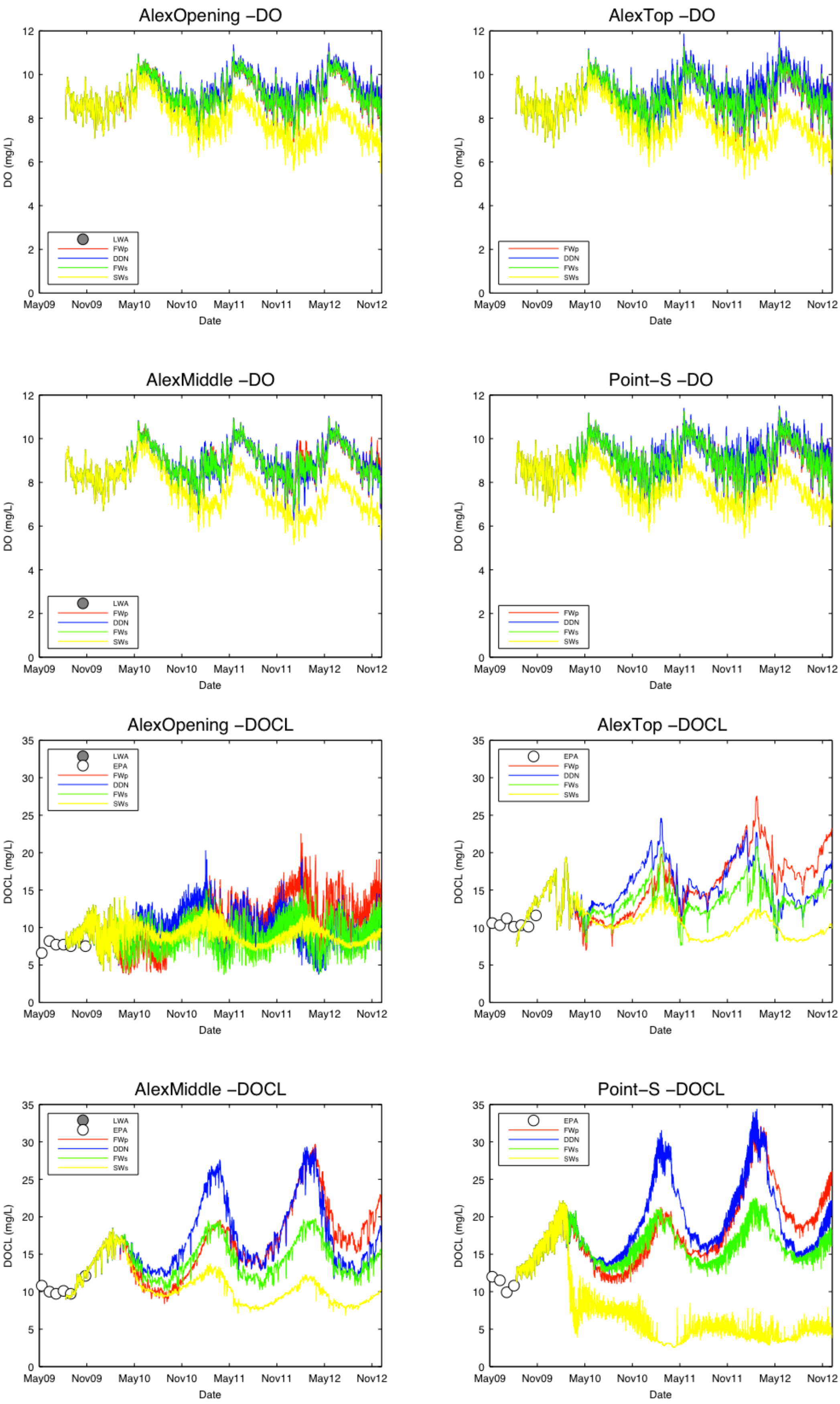

Figure 7.23: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) dissolved oxygen (DO, mg L-1) and dissolved organic C (DOCL, mg L-1) for four sites in Lake Alex.

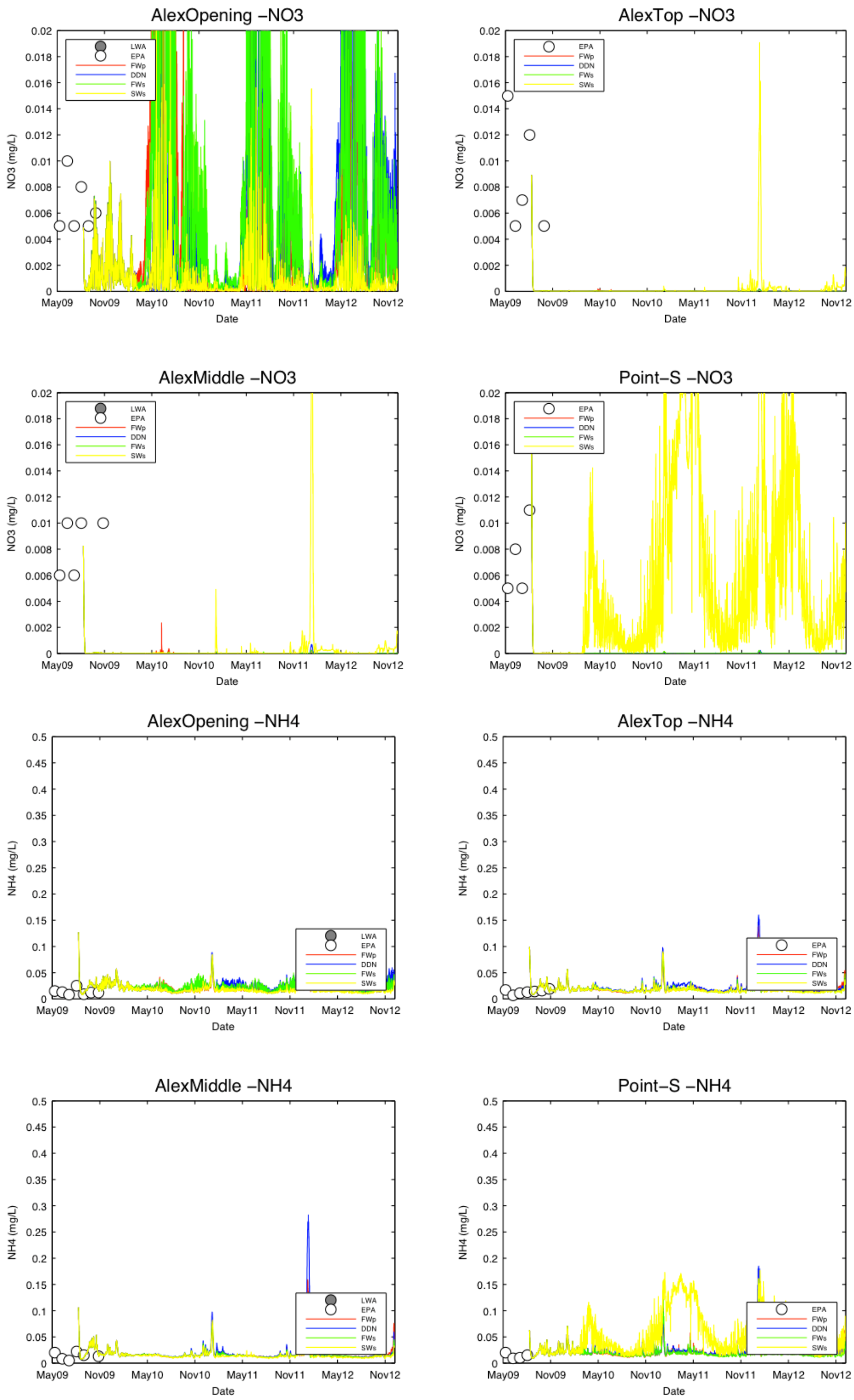

Figure 7.24: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) nitrate+nitrite (NO3, mg L-1) and ammonium (NH4, mg L-1) for four sites in Lake Alexandrina.

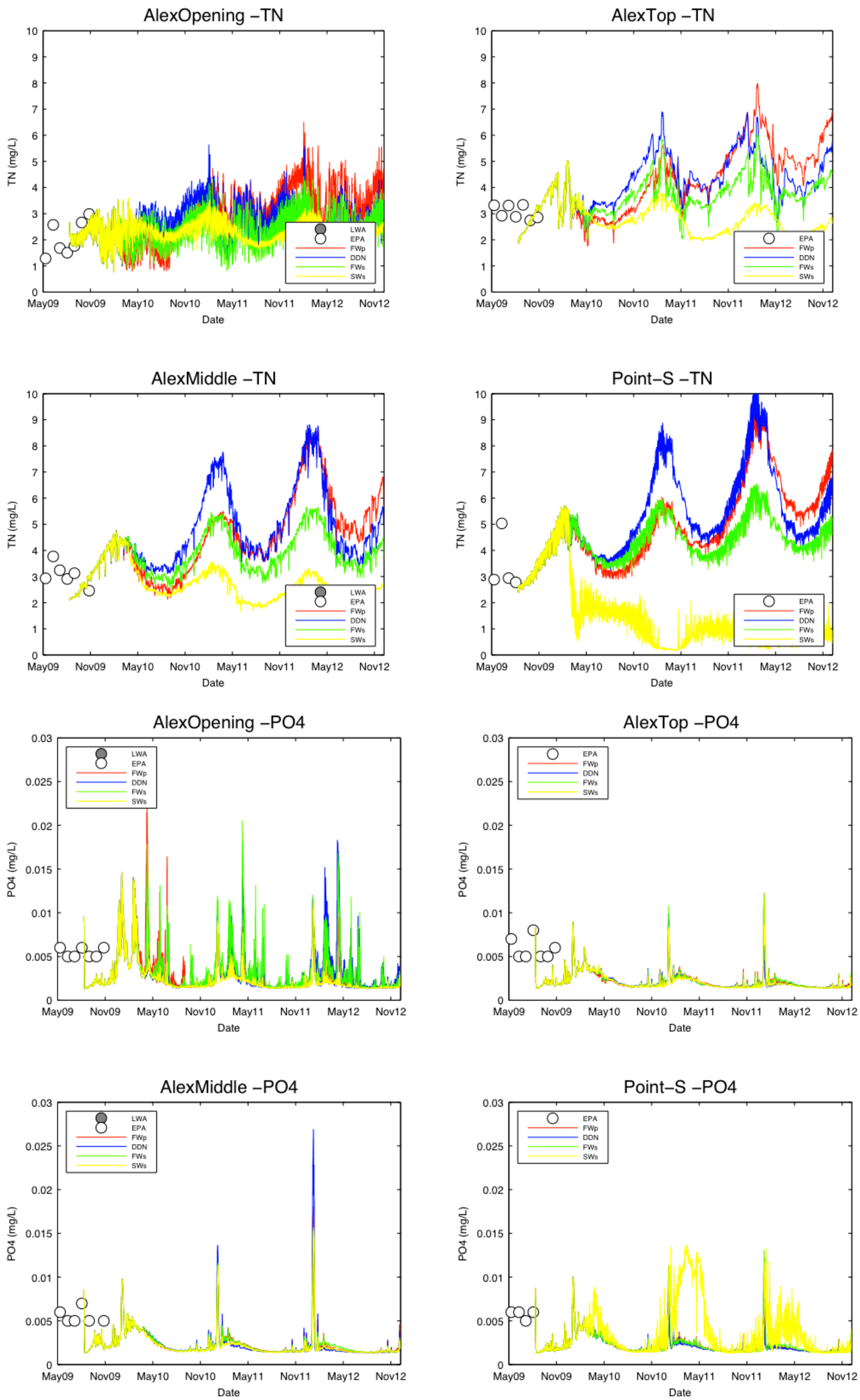

Figure 7.25: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) total N (TN, mg L-1) and orhto-phosphate (PO4, mg L-1) for four sites in Lake Alexandrina.

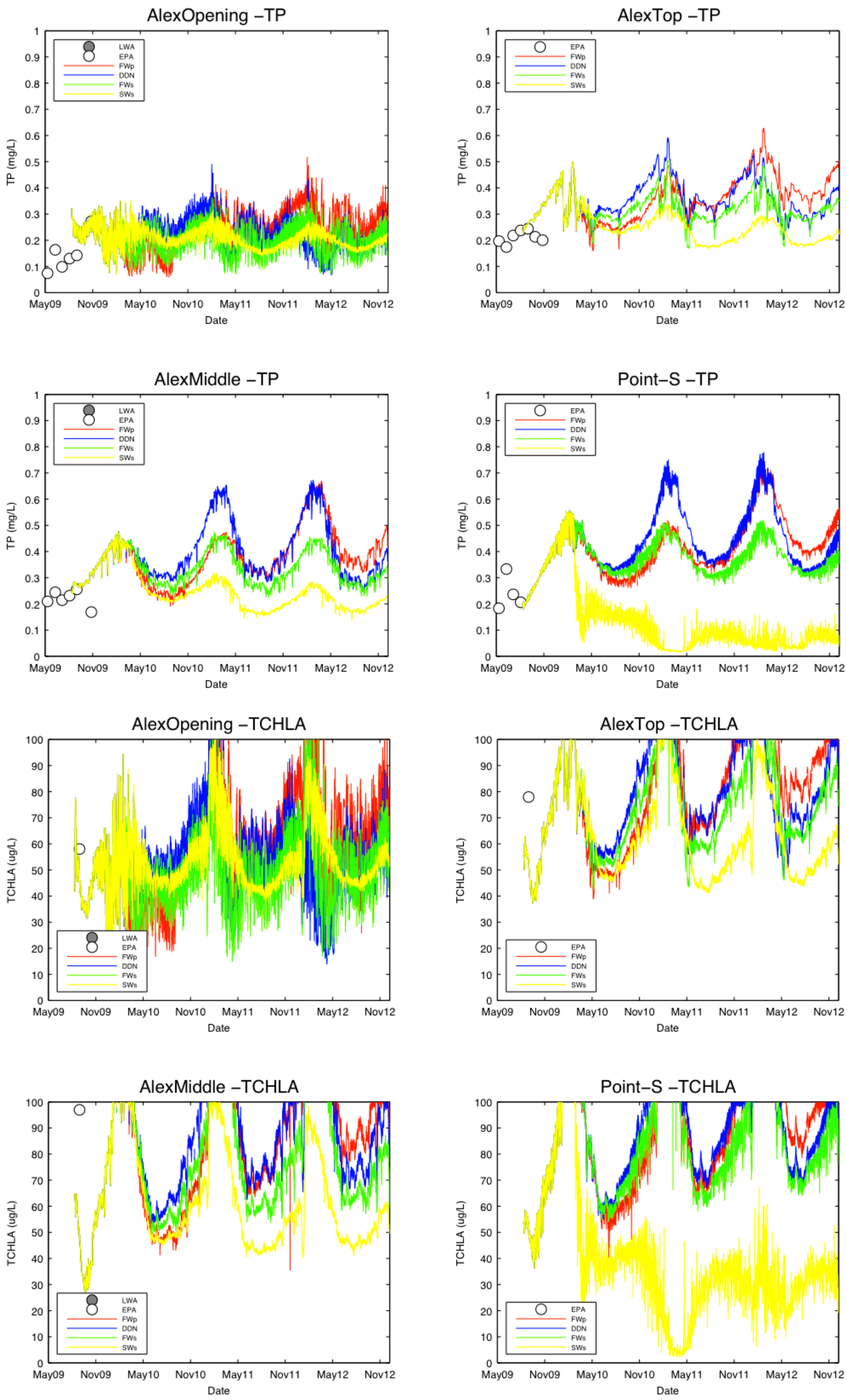

Figure 7.26: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) total P (TP, mg L^{-1}) and total chlorophyll-a (TCHLA, ug L^{-1}) for four sites in Lake Alexandrina.

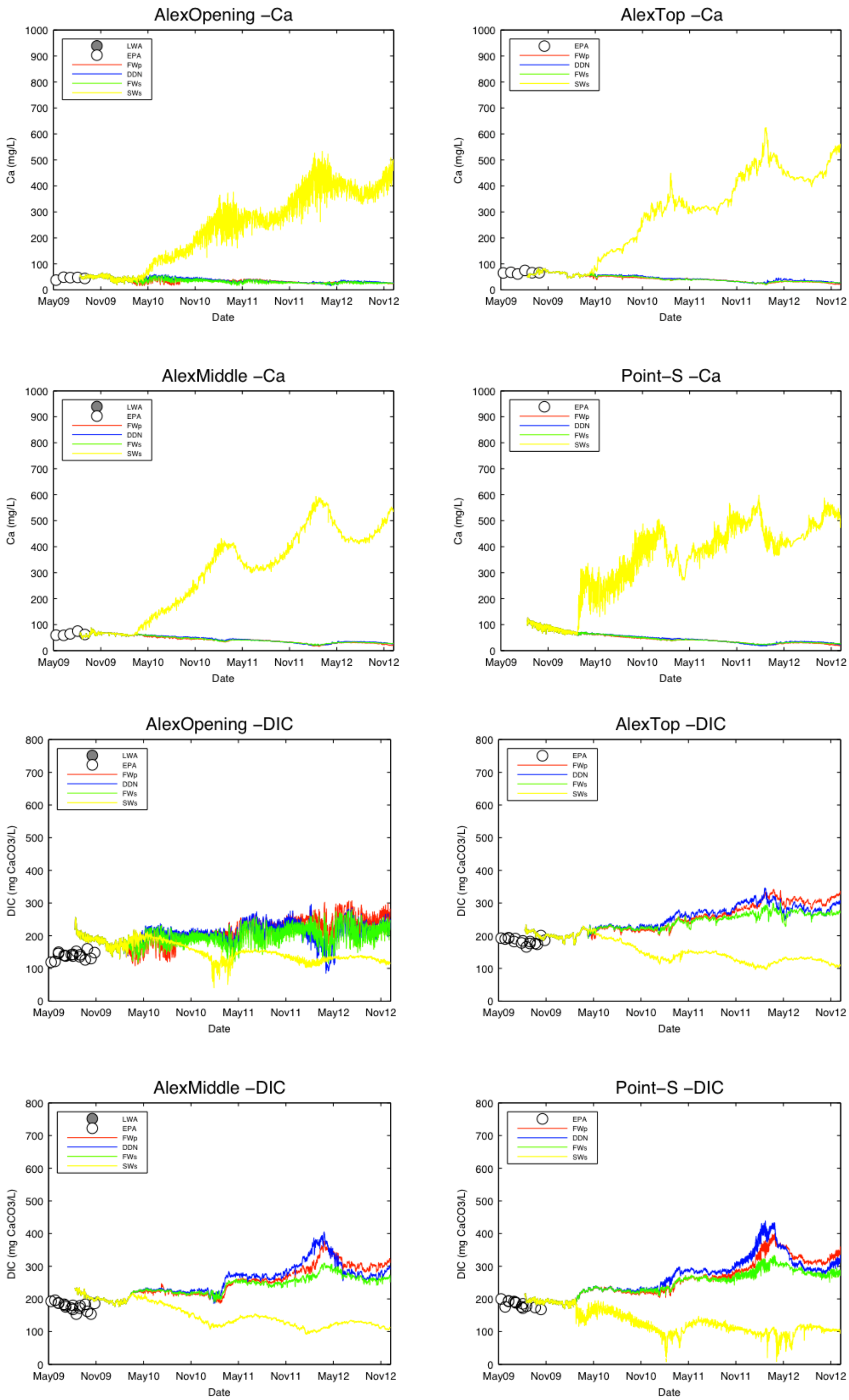

Figure 7.27: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) calcium (Ca, mg L^{-1}) and carbonate alkalinity (DIC, mg CaCO3 L^{-1}) for four sites in Lake Alex.

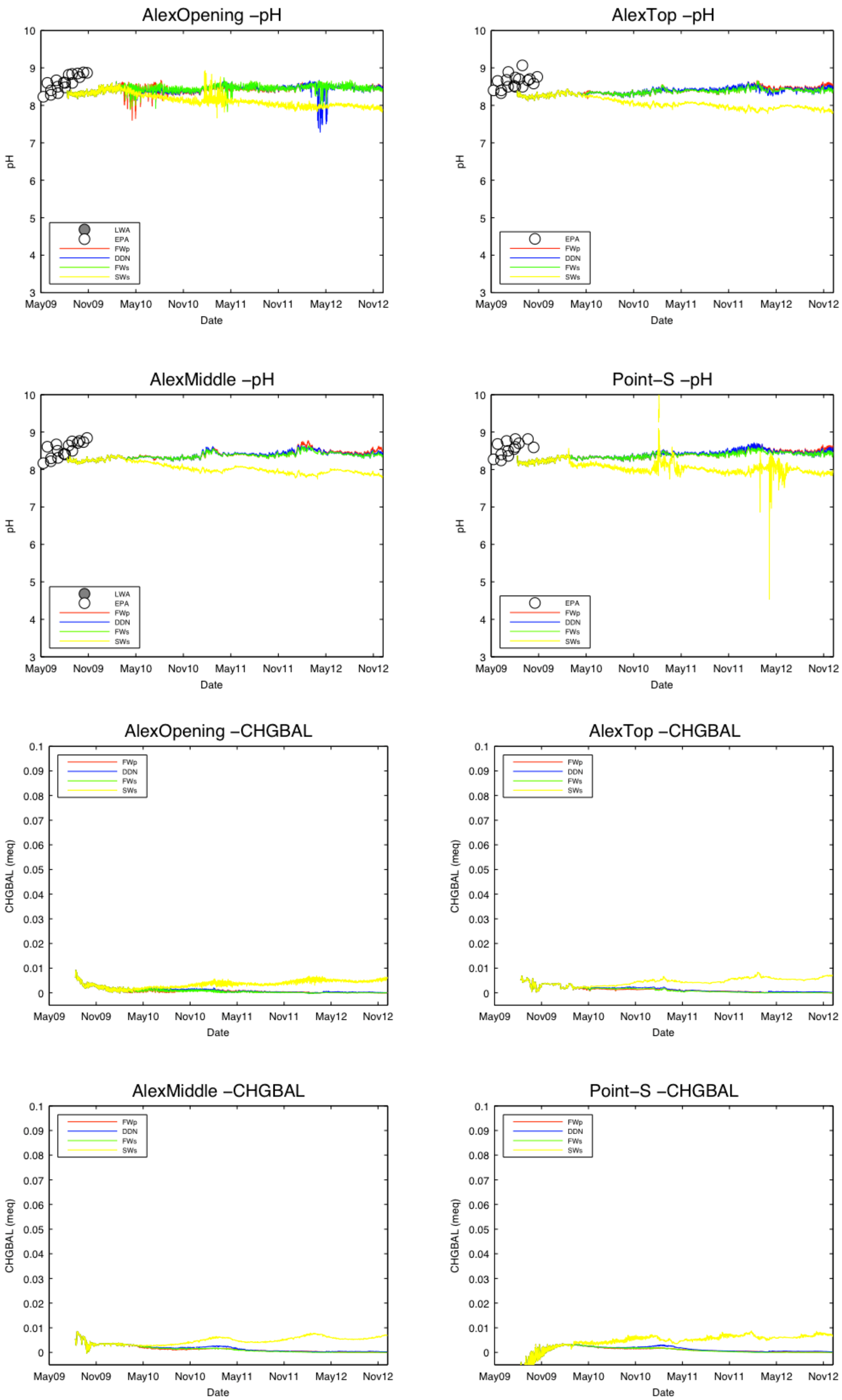

Figure 7.28: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) pH and charge imbalance (CHGBAL, meq) for four sites in Lake Alexandrina.

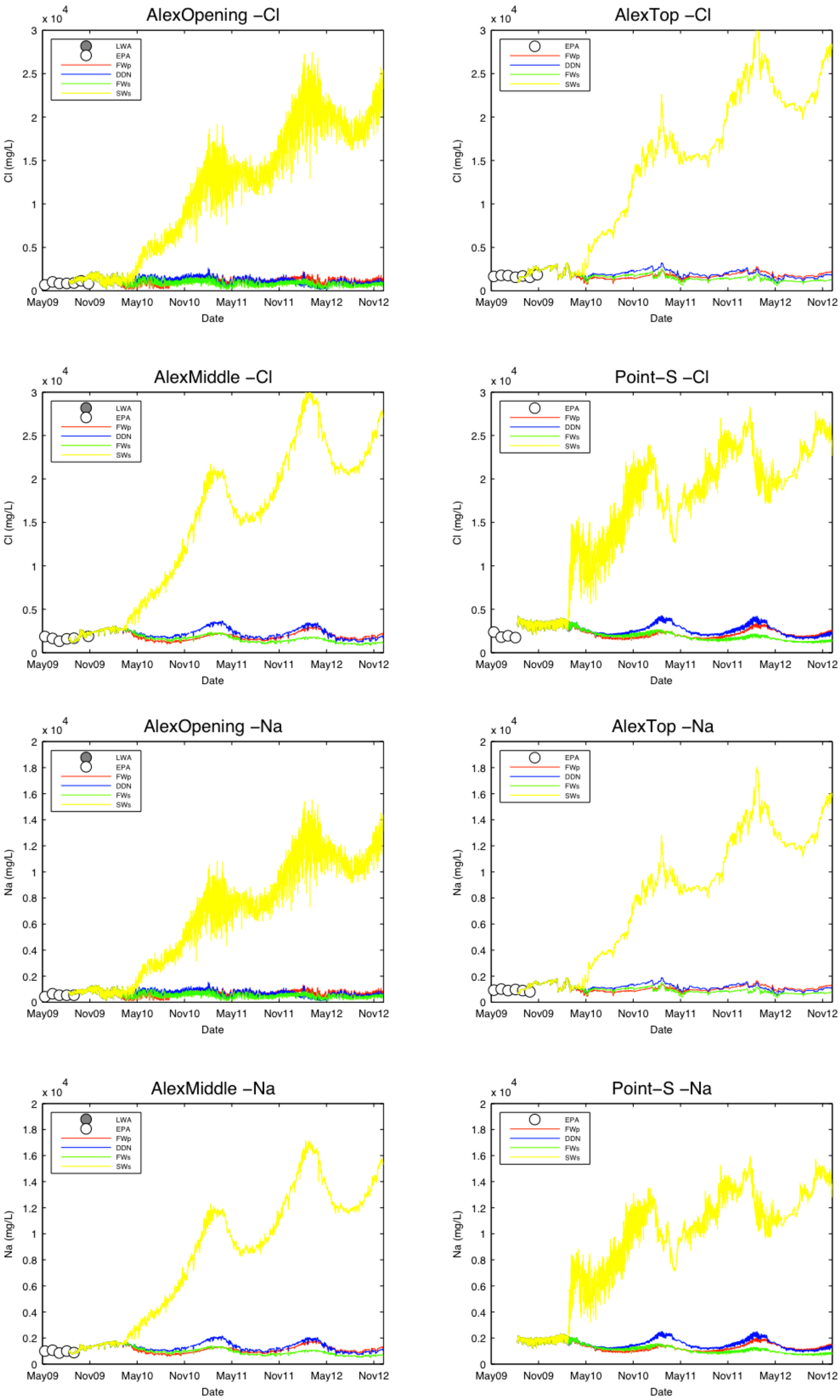

Figure 7.29: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) chloride (Cl, mg L^{-1}) and sodium (Na, mg L^{-1}) for four sites in Lake Alexandrina.

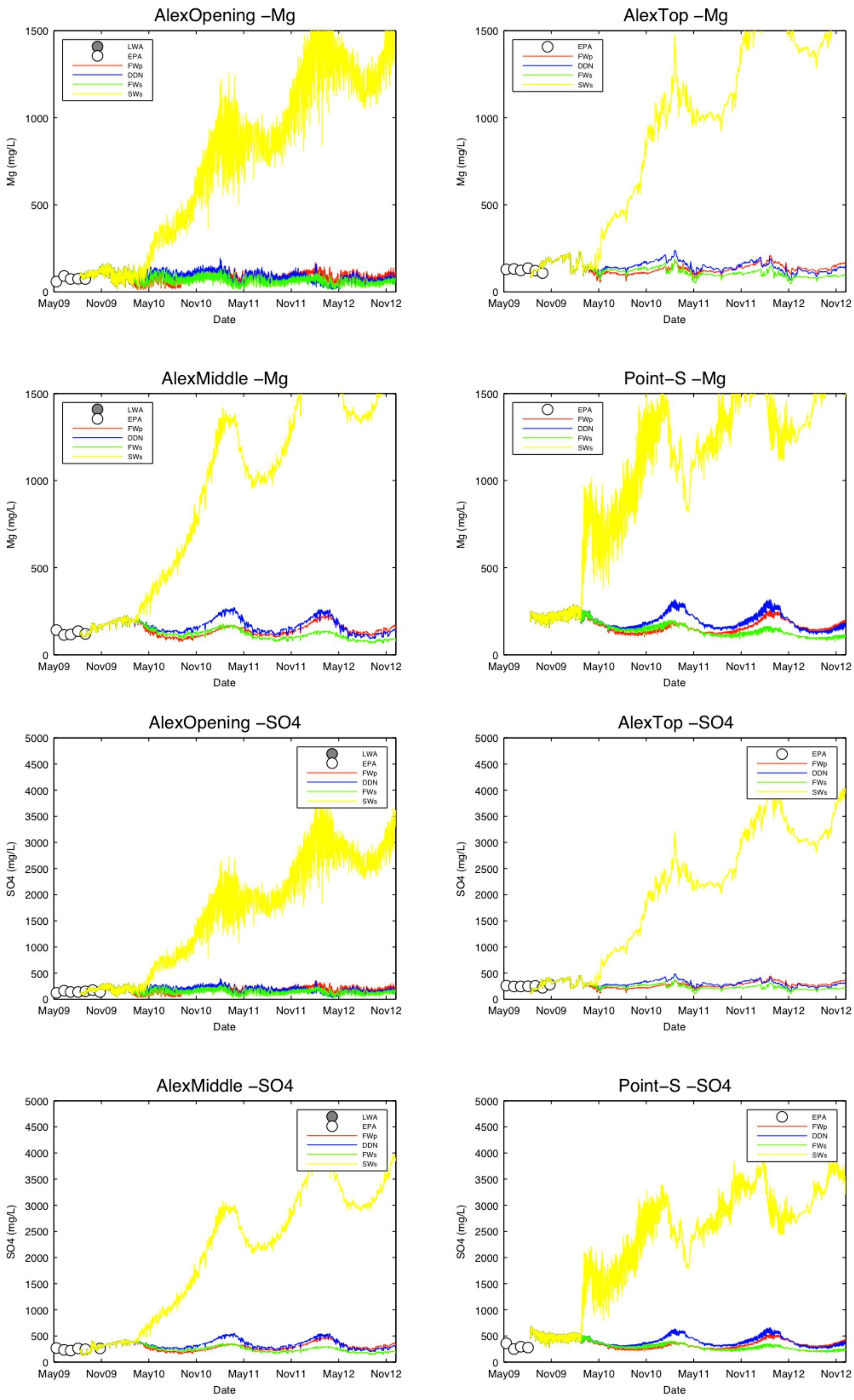

Figure 7.30: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) magnesium (Mg, mg L^{-1}) and sulfate (SO4, mg L^{-1}) for four sites in Lake Alexandrina.

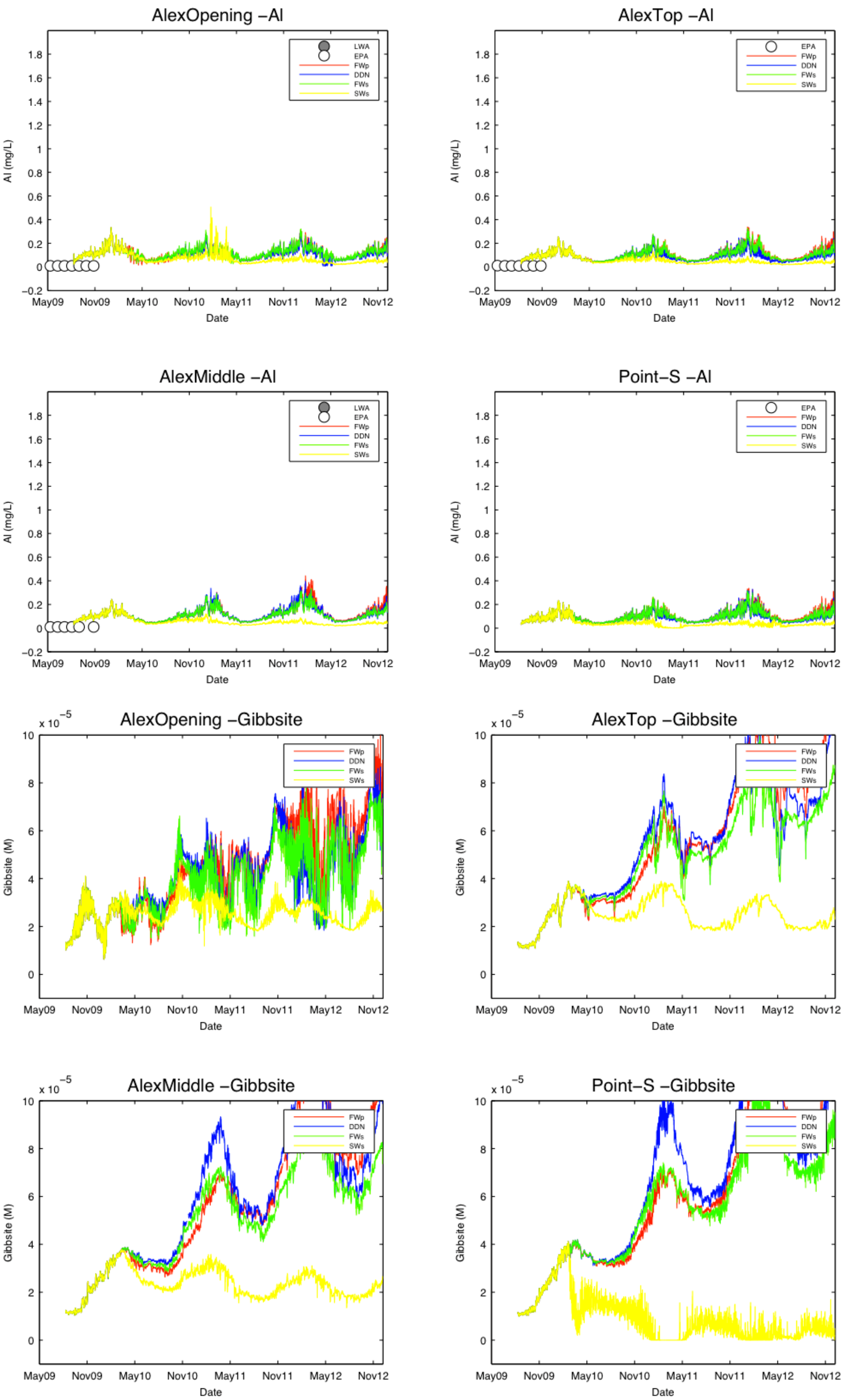

Figure 7.31: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) dissolved Al (Al, mg L^{-1}) and particulate Al (Gibbsite, mol L^{-1}) for four sites in Lake Alexandrina.

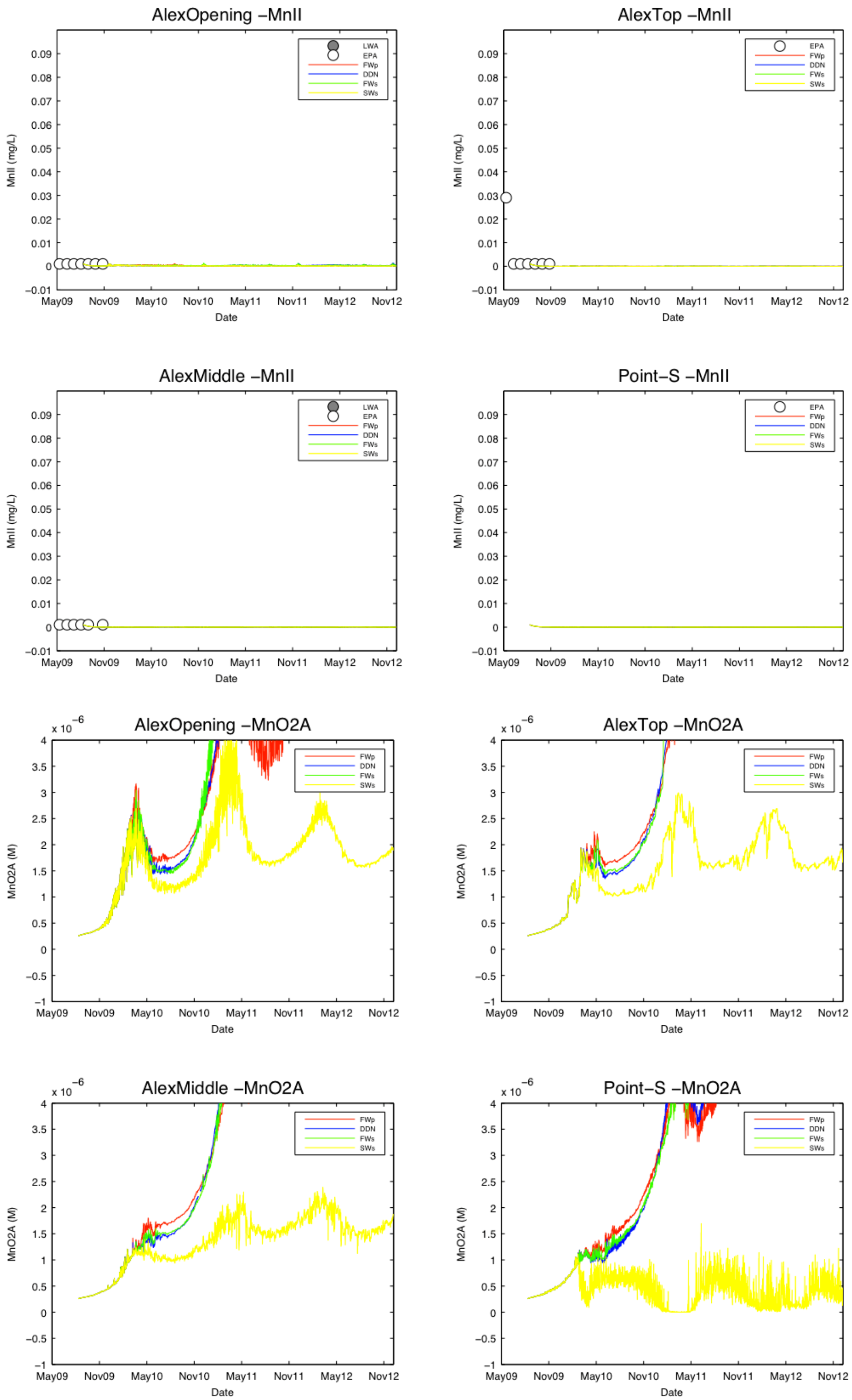

Figure 7.32: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) dissolved Mn (MnII, mg L-1) and particulate Mn (MnO2A, mol L-1) for four sites in Lake Alexandrina.

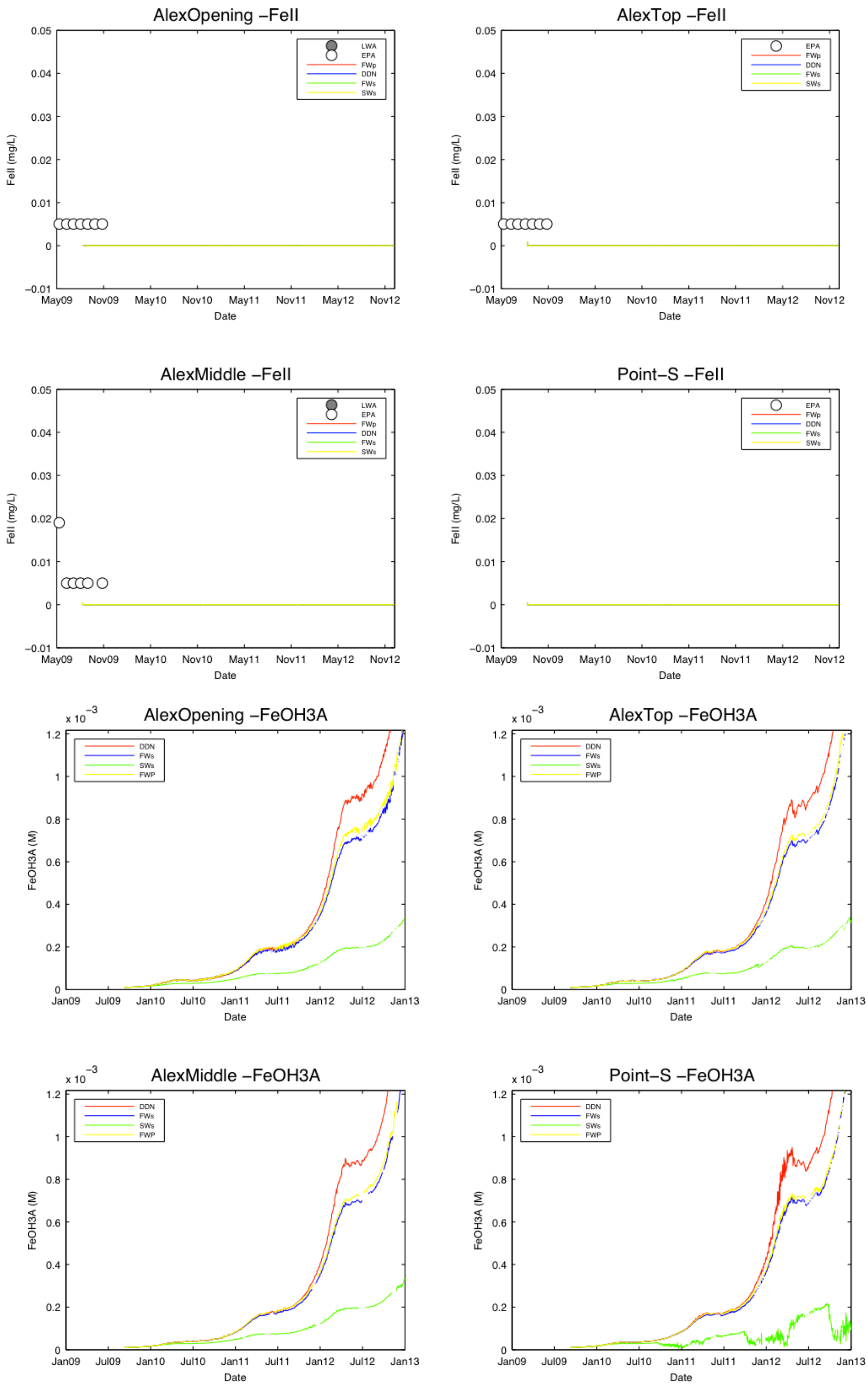

Figure 7.33: Forecast scenarios of modelled (DDN, FWp, FWs, SWs) dissolved iron (FeII, mg L^{-1}) and particulate ferric iron (FeOH3A, mol L^{-1}) data for four stations within Lake Alexandrina.

Lake Alexandrina acid sulfate soil analysis

Here we aim to gain insights into the process controlling the acidity dynamics and identify the key sensitive processes by examining spatial variability and integrated process rates. The hydrology output from a single sandy cell near Pt Sturt is shown in Figure 7.34, and highlights the magnitude of the different fluxes over the drying/wetting cycle. Most notable is the magnitude of the overland and throughflow component resulting from saturation/infiltration excess generated during 2009-2010, however this becomes less as the water table deepens and the soil infiltration capacity increases. The chosen cell is sandy so the rate of evaporation and drainage is higher than the example cell plotted for Lake Albert; this is reflected in the depth of the drainage that occurs, which is around 0.75m over the 3yr simulation period. Here the top 60cm is oxidised, and a considerable amount of pyrite is consumed (Figure 7.35).

The spatial plots of pH and soil model output for Lake Alexandrina(Figure 7.36-7.40) show the annual change in the key acidity pools, the key processes controlling acidity mobilisation, and how these vary across the lake. The pH/alkalinity first becomes unstable at the north-western end of the lake, and then on the south-western edge west of Pt Sturt. The southern reach also shows a modest acidity contribution. The lake edge soil properties are patchy due to large variability in soil type (clay or sand) and chemical properties.

The initial shallow water table depths (<0.3 m deep) increase substantially over the 2009-2010 summer, particularly within the sandy regions. By the end of winter 2010, the lake perimeter shows sands of ~0.5m deep that have become unsaturated and clays becoming unsaturated to ~0.3m deep (Figure 7.37). By Sep 2011, the sands are even further exposed (up to 1.0m deep) and the clays are unsaturated down to ~0.5m. The unsaturated zone in the clays remains at a moisture content of about 30%; the sands are fairly dry and on average are down to ~10%.

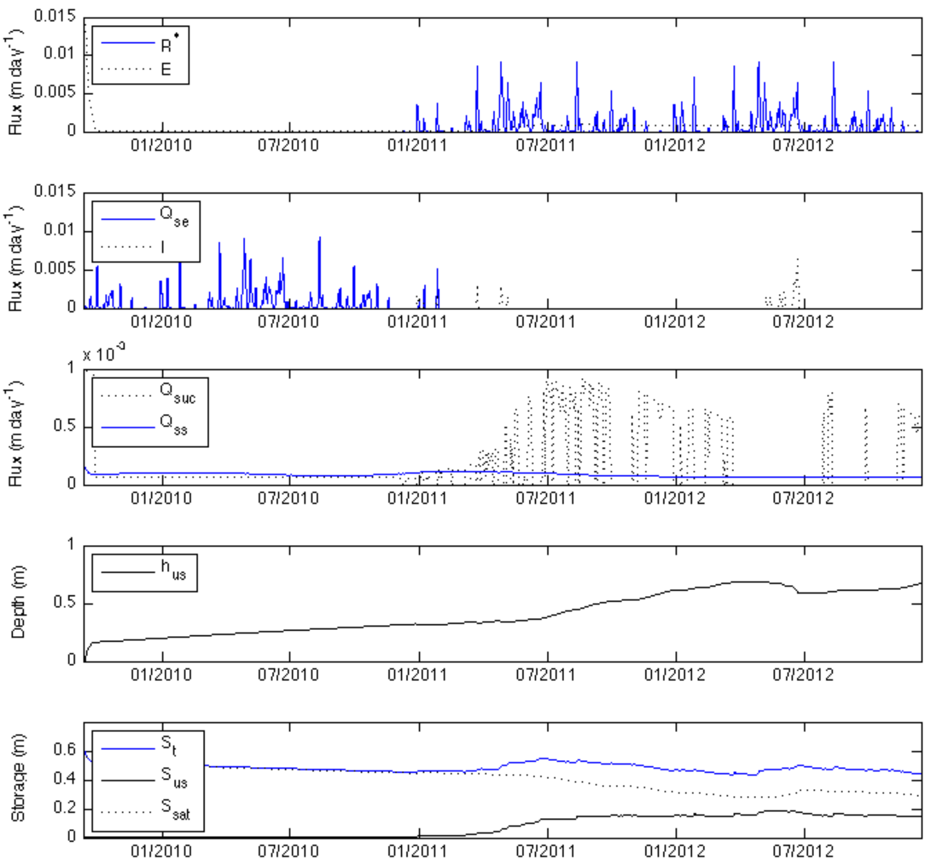

Figure 7.34: Hydrology fluxes in Lake Alexandrina drawdown simulation for a boundary sand cell. Refer to Figure 4.2 for symbol definitions and the hydrological conceptual model.

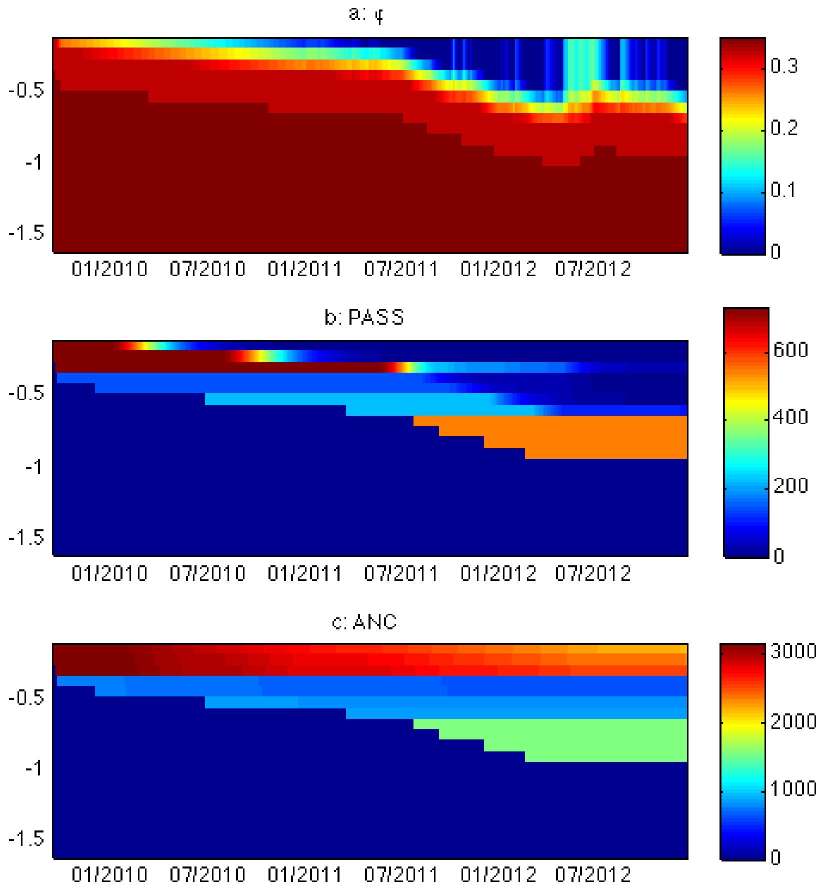

Figure 7.35: Vertical soil profile for a single clay cell on the boundary of Lake Alexandrina during the -1.5m AHD stabilisation showing a) moisture content, b) PASS concentration (mol H+ kg^{-1} $cell^{-1}$) and c) ANC (mol H+ kg^{-1} $cell^{-1}$) evolution.

The pH and DIC remain fairly stable in the Lake Alexandrina domain during stabilisation, with some limited perimeter acidification events occurring in disconnected pools (Figure 7.36). The initial ring of sulfidic material (PASS) rapidly expands in width of the 2009-2010 summer and this is subsequently transformed into available acidity (AASS) and this proceeds rapidly (Figures 7.37-7.38). By late 2011 the low lake level means that a significant area of lake perimeter has become exposed and a considerable fraction is oxidised to available acidity.

The flux of acidity is predominantly from the sands around the edge of the lake following the autumn/winter rainfall period. The area of material contributing to the baseflow/seepage flux has a seasonal cycle of increase following a period of water level stabilisation (Figure 7.39). The area contributing to the rewetting flux is a thin ring around the edge of the lake that occurs during periodic refilling stages.

The neutralisation processes (Figure 7.40) are also documented and these show the gradual consumption around the perimeter due to ANC, and the magnitude and variability of SO_4 reduction in the inundated lake sediment. This value varies considerably due to the variable concentrations of SO_4 across the lake, in line with Eq. 4.22.

The integrated process trends summarise the dynamics as the lake draws down. For the base "do nothing" lake drawdown scenario the total area of mostly sulfuric soil exposed is approximately 550 km^2 for most of the period from 2010 onwards. A further 50-100 km^2 becomes inundated by the lake during the peak of the seasonal rise in water level during the winter of 2011 and 2012, although this is quite small throughout 2010. The total amount of sulfidic material exposed to oxygen, integrated over the lake, peaks at around 300,000 tonnes of H_2SO_4 acidity equivalents, when the lake gets below -1.5m, of which a small fraction (<10%) is oxidised to form available acidity within the unsaturated zone over the simulation period. During the autumn and winter of each year, a substantial fraction of the acidity within the unsaturated porewaters percolates down to the

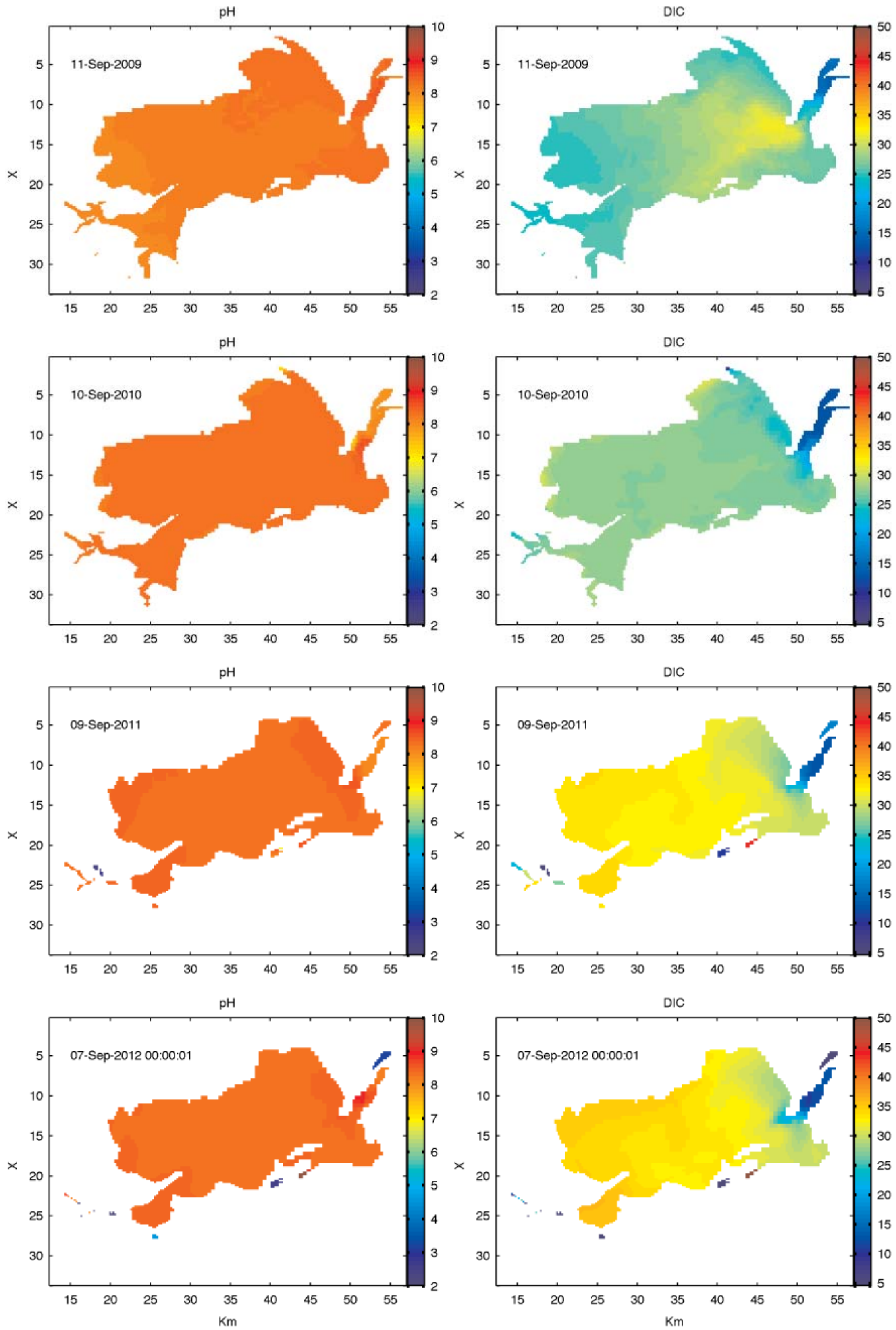

Figure 7.36: Plots of pH and dissolved carbonate alkalinity DIC (mg C L-1) for Lake Alexandrina at annual intervals for the -1.0m AHD water level stabilisation scenario.

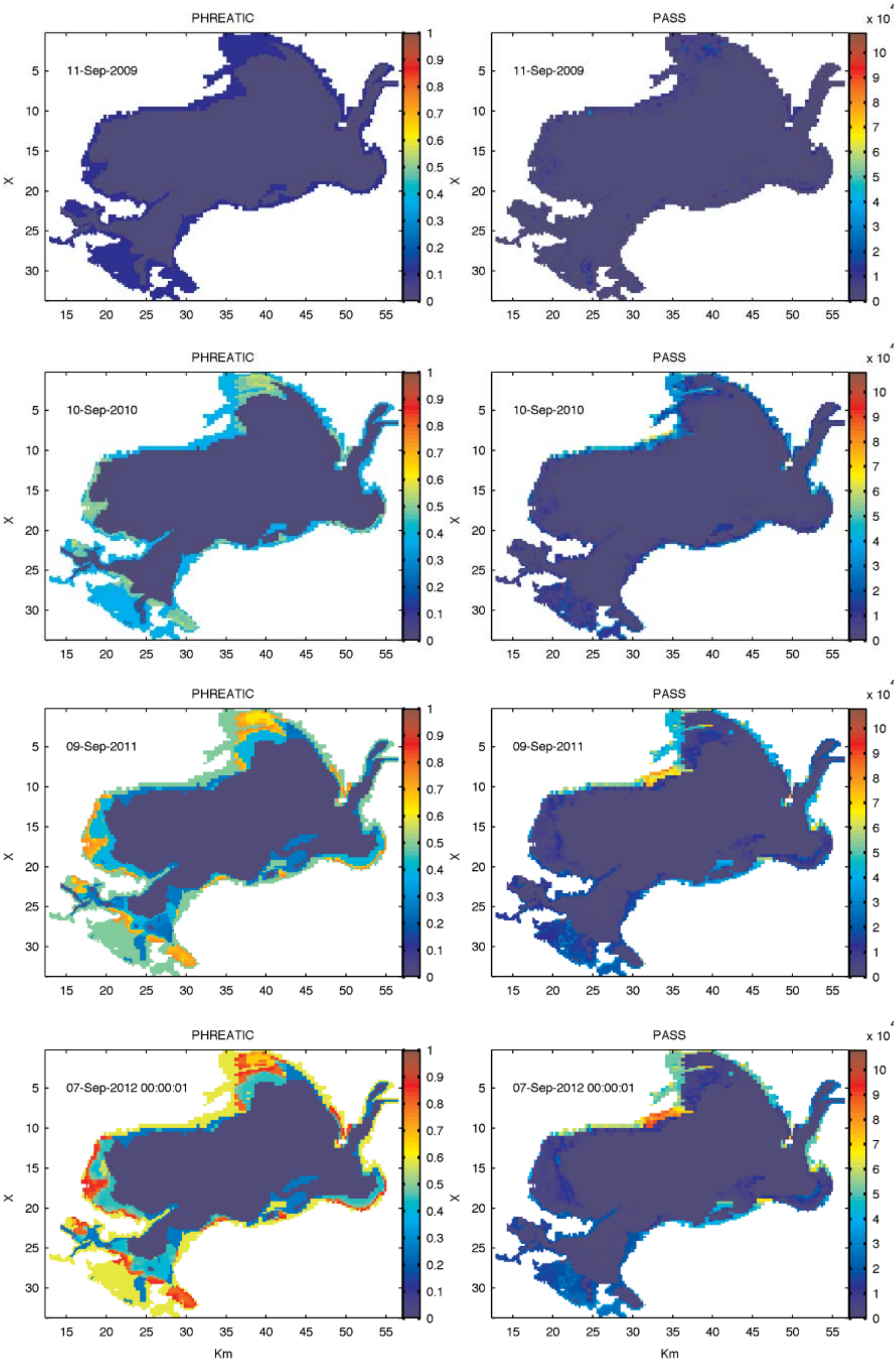

Figure 7.37: Plots of water table depth (PHREATIC, m from surface) and exposed pyritic material (PASS, mol H^{+}) at annual intervals from 2009-2012 for the lake drawdown scenario (DDN).

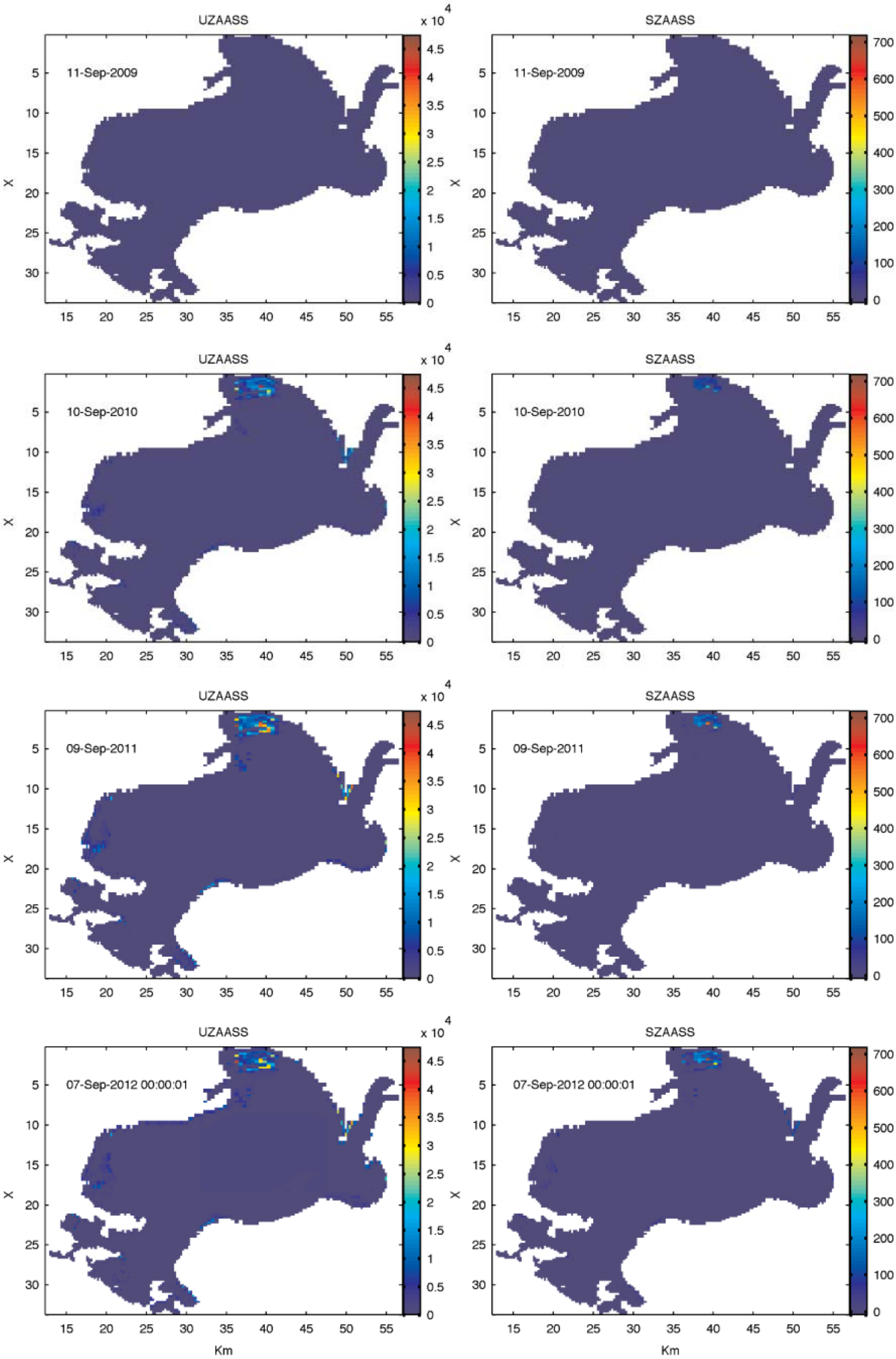

Figure 7.38: Plots of unsaturated zone acidity (UZAASS, mol H+) and saturated zone acidity (SZAASS, mol H+) at annual intervals from 2009-2012 for the lake drawdown scenario (DDN).

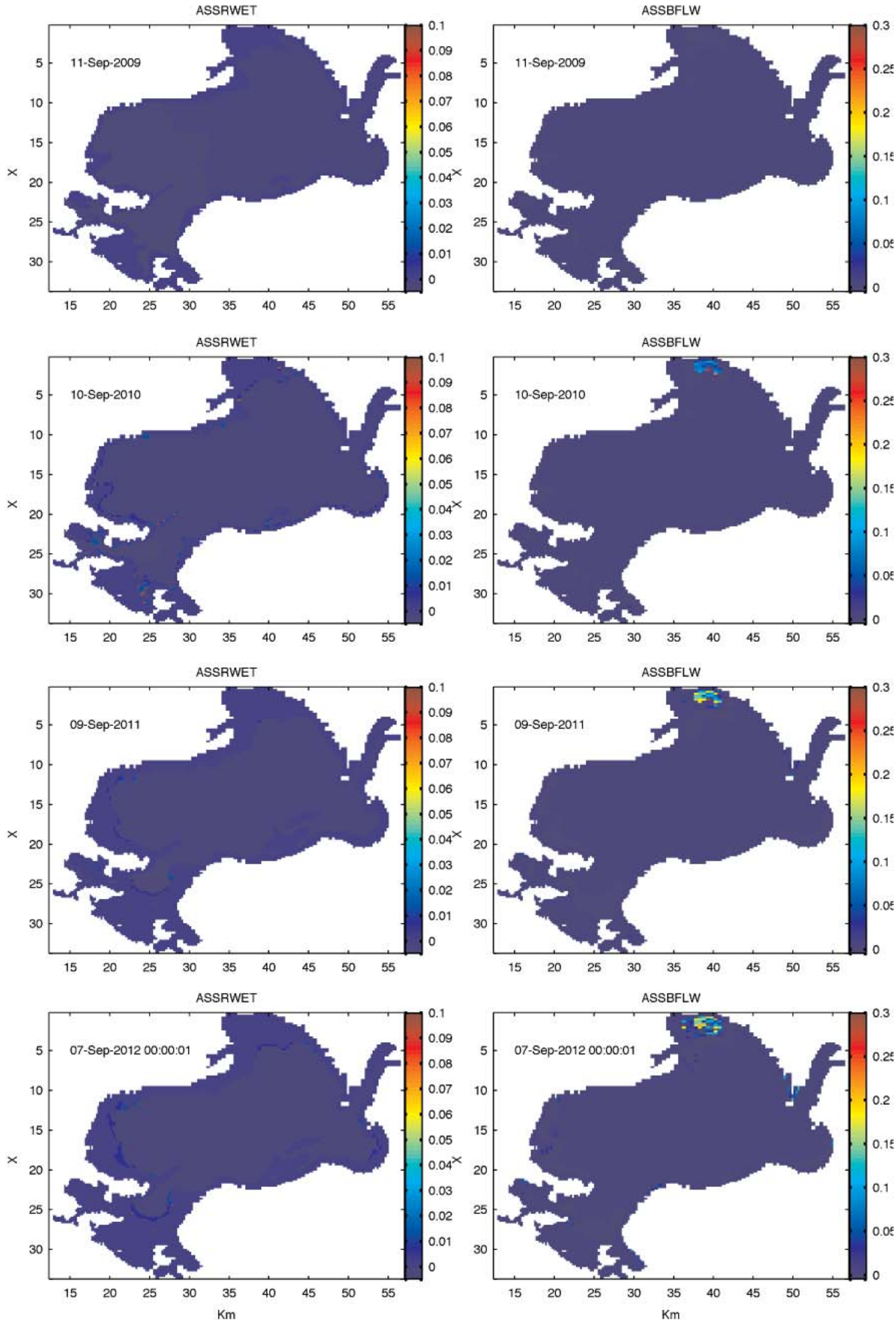

Figure 7.39: Plots of acidity re-wetting flux (ASSRWET, mol H^+ m^{-2} day^{-1}) and baseflow/seepage acidity flux (ASSBFLW, mol H^+ day^{-1}) at annual intervals from 2009-2012 for the lake drawdown scenario (DDN).

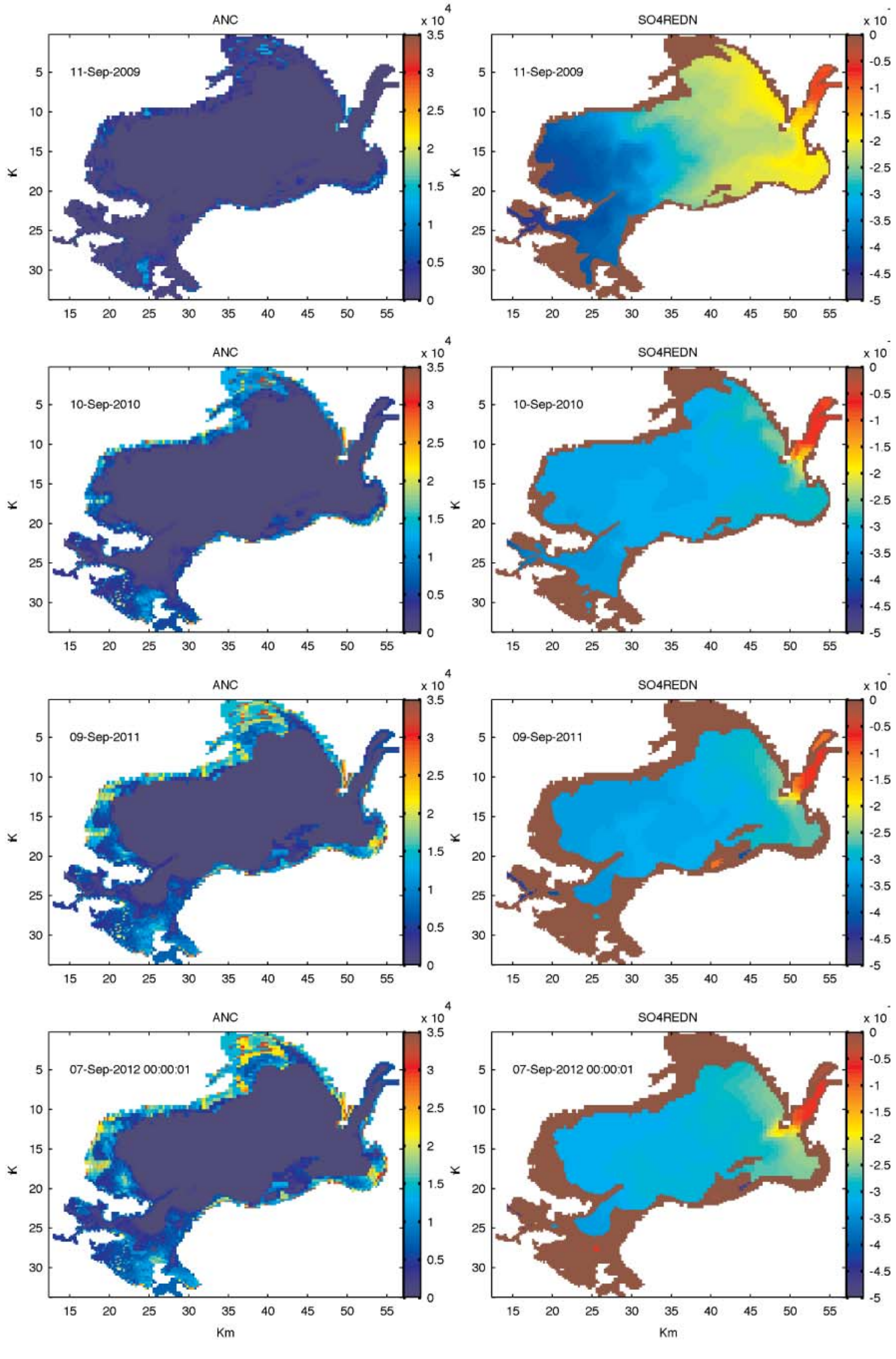

Figure 7.40: Plots of acid neutralising capacity (ANC, mol H^{+}) and submerged sediment alkalinity flux (SO4REDN, mol m^{-2} day^{-1}) at annual intervals from 2009-2012 for the lake drawdown scenario (DDN).

saturated zone; this pool gradually reduces due to a combination of baseflow mobilisation and saturated zone neutralisation processes. The baseflow component is initially small but becomes substantial and increases further as the water level declines. Because of the slow rate of groundwater movement towards the lakes, there is a substantial lag between when the acidity is generated and delivered to the water table, and when it is received by the waterbody. In contrast, the ability of overland and throughflow generated by intense storms to wash in surficial sediment with high available acidities is able to deliver a large acidity load over a very short period (~days to weeks).

The rewetting pulse of acidity during the seasonal inundation of previously exposed sediment in winter generates a peak acidity flux of 2 tonnes H_2SO_4 per day, which is compared to a more constant total alkalinity release rate of around 0.3 tonnes H_2SO_4 per day due to SO_4 reduction processes in the submerged, organic rich lake sediment. Although the acidity flux rates per m^2 are much higher than the equivalent SO_4 reduction rates in the anoxic sediment, the much higher areas of alkalinity producing sediment mean that the total alkalinity production is actually greater than that caused by re-inundation of acid sulfate soil material.

To test the sensitivity of the pH predictions to key processes several simulations were conducted with adjusted values of acid mobilisable fraction (f_{mob}) and ANC neutralisation rate (k_{ANC}). These are denoted '021', '022' and '23f' in Figure 7.42:

- 021 has high ANC consumption (40% year^{-1}) and a low acidity mobilisable fraction (f_{mob}=0.5);
- 022 has lower ANC consumption (20% year^{-1}) and a low acidity mobilisable fraction (f_{mob}=0.5);
- 23f has lower ANC consumption (20% year^{-1}) and a high acidity mobilisable fraction (f_{mob}=0.75);

The simulations were otherwise configured identically, and used 'default' acid sulfate soil and lake model parameters as presented in Table 4.2. The results indicate a relatively low sensitivity to the ANC neutralisation rate, and a higher sensitivity to the mobilisable fraction. From the Currency/Finniss validation, the observed data was between the 021/022 and 23f sensitivity simulations and so this is considered to be a reasonable representation of the uncertainty in the predicted alkalinity concentrations. The 23f scenario does appear to start to create a noticeable lowering of the pH and alkalinity compared to the 021/022 suggesting that a continuation of this simulation would potentially lead to an acidification event.

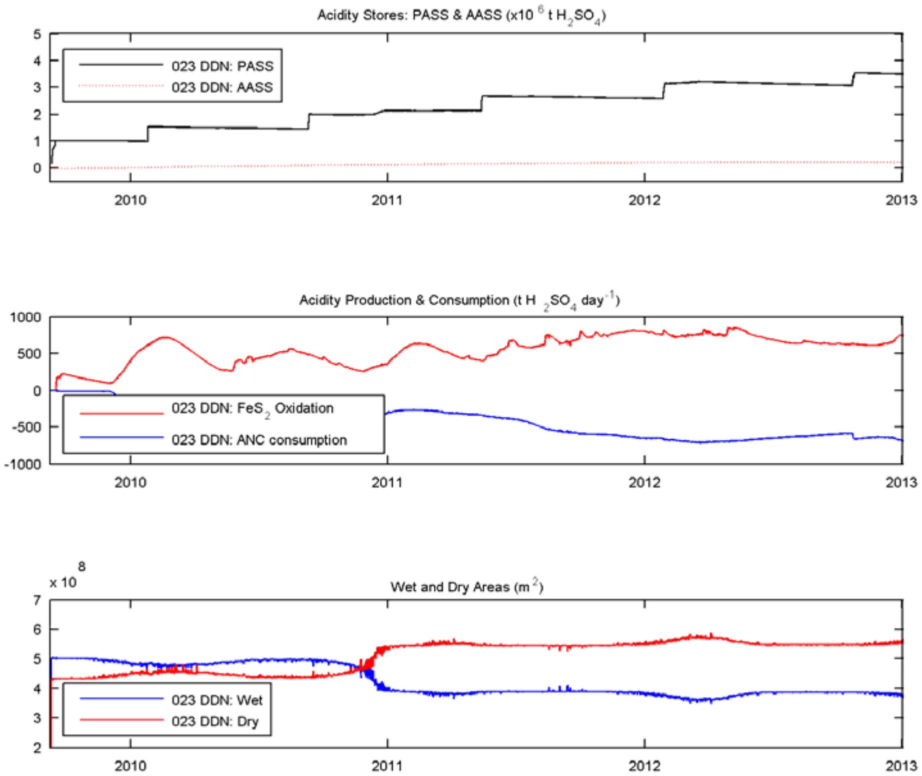

Figure 7.41a: Analysis of spatially-integrated acid sulfate soil model outputs from the base drawdown simulation showing accumulation of exposed PASS and subsequent AASS production and consumption.

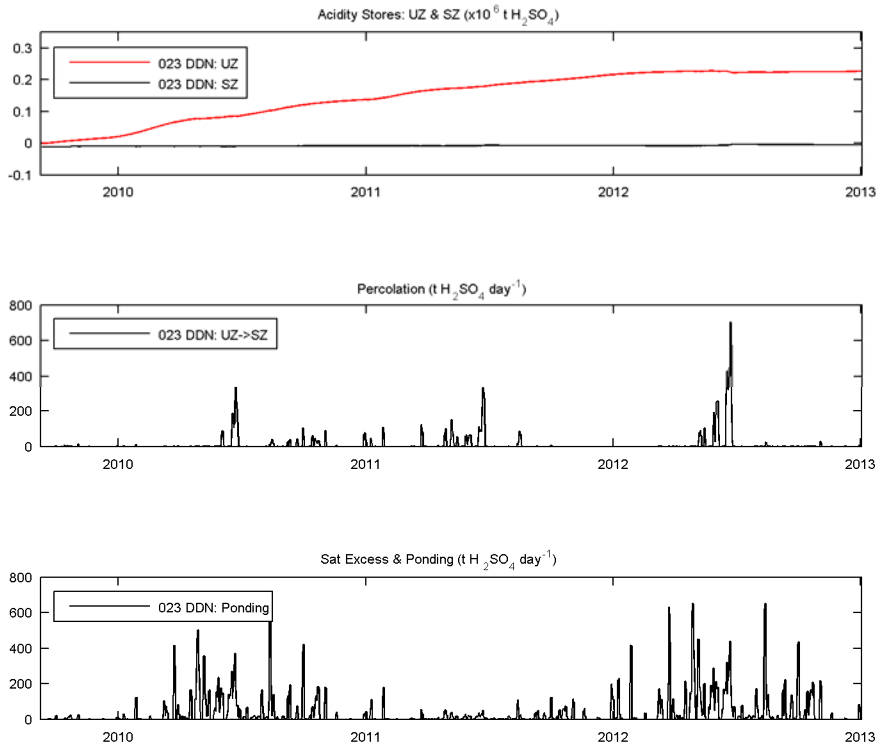

Figure 7.41b: Analysis of spatially-integrated acid sulfate soil model outputs from the base drawdown simulation showing the accumulation of acidity in the unsaturated and saturated zone, and processes controlling mobilisation.

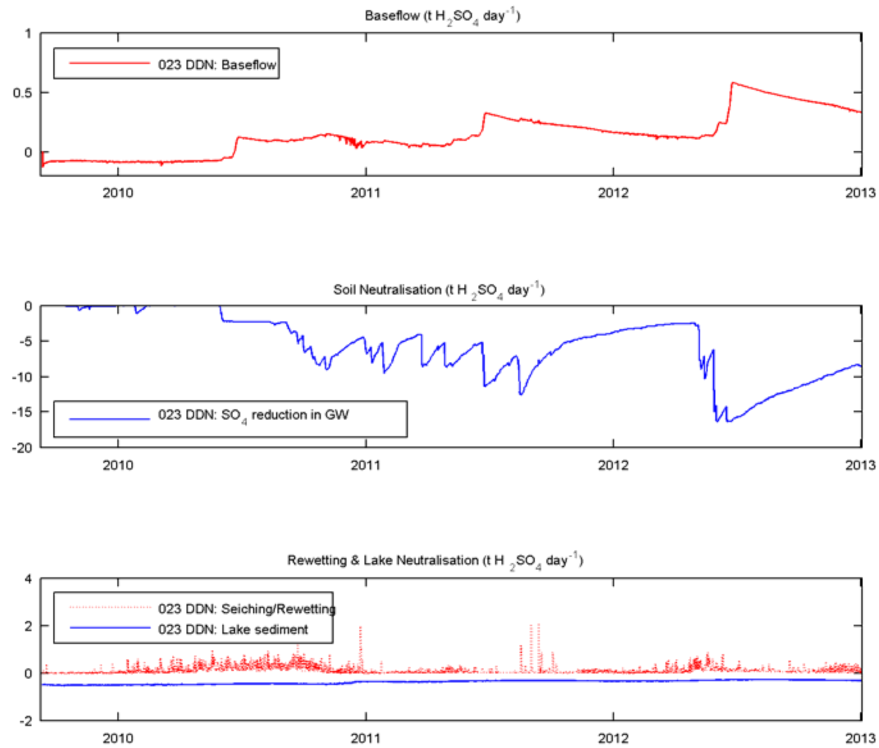

Figure 7.41c: Analysis of spatially-integrated acid sulfate soil model outputs from the base drawdown simulation showing the baseflow/seepage acidity flux rate, the in-soil neutralisation of acidity by sulfate reduction in the groundwater, and the rewetting flux and in-lake alkalinity flux.

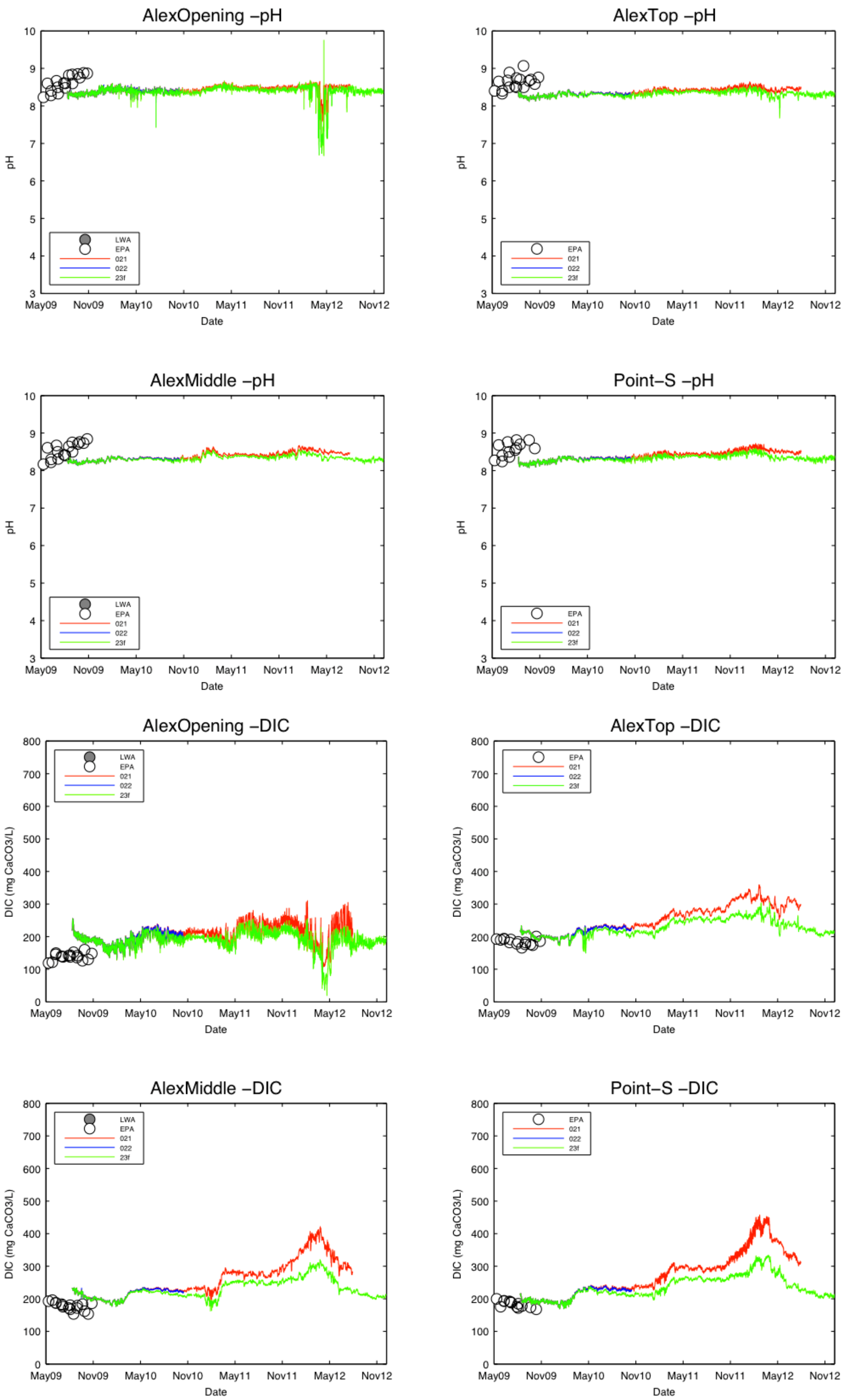

Figure 7.42: Comparison of pH (top) and DIC (bottom) for three simulations for the lake drawdown scenario (DDN), testing sensitivity to the acid neutralisation and mobilisation parameters.

Annual average budgets of key acidity fluxes and stores of acidity were compiled for the years 2010 and 2012 to gain insights to how the dominant drivers of the acidification process change over time (Figure 7.43). These sums indicate that the amount of available acidity doubles over this period (these sums assume continued drawdown until 2012) and substantial transport of available acidity to the water. In 2010 this is around 10% of the oxidised acidity, but this reduces to ~8% in 2012. However, by 2012 the store of acidity available for mobilisation is significantly greater (increased from 90,000 to 225,000 tonnes from 2010-2012 in the unsaturated zone). Diffusive fluxes from rewetting and seiching are small during the drawdown (0.25-0.31 tonnes day^{-1}). The dominant mechanisms for delivery of acidity to the lake water is the ponding, overland flow, and throughflow, as for the other domains reported previously.

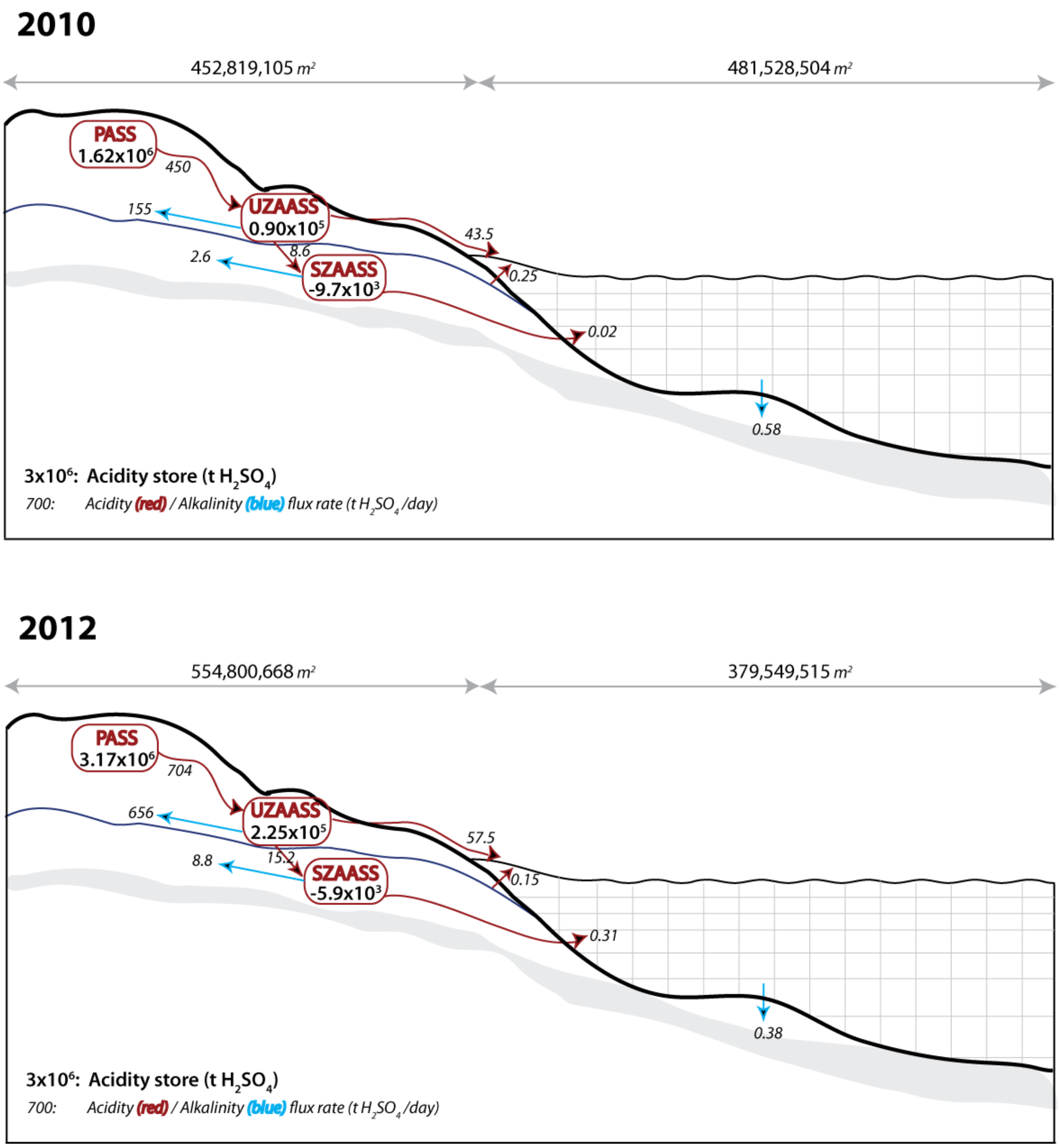

Figure 7.43: Annual average budgets of acidity stores and fluxes for Lake Alexandrina in 2010 and 2012. Data from drawdown (DDN) simulation.

7.4 Recommendations for water level stabilisation

The acidification 'trigger level' analysis conducted here considers all the drawdown simulations conducted to date in addition to the various filling scenarios, since flooding of previously acidified sediment may mean that acidic conditions take some time to manifest and may in fact be realised during the re-filling process. The trigger level below which the risk of acidification becomes too high is therefore defined as the lowest level the lake gets to prior to pH dropping below 6, even if this occurs at some time in the future. Here we also define the target 'water management level', which is the level the lake should be maintained at to avoid acidification, and given the inherent uncertainties in our understanding and the model simulations, this includes some conservative adjustments to the trigger level. Importantly, the significant role of rainfall-induced lateral flow mechanisms in controlling the acidity flux to the lake means that acidification is very much related to the time of year that the acidity is flushed from the exposed soil by rainfall, regardless of the water level at that time. Therefore, the target water management level must be considered within the context of the annual rainfall cycle.

Note that the management scenarios presented in this report and the volume fluxes used in the simulations presented here are indicative for the purposes of testing acidification dynamics and at this stage they are not meant to imply any endorsed strategy.

During the early stages of drawdown (i.e., no active water level management) before the water levels drop significantly, the overall acidity load was largely insensitive to rewetting (since only seasonal scale re-inundation of acidic sediment occurs during the lake drying phase) and in-lake alkalinity generation processes. This is because the main acidity contribution occurs during seasonal pulses triggered by prolonged and intense rainfall driving overland and throughflow processes. However, diffusion of acidity from acidified clays in Lake Albert was a notable risk under certain conditions. Variability in these processes results from sensitivity to the soil type, the vertical percolation of acidity in response to rain, generation of lateral flow from saturated soil, and the in situ soil neutralisation processes.

Lake Albert

- Any simulations that went below -1.0m AHD, regardless of timing or ASS model parameters tested, indicated significant lake acidification at a potentially irreversible level. While stabilisation at -1.0m AHD may prevent large-scale acidification, large regions of the lake would be significantly impacted and large area so f soil acidification would also present numerous significant management challenges.
- Stabilisation at -0.75 and -0.5m AHD appeared to prevent large-scale deterioration, however the alkalinity in the '*23f*' simulation, which arguably gave a better validation to the observed Currency Creek acidification data, did show very low alkalinities and pH instabilities at perimeter regions of the lake even at -0.5m AHD. However, the *23f* simulation also showed partial and temporary acidification of the north region of the lake in late 2009, which is not reflected in the field observations, so it could be considered that this particular simulation is an over prediction.
- **Recommendation: stabilise above -0.75m AHD; aim for +/- 25cm oscillation around -0.5 mAHD.**
- **Stabilising at -0.5m AHD or above will significantly reduce risk.**

Lake Alexandrina

Across the simulations conducted to date, the lake system appears to cross a threshold at a depth of < -1.75mAHD, where the volume of acidity stored in the soil is considerable compared to the lake alkalinity stores and generation mechanisms. Whilst the soil accumulates acidity, the important delivery mechanism is the movement of this acidity to the water column, and since this occurs over a short period (~1-3 months) when the rainfall amount is sufficient to drive lateral flows, the simulations suggest that in this case there is relatively little time for soil neutralisation processes to make an appreciable impact on the acidity entering the water.

- Even though both the drawdown and stabilisation scenarios using the base validation configuration showed no whole-lake acidification over the period to the end of 2012, the model does indicate several management issues:

- North-western region shows temporary acidification in the drawdown simulation, especially with *23f* configuration (note: during final review of this report this was observed in May 2010 and this model prediction therefore was proven accurate);
- Seawater entrance is predicted to create some acidification in the south reach of the lake around Pt Sturt;

- Inertia of groundwater acidity via high accumulation of acidic material in the unsaturated zone indicates that longer simulations beyond 2012 would eventually deteriorate if levels were maintained below -1.75m AHD.
- Water level management scenarios simulated included a switch to 1850GL allocation to stabilise the lake around -1.0m, as well as one scenario that explored the impacts of seawater flooding with the aim of maintaining the lake level immediately at -1.0 m. The model shows enhanced baseflow/seepage contributions as the water drops, and a progressive increase in the importance of the rewetting flux as more sulfuric soil is inundated as water levels increase at a later stage. The simulations show that seawater is more efficient at mobilising acidity (in accordance with the observational data) and so freshwater is able to prolong pH neutral conditions for longer.
- **Recommendation: stabilise above -1.75 mAHD; aim for +/-25 cm oscillation around -1.5m AHD to avoid acidification.**
- **Stabilising at -1.5m AHD or above will significantly reduce risk**

Note that while the focus of this section is on pH, the model indicates that stabilisation at these levels will avoid acidification, however, it should be noted that large areas of sulfuric and poor quality soil will be exposed, and traditional water quality problems such as elevated nutrients and reduced clarity will become a persistent feature. In particular salinity issues when the lake levels are low will become a significant management challenge, particularly where seawater is introduced.

8 Conclusions

8.1 Model development and validation

Whilst acidification of lake ecosystems has been previously documented around the world, and attributed to various underlying mechanisms (mainly acid rain), the present case of acidification of the Murray Lower Lakes is unprecedented. The rate of water level change and amount of potentially oxidisable sulfidic minerals make the scale of the acidification threat beyond previous experience and it is therefore not surprising that models of acid sulfate soils relevant to lake ecosystems have not previously been developed. The challenges of the present project were to develop a model able to spatially resolve acid sulfate soil dynamics, whilst also accounting for lake hydrodynamics and key biogeochemical processes, and for the coupled model to be able to simulate multiple years of management scenarios. Following a substantial review of the literature and available models for acid sulfate soil dynamics, there was no platform that could be readily applied for the present investigation. Models of acid sulfate soil dynamics are largely 1-dimensional and are based on the solution of the Richard's equation, coupled with pyrite oxidation and acidity neutralisation chemical processes, and the associated solute transport equations. Whilst these approaches were scientifically sound for the present case, there application to the lake where large spatial heterogeneity in soil type, salinity and sulfide concentrations meant that computational constraints were insurmountable given this approach is so numerically intensive. Instead, here we have developed a new soil hydro-geochemical model with a simplified vertical representation, but which was able to represent spatial heterogeneity and dynamically link with an existing 3D lake hydrodynamic-biogeochemical model. The vertical structure of acid sulfate soils can not be overly simplified due to the importance of the unsaturated zone soil moisture profiles and the variability of pyrite with depth, and so the present approach does not entirely lump vertical processes into an averaged unit, but instead resolves the vertical profile in a simplified manner that avoids the full Richard's equation solution. This approach does not preclude the implementation of a more complete Richard's equation solution in subsequent studies, and in fact the model has been designed to incorporate this option into future revisions when computational constraints can be addressed. The present approach is justified, however, given the relatively long time integrations the model is being applied over (i.e., monthly to decadal), and at this time scale simpler models are known to provide an adequate representation.

The coupled model, termed ELCOM-CAEDYM-ASS, was configured on a range of model subdomains, representing i) Lake Alexandrina, ii) Lake Albert and iii) a high-resolution domain for the Currency Creek, Finniss River and Goolwa Channel region. The simulated variables in all domains were identical and included velocity, temperature, salinity, nutrients, algae, major ions, pH and alkalinity and solid phase precipitates. The acid sulfate soil module parameters were based on the associated research programs (and summarised in Table 4.2), and literature values, where available. The model was validated against a large variety of parameters from extensive available data sets for the water column, and to more limited available data for the soil conditions.

Generally, the model performed well against lake physical properties (water level, temperature and salinity) in each of the domains, and also the behaviour of oxygen and conservative ions were also accurately captured, with the exception of where missing data for the water and mass inputs for the model domain resulted in uncertainty in model input data. The nutrients and chlorophyll-a values were reasonably well predicted although there were seasonal or site-specific errors that could be improved given continued calibration. The pH and alkalinity dynamics were also well predicted in cases where no acidification was reported. In areas where acidification has been reported, the model was competent in predicting when and where pH would fall, particularly in the main Currency Creek tributary area in 2009. There were some areas that were predicted to acidify in the model that were not observed to acidify in reality; this highlights the uncertainty in the model predictions and underlines that, rather than being used in isolation, the model as a predictive tool should be applied within an adaptive monitoring framework that will guide further improvements in model process descriptions and parameter values, and also optimize collection of input and validation data.

Where possible the parameterisations used in the model have been taken directly from the associated field and laboratory research without adjustment. Available qualitative information has also been compared to model results, in an attempt to further ground truth model performance. However, the processes indicated by the model to be the key drivers of the acidification dynamics require further validation at a system-scale. The model is also highly sensitive to the spatial input data with respect to soil type and chemistry, which is used to drive the predictions.

Significant error resulting from input uncertainty, or simplification of these properties, thus also needs to be considered. Further opportunities to improve the model performance are outlined in detail below.

8.2 Recommendations for management

The model developed, and associated scenarios reported here, builds on previous work that has attempted to forecast ecosystem conditions under a range of potential future flow and management regimes. Despite the increased sophistication of the model and rigour of testing and validation compared to earlier work (e.g., Hipsey and Salmon, 2008), the present analysis confirms the magnitude of the risk of acidification of the standing water is substantial in both Lake Alexandrina and Lake Albert and needs to be actively managed.

The outputs of the model suggest that the amount of pyrite in exposed soil that is able to oxidise is potentially orders of magnitude larger than that able to cause water body acidification, however limitations on the oxidation rate, and transport of acidity to the lakes, introduce complexities in interpreting the time, or water level, where acidification risk becomes unacceptably high. In this study the rate of oxidation was generally found to be high enough to generate ample acidity to create management problems, however the dominance of vertical transport processes and the slowly moving groundwater meant that the dynamics of the soil hydrology are of critical importance in determining the predicted outcome. In particular, it is predicted that large threshold rain events overwhelm the vertical percolation rate, which generates temporary ponding and throughflow processes and leads to delivery of large loads of acidity to the lake boundaries. These large events typically occur infrequently, however as they are the dominant mechanism controlling the acidity flux to the lake, the implication of this is that acidification is related to the time of year that the acidity is flushed from the exposed soil by rainfall, regardless of the water level at that time. This makes prediction of acidification trigger levels uncertain. The role of acidity diffusion into the water column following reflooding of acidified clays, particularly in Lake Albert, was also identified as a potentially significant to loading, and therefore assessment of trigger levels must not only consider the dynamics during drawdown, but also during refill.

To investigate the different future states of the lake in terms of drying-flooding cycles, a range of scenarios were conducted and the results were used to recommend a water management target level for both Lake Alexandrina and Lake Albert. The scenarios included sourcing extra water (above the minimum flow allocation to the lakes) from either increased freshwater allocation to the lakes, or alternatively from the Coorong and Murray Mouth region by opening part of Tauwitchere barrage.

Although the acid sulfate soil module is sensitive to variations in salinity, due to its effect on acidity diffusion during reflooding, the impact of flooding with seawater as opposed to freshwater did not greatly increase the risk of acidification, but did however lead to high salinities, often above that of seawater.

For Lake Albert, the lake went acidic for all model simulations that went below a water level of -1.0 m AHD. Sensitivity testing of the model did not significantly change this prediction. Stabilisation at -0.75m AHD and -0.5m AHD appeared to prevent any large scale deterioration until the end of 2012. However, pH instabilities at the lake margins were observed even at -0.5m AHD. This agreed with field observations of soil and water acidification in localised areas around the lake margins over the winter of 2009. Based on these modelling results, the key management recommendation to prevent lake acidification is to maintain water levels above - 0.75m AHD in Lake Albert.

For Lake Alexandrina, the main lake body maintained satisfactory pH and alkalinity up until the end of 2012 for all stabilisation and drawdown scenarios. However the model indicated several issues:

1. The north-western region shows temporary acidification during lake drawdown during May 2010, which was later confirmed in the observed data;
2. Seawater entrance does create some acidification in the south reach of the lake around Pt Sturt and alkalinity declined over the whole lake area. Seawater salinities are rapidly established across the whole lake area in the -1.0m AHD water level stabilisation scenario.
3. A high accumulation of acidic material in the soil occurs, with a lag in delivery of the acidity in shallow groundwater. This indicates that longer simulations beyond 2012 may eventually deteriorate if levels were maintained below -1.5m AHD. Longer term simulations being run as part of the seawater Environmental Impact Assessment confirm this.

Based on these issues, the key management recommendation to prevent large-scale lake acidification is to maintain water levels above -1.75m AHD in Lake Alexandrina. Fringing waterbody regions with poor connection are likely to continue to acidify in response to rainfall even when the lake remains above this level.

In all simulations conducted, the area of sulfuric soil continues to expand until lake water level stabilization; acidity levels in the soil remain high despite ongoing fluxes to the lake, due to the large reservoir of accumulated acidity in the oxidized soil profile. Therefore a soil hazard will continue to remain around the margins of the lake.

Further, while the focus of this report has been acidity/alkalinity and pH, historical water quality problems such as elevated nutrients and reduced clarity will become a persistent feature even at the recommended management levels.

8.3 Recommendations for further research

While the model has accounted for a wide range of biogeochemical parameters, the focus of the report has been on acidity and pH, and only to a lesser extent on the nutrients, metals, algae and turbidity. Further advances can be made to the calibration presented in this report through further time spent with calibration of relevant nutrient cycling, sediment and biological parameters. It is suggested therefore that the model results can be further improved with minimal effort as further monitoring data is collected.

Furthermore, the model outputs should be carefully considered when designing and costing future monitoring programs, within the spirit of adaptive water quality management. Outputs from the model can guide monitoring of potential hotspots, and in turn such strategically collected data can be used to address remaining uncertainty within the long-term predictions by improving the calibration and parameter estimation.

Recent increases in flows to the Lower Lakes (Winter 2010) will give an opportunity to collect important data to help validate the model during the recovery process and so it is recommended that monitoring intensity be maintained despite potential increases in water level. Periods of change in the system offer a means to test the ability of model to capture dynamic processes as indicated by the system response observed in the field.

Further work is recommended on key biogeochemical model components in order to reduce uncertainty and further improve confidence in the predictions:

- Unsaturated zone hydrology: it is recommended that the vertical hydrology model be extended to included a vertically resolved Richard's equation option in order to reduce uncertainty in soil moisture prediction and associated solute dynamics. While this option has not been adopted throughout this report due to computational constraints, its application to the Currency Creek sub-domain for a time period less than one year would be achievable and will help unravel the key controls on acidification dynamics.
- Inclusion of metal and ion dynamics in pore-water leachate: improved breakdown of pore-water leachate geochemistry will help ensure that the connection between the water and soil is mass-conservative, and also that the mobilisable acidity fraction parameter is dynamic and able to respond to soil acidity.
- Improved prediction of lateral flows using two-dimensional transport model: the dynamics of lateral transport of acidity arep complicated and it is recommended that further 2D cross-sectional work be conducted to understand how ponding and throughflow dynamics occur following high rainfall events.
- Improved assessment of sediment fluxes within the lake and measurement of alkalinity production (e.g., sulfate reduction), including spatially variable flux rate estimates.

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A1 Appendix 1: Sensitivity analysis of key model processes

Scenario matrix and uncertainty testing

To ascertain sensitivity of the lake system to acidification a range of scenarios have been conducted throughout the project with different river and seawater inflows, Lake Albert pumping conditions and model parameters (Table A1.1). The results presented here do not use the final parameter set and model as described in the report due to updates that occurred throughout the project. The pH predictions presented here are therefore not current. However, they are included here as they do provide insight into the sensitivity of the model predictions to key processes, as described next.

Table A1.1: Summary of simulations run for sensitivity testing and uncertainty estimation. In this table '0' implies a median parameter value used and '+' / '++' / '+++' indicates successive increases and conversely '–' indicates a decrease.

Scenario	Rewetting Flux (F1sts, Fdifs; F1stf,Fdiff)	Lake Alkalinity Generation (SSO4)	Soil Acidity Consumption (kANC; kSZ)	Oxidation Rate (Rox)	Baseflow Flux Rate (ass)	Percolation Efficiency (n)	Sand Depth (Zmax)
Lake Alexandrina							
Do Nothing – Continued 896GL allocation at SA Border, + 170GL extra in 2009-2010	RW- 0 RW+ RW++	SR- 0 SR+	ANC1% 0 ANC20% SZN+ SZN++ SZN+++	Ox- 0 Ox+	NoBF BF- 0 BF+	0 -Per	0 +SD
Freshwater stabilisation – 1850GL allocation at SA Border from -1.5 mAHD	0 RW++	0	0 SZN+	0	NoBF 0	0	0
Seawater stabilisation – 1850GL allocation at SA Border from -1.5 mAHD	0	0	SZN+	0	NoBF 0	0	0
Seawater flooding – Maintain -1.5 mAHD	0	0	0 SZN+	0	NoBF 0	0	0
Lake Albert							
No Pumping post Jan 2010	0	0	SZN+	0	0	0	0
Continued pumping from Alex to maintain -1.0mAHD for 2010-2011				0	0	0	0
Continued pumping from Alex to maintain -0.75mAHD ongoing							
Continued pumping from Alex to maintain -0.5mAHD ongoing							
Currency/Finniss							
Hindcast validation sim	0	0	+ 0	+ 0		+ 0	

Simulations conducted with 10% ANC consumption per year and with 10% ANC consumption per year + in situ acidity consumption within saturated regions of the soil column of 1% per day highlight that the time between acidification of the main lake body shifted by 2 months. Simulations run with 2-5% saturated zone neutralisation per day were able to prolong the acidification threshold for a further 12 months until the following winter (winter 2011).

Sensitivity to the oxidation rate is relatively subdued, since at the current oxidation rate, the acidity generation is ample relative to the acidity mobilisation and neutralisation rate.

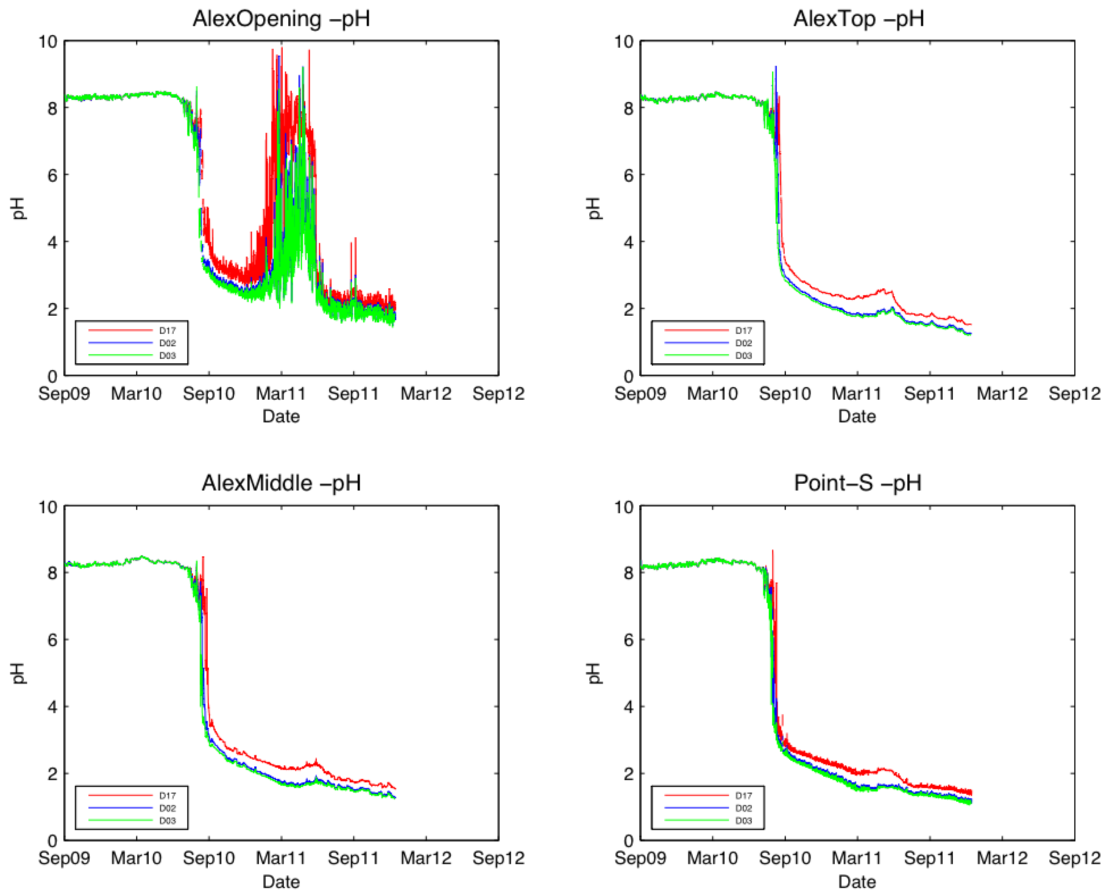

Figure A1.1: Time-series of pH at four locations within Lake Alexandrina for a range of drawdown simulation run with different rewetting flux (D02 = RW+; D03 = RW-) parameters.

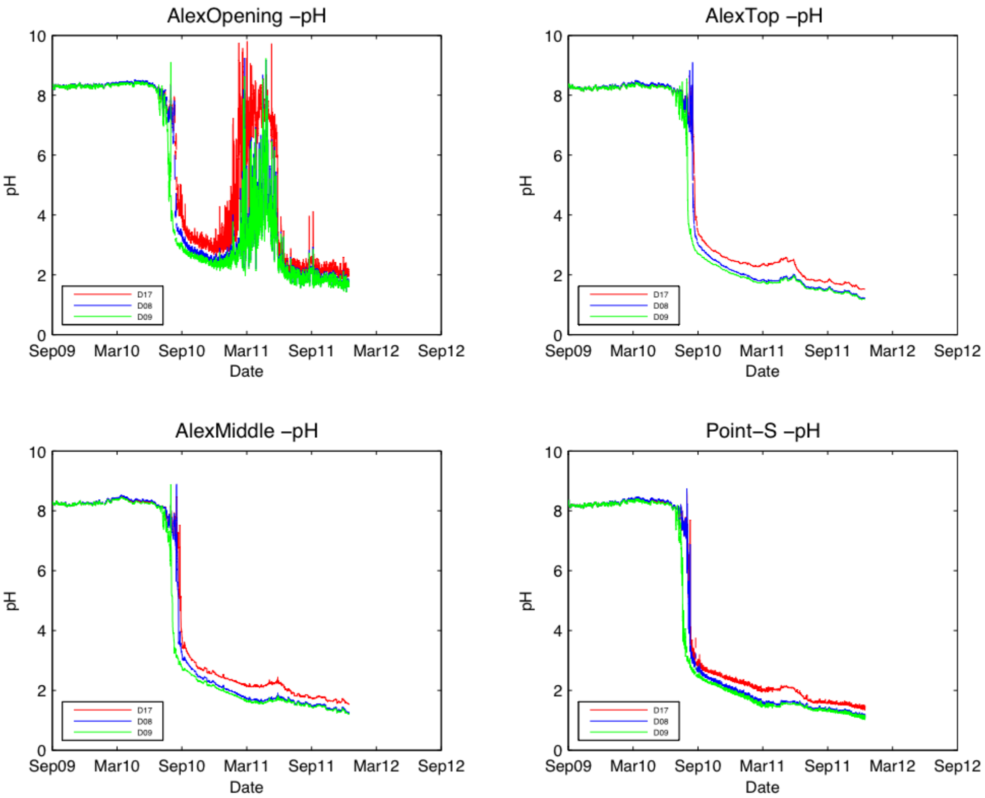

Figure A1.2: Time-series of pH at four locations within Lake Alexandrina for a range of drawdown simulation run with different lake sediment alkalinity generation rate (D08 = SO4+; D09 = SO4-) parameters.

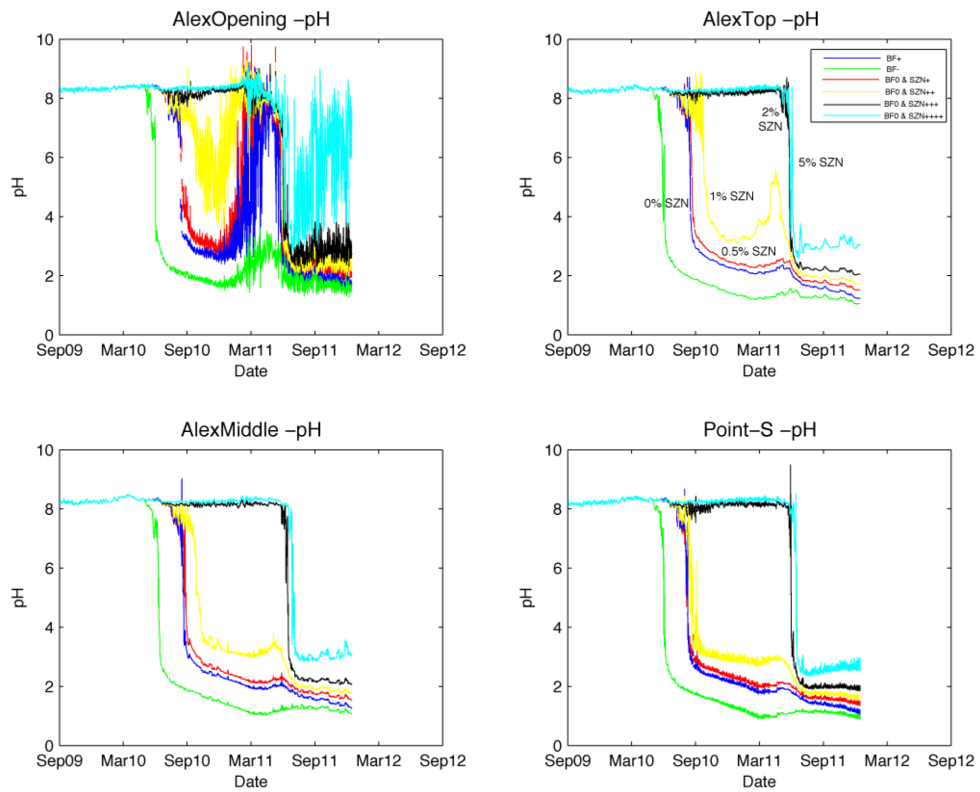

Figure A1.3: Time-series of pH at four locations within Lake Alexandrina for a range of drawdown simulation run with different baseflow (BF0, BF+ and BF-) and saturated zone acidity attenuation (SZN) parameters. Top right plot highlights the simulation with 5%, 2%, 1% and 0.5% saturated zone acidity neutralisation (SZN) per day.