Investigations to inform diversion rules for the South East Flows Restoration Project in the Drain L catchment

Government of South Australia
Department of Environment, Water and Natural Resources

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March 2014

Published by the Department of Environment, Water and Natural Resources
Government of South Australia
March 2014

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ABN 36702093234
ISBN 978-1-922174-13-0

Preferred way to cite this publication

Taylor, B., Gibbs, M., Hipsey, M., Lewis, M., Sharath, I., Brookes, J., Nicol, J., Clarke, K., Dalby, P., Clark, M. and Bice, C. (2014). *Investigations to inform diversion rules for the South East Flows Restoration Project in the Drain L catchment,* Government of South Australia, through Department of Environment, Water and Natural Resources, Adelaide.

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FOREWORD

The investigations described in this report were undertaken primarily to inform diversion rules for the South East Flows Restoration Project (SEFRP) in the Drain L catchment, south-eastern South Australia. When these investigations were commissioned, the SEFRP was in its feasibility stage and the diversion of water from the Drain L catchment towards the Upper South East and Coorong was being actively considered. Subsequently, the geographic scope of the SEFRP has been reduced. The Project no longer involves diversion out of the Drain L catchment. The SEFRP is proposed to divert only the waters of the Blackford Drain, which currently flows to sea north of Kingston, northwards toward the Coorong via the wetlands of the Taratap and Tilley Swamp areas. The SEFRP diversion rules for the Drain L catchment proposed herein are therefore no longer relevant. However, these investigations have greatly improved the scientific understanding of the Drain L catchment and its high conservation value wetlands, specifically the Lake Hawdon system and the Robe Lakes. Irrespective of the scope of the SEFRP, the findings reported herein have implications for the management of this important catchment, and for water management generally in the South East region of South Australia. Additionally, this report presents an innovative, multi-disciplinary approach to the determination of environmental water requirements and makes a valuable contribution to this evolving discipline.

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CHAPTER 1: Overview

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1.1 Key Points

The key findings to emerge from modeling and analysis that were undertaken to propose preliminary diversion rules for the South East Flows Restoration Project (SEFRP) in the Drain L catchment are:

- On average, 17 GL (median of 13.9 GL) of water can be diverted by the SEFRP from Drain L, and still maintain the current hydrograph of Lake Hawdon North, and the contemporary salinity and water levels of the Robe Lakes in most years. The diversions rules that meet these objectives are:
    - Flows of between 0 and 250 ML/day can be diverted at each of two diversion points: Wilmot Drain and Drain K:
    - a regulator be installed on Drain L at the mouth of Lake Hawdon North that allows flows of up to 100 ML/day to pass through, but holds back larger flows. The regulator also provides an opportunity to restore a more ecologically appropriate hydrograph to the Lake.
- Small changes in the water levels and salinities of the Robe Lakes may occur as a result of these diversion rules, but only in dry and medium years. The models used could not be calibrated sufficiently to account for the behavior of water at very low flows. However, it is expected that adaptive management based on water quality monitoring of the Robe Lakes can be used to adjust water levels and salinities if water is available/required, without causing a significant reduction in the average diversions to the Upper South East wetlands and Coorong South Lagoon.
- Inundation extent in both Lake Hawdon North and South was most strongly correlated with the current month's drain flow, but still very strongly correlated with the previous month's drain flow. This suggests that Lake Hawdon North is filled quickly by, and drains quickly (possibly in less than a month) into Drain L. This also suggests that runoff from rainfall events that determine Drain L flow take less than a month to reach Lake Hawdon North.
- Over the past 50 years, there has been a considerable change to the vegetation of Lake Hawdon North that is indicative of a drying trend. The vegetation of adjacent Lake Hawdon South has changed only minimally over the same time period. This result suggests that the construction of Drain L through Lake Hawdon North has had the overall effect of drying out this wetland.
- The analysis of satellite and aerial imagery has been demonstrated to be useful for:
    - The identification of historical changes in wetland vegetation composition over time; and
    - The calibration of hydrological models when there are no other historic hydrological measures for calibration.
- The final set of preliminary diversion rules proposed as a result of these investigations includes a base flow of 1 ML/day from each of the two upstream SEFRP diversion points - to maintain saturated soils in Drain L, provide water for aquatic biota confined to drain habitat immediately downstream and to permit the passage of fish and other biota past the diversion points at low flows. Therefore the diversion rules recommended are:
    - Flows between 1 and 251 ML/day can be diverted at each of two diversion points: Wilmot Drain and Drain K:
    - a regulator be installed on Drain L at the mouth of Lake Hawdon North that allows flows of up to 100 ML/day to pass through, but holds back larger flows.
- The system is likely to be best managed in an adaptive way, for example by:
    - allowing reductions in the flow that bypasses the Lake Hawdon North regulator when it is desirable for the needs of Lake Hawdon North and not required for the Robe Lakes,
    - ceasing diversions out of the catchment at Drain K and/or Wilmot Drain to allow water from summer base-flows to persist in the system to reduce the salinity in Robe Lakes if required.

1.2 Introduction

The South East Flows Restoration Project (SEFRP) has been proposed as a long-term strategy for improving the ecological conditions of wetlands in the Upper South East, improving the marine environment of the South East and to help maintain appropriate salinity levels in the Coorong South Lagoon. The SEFRP proposes to divert water from the Drain L catchment in the South East of South Australia towards the Coorong South Lagoon, which would result in reduced water inflows to Lake Hawdon North and the Robe Lakes.

Water inflows to these lake systems (Lake Hawdon North and Robe Lakes) have dramatically increased since Drain L was constructed in the 1950's and the ecology of these systems has adapted in response. The local community and other stakeholders have expressed a desire for the lakes to retain their current hydrological and ecological character if SEFRP is established.

A team of scientists from the Department of Environment, Water and Natural Resources (DEWNR), University of Adelaide, University of Western Australia, the South Australian Research and Development Institute (SARDI) and In Fusion Consulting developed a cooperative program of modelling and analysis. The intention of the research was to determine what diversion rules could be put in place in the Drain L catchment to maximise the flow of water towards the wetlands of the Upper South East and the Coorong South Lagoon, without significantly affecting the hydrological or ecological character of either Lake Hawdon North or the Robe Lakes. The team has assumed that the ecological character of these wetlands would change if either the pattern of wetting and drying was changed, or the water quality was significantly altered.

The program of research is summarised, with some additional commentary, in this Overview, and reported on in more detail in remainder of this report:

- Review of the Ecologically Ideal Hydrograph for Lake Hawdon North
- Lake Hawdon Inundation Regime Characterisation by Remote Sensing
- Hydrodynamic Model for the Robe Lakes and the Implications of Management Scenarios on Lake Height, Mouth Openness and Salinity
- Diversion Rules for the Drain L Catchment Subject to Downstream Environmental Water Requirements

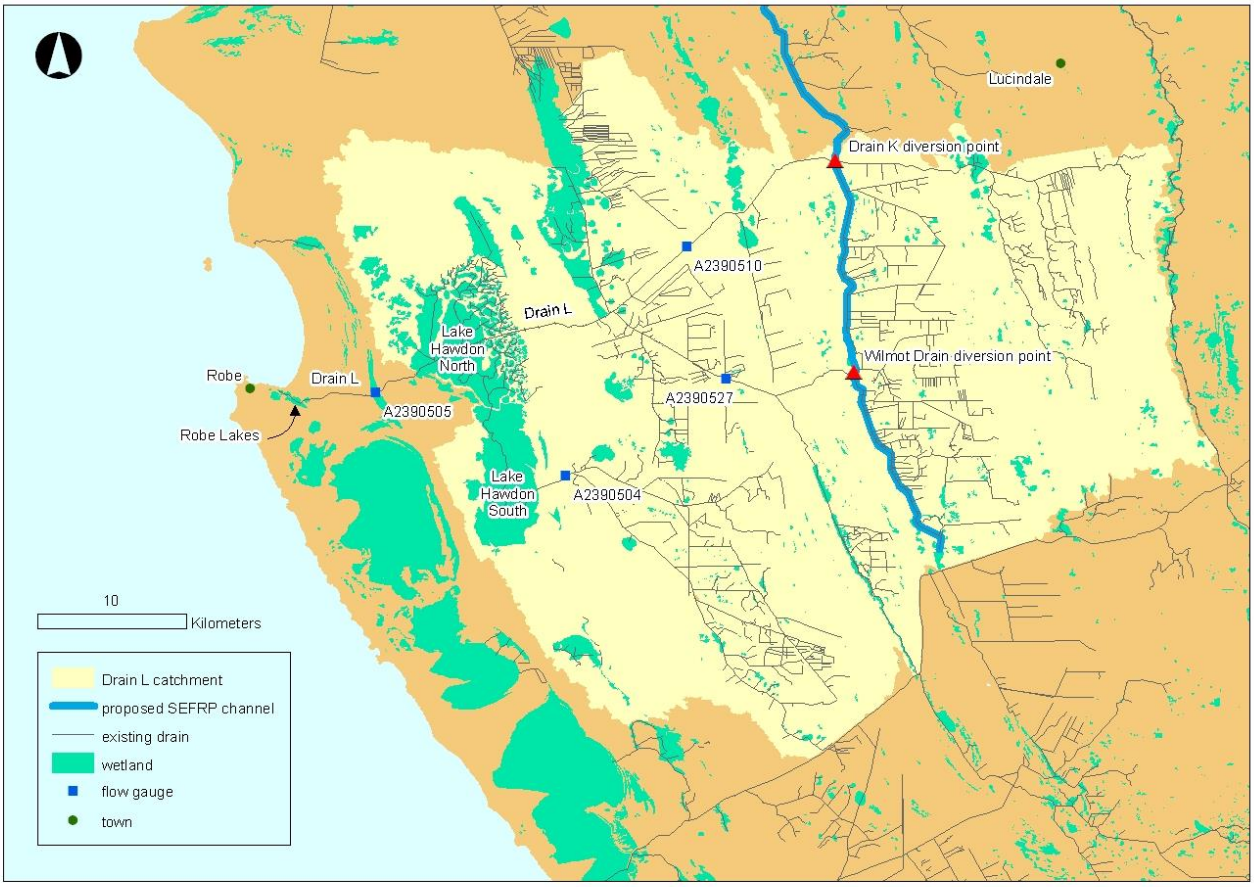
Prior to European settlement, Lake Hawdon North was a seasonal wetland that filled during winter and spring and dried over summer and autumn; however, because it was a terminal basin, it was most likely a saline or brackish system (Ecological Associates 2009b). The construction of Drain L (Figure 1) converted Lake Hawdon North to a 'flow-through' system (i.e. the system is hydraulically similar to a floodplain) with a likely shorter period of inundation and lower salinity. Inundation of the lake currently occurs when flows exceed the capacity of the drain within the wetland (Ecological Associates 2009b). A total volume of 5.6GL of water is required to fill Lake Hawdon North to its recent historic maximum (ie. post construction of Drain L). Total annual flow in Drain L has been lower than 5.6GL on only two occasions out of the 22 years that complete flow records exist and the mean discharge from Drain L is 50.9GL. Therefore, it may well be possible to fill Lake Hawdon North, provide sufficient water for downstream Robe Lakes and divert water out of the catchment and towards the Coorong South Lagoon in most years.

Due to the requirement of a high flow rate in Drain L for inundation of Lake Hawdon North to occur, the SEFRP, by reducing the frequency of high flows, has the potential to reduce the frequency, depth and duration of inundation of Lake Hawdon North. This would likely result in changes to the ecological character of the wetland. However, these changes may be prevented by the construction of a regulator across Drain L at the outlet of Lake Hawdon North.

The Robe Lakes are a man-made estuary with permanent connection to the sea at the mouth of Drain L. As an estuary, the ecological character of the system is likely to be strongly influenced by annual cycles of salinity, water level fluctuations and the maintenance of a permanently open mouth. The SEFRP, by reducing inflows from Drain L, has the potential to change mouth openness, salinity and water levels. The volume of the Robe Lakes is small (400 ML) compared to average annual inflows from Drain L (50.9 GL). It is therefore likely that inflows could be considerably reduced without affecting the ecological character of the system.

Figure 1. The catchment of Drain L is comprised of an extensive drainage network draining an area of 1642km^2.

Proposed Drain K and Wilmot Drain diversion points are indicated on the map as red triangles.



1.3 Studies Undertaken

The following studies were undertaken to determine diversion rules in the Drain L catchment that would maximise flows to the wetlands of the Upper South East and Coorong, whilst maintaining the existing ecological and hydrological condition of Lake Hawdon North and the Robe Lakes.

To determine what flow regime would be required to maintain or enhance the ecological character of Lake Hawdon North, studies were undertaken to understand the link between water flow rates through Drain L, inundation of Lake Hawdon North and subsequent responses by aquatic vegetation.

- An assessment of an ecologically ideal hydrograph for Lake Hawdon North that had been developed by the Department for Environment Water and Natural Resources was reviewed independently by researchers from SARDI to determine its appropriateness (Chapter 2).

- Historic Inundation: To recreate flooding patterns for Lake Hawdon North, researchers from the University of Adelaide used remote sensing techniques to identify inundation periods from 2000 to 2011 and to map inundation extent for selected dates between 1989 and 2011 (Chapter 3). This was required to calibrate and validate a hydrological model for the Lake, in the absence of any other information on flooding extent.
- Change in the distribution of vegetation: The distribution of vegetation complexes within Lake Hawdon in 1958, 1988, 1999 and 2008 was determined using remote sensing methods (Chapter 3) to indicate the response of vegetation in the Lake to changing hydrological patterns.

Water from Drain L passes through Lake Hawdon North and continues to flow through to the Robe Lakes (four connected lakes – see Figure 3. below) that finally open to the sea. The total volume of the four Robe Lakes is small (400 ML), and it is expected that most water from Drain L passes quickly through the lakes and is not required to maintain the salinity or water level.

- Hydrodynamic modelling was undertaken by the University of Western Australia and University of Adelaide to assess the natural variation in water height and salinity in the lakes. The salinity and water heights of the lakes with and without diversion rules in place was modelled and compared. A range of climate scenarios were tested (Chapter 4).

To determine appropriate diversion rules for the catchment upstream of Lake Hawdon and Robe Lakes:

- Different diversion scenarios were assessed at two upstream locations (Wilmot Drain and Drain K) to identify suitable diversion rates that: 1) meet an ecologically ideal hydrograph for Lake Hawdon North (assuming a regulator in place); as well as 2) providing sufficient flows to maintain water quality and height in the Robe Lakes (Chapter 5).

1.4 Program Development

The program of modeling and analysis was developed through a facilitated discussion between staff from the Department of Environment, Water and Natural Resources (DEWNR) who sought advice on diversion rules and scientists and technical experts from state government and research organisations. An initial brief was provided by staff from DEWNR, and a number of facilitated workshops were held to refine the questions and the research program.

The proposed program of work was collaboratively developed by Departmental staff and external researchers. The final agreed set of tasks was incorporated into a series of interconnected work plans (Table 1). Figure 2 illustrates the dependencies between the tasks.

Table 1. List of Program Tasks.

ID	Tasks
Project 1. Review of Ideal Hydrograph	
1.1	Provide critique and possible improvements of method used to determine ideal hydrograph for Lake Hawdon North
Project 2. Hydrological model development, calibration and modelling of diversion rules	
2.1	Water Balance Model of Lake Hawdon North and South
2.2	Surface water – Groundwater (SW – GW) Interactions in Drain L
2.3	Improved Catchment Modelling
2.4	Scenario Modelling and Reporting
Project 3. Remote sensing to determine historic water and vegetation of Lake Hawdon North	
3.1	Temporal wetland vegetation growth and inundation patterns (from MODIS)
3.2	Inundation extent (from Landsat)
3.3	Mapping historic changes in spatial distribution of vegetation communities
3.4	Final report
Project 4. Hydrodynamic model development, calibration and modelling of diversion rules	
4.1	Review
4.2	Bathymetry and model grid development
4.3	Setup and assessment of hydrodynamic model
4.4	Scenario modelling
4.5	Final Report
4.6	Presentation to stakeholders

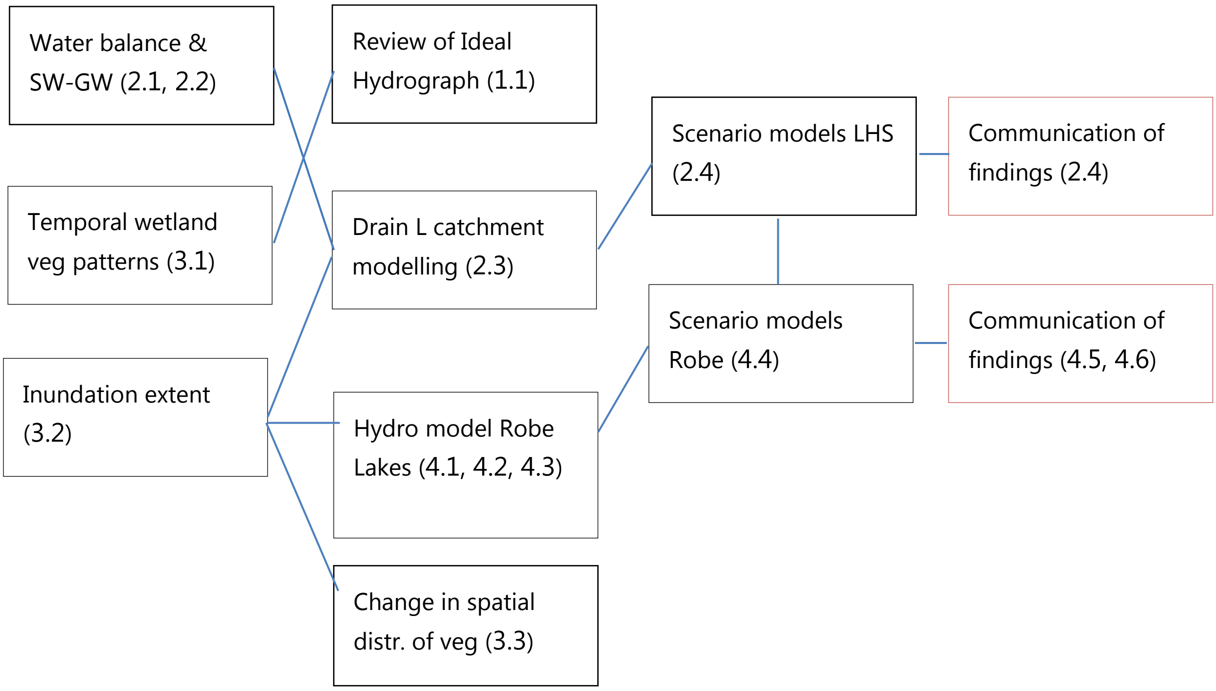


Figure 2. Program tasks and their dependencies (LHS = Lake Hawdon South, SW-GW = Surface water – Groundwater).

There was some interdependency of tasks. Information from vegetation mapping was used to help calibrate the hydrological modeling. The hydrodynamic modeling of the Robe Lakes established some boundaries for the hydrological modeling. The hydrological modeling then provided outputs which were fed back into the hydrodynamic modeling.

An independent project manager was contracted to assist in the preparation of templates for project plans, to facilitate workshops to refine the questions, act as a program manager for the entire program and assist with the interpretation of final results.

As a formal component of the project, workshops were undertaken with the research team to: prepare the initial project plan; review findings and how they could be used across projects during the life of the project; to review the final results and approve the final communication products.

The communication of results to a broader group of stakeholders was an important task of the project and ensured that the results were understood by the managers inside DEWNR.

1.5 Summary of Findings

Hydrological & ecological character of Lake Hawdon North

The maximum extent of inundation in Lake Hawdon North is highly variable between years. Table 2 below shows the estimated area of inundation in late winter/spring based on interpretation of satellite imagery from Chapter 3. The maximum area of inundation was over 2,300 ha in winter of 1992, but in the drought years of 2005 and 2006, the maximum area of inundation was 90 ha or less. Note some caution is required in the interpretation of these results as the presence of vegetation on the lake bed can obscure the inundation signal.

Table 2. Landsat mapped inundation extent for Lake Hawdon North and South. Inundation mapping was restricted to the wetland extent shapefile.

Inundated area (ha)			
Date	**Total**	**North only**	**South only**
20-Nov-89	1924.83	671.85	1252.98
24-Aug-92	3994.20	1814.76	2179.44
11-Oct-92	3882.24	1977.21	1905.03
11-Oct-92*	4341.24*	2331.90*	2009.34*
24-Oct-99	1138.32	398.16	740.16
09-Jul-01	1112.58	312.39	800.19
25-Jul-01	975.78	329.49	646.29
07-Sep-01	1532.70	605.79	926.91
14-Sep-02	2031.66	853.47	1178.19
16-Aug-03	3484.89	1738.08	1746.81
20-Jul-05	506.97	90.63	416.34
08-Aug-06	227.79	0.81	226.98
26-Jul-07	648.81	222.21	426.60
27-Aug-07	1070.91	445.50	625.41
27-Jul-08	620.19	183.87	436.32
06-Oct-10	2063.61	859.50	1204.11
21-Jul-11	1048.59	442.62	605.97
22-Aug-11	1402.56	677.16	725.40
07-Sep-11	1040.58	409.77	630.81

*Inundated area on this date was not restricted to the wetland extent shapefile. On this date, inundation area was calculated within a 2 km buffer of Lake Hawdon North and South.

Inundation extent in both Lake Hawdon North and South was most strongly correlated with the current month's drain flow (R^2 = 0.83 and R^2 = 0.71 respectively), but still very strongly correlated with the drain flow in the preceding month and the month before that (R^2 = 0.71 and R^2 = 0.66 respectively). This suggests that Lake Hawdon North is filled quickly, and drains quickly (possibly in less than a month) into Drain L (Chapter 3).

Based on an analysis of aerial imagery (Chapter 3), vegetation has changed markedly for Lake Hawdon North between 1958 and 1988: in 1958 it was largely an unvegetated pan (Figure 3), colonised by localised areas of vegetation by 1969. This vegetation expanded and consolidated by 1978, and remained relatively stable in distribution through to 2008. By contrast, the overall distribution of vegetation in Lake Hawdon South has remained relatively stable between 1958 and 2008, with some increase in vegetated area at the expense of open pans (Figure 3).

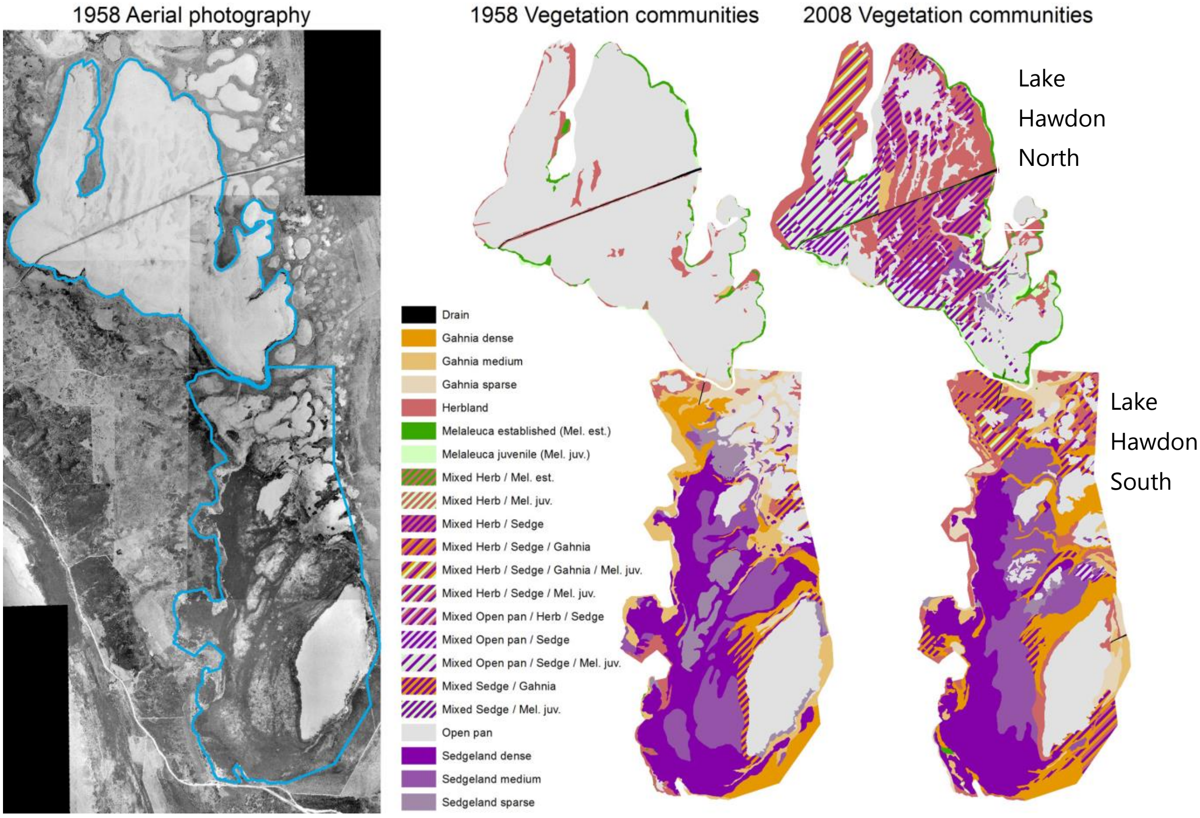


Figure 3.Change in the distribution of all vegetation communities in Lake Hawdon North and South from 1958 (left) to 2008 (right) derived by expert interpretation aerial photography. Original aerial imagery from 1958 (far left).

The comparative photo-interpretation has revealed considerable change in the composition of the wetland vegetation. The overall story of vegetation community change in Lake Hawdon is one of invasion and change. In 1958 mixed vegetation communities accounted for only a small area of Lake Hawdon South, suggesting that the inundation regime in Lake Hawdon North and South had been relatively stable for a long time. By 2008 mixed communities accounted for more of Lake Hawdon South, and the majority of Lake Hawdon North, suggesting that there has been a considerable change in the inundation regime of Lake Hawdon North, and a moderate inundation regime change for Lake Hawdon South.

Table 3 presents the ecologically ideal hydrograph based on the current wetland vegetation present in Lake Hawdon North (Chapter 2). This hydrograph has been designed to maintain the current plant community and represents a seasonal hydrograph of winter/spring flooding and summer/autumn drawdown. Ecological Associates (2009b) reported significant *Melaleuca halmaturorum* encroachment onto the bed of Lake Hawdon North since 1981. To maximize biodiversity in the lake, it would be desirable to limit *Melaleuca* extent and encourage sedges and rushes.

Table 4 describes a hydrograph designed to arrest *Melaleuca halmaturorum* encroachment onto the wetland bed and restrict this species to the fringes (Chapter 2). It would also promote sedges and rushes such as *Baumea* spp. and *Juncus* spp. in areas that flooded and dried each year and the lower elevations would support amphibious herblands. This is expected to maintain or increase biodiversity within the Lake system.

Table 5 describes the hydrological targets used in the hydrological modeling described in this report. The targets are based on the ideal hydrograph in Table 3, but slightly extends the duration of inundation to provide shallow summer mudflat inundation for migratory waders.

Table 3. Ideal hydrograph to support the current wetland vegetation of Lake Hawdon North based on the method of Ecological Associates (2009b). Depths refer to the deepest point of the wetland.

		Duration	
Depth (m)	**Water Surface Elevation (m AHD)**	**Annual**	**1 year in 3**
dry	<3.65	4	2
waterlogged	3.65	2	2
0.2	3.85	2	2
0.4	4.05	2	2
0.6	4.25	2	2
0.8	4.45	0	2

Table 4. Proposed hydrograph to reverse *Melaleuca halmaturorum* encroachment on to the bed of Lake Hawdon North.

		Duration	
Depth (m)	**Water Surface Elevation (m AHD)**	**Annual**	**1 year in 3**
dry	<3.65	4	2
waterlogged	3.65	4	2
0.2	3.85	4	2
0.4	4.05	4	2
0.6	4.25	4	2
0.8	4.45	3	2
1.0	4.65	0	2

Table 5. Final set of targets used for the hydrological modelling in this report based on recommendations from Table 4.

Month	Hydrological target	Month	Hydrological target
Jan	3.80 mAHD	July	3.90 mAHD
Feb	regulator completely open	Aug	4.20 mAHD
Mar	regulator completely open	Sep	4.40 mAHD
Apr	regulator completely open	Oct	4.40 mAHD
May	regulator completely open	Nov	4.20 mAHD
June	3.70 mAHD	Dec	4.00 mAHD

The hydrological character of the Robe Lakes

The Robe Lakes (Figure 4) is an estuarine system of four interconnected lakes located at the terminus of Drain L within the township of Robe. The system consists of Lake Battye, Lake Nunan, The Pub Lake and Lake Fox. Inflows to the system are assumed to include:

- Freshwater inflows from Drain L;
- Inflows of seawater through the permanently open mouth;
- An unknown but potentially significant groundwater contribution;
- Local runoff; and
- Direct rainfall.

Proposed diversion points for the SEFRP are located in the Drain L catchment upstream of the Robe Lakes (Figure 1), thus inflows to the Robe Lakes will be reduced by the SEFRP. The Lakes have a combined total volume of 400 ML when water levels are high, while average inflows from Drain L are 50.9 GL[1]. Thus, in an average year, inflows to the Lakes are equivalent to 127 times their total volume. It is assumed that Drain L inflows to the Robe Lakes under existing management arrangements greatly exceed their environmental water requirement (EWR) in most years. However, the EWR of the system has not been determined.

It is an objective of the SEFRP that the current ecological character and other values (e.g. amenity, recreation) of the Robe Lakes be maintained. The ecological character and values of the Robe Lakes are assumed to be strongly influenced by:

- Salinity, including both spatial and temporal variation;
- Water level regime; and
- Degree of mouth openness.

Thus, to ensure the ecological character of the Robe Lakes are maintained, salinity, water level and mouth openness need to be maintained close to their current range. This requirement is likely to influence the amount of water than can be diverted away from the Robe Lakes by the SEFRP.

[1] http://www.waterforgood.sa.gov.au/news-info/publications/waterconnect/

Figure 4. The Robe Lakes comprise a string of connected lakes receiving water from Drain L to the east and water flowing north-west to exit to the ocean north of Lake Fox.

For the purposes of hydrodynamic and hydrological modelling, a revised bathymetry of both the Robe Lakes and Lake Hawdon South was developed (Taylor, B., unpublished). The existing South East regional digital elevation model (DEM) was inaccurate for these wetlands due to the presence of surface water and/or dense vegetation, which had influenced the LiDAR results used to create the DEM. Validated survey data was used to improve the alignment of the DEM with measured real world topography.

Salinity in the Robe Lakes is influenced by both flows from Drain L and tidal inputs from the ocean. Limited data is available, however data collected by the South East Water Conservation and Drainage Board from August 2006 to June May 2007 (de Jong 2007) the electrical conductivity in Pub Lake was measured to be between 4,170 µS/cm and 54,100 µS/cm over a two year period of monitoring. Lake Battye is further upstream and appears to be less influenced by tidal intrusions but still experienced salinity up to approximately half that of seawater.

Temperature data for the Robe Lakes collected during the same period showed seasonal oscillation between approximately 12^{o}C and 25^{o}C.The monthly spot measurements do not provide any information on stratification and mixing behaviour. However it can be assumed that stratification behaviour would not change with a diversion strategy that does not alter summer inflow hydrology to the lakes.

Nutrients and changes to nutrient dynamics were not considered in the diversion scenario modelling but the nutrient concentrations in water destined for diversion is noteworthy. Nutrient data is available for Pub Lake and Lake Battye (de Jong 2007), but only Pub Lake data is considered for the purposes of this research; Ammonia concentrations range from the minimum level of detection (0.01 mg/L) to 0.16 mg/L; Nitrate ranged from the minimum limit of detection to 0.08 mg/L; total nitrogen (TKN) had a maximum of 1.8 mg/L; Total Phosphorus ranged between 0.03 and 0.21 mg/L; and Filterable Reactive Phosphorus ranged between the minimum level of detection and 0.068 mg/L. These concentrations are high enough at times to be considered eutrophic.

There was insufficient information available to determine the impact of reduced water flows on mouth openness, so the reduction in salinity at the ocean site was used as a proxy for the erosive potential of flood flows in regulating the mouth opening. This issue will be best managed using an adaptive approach. Detailed bathymetric information collected at the mouth of Drain L in 2011 comprises a baseline against which to measure future change to mouth openness. It is important to note that the SEFRP will divert a maximum of 500 ML/day out of the Drain L catchment, yet peak Drain L flows over 2000 ML/day have been recorded. Therefore peak flows in excess of 1500 ML/day can be anticipated in Drain L under an SEFRP scenario.

Scenarios: The impact of diversion rules on Robe Lakes

A hydrodynamic model of the Robe Lakes was developed and calibrated for the purpose of assessing the impact of SEFRP diversion scenarios upon the salinity and water level of the Lakes system. To narrow down the set of possible diversion rules that could maintain hydrological conditions in the Robe Lakes, five scenarios of diversion rules were tested with four years of flow data - to represent different flow patterns (Figure 5).

- The years chosen to represent a range of flow regimes were 2004 (indicative of a wet year; peak flows of >2,000 ML/day), 2010 (indicative of a medium year; 1,000 to 1,100 ML/day) and 2007 & 2008 (indicative of dry years; 40-50 ML/day and 150 – 180 ML/day respectively).
- Five diversion rules scenarios were constructed by setting lower and upper bounds on diversions upstream of the Robe Lakes.
    - These diversion rule scenarios were designed to reflect likely diversion rules if the SEFRP was put into place. A lower diversion limit ensures flow reductions are not exacerbated under naturally dry conditions. An upper flow diversion limit was set to ensure higher flow peaks are still able to enter the system, as they are required for periodic flushing of the system, to prevent sedimentation of the mouth, and for coastal wetland flooding.
    - The lowest diversion tested was 40 ML/day, just below the peak of the low flow year (2007). It was assumed that continually subjecting the lakes to flow rates below this would be undesirable over the medium- to long-term.
    - For each of the five scenarios tested, only water between June and November was diverted.

		Year:	**2004**	**2007**	**2008**	**2010**
		Indicative Flow:	>2000	40-50	150-180	1000-1100
			Wet	Dry	Dry	Medium
Scenario:	Diversion envelope (ML/day)	Maximum total diversions away from Robe Lakes (ML/day)	Able to run the computer simulations for this scenario?			
E	40-440	400	Y	Y	Y	Y
C	80- 580	500	Y	N	Y	Y
D	100-600	500	Y	N	Y	Y
A	100-1000	900	Y	N	N	Y
B	150-1000	850	Y	N	N	Y

Figure 5. Flow diversion scenarios able to be tested for different flow years, showing the diversion envelope and maximum daily diversions away from the Robe Lakes. The diversion envelope describes the lower and upper thresholds for flow rate in Drain L within which flows are diverted away from the Robe Lakes.

The effects of the diversion scenarios on the lake system were assessed by comparing changes in water level, changes in the salinity time-series, and changes in the salinity exceedence probabilities for four sites in the lake system (Ocean entrance, Fox-Pub Lake, Lake Nunan and Lake Battye - Jumbo's Jetty).

In general, the water level variation caused by the diversion scenarios was not significant (Figure 6).

In addition an assessment was made of the number of days where salinity at the four representative locations was below an assumed salinity "metric" or boundary, which was set based on a subjective assessment as to what was a typical value for each site during peak flow (based on existing data):

1. *ocean* – 25 parts per thousand (ppt)
2. *foxpub* – 15 ppt
3. *nunan* – 10 ppt
4. *battye* – 5 ppt

Figure 7 and 8 are examples of an analysis of the number of days where the salinity fell below these boundary values. For the 2007 case (dry year), only scenario E (40-440 ML/day diversion rules) had any impact on flows; the flow in this year was not high enough to trigger a diversion under the rules set for scenarios A-D. The 2008 (dry) year was the most sensitive to diversions; scenario E caused a 50% reduction in the number of days in which the salinity value was above the 'metric', or boundary set for each location (Chapter 4). Salinity levels in higher flow years of 2010 and 2004 were less sensitive to the diversion rules. For scenario C and D, the number of days that salinity exceeded the set boundary was reduced by a relatively small amount compared to the large variation seen between the years simulated.

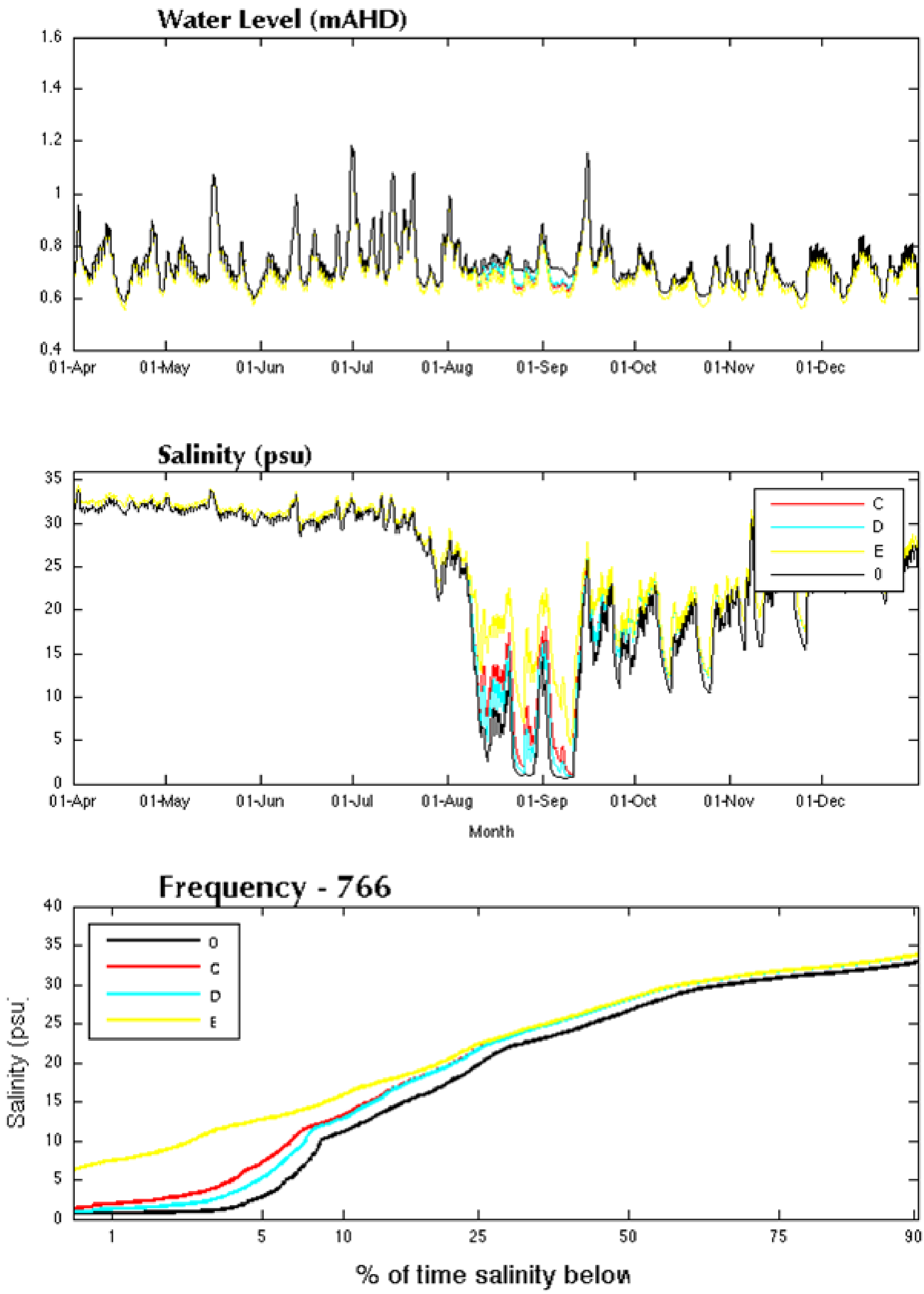


Figure 6. Water level, salinity, and salinity frequency curve for the year 2008 (low flow), for the Fox-Pub Lake station, cell 766 in the model grid (see Chapter 4). Note that the treatment described as zero is the control: i.e. no water is removed from the flows to the system.

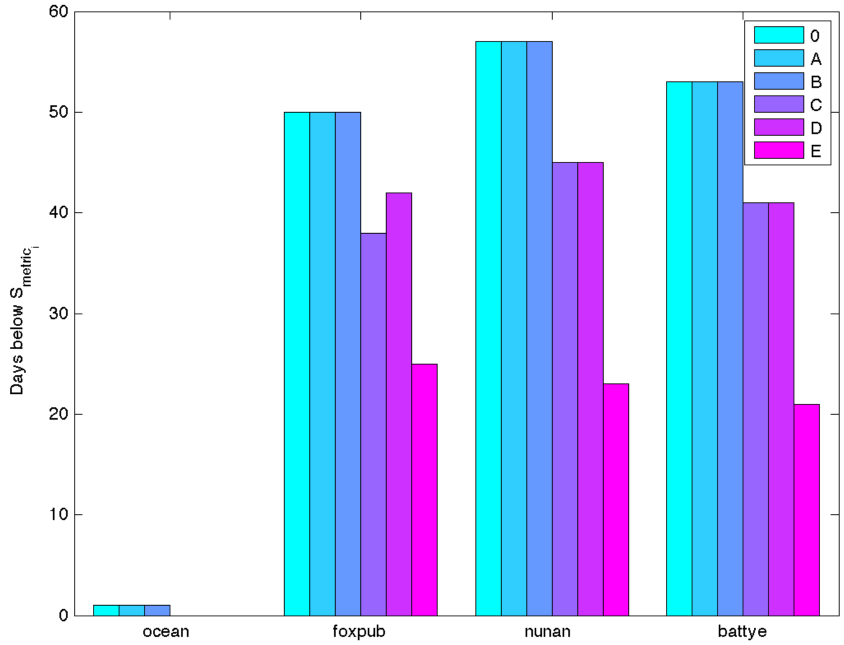


Figure 7. Number of days salinity is below S_{metric} (defined above) for 2008 (dry year) at four locations, including foxpub, nunan and battye within the Robe Lakes.

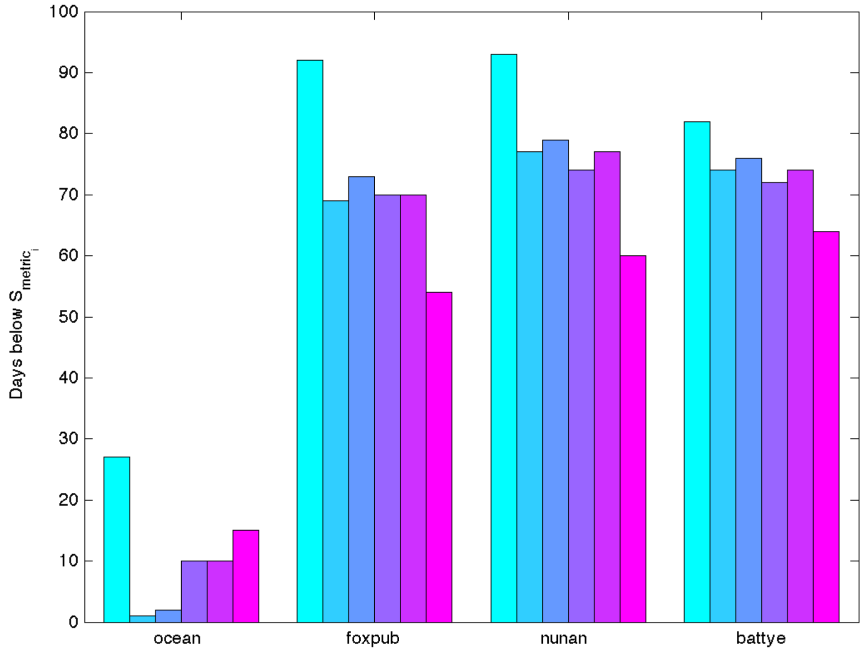


Figure 8. Number of days salinity is below S_{metric} (defined above) for 2010 (medium year) at four locations, including foxpub, nunan and battye within the Robe Lakes. Note the difference in scale between Fig 7 and 8.

The scenario modelling suggested that a diversion envelope of 80 – 580 ML/day (Scenario C) or 100 – 600 ML/day (Scenario D) was the optimum balance between limiting the impact to the general salinity structure of the Robes Lakes system, and providing the most volume of water for diversion. Other possible ecosystem impacts of flow diversion such as control of sand incursion and maintenance of an open estuary mouth, nutrient delivery to the estuary and flow cues for fish movement were not considered.

Overall, scenario D (divert >100 and <600 ML/day) appears to be the optimum balance in meeting the estuary EWR and diverting water towards the wetlands of the Upper South East and the Coorong South Lagoon. In particular, under this scenario:

- The number of freshwater days in the Lakes is reduced by 8-20% (dependent upon location) compared to the no-SEFRP scenario for medium years and is comparable to scenarios A-C ;
- Mouth scouring flows are still present in wet and medium years, and water levels are virtually unaffected compared to the no-SEFRP scenario;
- There is minimal change in hydrology in low flow (dry) years because all flows less than 100ML/day are allowed to flow directly from Lake Hawdon North to the Robe Lakes.

However, there was only a limited difference between scenarios D and C; and the 80-580GL diversion range has only slightly more impact on salinity and water levels.

Final diversion rules impact on the Robe Lakes

The results of the five scenarios described above were used to inform hydrological modelling of 'most likely' diversion rules (described in Chapter 5 and below). Hydrological modelling was used to determine the water flows into the Robe Lakes of the following diversion rules:

- Flows between 0 and 250 ML/day can be diverted at each of two diversion points: Wilmot Drain and Drain K (see Figure 1);
- a regulator be installed on Drain L at the mouth of Lake Hawdon North that allows flows of up to 100 ML/day to pass through, but holds back larger flows. The regulator also provides an opportunity to restore a more ecologically appropriate hydrograph to the Lake, with likely benefits for wetland dependent species.

The flow scenarios assessed here use idealized flow diversion rules and provide guidance on the setting of lower and upper limits and the daily flow diversion amounts. In a real situation the lakes water levels and water quality can be accommodated through adaptive management of flow diversion volumes in response to decisions in the upper catchment.

Modelling Diversion Rules

Two hydrological models were developed to investigate the impact of diverting flow from the Drain L catchment on the inflows to and water regime of Lake Hawdon and the Robe Lakes. Firstly, a rainfall – runoff model of the catchments contributing to Lake Hawdon was required to estimate inflows, and secondly, a lake – storage model to represent the interactions between Lakes Hawdon (North and South), drains and proposed regulator. Both models were applied to the period 1992 – 2011.

For the modelling, a previously identified optimal maximum diversion rate of 250ML/day at both diversion points was adopted. The modelling indicated that no minimum flow rate is expected to be necessary at these diversion points to support the downstream environmental water requirements (EWRs) of Lake Hawdon and the Robe Lakes (although see final section of this report). This is because the unaffected downstream catchment area is sufficient to provide the lower flow requirements of Lake Hawdon North and the Robe Lakes. The catchment area contributing to the two diversion points is 554km^2, however there is still a catchment area of 1087km^2 downstream of the diversion points that will continue to flow unimpeded toward Lake Hawdon North and South. Construction of a regulator on Drain L at the outlet of Lake Hawdon North is assumed to be necessary to maintain the current water regime under a scenario of reduced inflows.

Both permanent and winter-only diversion scenarios were considered. Given that the majority of flow occurs over the winter period, the two diversion results were found to have little difference on the water levels of Lake Hawdon North. However, allowing the summer base flows to remain in the system did result in higher flows at the outlet of Lake Hawdon North.

The ideal hydrograph of Lake Hawdon North (Chapter 2 and Table 5) was met at the same frequency as would have occurred historically (without diversions or a regulator) when the diversion rules were adopted: 0-250ML/day from both Wilmot Drain and Drain K and a regulator on Drain L at the outlet of Lake Hawdon North that includes a 100 ML/day bypass to support the Robe Lakes downstream (Figure 9).

Based on the maximum divertible flow rate of 250 ML/day, and no requirement for a minimum flow rate to pass the diversion points, the annual volume that can be diverted to by the SEFRP toward the CSL has been estimated. For permanent diversions, on average, the divertible volume from the Wilmot drain diversion point is 9.1 GL/year and 7.9 GL/year from Drain K diversion point. Median divertible volumes are 7.5 GL/year and 6.4 GL/year from the Wilmot and Drain K catchments, respectively.

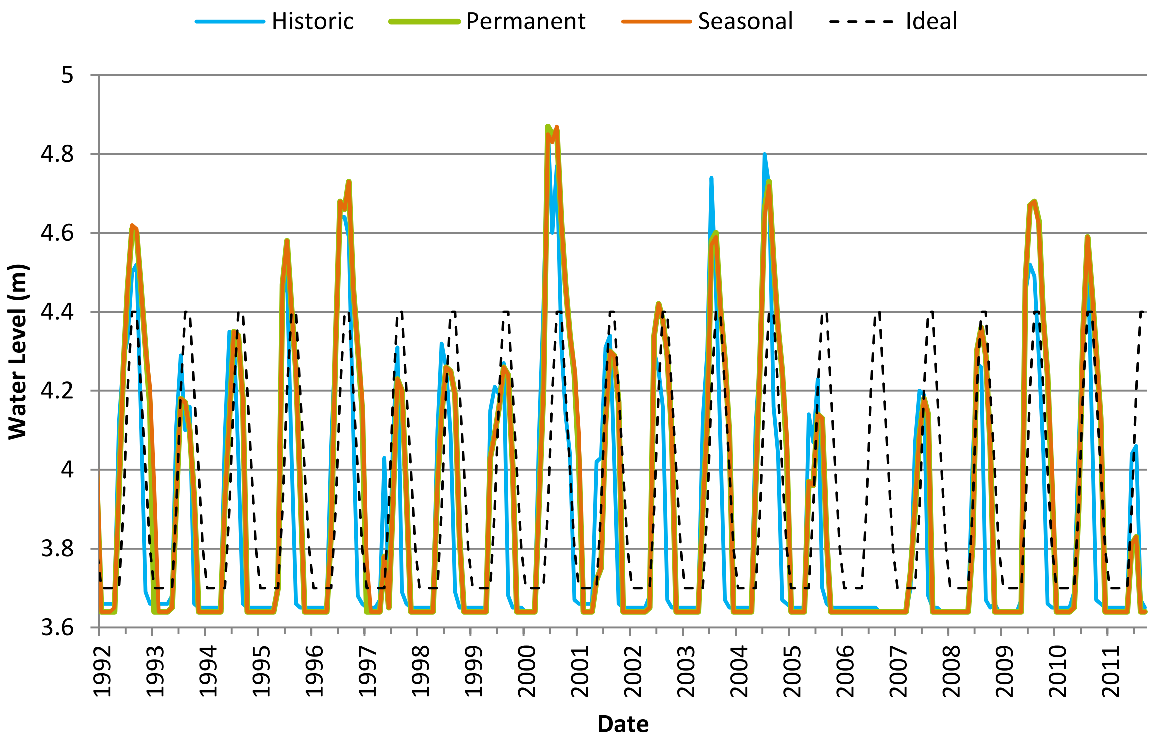


Figure 9. Simulated water levels in lake Hawdon North for the historic case (blue line), as well as seasonal (green line) and permanent (red line) upstream diversions using a regulator, compared to the ideal hydrograph.

The seasonal divertible volume has also been calculated, as not diverting flow to the north over the period December to May inclusive would be expected to reduce the volume available to be diverted. For this case the average divertible volume is 8.3 GL/year and 7.0 GL/year from the Wilmot and Drain L catchments, respectively. The median flows are 6.7 and 5.7 GL/year from the Wilmot and Drain L catchments, respectively. As such, not diverting for the summer period 6 months of the year is expected to reduce the total divertible volume by approximately 10%, or around 800 ML, at both diversion points.

Based on the modelling presented in this report, the most extreme case considered, to divert all flows below 250 ML/day at the Drain L and Wilmot Drain diversion points and allow 100 ML/day past a regulator on Drain L at the outlet at Lake Hawdon North, is expected to meet the specified ideal hydrograph at the same frequency as occurred historically without diversions or a regulator. The 100 ML/day flow past the regulator is also expected to maintain salinity and water level EWRs in Robe Lakes (Chapter 4).

Inclusion of a low flow by-pass

Since the completion of the project, the DEWNR team have proposed a minor modification to the diversion rules. Instead of diverting all water at Wilmot Drain and Drain K diversion points up to 250ML/day, a small bypass of 1 ML/day will be incorporated into the design. The purpose of allowing a small base flow is to protect aquatic habitat and biota confined to the drains immediately downstream of the diversion points, and to allow passage of biota past the diversion points in low flows.

Implications of diversion rules in drought years

To understand the implications of this final set of diversion rules in a very dry year (using 2007 as our example), a review of gauged flow data for the two gauges located downstream of the SEFRP diversion points in the Drain L catchment shows that:

- Flows below the Drain K diversion location (gauge A2390510), peaked at 1.1 ML/day in the 2007 dry year winter/spring flow. Thus it can be confidently predicted that the SEFRP would have had no impact on flows to either Lake Hawdon North or the Robe Lakes in that year if a 1 ML/day low flow bypass was incorporated at this diversion point.
- Flow below the Wilmot diversion location (gauge A2390527), was 0 ML/day for considerable stretches of time in the 2007 dry year winter/spring flow (1 May to 30 September). However there were several short bursts of higher flow up to 16.8 ML/day. A subsequent analysis of the impact of the Wilmot diversion (with a 1 ML/day bypass) on flows into the Robes Lakes during the same period shows that flows would have been reduced from 3370 ML to 3240 ML (a reduction of 130 ML, or 3.9%) with the 1 ML/day bypass and maximum of 250 ML/day diversion in this year.

The system is likely to be best managed in an adaptive way, with the ability to reduce the flow bypassing the Lake Hawdon North regulator when it is desirable to maintain the water level in Lake Hawdon North for longer periods of time (for example, after a number of sequential dry years), as well as allow summer baseflows to persist in the system when these flows may be desirable to reduce the salinity in Robe Lakes.

CHAPTER 2. Review of the Ecologically Ideal Hydrograph for Lake Hawdon North

Jason M. Nicol and Chris Bice

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2.1 Summary

Hydrology is the major driver of biotic communities in wetland ecosystems and changes to the hydrology will result in changes to biota. Lake Hawdon North is a highly modified system that plays an important role in the landscape in the South East as a brackish/fresh seasonal wetland. A regulator is proposed for the outlet of Lake Hawdon North to maintain the current hydrological regime (or extend the hydroperiod) using a smaller volume of water in order to direct water towards the South Lagoon of the Coorong. The aim of this component of the project is to provide a critique of the method used to determine the ecologically ideal hydrograph for Lake Hawdon North.

The ecologically ideal hydrograph was determined using wetland vegetation components (WVC), which use the water requirements of the plant communities present at different elevations to determine the hydrograph of the wetland. The method is appropriate for use in Lake Hawdon North because there is more information regarding the plant community than other biotic groups and there is historical qualitative information from aerial photographs that gives an indication of change through time. However, the proposed hydrograph would maintain the communities present, which may not be desirable due to the significant *Melaleuca halmaturorum* encroachment onto the wetland bed since 1981. Therefore, a hydrograph with longer hydroperiod and greater maximum depth was proposed to reverse the *Melaleuca halmaturorum* encroachment and provide more favourable conditions for sedges, rushes and amphibious herbs.

Lake Hawdon North requires 5.6 GL to fill and total annual flow in Drain L has been lower than 5.6 GL on only two occasions out of the 22 years that complete flow records exist. Therefore, it is possible to fill Lake Hawdon North, provide sufficient water for downstream wetlands and divert water to the South Lagoon of the Coorong in most years if a regulator is constructed on the outlet.

The use of WVCs does not take into consideration other biotic groups that may have different water requirements to the plant communities. Lake Hawdon North and Drain L contain significant populations of threatened fish species, two of which may be diadromous (and aestivate). Therefore, the water and movement requirements of these species need to be taken into consideration when designing and operating the outlet regulator.

An exercise similar to the one undertaken for the Chowilla environmental regulator that simulated real time operation of the regulator is recommended for the Lake Hawdon North outlet regulator prior to construction. The exercise used the expertise of ecologists, river operators, managers and hydrologists and recorded the proposed operation of the regulator step by step in four week intervals over a 15 year period in real time (given the antecedent conditions, current conditions, predicted flow, modelled natural flow and ecological objectives). A similar exercise for Lake Hawdon North will give an indication of how the regulator will need to be operated to achieve the ecological objects set for Lake Hawdon North, provide water for downstream wetlands and how much water will be available to be directed to the South Lagoon of the Coorong.

2.2 Introduction

Hydrology is the major driver of biotic communities in wetland ecosystems (Mitsch and Gosselink 1993). Hydrology influences germination and seedling recruitment (Keddy and Ellis 1985; Keddy and Constabel 1986) as well as growth of macrophytes (Keddy 1983; Coops and Van der Velde 1995; Coops *et al.* 1996) and plays an important role in structuring the composition and zonation of vegetation as water levels rise and fall (e.g. Blanch *et al.* 1999).

The South East Flows Restoration Project (SEFRP) proposes to divert water from existing drains in the South East and direct water into the South Lagoon of the Coorong. Proposed diversion points in the Drain L catchment are located upstream of Lake Hawdon North, a regionally important wetland (Taylor 2006).

Prior to European settlement, Lake Hawdon North was a seasonal wetland that filled during winter and spring and dried over summer and autumn; however, because it was a terminal basin, it was most likely a saline or brackish system (depending on inflows and water level) (Ecological Associates 2009b). The construction of the South East drainage scheme converted Lake Hawdon North to a flow through system (i.e. the system is hydraulically similar to a floodplain) with a shorter hydroperiod and lower salinity. Drain L passes through Lake Hawdon North (the drain was excavated from the bed of the lake) and can pass relatively high flows without spilling into the lake (Ecological Associates 2009b). Inundation of the lake occurs when flows exceed the capacity of the drain within the wetland (Ecological Associates 2009b). The reinstatement of the pre-European hydrology is not feasible; therefore, it has been decided that maintaining or improving the current ecological character of the lake is appropriate.

The SEFRP has the potential to reduce the frequency, depth and duration of inundation of Lake Hawdon North due to reduced water availability downstream of the diversion points (Ecological Associates 2009b). Changes to the hydrological regime brought about by the SEFRP are likely to result in changes to the ecological character of Lake Hawdon North. However, these changes may be mitigated by the construction of regulator at the outlet of Lake Hawdon North (Ecological Associates 2009b). A regulator on the outlet will provide the ability to maintain or increase the current hydroperiod with a smaller volume of water (allowing water to be diverted into other wetlands and the Coorong) and provide managers with a large degree of flexibility. Such a structure would enable managers to intensively manage the hydrograph (if required) to achieve the desired ecological outcomes.

The aim of this component is to provide a critique of the methodology used to determine the ecologically ideal hydrograph for Lake Hawdon North as outlined by Ecological Associates (2009a) and Taylor (2011).

2.3 Methodology

The methodology used to determine the ecologically ideal hydrograph for Lake Hawdon North is described in Ecological Associates (2009a) and Taylor (2011). They proposed the use of Wetland Vegetation Components (WVC), the semi-discrete plant communities present at different elevations in wetlands (*sensu* Spence 1982) to determine the target hydrological regime for a wetland. Using WVCs the target hydrograph for the wetland is determined by providing a water regime that will support the WVCs present (or WVCs determined by management targets) in the wetland.

The critique of the aforementioned method is based on expert opinion (the authors of this section) and supported by published studies where possible.

2.4 Results

Designing a hydrograph based on the requirements of vegetation communities (WVCs) is appropriate for Lake Hawdon North because it is the biotic group for which there is the largest amount of current information (Ecological Associates 2009a; Ecologcial Associates 2009b). In addition, it is possible to gain a qualitative indication of the change in the extent of dominant plant communities through time using historical aerial photography. Information about less-dominant biotic groups should be considered once it becomes available, to determine whether there are any refinements that need to be considered with regards to water regime requirements for the lake to meet the needs of all biotic groups.

Table 6 (Taylor 2011) presents ecologically ideal hydrograph based on the WVCs present in Lake Hawdon North. This hydrograph would probably maintain the current plant community and represents a seasonal hydrograph of winter/spring flooding and summer/autumn drawdown. Inter-annual variability is also included in this hydrograph and under managed inundation could reflect the climatic conditions at the time (i.e. lower water levels in dry years and higher water levels in wet years). However, this may not be appropriate during an extended drought where it could be desirable to increase water levels and extend the hydroperiod beyond what is occurring naturally to maintain ecological character or meet specific management targets.

Table 6. Ideal hydrograph to support the wetland vegetation of Lake Hawdon North based on the method of Ecological Associates (2009a). Depths refer to the deepest point of the wetland (from Taylor 2011).

		Duration (months)	
Depth (m)	**Water Surface Elevation (m AHD)**	**Annual**	**1 year in 3**
dry	<3.65	4	2
waterlogged	3.65	2	2
0.2	3.85	2	2
0.4	4.05	2	2
0.6	4.25	2	2
0.8	4.45	0	2

Table 6 represents a hydrograph that will maintain the current plant community, which may not be desirable. Taylor (2011) and Ecological Associates (2009b) reported significant *Melaleuca halmaturorum* encroachment onto the bed of Lake Hawdon North since 1981. Therefore, periods of higher water levels (4.6-4.8 m AHD) may be required one year in three (on average) for two months, and increased frequency and duration of water levels between 3.65 and 4.45 m AHD (Table 7). Such a hydrological regime would arrest *Melaleuca halmaturorum* encroachment onto the wetland bed and restrict this species to the fringes. It would also promote sedges and rushes such as *Baumea* spp. and *Juncus* spp. in areas that flooded and dried each year and the lower elevations would support amphibious herblands.

Table 7. Proposed hydrograph to reverse *Melaleuca halmaturorum* encroachment on to the bed of Lake Hawdon North.

		Duration (months)	
Depth (m)	**Water Surface Elevation (m AHD)**	**Annual**	**1 year in 3**
dry	<3.65	4	2
waterlogged	3.65	4	2
0.2	3.85	4	2
0.4	4.05	4	2
0.6	4.25	4	2
0.8	4.45	3	2
1.0	4.65	0	2

2.5 Discussion

The method used to determine the ecologically ideal hydrograph using WVCs is appropriate for Lake Hawdon North because it is the biotic group, which there is the largest amount of current information (e.g. Ecological Associates 2009a; Ecologcial Associates 2009b). However, some modification may be required if there is a management aim to change the plant communities present, which is identified by Ecological Associates (2009a) as a shortcoming of the method. Nevertheless, the water regime requirements of the target WVCs can be used to determine the hydrograph.

The suggested changes from the original hydrograph have not taken into consideration flooding of surrounding land, which may occur at water levels above 4.45 m AHD. If this is the case, increased frequency and duration of inundation at 4.45 m AHD should still result in reversal of *Melaleuca halmaturorum* encroachment because they are intolerant of continual inundation for longer than 14 weeks (especially as juveniles) (Denton and Ganf 1994) and will not germinate whilst submerged (Nicol and Ganf 2000).

A total of 5.6 GL is required to fill Lake Hawdon North to 4.30 m AHD (AWE 2009). Taylor (2001) reported that total annual Drain L flow was less than 5.6 GL only on two occasions in the 22 years where complete flow records exist. Therefore, under current flow conditions, it is possible to fill Lake Hawdon North nearly every year using a regulator. However, filling Lake Hawdon North every year may not be desirable and, providing the water requirements of systems downstream are met, the excess water could be diverted in the South Lagoon of the Coorong.

Using WVCs to determine wetland hydrology does not take into consideration other biota. Several small-bodied fishes of conservation significance, including the largest population of the critically endangered (in South Australia) Australian mudfish and the threatened dwarf galaxias, have significant populations in Lake Hawdon South and Drain L (Hammer 2002; Hammer 2009; Hammer and Tucker 2011). No Australian mudfish or dwarf galaxias were recorded in the first ever fish survey of Lake Hawdon North undertaken in spring 2011 and it was concluded that the current conditions were unsuitable in Lake Hawdon North (Hammer *et al.* 2012). Australian mudfish and dwarf galaxias have the capacity to aestivate, which indicates an adaptation for persisting in temporary wetlands. Therefore, the proposed hydrograph for Lake Hawdon North should favour these species unless the increased duration and frequency of flooding puts them at a competitive disadvantage to other species. Very little is known on the life history and movement of Australian mudfish, particularly in the South East. Australian mudfish may be diadromous and if so, movement between marine/estuarine and freshwater environments will represent an obligate life history process. If this is the case, fish must move through Lake Hawdon North in order to migrate to Lake Hawdon South. Hence, the timing of downstream spawning migrations and corresponding but opposite upstream migrations of juveniles into Lake Hawdon South must be known when designing the regulator, fishway and their operation.

The obligate freshwater species southern pygmy perch have also been recorded in Drain L and Lake Hawdon North (Hammer 2002; Hammer *et al*. 2012). These species require permanent freshwater refuges with dense submergent vegetation (Hammer 2002), which would only be present in Drain L proper. Therefore, it is important that Drain L flows year round and these permanent fresh pools are maintained.

An exercise that was recently undertaken regarding the potential operation of the Chowilla environmental regulator (the approach is documented in Wallace and Whittle 2012) is recommended for the proposed Lake Hawdon North outlet regulator. The exercise involved managers, river operators, hydrologists and ecologists working through a real 15 year hydrograph step by step (four week intervals) and documenting regulator operation given the antecedent conditions, modelled natural flow, predicted flow, current flow conditions and ecological objectives. The hydrograph was revealed in four week intervals (participants could not see the whole hydrograph) to simulate real time operation of the regulator. Whilst the information required would be different for Lake Hawdon North, there are 22 years of complete flow records that could be used to simulate real time operation of regulator given antecedent conditions, current flow, ecological objectives, requirements of downstream wetlands and potential diversion to the South Lagoon of the Coorong.

A flexible, adaptive approach needs to be taken to applying the recommended hydrograph. Changes to the hydrograph must be possible should unacceptable changes to the character of the system occur as a result. This will require a monitoring program with results available to managers in a timely fashion to enable decisions to be made in real time. This can be achieved by selecting indicators or trigger levels for management actions; however, indicators need to be supported by a sufficient data to ensure they are defensible. Finally, factors other than hydrology such as grazing and mining need to be taken into consideration when managing Lake Hawdon North, which have not been addressed. Table 8 lists a series of research questions and knowledge gaps regarding the ecology and hydrology of Lake Hawdon North

Table 8. Knowledge gaps and further research regarding the ecology and hydrology of Lake Hawdon North.

Question	Justification	Priority
What are the biotic communities in Drain L proper?	This section of the lake, despite being only a small percentage of the total area) represents the wettest elevations and there is no mention of provision of water for these habitats. If drain L water is diverted, there needs to be sufficient water to maintain these habitats (especially permanently inundated areas which may be import refuges) and prevent deterioration of water quality. This may not be a problem if permanent flow is maintained in Drain L is maintained.	Immediate: needs to be undertaken prior to the construction of the regulator.
What are the potential impacts of climate change on Drain L flow and the potential impacts for the biota?	The regulator may be tool that can mitigate the impacts of climate change to maintain the character of Lake Hawdon North.	Within 2-3 years operation, this will largely be a modelling project.

Question	Justification	Priority
What is the potential for blackwater events?	There is potential for terrestrial species to colonise the wetland bed during the drawdown phase, which will decompose when flooded deoxygenating the water column. The greatest risk is when high elevation areas are flooded.	Immediate: needs to be undertaken prior to the construction of the regulator.
What are the ecosystem services that Lake Hawdon North provides at the landscape scale and are there any specific ecosystem services provided by Lake Hawdon North not provided by other wetlands in the region?	There has been extensive draining of wetlands in the South East; therefore, any remnant wetlands are regionally important for biodiversity conservation. There is little information regarding the role that Lake Hawdon North plays in the landscape and whether other wetlands in the region play the same role. In addition, will this role be put at risk or change by construction of the regulator.	Immediate: needs to be undertaken prior to the construction of the regulator.
What are the key processes, other than hydrology, that determines the composition of the biotic communities?	Grazing and mining is undertaken in Lake Hawdon North and the impacts of these activities are not well understood.	Within 2-3 years operation or ongoing, could be answered mainly through well a designed monitoring program.
What are the functions of specific WVCs?	Patterns and the processes behind the patterns in South East wetlands have been investigated but the link between pattern, process and function is not well understood. Hence, the role that WVCs play in wetland function (i.e. primary production, habitat, nutrient cycling) are not well understood.	Within 2-3 years operation or ongoing, could be answered mainly through well a designed monitoring program and targeted research questions throughout the region.
Understanding the temporal variability of the system is needed to develop the hydrograph and determine limits of acceptable change.	All of the studies undertaken to date have been one off snapshots and temporal changes (seasonal or longer-term) have not been investigated.	Immediate: needs to be undertaken prior to the construction of the regulator but will require ongoing and could be answered through well a designed monitoring program.

Question	Justification	Priority
Fish movement within the Drain L – Lake Hawdon North System. What species are likely to utilise a fishway if constructed on the proposed regulator? What is the timing and direction of movement of the above species?	Whilst there is information regarding the fish community present in Lake Hawdon North and the Drain L system, these have been snapshots and there is little information regarding movement of fish (spatial and temporal) through the system. Two of the species present may be diadromous and require passage between the lake and sea.	Immediate: needs to be undertaken prior to the construction of the regulator but will require ongoing and could be answered through well a designed monitoring program.
Backwater effect between Lake Hawdon North and Lake Hawdon South and the impact of higher water levels and increased duration of inundation.	It is likely that there is a backwater effect between Lake Hawdon North and Lake Hawdon South. Extended inundation in Lake Hawdon North may result in extended inundation in Lake Hawdon South, which will have consequences for the biota in Lake Hawdon South.	Immediate: needs to be undertaken prior to the construction of the regulator but will require ongoing and could be answered through well a designed monitoring program.

Chapter 3. Lake Hawdon Inundation Regime Characterisation by Remote Sensing

Ken Clarke, Michelle Clark and Megan Lewis

University of Adelaide

3.1 Summary

Lake Hawdon North and Lake Hawdon South are neighbouring wetlands inland from Robe in the south-east of South Australia. Changes in land cover from native vegetation to cropping and pasture, and the installation of artificial drainage channels have altered the natural inundation regime of both lakes. To improve wetland management and water allocation budgets it is necessary to understand Lake Hawdon's historical inundation regime.

Drain L, a major drainage channel that runs through and feeds Lake Hawdon North, may carry more than enough water to maintain the wetland communities of the two lakes. If this is the case excess water could be diverted for other environmental needs. However, while Drain L flow records exist, there are no records of the extent of inundation of Lake Hawdon. While inundation levels may be estimated with hydrological models, the accuracy of these models is unknown. Consequently the environmental water requirements of Lake Hawdon (timing and volume of water) are currently unknown.

This project aimed to characterise the historical inundation regime of Lake Hawdon using remote sensing methods to provide a means of validating hydrological models. Furthermore, the project aimed to map historic and current vegetation community extent for Lake Hawdon to provide evidence for historic vegetation community distribution and structure, and allow informed management of the Lake Hawdon inundation regime.

The three specific aims of this project were to:

1. Characterise the **temporal pattern of inundation** with MODIS satellite imagery (from 2000 to 2011), to provide insight into the typical timing and duration of inundation and vegetation growth;
2. Map the **historical extent of inundation** with Landsat satellite imagery (from 1989 - 2011) on or near high drain flow periods, so that an understanding of the relationship between drain flow volume and inundation extent might be developed; and
3. Map decadal **change in vegetation communities** within the lakes from aerial photography (from 1958 to 2008).

Temporal pattern of inundation

Complete temporal coverage of MODIS satellite imagery from 2000 to 2011, one image every 16 days, was used successfully to determine the timing and duration of inundation in Lake Hawdon. In Lake Hawdon North timing and duration were reasonably consistent, usually beginning in May/June and lasting until October, or in some years as late as December. In Lake Hawdon South the timing and duration of inundation was likewise quite consistent. However, while the inundation events in Lake Hawdon South started at the same time, they usually lasted one to three months longer.

Historical extent of inundation

The inundation extent was mapped from digital analysis of Landsat satellite images on 18 dates from 1989 to 2008 and presented as maps with tabulated inundation extent. The Landsat-mapped inundation extent and same-month Drain L flow were very strongly correlated (Lake Hawdon North R^2 = 0.83 and Lake Hawdon South R^2 = 0.66), providing confidence in the Landsat inundation mapping. The maps provided a powerful visualisation of the temporal inundation extent, and objective historical evidence for evaluating the accuracy of hydrological models.

Change in vegetation communities

Major vegetation communities were mapped successfully through visual interpretation of aerial photography for 1958, 1988, 1999 and 2008. The overall story of vegetation community in Lake Hawdon is one of invasion and change. In 1958 mixed communities accounted for only a small area of Lake Hawdon South, suggesting that the inundation regime in Lake Hawdon North and South had been relatively stable for a long time. By 2008 mixed communities accounted for more of Lake Hawdon South, and the majority of Lake Hawdon North, suggesting that there has been a considerable change in the inundation regime of Lake Hawdon North, and a moderate inundation regime change for Lake Hawdon South.

Conclusions

This study succeeded in characterising the historical inundation regime of Lake Hawdon using three complementary remote sensing methods. Furthermore, the results demonstrate that analysis of past remote sensing records can provide valuable objective evidence of historic environmental change to assist current and future management decisions.

3.2 Introduction

Lake Hawdon North and Lake Hawdon South are neighbouring wetlands inland from Robe in the south east of South Australia. Due to land cover change, from native vegetation to crop and pasture, and the installation of artificial drainage channels, the inundation regime of Lake Hawdon may have changed over the last six decades. However, the nature and magnitude of changes, if any, is unknown.

The University of Adelaide Spatial Science and Remote Sensing Group (SSRSG) was engaged by the DEWNR to characterise the historical inundation regime of Lake Hawdon using remote sensing methods.

Scope of work

This study focussed on Lake Hawdon North and Lake Hawdon South (Figure 10), linked seasonally inundated wetlands in the south east of South Australia. As defined by the DFW vegetation mapping (Figure 10), the wetlands cover 2517 ha and 3219 ha respectively and are among the largest wetlands in the region.

The three main aims of the project were to:

1. Characterise the temporal pattern of inundation with MODIS imagery (from 2000 to 2011), to provide insight into the typical timing and duration of inundation and vegetation growth;
2. Map the extent of inundation with Landsat imagery (from 1989 - 2011) on or near high drain flow periods, so that an understanding of the relationship between drain flow volume and inundation extent might be developed; and
3. Map decadal change in vegetation communities within the lakes from aerial photography (from 1958 to 2008).

Within the broader project context, outputs from components 1 and 2 aimed to provide a new means of validating hydrological models of Drain L flow and lake inundation. The history of vegetation communities resulting from component 3 sought to improve understanding of wetland response to past and recent hydrological regimes in the lakes.

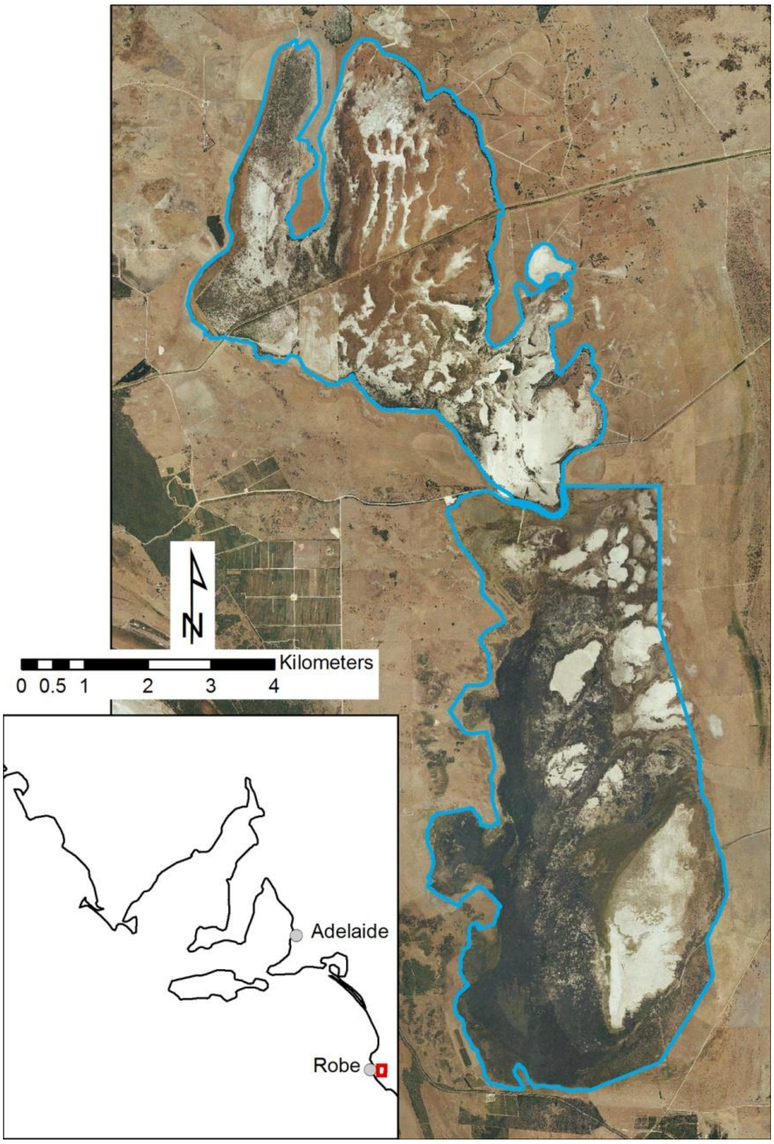


Figure 10. Location of Lake Hawdon North and Lake Hawdon South.

3.3 Methods

Data

MODIS satellite imagery

The MODIS instrument records data in 36 spectral bands ranging from 0.4 µm to 14.4 µm and in spatial resolutions ranging from 250 m to 1 km. The Terra and Aqua polar-orbiting satellites each carry a MODIS instrument and together image the entire Earth surface every 1 to 2 days. In addition to supplying the raw reflectance data, NASA produces several highly validated image products from MODIS data, including the MOD13Q1 vegetation indices product.

This project used the MOD13Q1 version 005 Normalised Difference Vegetation Index (NDVI) product, which is available at 250 m resolution once every 16 days. The MOD13Q1 NDVI is a cloud-free composite product created from all MODIS images over a given area within a 16 day period, and prioritising retention of image elements (pixels) with no cloud-contamination and near to nadir (looking directly down) view angle.

Complete temporal coverage of MOD13Q1 NDVI was acquired from the start of the MODIS archive (18 February 2000) to 18 December 2011. In total 272 MOD13Q1 images were acquired and analysed in this project. The first date of each image composite, the 'image start day' is presented in Appendix 1.

Landsat 5 and 7 imagery

The Landsat 5 and 7 satellites carry the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors. For the purposes of this project, the TM and ETM+ sensors can be considered identical, and will be referred to simply as the 'TM sensor'. The TM sensor collects data in seven spectral bands covering blue (band 1), green (band 2), red (band 3), near-infrared (band 4), mid-infrared (bands 5 and 7), and the far-infrared, or thermal (band 6). Spatial resolution is 30 m for all bands, except the thermal (band 6), which is 120 m (TM) or 60 m (ETM+). Each Landsat satellite passes overhead once every 16 days.

This project used georectified Landsat imagery downloaded from the USGS Global Visualization Viewer (GLOVIS). As inundation was expected to result from significant drain flow, the drain flow records supplied by DFW were examined to determine periods of major drain flow within each year from 1989 to present. A search was conducted for Landsat imagery within the month of peak drain flow, or one month either side of major drain flow, and all cloud-free images were acquired. Where no cloud-free imagery was available within the three months around peak drain flow a search was conducted for any cloud-free imagery within that year. In some years no cloud-free imagery was available. In total 18 Landsat 5 and 7 images were acquired and analysed (Table 9).

Table 9. Date of acquisition of Landsat images for inundation extent mapping.

Landsat imagery dates		
20-Nov-89	24-Aug-92	11-Oct-92
24-Oct-99	09-Jul-01	25-Jul-01
07-Sep-01	14-Sep-02	16-Aug-03
20-Jul-05	08-Aug-06	26-Jul-07
27-Aug-07	27-Jul-08	06-Oct-10
21-Jul-11	22-Aug-11	07-Sep-11

Aerial photography

Approximately decadal aerial photography coverage of Lake Hawdon from 1958 to 2008 was obtained from Department of Environment and Natural Resources (DENR) archives to enable mapping of change in vegetation communities. The photographs were scanned at 800 dpi by DENR and provided as digital files. The spatial and spectral characteristics of the imagery varied from date to date (Table 10).

Table 10. Spatial and spectral characteristics of aerial photography.

Year of photography	Photo spatial scale	Colour / B&W
1958	1 : 59,000	B&W
1969	1 : 67,000	B&W
1978	1 : 40,000	B&W
1988	1 : 40,000	False-colour infrared
1999	1 : 40,000	False-colour infrared
2008	90 cm digital	Pseudo true-colour

Frequency of inundation from MODIS satellite imagery

The Normalised Difference Vegetation Index (NDVI) is potentially a useful tool for monitoring vegetation growth and death cycles, as well as water inundation and drying cycles. The NDVI is based the contrast between red (R) and near infra-red (NIR) reflectance. There is a large difference in R and NIR reflectance for green vegetation, and a small difference for other cover types (

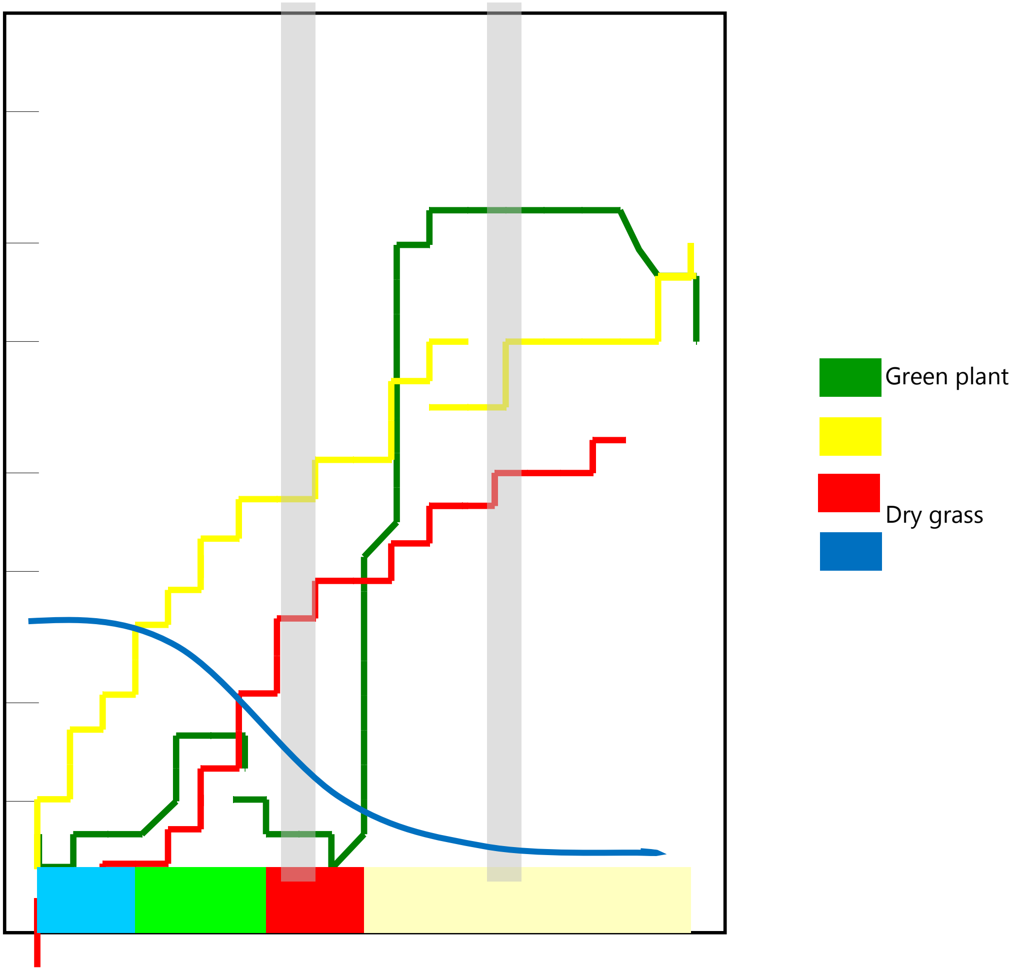


Figure 11. Reflectance signatures of plants, soil and water, showing the large difference between red and near infra-red reflectance for green plants.

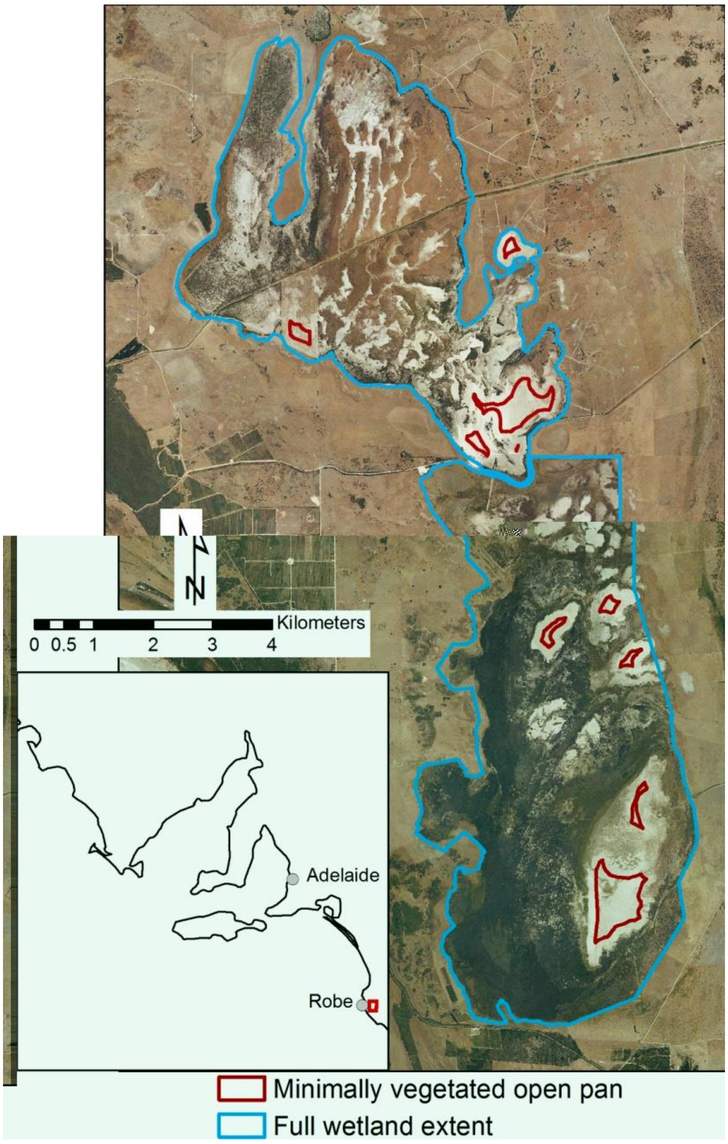


Figure 12. Lake Hawdon full wetland extent, and minimally vegetated open pan extent for the purposes of analysis.

Mean NDVI values were extracted from the MODIS time-series for Lake Hawdon North and South, as defined by the DFW vegetation mapping for these two areas (Figure 10). To aid in the interpretation of inundation frequency, and to allow examination of the impact of inundation on vegetation growth, separate temporal traces were produced for the entire wetland extent and for a minimally vegetated open pan sub-area (henceforth 'open pan') (Figure 12). It was hoped that the NDVI signal from the open pan area would be primarily influenced by inundation, and less confounded by vegetation growth than the NDVI signal from the entire wetland extent.

Extent of inundation from Landsat satellite imagery

Two established remote sensing methods for identifying inundation were trialled in the study area; unsupervised classification (*e.g.* Johnston and Barson 1993) and Band 5 (infra-red) density slicing (*e.g.* Thomas et al. 2011). Landsat band 5 density slice classification exploits the very strong absorption of mid-infrared radiation by water, which contrasts with the moderate to strong mid-infrared reflectance of most other land covers. Water boundaries can be interrogated to determine the maximum mid-infrared reflectance expected for water in a given image. This threshold is then applied to the image: all pixel values below this threshold are mapped as inundated, and all values above are mapped as dry.

In the absence of field validation data, success of these methods was evaluated against known inundated areas (Lake Eliza and Lake George), and known dry areas (the nearby coastal dunes).

The methods were trialled on two Landsat images from periods with differing levels of inundation. The first image was acquired on 11 October 1992 from a period of high inundation, and the second image was acquired on 9 July 2001 during a period of moderate inundation.

The Band 5 density slicing method was less time-consuming, and marginally more accurate than unsupervised classification. Hence the Band 5 density slicing method was used for all Landsat inundation extent mapping in this report. Prior to density slicing, all images were masked to the wetland extent shapefile to minimise visual clutter in the inundation maps.

Full extent of inundation mapping, 1992

Ben Taylor (DFW) requested a map of inundation extent not restricted to the wetland-extent shapefile during a period of major inundation. The largest drain flow rate in the period 1989 to 2011 was 306.66 ML/day, and occurred closest to the 11 Oct 1992 Landsat image. Un-bounded inundation extent mapping was performed for this date.

Inundation area and interpretation

Inundation area was calculated from each image for Lake Hawdon North, Lake Hawdon South, and the combined North and South Lake Hawdon. The area was calculated from the number of image pixels flagged as inundated, multiplied by the area of a Landsat pixel (30 m x 30 m = 900 m^2).

Inundation area is expected to be determined by current or recent drain flow rates. To examine this and to validate the Landsat inundation extent mapping, the mapped inundation extent on each image date was compared to the current month drain flow, and the drain flow from previous months, up to three months previous.

Vegetation community change from aerial photography

Changes in vegetation communities in Lake Hawdon North and South from 1958 to 2008 were mapped by expert interpretation of aerial photography. An interpreter is trained to recognise photograph characteristics (colour, intensity, texture and pattern) of known ground classes in one image date, and then applies their understanding of these characteristics to map the classes of interest on other image dates.

In this project the expert trained on the 2008 aerial photographs and existing Lake Hawdon vegetation mapping produced by Ecological Associates in 2008 and 2009 using a combination of photo interpretation and extensive field verification. Despite this existing vegetation mapping, new interpretation was performed on the 2008 aerial photography, because classes discernable through visual interpretation alone were not identical to those derived from image interpretation augmented by field surveys as presented by Ecological Associates (2008, 2009). This ensured the 2008 vegetation map was comparable to the earlier aerial photography derived-maps.

The vegetation communities were then mapped from the 1958, 1988, 1999 and 2008 aerial photography, displayed at a scale of 1:6000. Where reasonably pure vegetation communities were present the outer boundary of each community was digitised. For mixed communities a separate mixed class was created, defining the full area inhabited by both species. Mapping was restricted to the area mapped by Ecological Associates.

After consultation with Ben Taylor (DFW), it was decided that the following vegetation cover classes could be resolved from the aerial photography based on colour, intensity, texture and pattern:

- Sedgeland (sparse, medium and dense)
- *Melaleuca halmaturorum* (established, juvenile)
- Open pan
- *Gahnia* sp. (sparse, medium, and dense)
- Herbland (including non-native grassland)

Visual keys for each class (Table 11) were extracted from 2008 imagery, to be used as reference images for all further vegetation mapping. Field characteristics of these vegetation classes, as described by Ecological Associates (2008, 2009) are presented in

Table 11. Vegetation classes and corresponding visual keys for types mapped in Lake Hawdon North and South.

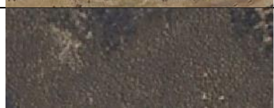
Vegetation Class and density	Visual key	Colour and intensity	Texture
Open pan		Very light white to light beige	Very smooth
Gahnia sp. (sparse)		Light brown	Slightly rough and very patchy
Gahnia sp. (medium)		Light brown	Slightly rough with some patchiness
Gahnia sp. (dense)		Light to dark brown	Slightly rough and clumped
Herbland		Pale beige to pale brown	Smooth
Melaleuca halmaturorum (established)		Dark green to dark brown	Rough and clumped
Melaleuca halmaturorum (juvenile)		Dark green to dark brown	Very rough and patchy
Sedgeland (sparse)		Dark brown to purple brown	Slightly rough and very patchy
Sedgeland (medium)		Dark brown to purple brown	Smooth and mottled
Sedgeland (dense)		Dark brown to purple black	Smooth

Table 12. Field characteristics of vegetation classes as described by Ecological Associates (2008, 2009).

Vegetation class	Field Characteristics
Gahnia sp.	Tall sedgeland species that grow in sparse to dense tussocks and can be saline tolerant.
Sedgeland	Low growing rush-like species that grow in dense, tufted, homogenous stands with low floristic diversity.
Herbland	Low growing short grasses and forbs
Melaleuca halmaturorum	Tall evergreen shrubland ranging from 2-5m in height

3.4 Summary

Inundation frequency: NDVI profile interpretation guide

In simple terrestrial systems an NDVI value of approximately 0.2 is indicative of exposed soil, or dead vegetation. NDVI values up to 0.8 are indicative of strong vegetation growth, and deep water can result in NDVI values of 0.0 or lower. In this complex system, where strong vegetation growth is present in association with extensive inundation the observed NDVI values will be the result of a combination of these influences.

As a guide, NDVI values below 0.2 should be considered indicative of extensive inundation, and values above 0.4 indicative of extensive and strong vegetation growth. However, it is essential to remember that these are not exclusive conditions, and an NDVI value below 0.2 does not mean there is little or no vegetation growth, only that inundation is having a stronger effect on the index than chlorophyll is. Likewise, NDVI values above 0.4 do not mean that there is no inundation, but instead mean that the chlorophyll signal is having a greater impact on the NDVI than the inundation. In this latter case, extensive inundation may result in strong growth of floating and anchored vegetation which will physically reduce the visible water area, and overwhelm the water effect on NDVI.

Interpretation is illustrated with an example in Lake Hawdon North.

NDVI profile interpretation

The following is a detailed explanation of our interpretation of timing and duration of inundation in Lake Hawdon North and South based on the temporal NDVI traces in Figure 13. A simplified summary of our interpretation of inundation duration is also presented in that figure as a blue line denoting the period when we are confident there was extensive inundation of the open pan area. Figure 13 also includes the flow rate in Drain L, which supplies Lake Hawdon North.

Interpretation can most easily be started by examining the open pan and total NDVI traces for Lake Hawdon North for 2006, and 2007. Rainfall and drain flow in 2006 was the lowest in the time covered by the NDVI traces, and was higher in 2007, but still very low. The total NDVI trace shows a steep rise around May 2006, indicating strong vegetation growth despite poor autumn rains. NDVI remains high until October then declines to a minimum in December 2006 and remains at that value until May 2007 when the pattern repeats.

Since there was minimal inundation in this period, this pattern of growth and senescence is a good typical example of the vegetation NDVI temporal signature we should expect for Lake Hawdon without the confounding effect of inundation.

This confounding effect is revealed through examination of the open pan temporal trace for the same 2006/07 period. The NDVI trace starts January 2006 around 0.3, indicating minimal vegetation and no inundation. The NDVI value increases (with some variation) to October 2006, the same time at which the total NDVI trace began to decline, then reaches a minimum value of 0.2 (indicative of bare soil or completely dead vegetation) at the end of December 2006 and remains there until May 2007. However, whereas the total NDVI trace for 2007 was virtually the same as for 2006, the open pan NDVI trace exhibits a key difference. There was more rain and higher drain flow in 2007. The open pan NDVI trace declines steeply from a value of 0.2 to approximately 0.03, a value only achievable due to inundation. This should be interpreted as inundation reducing the NDVI value, with minimal confounding from vegetation in the open pan area due the dry antecedent conditions. The open pan NDVI values then increase to 0.2 in October 2007, indicating the end of extensive inundation.

Finally, the total NDVI trace illustrates the combined vegetation/inundation effect on NDVI at the time that the open pan trace reaches its minimum value. There is a dip in the otherwise broad NDVI peak. This is most likely due to inundation decreasing the overall NDVI. As the inundation level declines (open pan trace increases) the vegetation continues to grow strongly, the confounding effect of inundation is removed and the total NDVI trace increases again and remains high until dry conditions in late spring cause vegetation vigour to decline.

This interpretation method was applied to estimate the timing and duration of inundation and vegetation growth in Lake Hawdon North, and then Lake Hawdon South.

NDVI profile interpretation, Lake Hawdon North

Interpretation of the 2006/07 period is explained in detail in the previous section.

Prolonged periods of very low values (open pan trace) in 2000, 2001, 2002, 2003, 2004, 2008, 2009, 2010 and 2011 are probably indicative of extensive and prolonged inundation. The "noise", or higher spikes in the time traces, is likely due to growth of floating vegetation in response to inundation. Concurrent peaks in the total NDVI trace indicate extensive vegetation growth across the wetland associated with these inundation periods. Dips in, or suppression of these peaks in 2000, 2002, 2003, 2004, 2008, 2009 and 2010 are likely due to extensive inundation in these years, reducing the overall NDVI of the wetlands.

The timing and duration of inundation appears reasonably consistent, usually beginning in May/June and lasting until October (2003, 2004, 2005), or sometimes as late as December (2000, 2002, 2008, 2009).

NDVI profile interpretation, Lake Hawdon South

Interpretation of vegetation growth and inundation timing in Lake Hawdon South is less tractable than Lake Hawdon North, due to the more extensive vegetation and smaller open pan extent. However, the same general patterns can be seen in the South and North lakes.

Starting with the two driest years, 2006 and 2007, we see almost exactly the same pattern as for Lake Hawdon North. Examining the total NDVI trace, January 2006 starts with moderate NDVI values, then increases steeply in May, remains high until October, declines to a minimum in December, and remains low until May 2007 when the same pattern repeats.

The temporal pattern of open pan NDVI trace for the same period, is again very similar to that for Lake Hawdon North. In 2006 the open pan NDVI trace follows the same annual vegetation growth pattern as the Total NDVI trace. In 2007 the open pan NDVI trace begins low, rises briefly (indicating some vegetation growth) then dips steeply in May 2007 from a value of 0.32 to 0.15. Ignoring some variation, probably due to confounding floating vegetation, the open pan NDVI trace remains very low until mid-December 2007, indicating that at least the open pan areas were inundated until this time. By comparison, Lake Hawdon North open pans were only inundated with certainty until October.

The inundation signal is more variable in Lake Hawdon South, but periods of generally low values (open pan trace) from May to December, or even January in the following year in 2000, 2001, 2002, 2003, 2004, 2005, 2007, 2008 and 2011 are probably indicative of extensive and prolonged inundation.

As in Lake Hawdon North, the variation in these inundation periods is probably due to growth of floating vegetation in response to inundation. Likewise, concurrent peaks in the total NDVI trace indicate extensive vegetation growth across the wetland associated with these inundation periods. The dips in growth peaks in the total NDVI trace, or suppression of the NDVI peaks, due to inundation, are less obvious in Lake Hawdon South. However, dips are still obvious on some occasions (e.g., September 2002), and suppression of the NDVI growth signal, due to inundation is probably responsible for the broad, lower than expected growth peaks (0.7 - 0.8 would be expected for strongly growing not-water-limited vegetation).

Inundation timing in 2009 and 2010 is difficult to interpret, and we caution against putting any weight on inundation duration estimates for these two years. Steep increases in open pan NDVI beginning in March probably result from vegetation growth due to rainfall. The steep decrease in NDVI values later in each year, in June or July, is probably due to inundation, rather than vegetation senescence. However, it is difficult to be certain, and NDVI

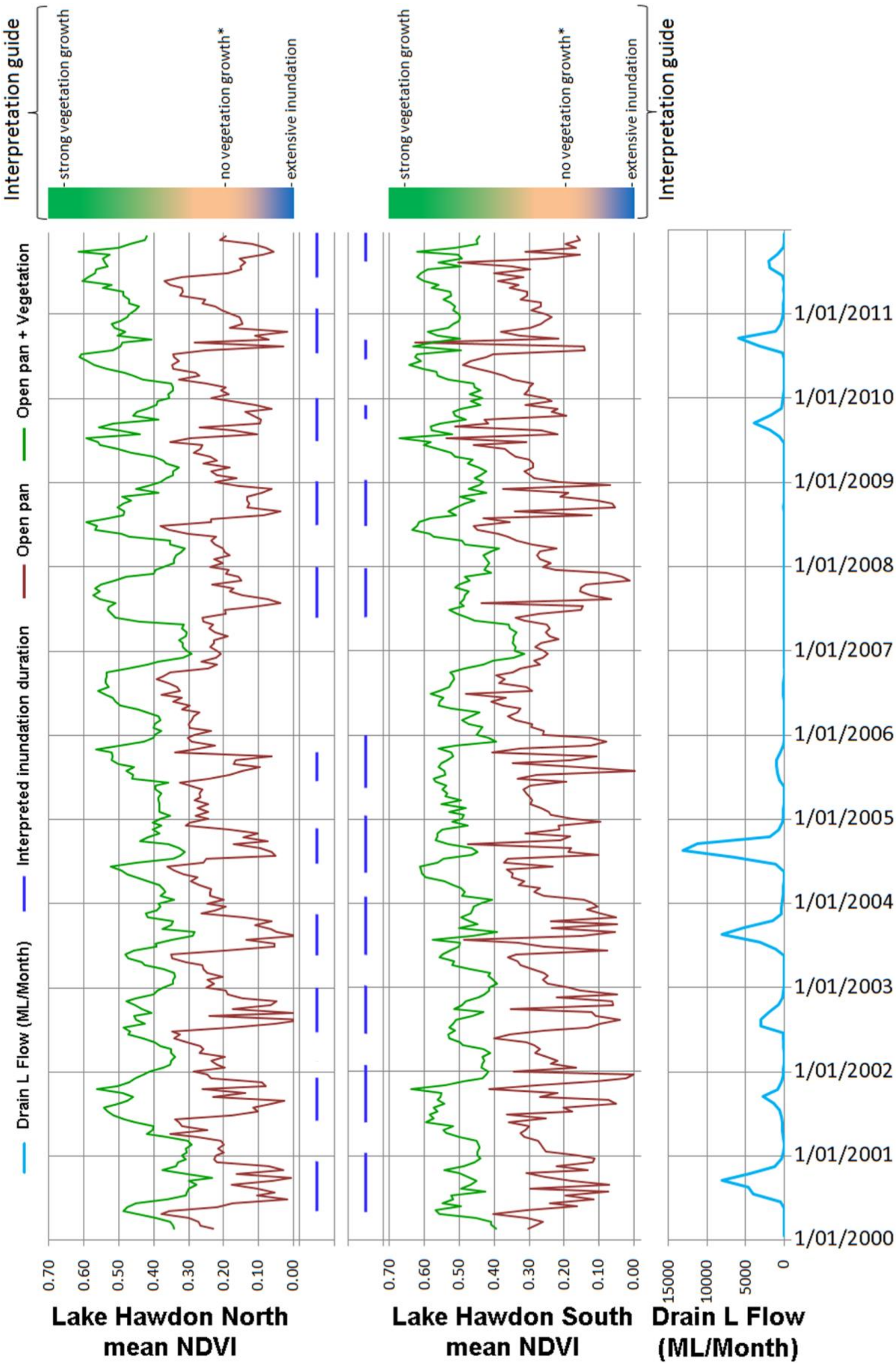


Figure 13. Temporal NDVI profiles for Lake Hawdon North and South, derived from MODIS imagery and Drain L flow records. Figure also contains expert interpretation of the timing and duration of extensive inundation of the open pan areas (blue line).

Inundation extent

This section presents inundation extent, mapped objectively by image analysis of Landsat imagery. Maps of inundation extent (constrained to the wetland extent shapefile) on each of the 18 Landsat image dates are presented first, followed by an unconstrained map of inundation extent for the Landsat image date (11 October 1992) closest to peak drain flow. This unconstrained inundation map allows examination of the effect of maximum inundation extent events on neighbouring properties. Inundation areas (ha) are presented for each Landsat image date for Lake Hawdon North, Lake Hawdon South, and the combined total Lake Hawdon area. Finally, this section finishes with an analysis of correlation between mapped inundation area and drain flow from the calendar month in which the Landsat image was acquired, and with drain flow lagged up to three calendar months.

Inundation map interpretation

Interpretation of the inundation extent maps is relatively simple. We are highly confident that the areas shown in blue are inundated. However, the approach we have used is inherently conservative, and some inundated areas will not have been detected due to vegetation over-storey obscuring standing water. This effect can be illustrated by comparing the far south-western portions of the inundation extent maps for 11 October 1992 and 16 August 2003. On both dates water levels were very high, yet some of the lowest elevation parts of Lake Hawdon South (the south-western corner) were omitted in the inundation maps. Comparing all the Landsat image dates, this area is rarely mapped as inundated, and yet is probably the most frequently inundated portion of the combined Lake Hawdon North and South wetlands. The sedgeland is so well watered and dense in this area that the vegetation (high infra-red reflectance) overwhelms the water (low infra-red reflectance) in many of the Landsat pixels in this area.

To reiterate, these inundation extent maps are conservative and areas mapped have been done so with a high degree of certainty. On the other hand, lower confidence should be given to areas not mapped as inundated, and judgement should be exercised in interpretation. Lower elevation, high vegetation cover areas not mapped as inundated may actually be inundated but covered by vegetation canopy. Higher elevation areas, or areas with low vegetation cover that are not mapped as inundated are very unlikely to be inundated.

Inundation maps

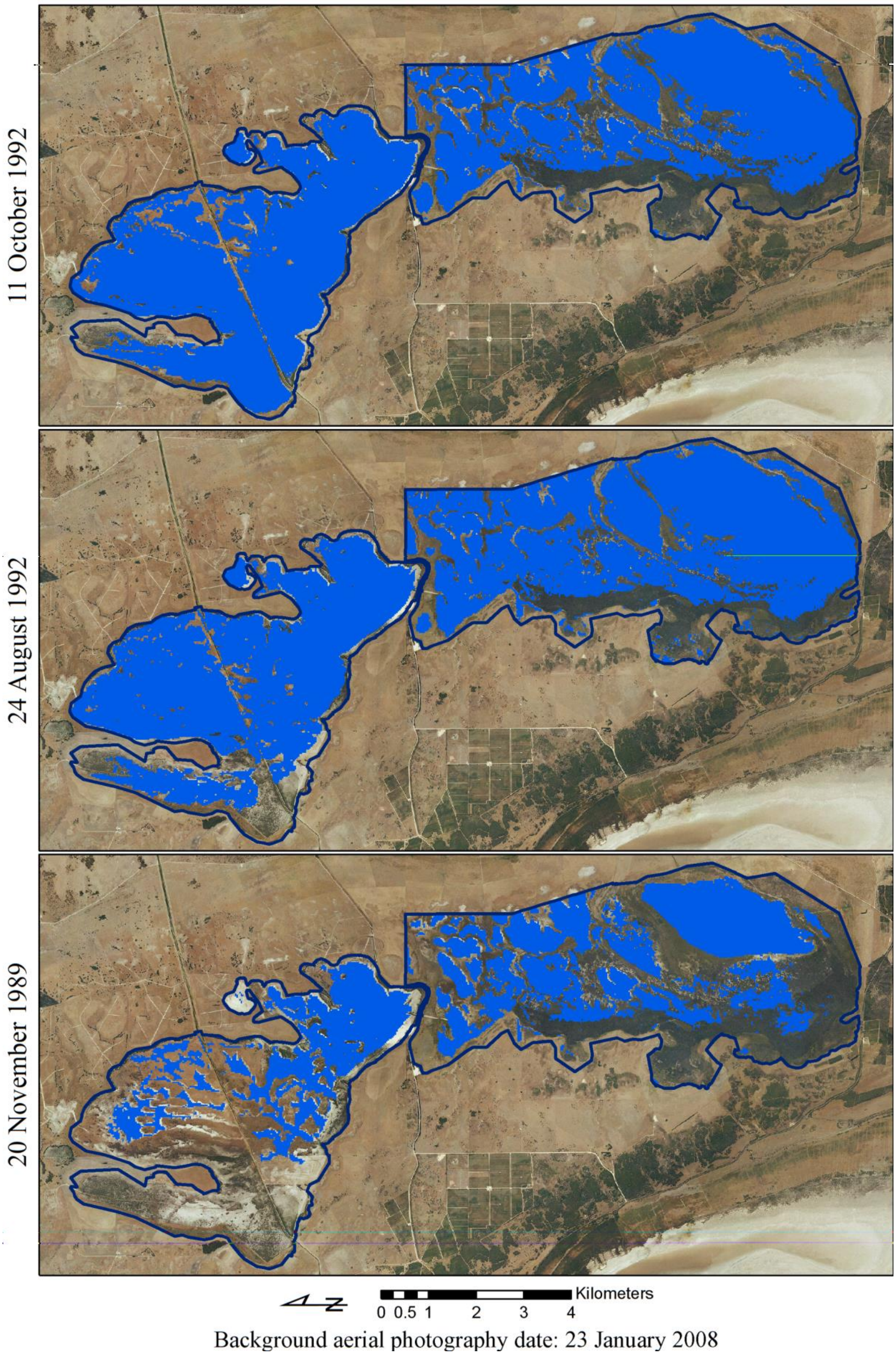


Figure 14. Lake Hawdon inundation extent as mapped from Landsat imagery from 1989 to 1992. Mapped extent is a conservative estimate.

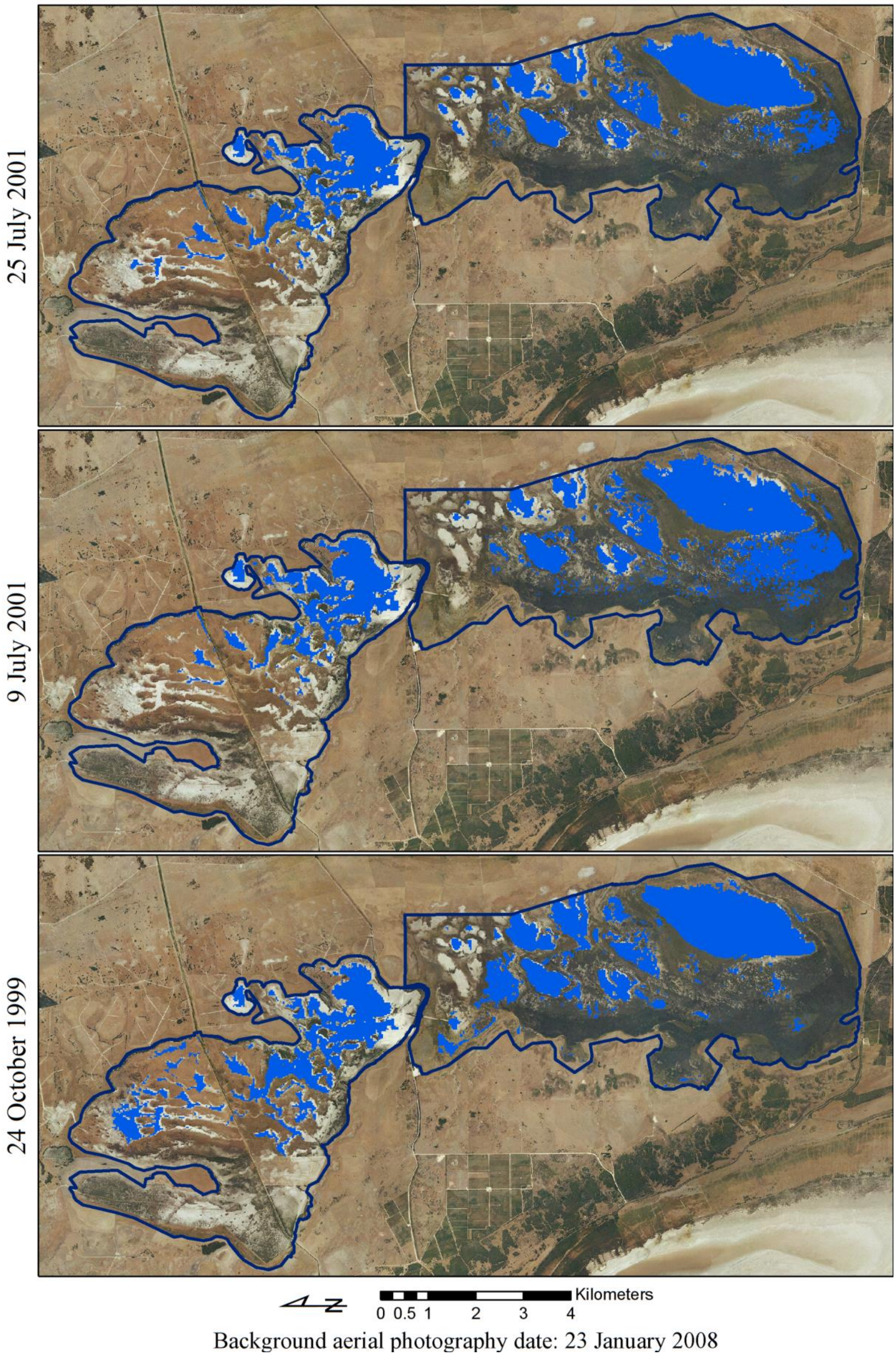


Figure 15. Lake Hawdon inundation extent as mapped from Landsat imagery from 1999 to 2001. Mapped extent is a conservative estimate.

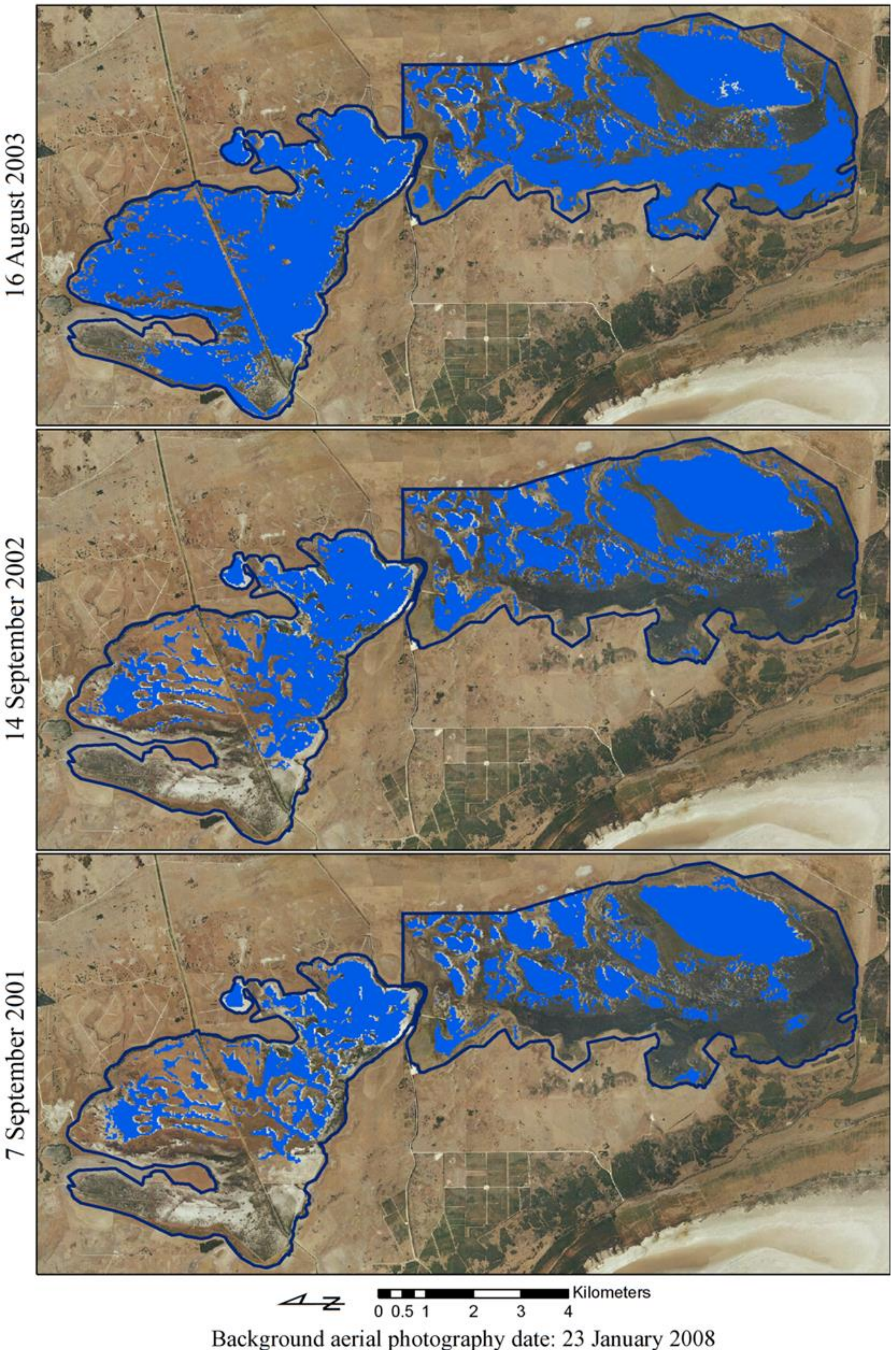


Figure 16. Lake Hawdon inundation extent as mapped from Landsat imagery from 2001 to 2003. Mapped extent is a conservative estimate.

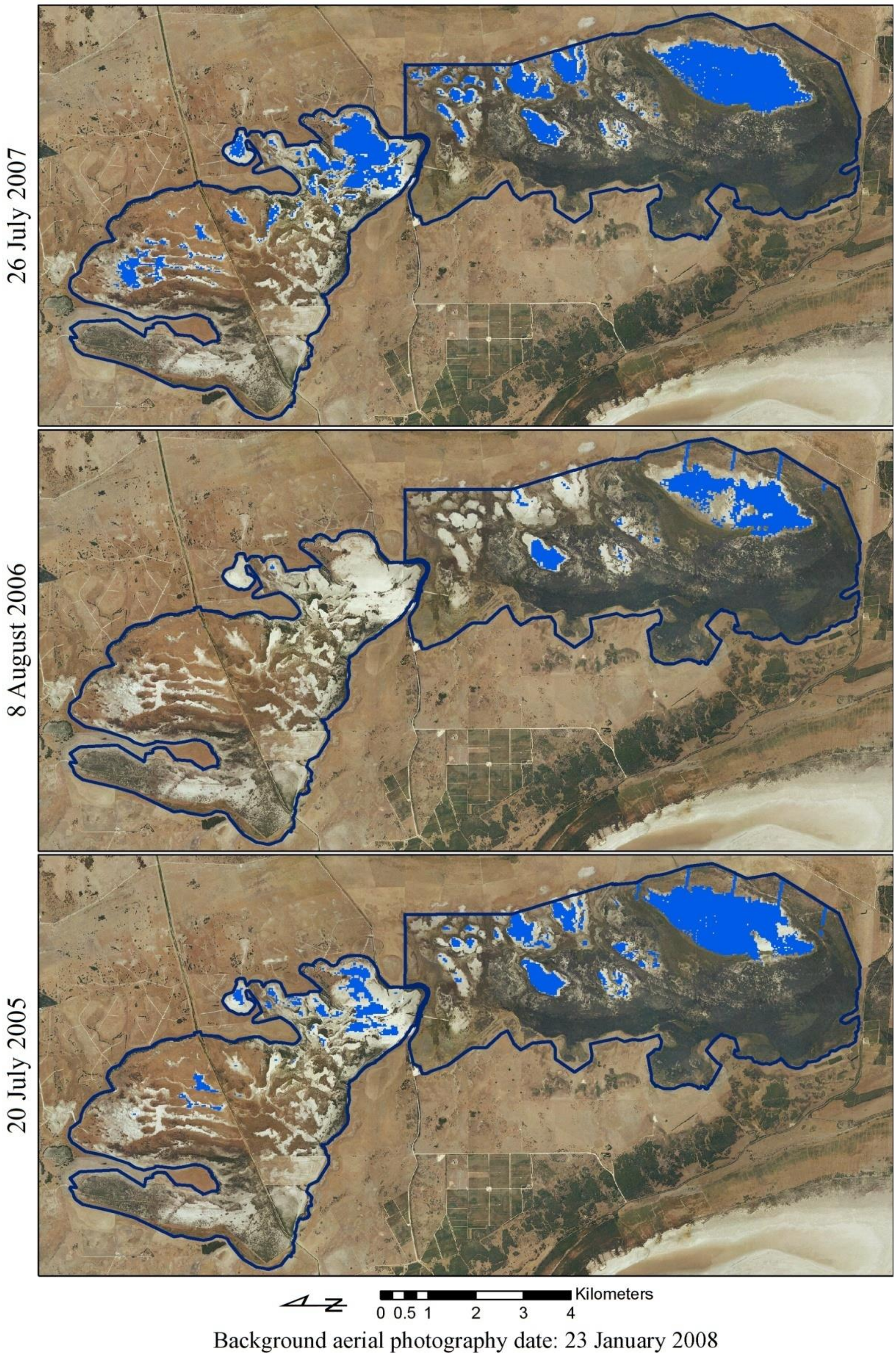


Figure 17. Lake Hawdon inundation extent as mapped from Landsat imagery from 2005 to 2007. Mapped extent is a conservative estimate.

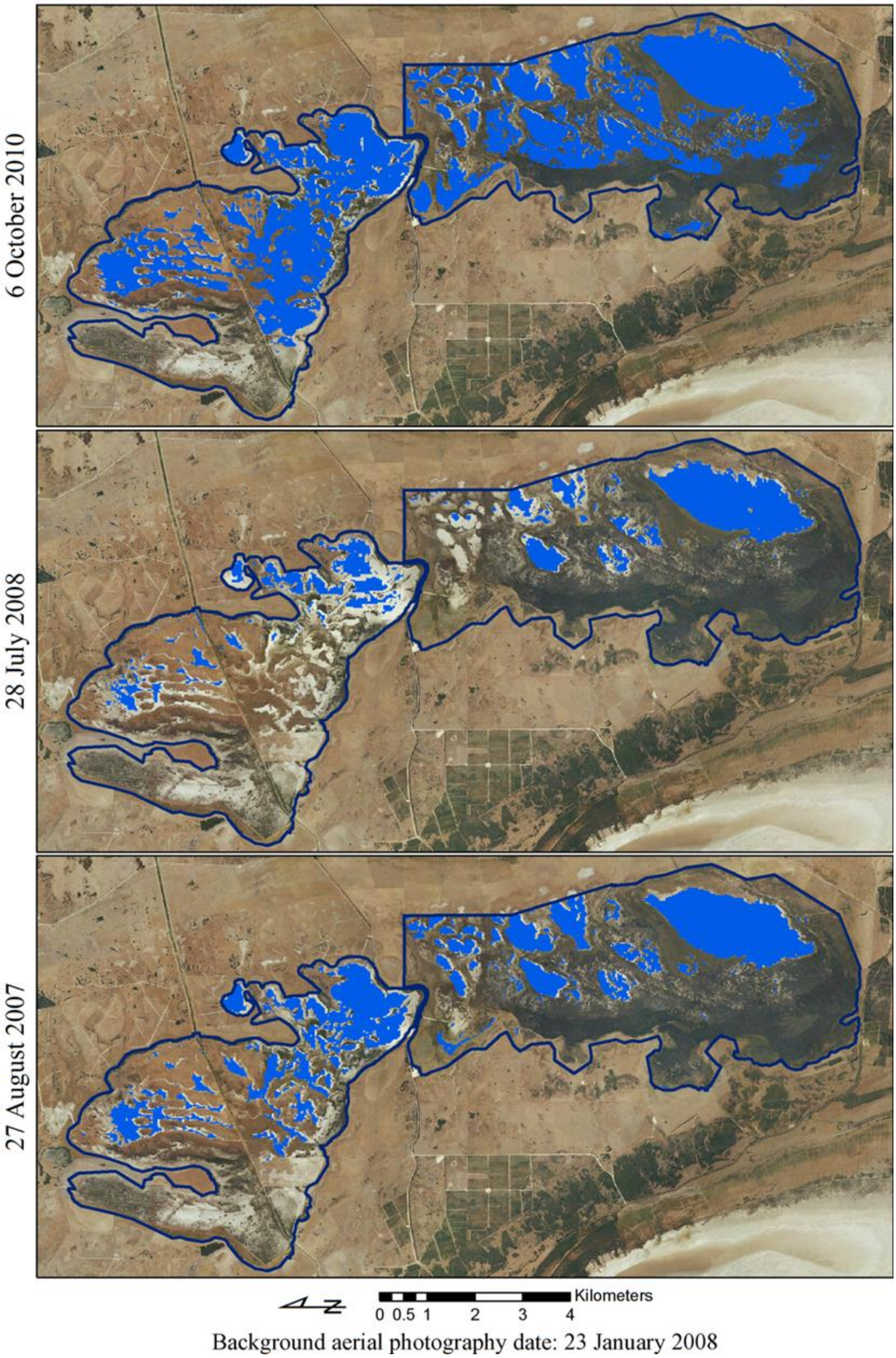


Figure 18. Lake Hawdon inundation extent as mapped from Landsat imagery from 2007 to 2010. Mapped extent is a conservative estimate.

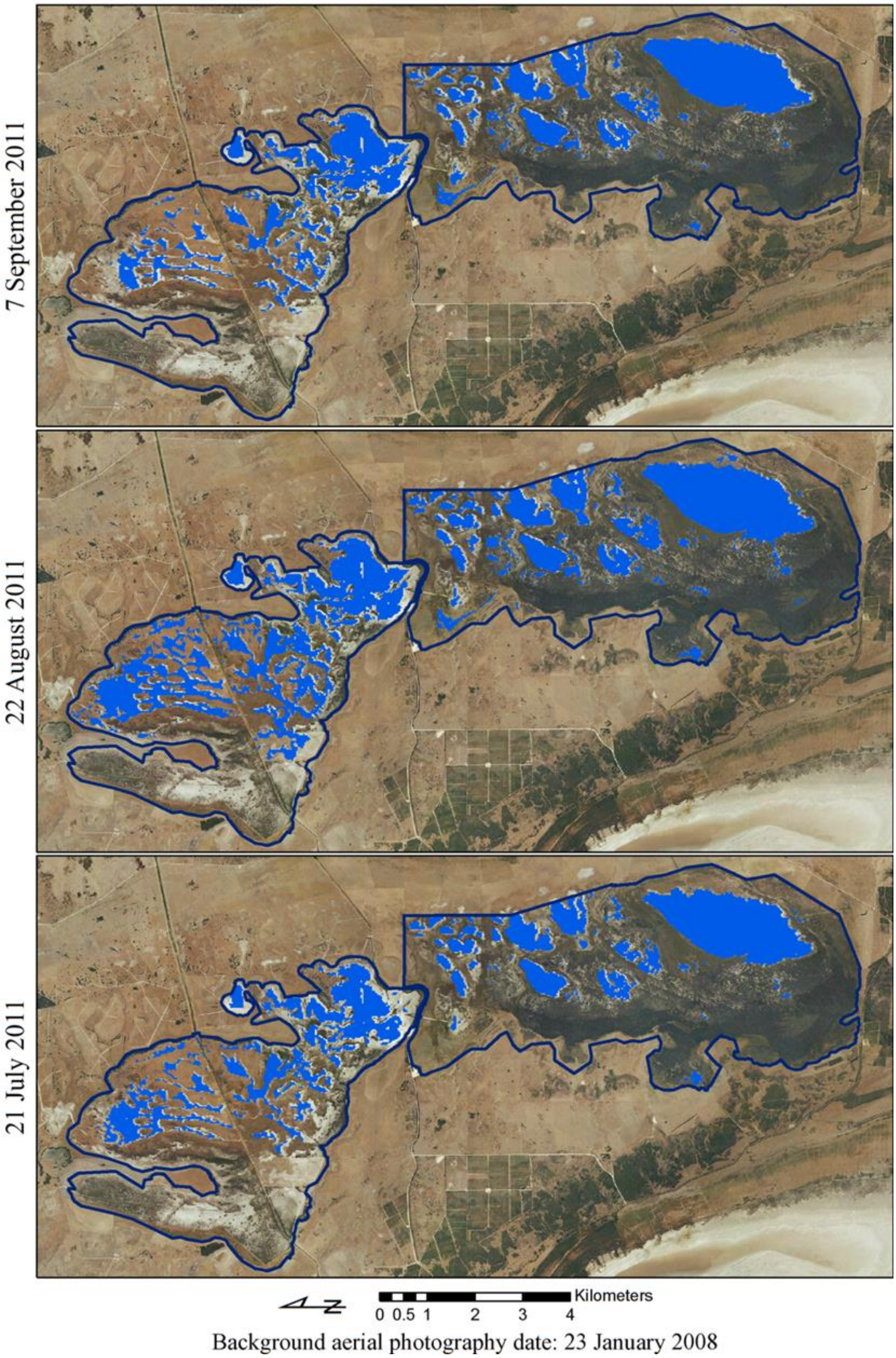


Figure 19. Lake Hawdon inundation extent as mapped from Landsat imagery from 2011. Mapped extent is a conservative estimate.

Special request: Full extent mapping, 11 October 1992

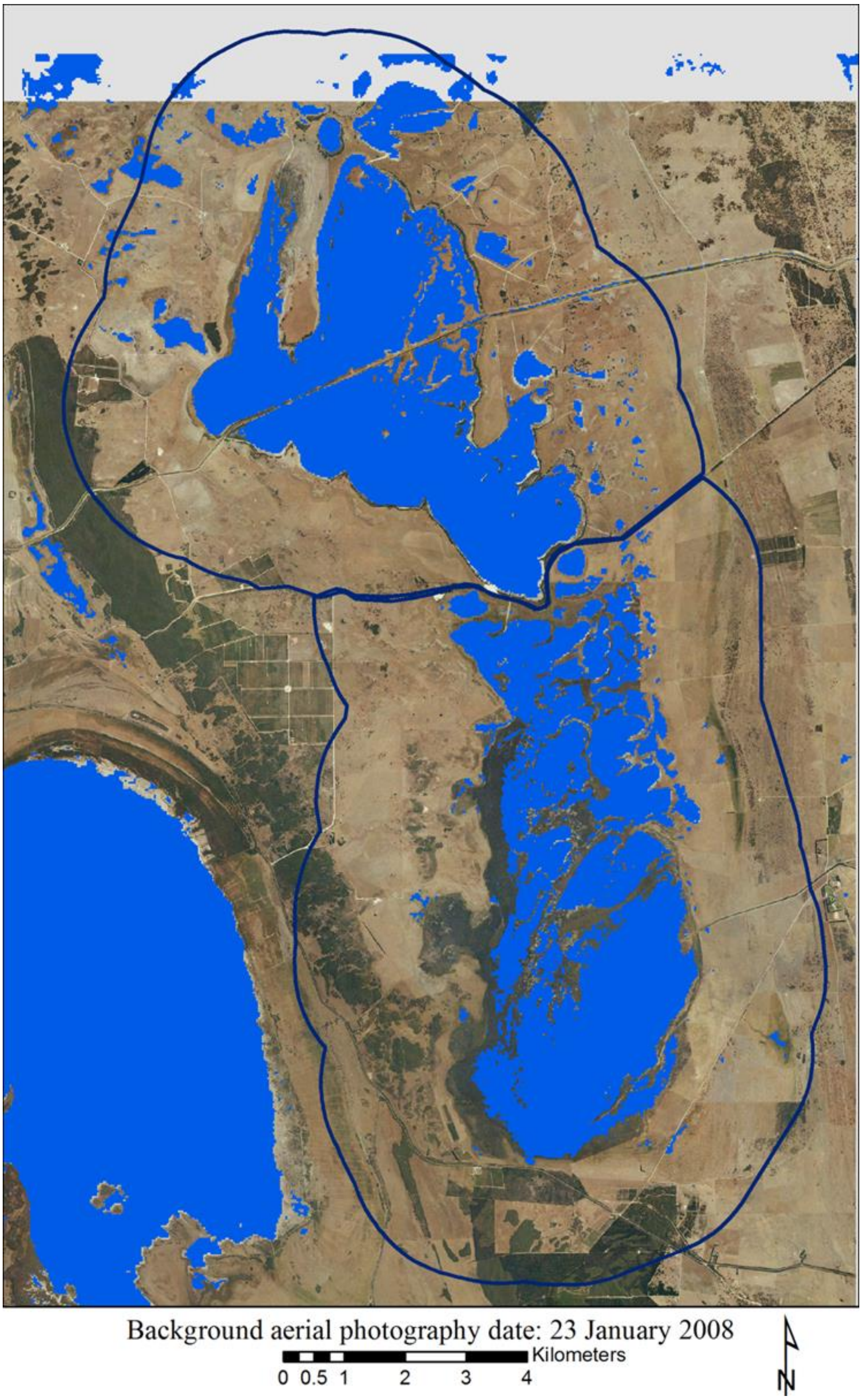


Figure 20. Lake Hawdon inundation extent as mapped from Landsat imagery captured on 11 October 1992. This mapping was not restricted to the wetland extent shapefile. A 2 km buffer of Lake Hawdon North and South is displayed as a dark-blue line, and was used to calculate the "inundated area" reported for this map/date in the next section. Mapped extent is a conservative estimate.

Inundation area and drain flow correlation

The Landsat-mapped inundation area in Lake Hawdon North and Lake Hawdon South (Table 13) was expected to correlate strongly with the flow in Drain L (Table 14). In the case of Lake Hawdon North strong correlation was expected because Drain L directly feeds the wetland. In the case of Lake Hawdon South a slightly weaker correlation was expected because, while not directly receiving input from Drain L, Lake Hawdon South is expected to receive runoff from the same rainfall events that lead to flow in Drain L. It was unclear how long it would take flow from Drain L and rainfall runoff to fill Lake Hawdon North and South, and therefore whether current inundation extent might be more strongly related to antecedent than to current flow rates. Consequently correlation was examined between mapped inundation extent and drain flow lagged up to three months prior to image acquisition (Table 15).

Inundation extent in both Lake Hawdon North and South was most strongly correlated with the current month's drain flow (R^2 = 0.83 and R^2 = 0.71 respectively), but still very strongly correlated with the previous month's drain flow (R^2 = 0.71 and R^2 = 0.66 respectively). This suggests that Lake Hawdon North is filled quickly by, and drains quickly (possibly in less than a month) into Drain L. This also suggests that runoff from rainfall events that determine Drain L flow rates take less than a month to reach Lake Hawdon South. The slightly weaker correlation with the previous month's drain flow could simply be a result of temporal autocorrelation, or could indicate that wetland filling and draining (and hence inundation extent) often takes more than one month. The slightly weaker correlation of Lake Hawdon South inundation extent with drain flow was expected since as described in the preceding paragraph, Lake Hawdon South is not directly filled by Drain L.

Table 13. Landsat mapped inundation extent for Lake Hawdon North and South. Inundation mapping was restricted to the wetland extent shapefile.

	Inundated area (ha)		
Date	Total	North only	South only
20-Nov-89	1924.83	671.85	1252.98
24-Aug-92	3994.20	1814.76	2179.44
11-Oct-92	3882.24	1977.21	1905.03
11-Oct-92*	4341.24*	2331.90*	2009.34*
24-Oct-99	1138.32	398.16	740.16
09-Jul-01	1112.58	312.39	800.19
25-Jul-01	975.78	329.49	646.29
07-Sep-01	1532.70	605.79	926.91
14-Sep-02	2031.66	853.47	1178.19
16-Aug-03	3484.89	1738.08	1746.81
20-Jul-05	506.97	90.63	416.34
08-Aug-06	227.79	0.81	226.98
26-Jul-07	648.81	222.21	426.60
27-Aug-07	1070.91	445.50	625.41
27-Jul-08	620.19	183.87	436.32
06-Oct-10	2063.61	859.50	1204.11
21-Jul-11	1048.59	442.62	605.97
22-Aug-11	1402.56	677.16	725.40
07-Sep-11	1040.58	409.77	630.81

*Inundated area on this date was not restricted to the wetland extent shapefile. On this date inundation area was calculated within a 2 km buffer of the Lake Hawdon North and South shapefiles.

Table 14. Flow rate in Drain L (ML/month) and the calendar month of Landsat image acquisition, and lagged drain flow up to three months prior to image acquisition date.

Drain flow (ML/month) and lag period				
Date	Current month	One month previous	Two months previous	Three months previous
20-Nov-89	1,292.82	3,347.30	11,480.88	14,377.11
24-Aug-92	3,995.87	2,954.99	1,264.49	600.82
11-Oct-92	6,525.77	7,966.35	3,995.87	2,954.99
24-Oct-99	201.16	797.99	1,830.32	1,696.12
09-Jul-01	690.03	416.36	238.17	293.81
25-Jul-01	690.03	416.36	238.17	293.81
07-Sep-01	2,746.99	1,409.69	690.03	416.36
14-Sep-02	1,833.14	3,075.93	3,018.63	113.54
16-Aug-03	8,076.63	3,194.86	1,168.27	4.72
20-Jul-05	847.33	642.17	44.90	42.35
08-Aug-06	70.82	69.12	58.59	24.15
26-Jul-07	19.51	7.26	1.60	-
27-Aug-07	30.02	19.51	7.26	1.60
27-Jul-08	4.66	2.32	0.79	-
06-Oct-10	1,128.01	5,937.47	3,316.37	203.94
21-Jul-11	1,886.42	224.69	53.76	91.35
22-Aug-11	2,023.91	1,886.42	224.69	53.76
07-Sep-11	835.06	2,023.91	1,886.42	224.69

Table 15. Correlation (r^2) of Landsat-mapped inundation extent with lagged drain flow.

Lagged drain flow period				
Region	0 months	1 month	2 months	3 months
Total	0.74	0.61	0.12	0.03
North only	0.83	0.71	0.12	0.03
South only	0.71	0.66	0.21	0.08

Vegetation community change (1958 – 2008)

This section presents maps of vegetation communities derived from digitisation of aerial photography of four image dates, 1958, 1988, 1999 and 2008. Imagery was acquired for two other dates, 1969 and 1978, but time constraints precluded mapping for these dates. Prior to vegetation community digitisation all aerial photographs were georectified and mosaiced (Appendix 3.2).

Maps including all vegetation communities and densities are presented (1958, Figure 22; 1988, Figure 23; 1999, Figure 24; 2008, Figure 25), but due to the number of pure cover classes, and especially the large number of mixed cover classes, are complex and difficult to interpret. To focus interpretation on change over time within vegetation types sets of four-date maps are also presented for the pure and mixed sub-classes: *Gahnia*, Figure 26; Herbland, Figure 27; *Melaleuca*, Figure 28; Open pan, Figure 29; Sedgeland, Figure 30. Only extent, not density, of *Gahnia* and Sedgeland were mapped in 1988 and 1999.

Vegetation community change interpretation

This section presents an interpretation of the stability or variability of vegetation communities within Lake Hawdon North and South by examining each of the per-cover-type tetraptychs in turn. This section concludes with an overall summary of vegetation community change in Lake Hawdon between 1958 and 2008.

Gahnia sp.

Gahnia distribution in 1958 was restricted to the higher elevation, presumably dryer, portions of Lake Hawdon South. In the three later epochs *Gahnia* extent increased slightly overall, with a significant new area of *Gahnia* in Lake Hawdon North. However, while *Gahnia* extent increased slightly, the area of mixed *Gahnia* communities increases progressively from 1988 to 2008, indicating an ongoing invasion of *Gahnia* communities by other community types.

Herbland

Herbland distribution in 1958 was restricted to the edges of the wetlands and areas of disturbance (the drain in Lake Hawdon North). In 1988 the Herbland area in Lake Hawdon South had increased slightly, but remained a pure class and was still largely restricted to the higher elevation edges of the wetland. Conversely, mixed Herbland / Sedgeland had colonised much of the higher elevation areas of Lake Hawdon North. In 1999 and 2008 mixed Herbland classes covered still more of Lake Hawdon North and some of Lake Hawdon South.

Melaleuca halmaturorum

Melaleuca halmaturorum distribution in 1958 was restricted almost solely to the fringes of Lake Hawdon North, and was almost all established (mature) *Melaleuca*. In 1988 juvenile *Melaleuca* had colonised some of the higher elevation areas of Lake Hawdon North and an area of lower elevation in the far west of Lake Hawdon North. In 1999 and 2008 the area of juvenile *Melaleuca* in Lake Hawdon North expanded further, and a formerly Open pan area in Lake Hawdon South was colonised by juvenile *Melaleuca*. In almost all cases juvenile *Melaleuca* occurred as a mixed class as it invaded other classes.

Open pan

In 1958 the majority of Lake Hawdon North was Open pan, and there were several large areas of Open pan in the eastern half of Lake Hawdon South. By 1988 the area of Open pan in Lake Hawdon North had diminished significantly, while in Lake Hawdon South some new areas of Open pan had appeared. In 1999 and 2008 the area of Open pan in Lake Hawdon North and South decreased further, with one exception. The large southern Open pan area in Lake Hawdon South was intermittently covered by Herbland in 1988 and 1999, and then relatively bare again in 2008. This suggests that, while the Herbland class is quick to colonise Open pan areas if inundation is too infrequent or short, Herbland areas can be returned to Open pan by reintroduction of inundation.

Sedgeland

The area of Sedgeland in 1958 is restricted to Lake Hawdon South, and is mostly pure Sedgeland (not mixed with other classes). The extent of this pure Sedgeland remains relatively unchanged through to 2008, indicating that this class has a low vulnerability to invasion. Conversely, this class appears to be quite invasive. The area of mixed Sedgeland in Lake Hawdon South increases slightly from 1958 to 2008, and in Lake Hawdon North increases dramatically over the same period. As with Herbland, Sedgeland invasion favoured higher elevation areas.

Summary

Change between 1958 and 1988 is most marked for Lake Hawdon North: in 1958 it was largely an unvegetated pan, colonised by localised areas of vegetation by 1969 (Appendix 3.2, Figure 19). This vegetation expanded and consolidated by 1978, and remained relatively stable in distribution through to 2008. By contrast, the overall distribution of vegetation in Lake Hawdon South has remained relatively stable between 1958 and 2008, with some increase in vegetated area at the expense of open pans.

In addition, the comparative photo-interpretation has revealed considerable change in the composition of the wetland vegetation. The overall story of vegetation community change in Lake Hawdon is one of invasion and change. In 1958 mixed communities accounted for only a small area of Lake Hawdon South, suggesting that the inundation regime in Lake Hawdon North and South had been relatively stable for a long time. By 2008 mixed communities accounted for more of Lake Hawdon South, and the majority of Lake Hawdon North, suggesting that there has been a considerable change in the inundation regime of Lake Hawdon North, and a moderate inundation regime change for Lake Hawdon South.

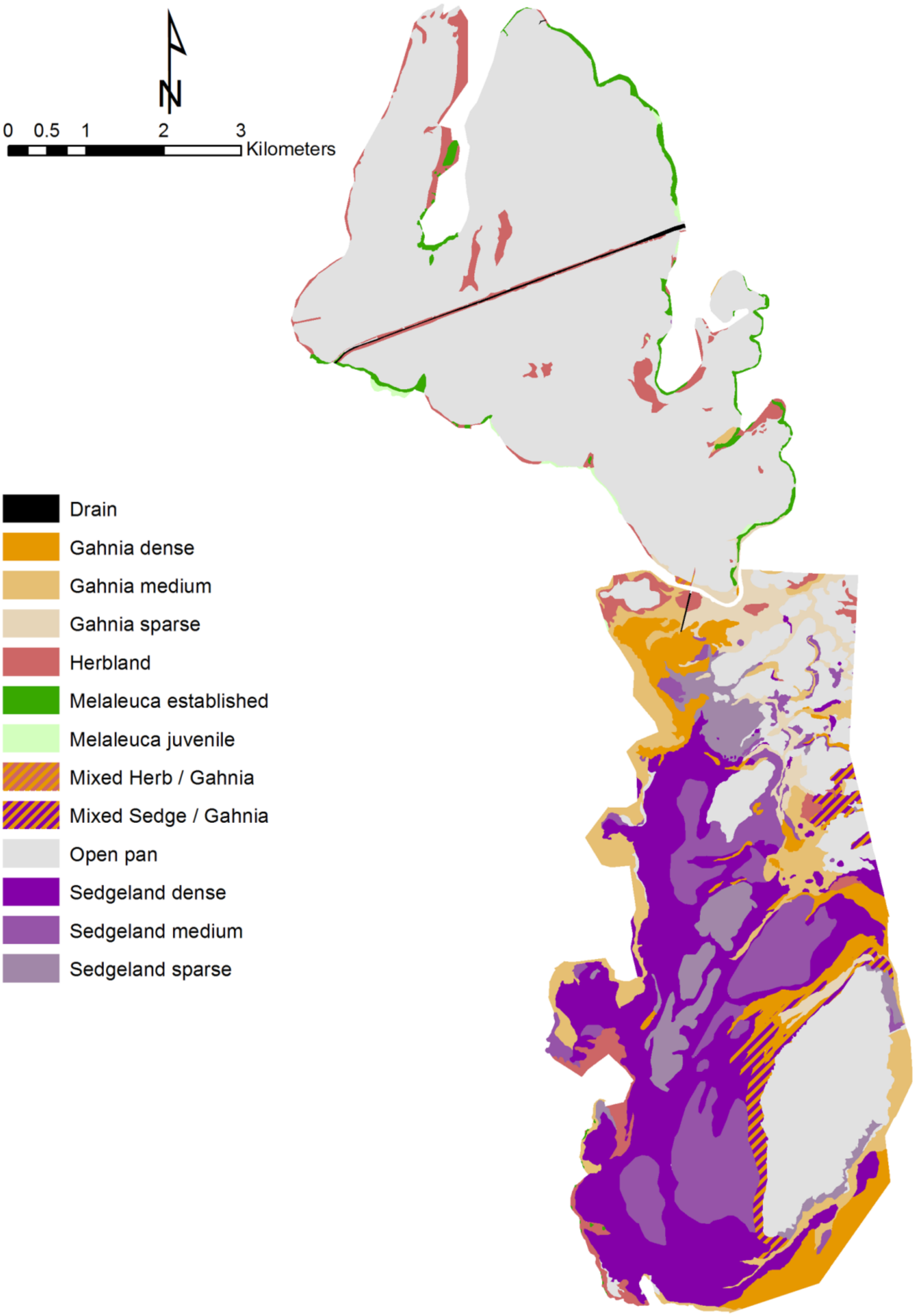


Figure 22. Distribution of all vegetation communities in Lake Hawdon North and South derived by expert interpretation of 1958 aerial photography.

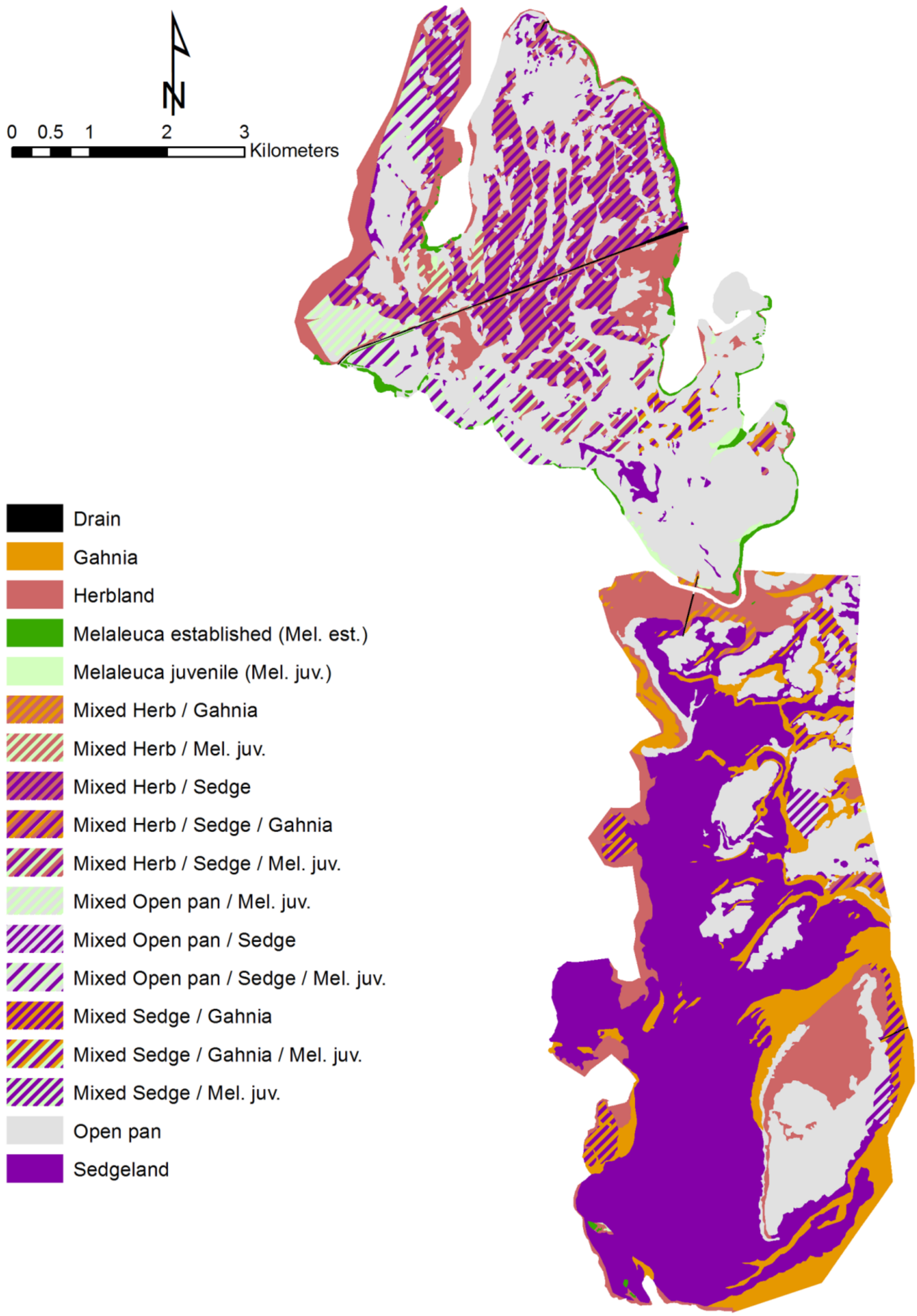


Figure 23. Distribution of all vegetation communities in Lake Hawdon North and South derived by expert interpretation of 1988 aerial photography.

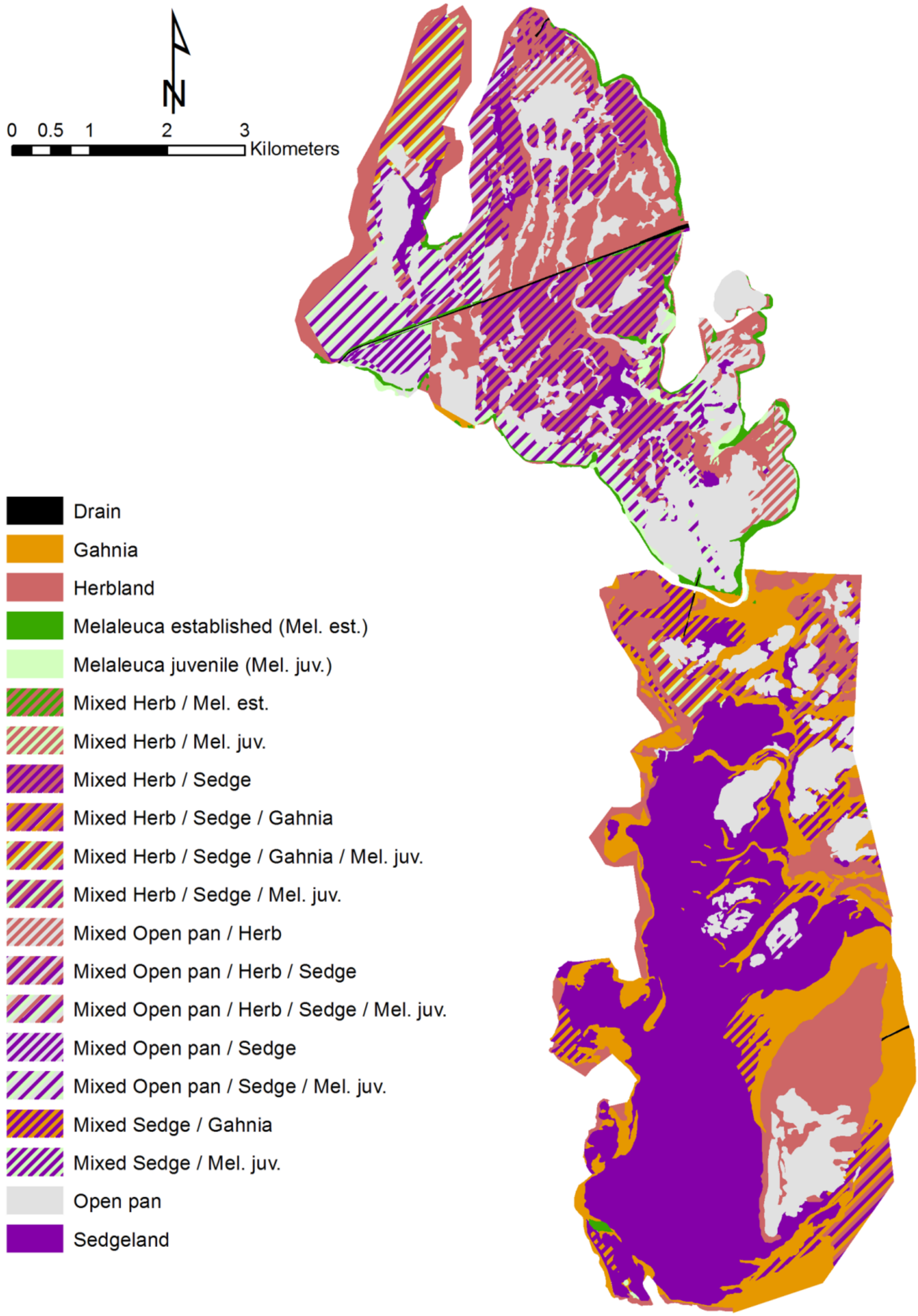


Figure 24. Distribution of all vegetation communities in Lake Hawdon North and South derived by expert interpretation of 1999 aerial photography.

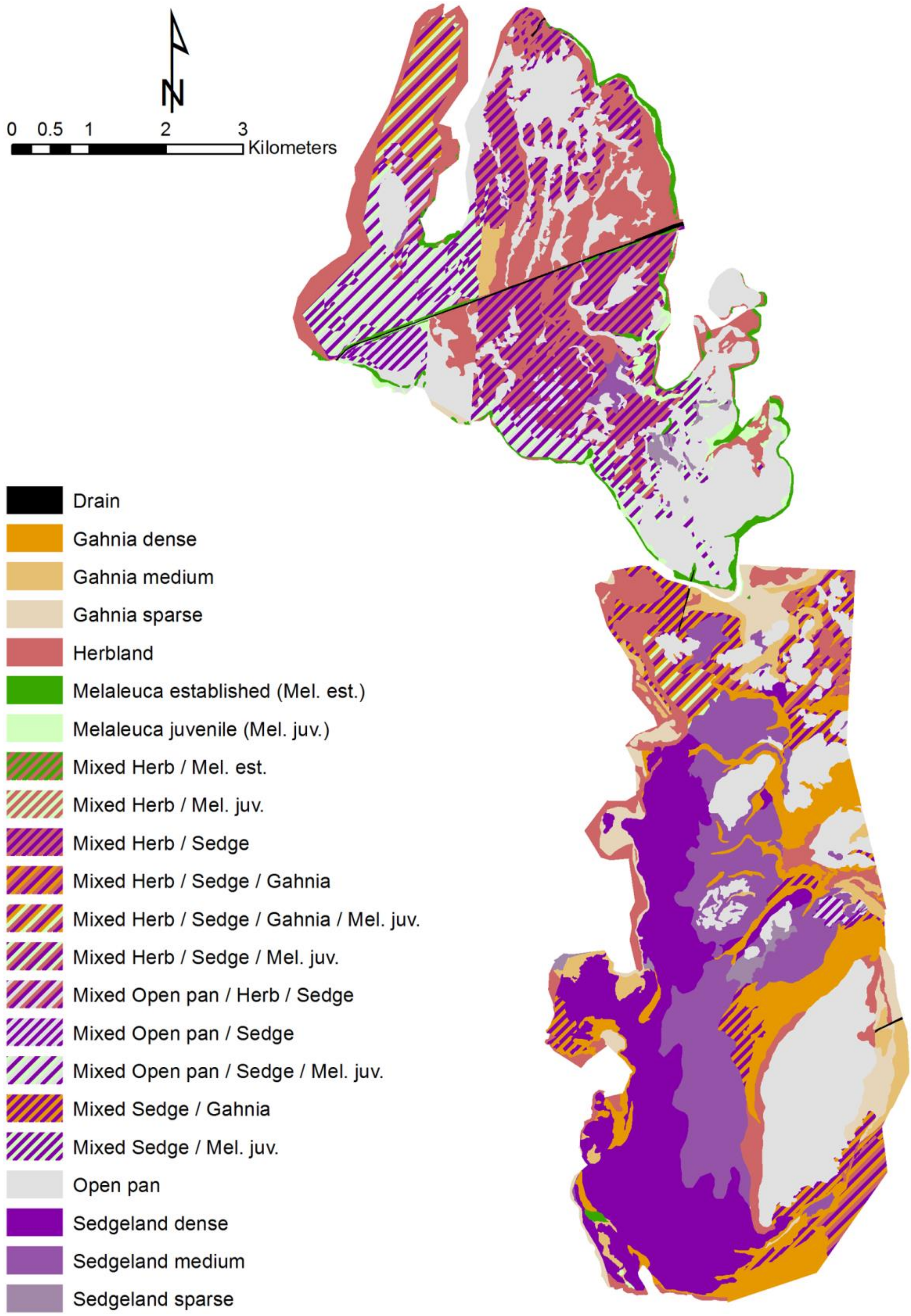


Figure 25. Distribution of all vegetation communities in Lake Hawdon North and South derived by expert interpretation of 2008 aerial photography.

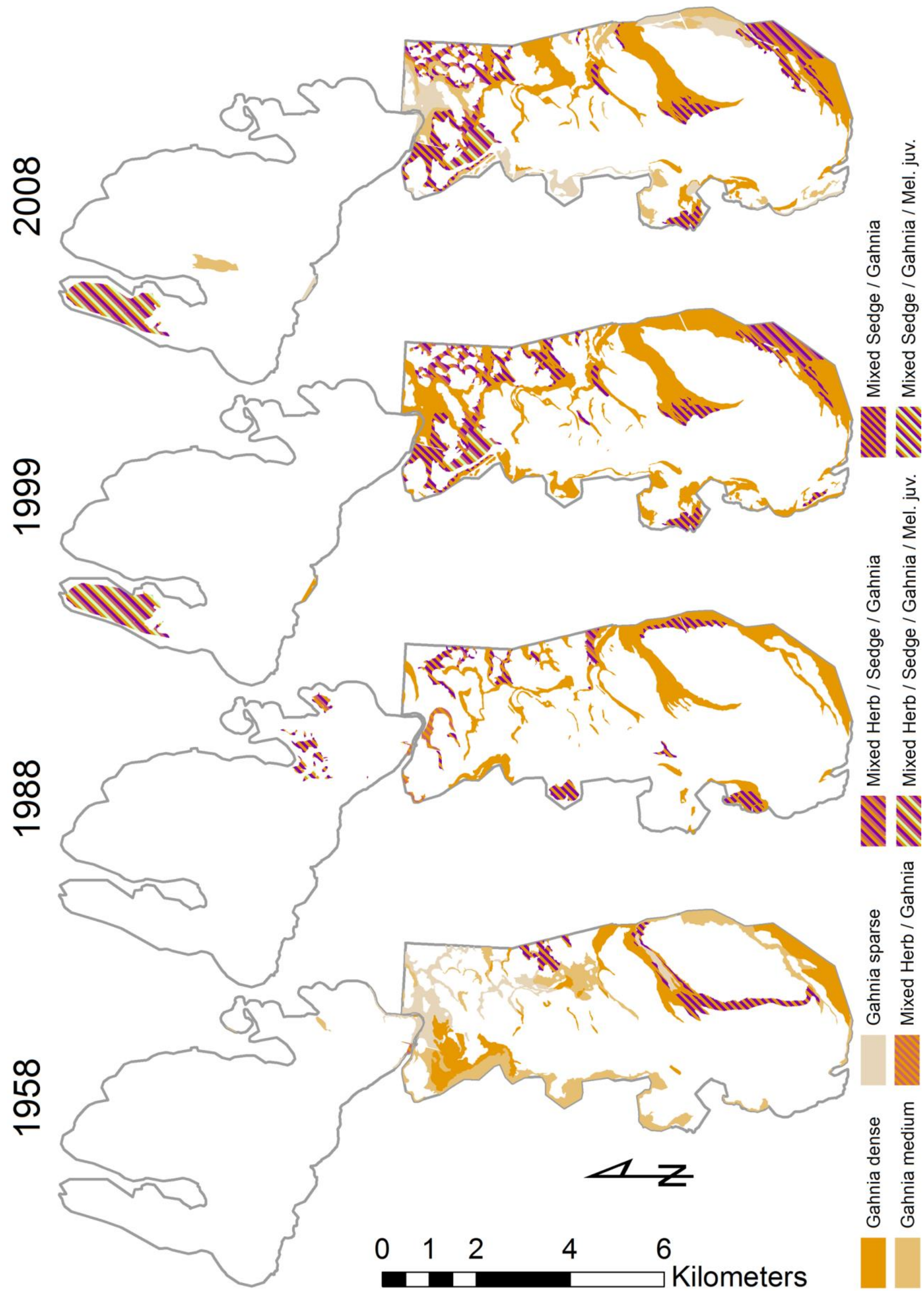


Figure 26. Change in distribution of *Gahnia* sp. In Lake Hawdon North and South derived by expert interpretation of 1958, 1988, 1999 and 2008 aerial photography.

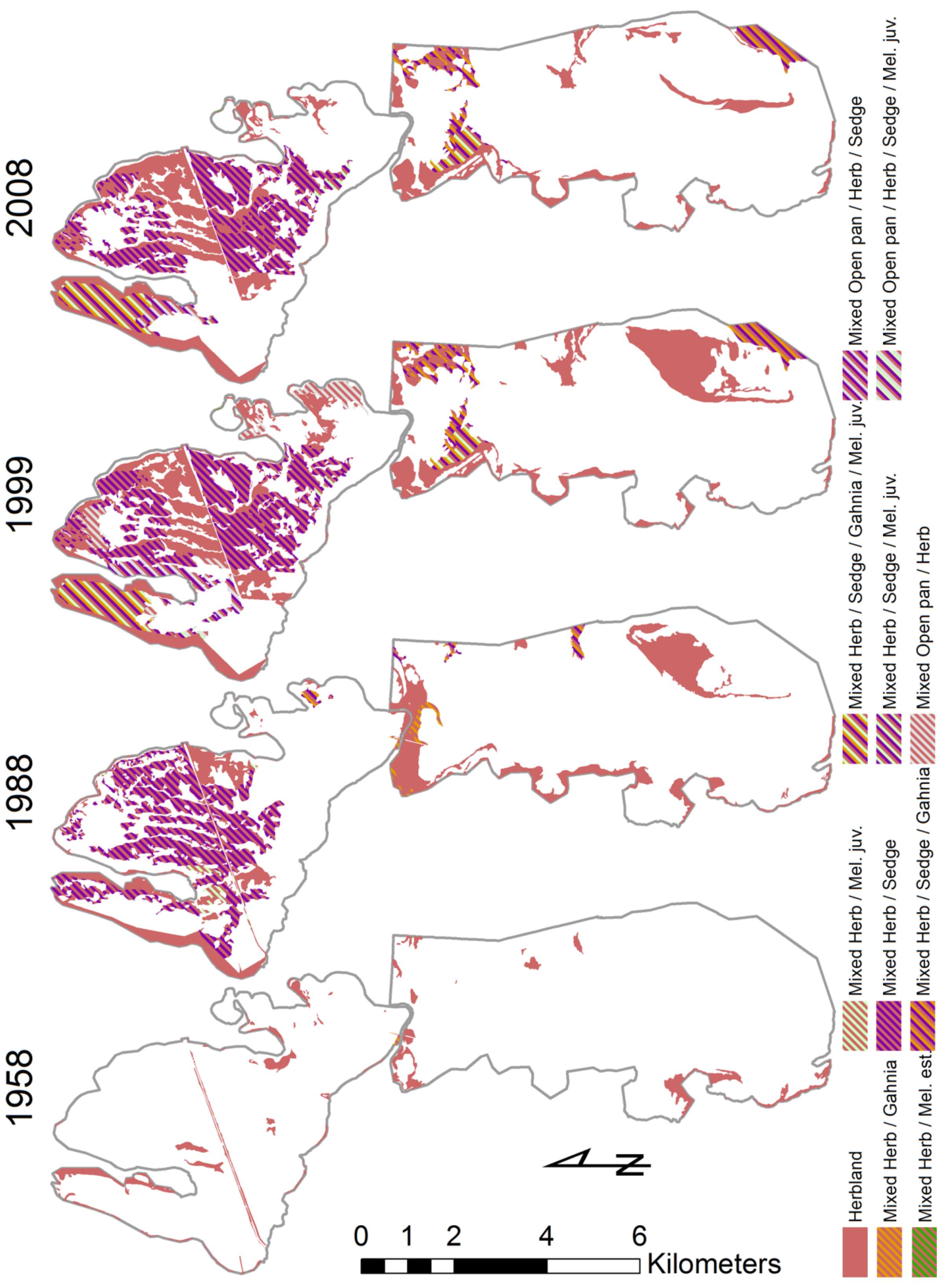


Figure 27. Change in distribution of Herbland in Lake Hawdon North and South derived by expert interpretation of 1958, 1988, 1999 and 2008 aerial photography.

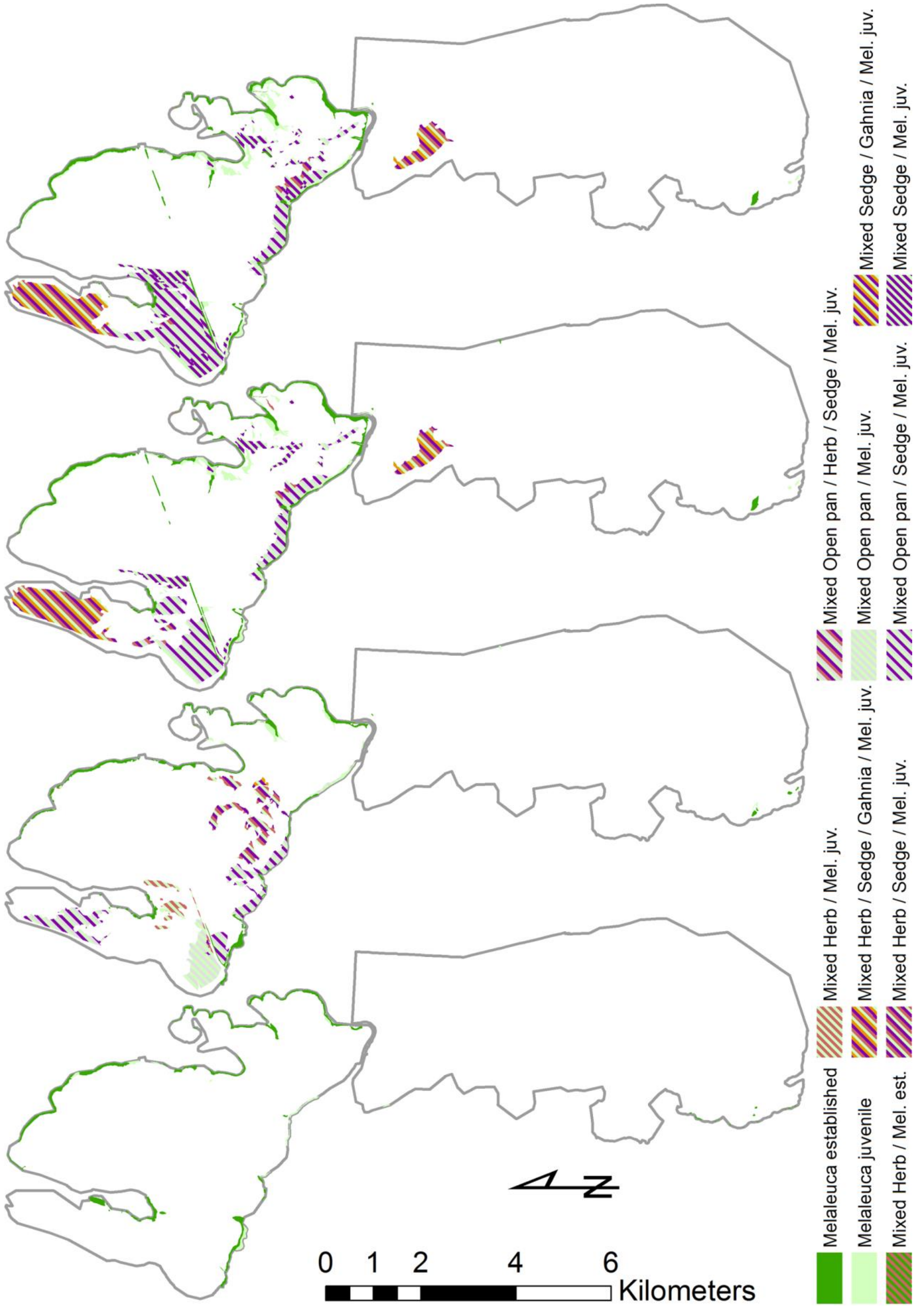


Figure 28. Change in distribution of *Melaleuca halmaturorum* in Lake Hawdon North and South derived by expert interpretation of 1958, 1988, 1999 and 2008 aerial photography.

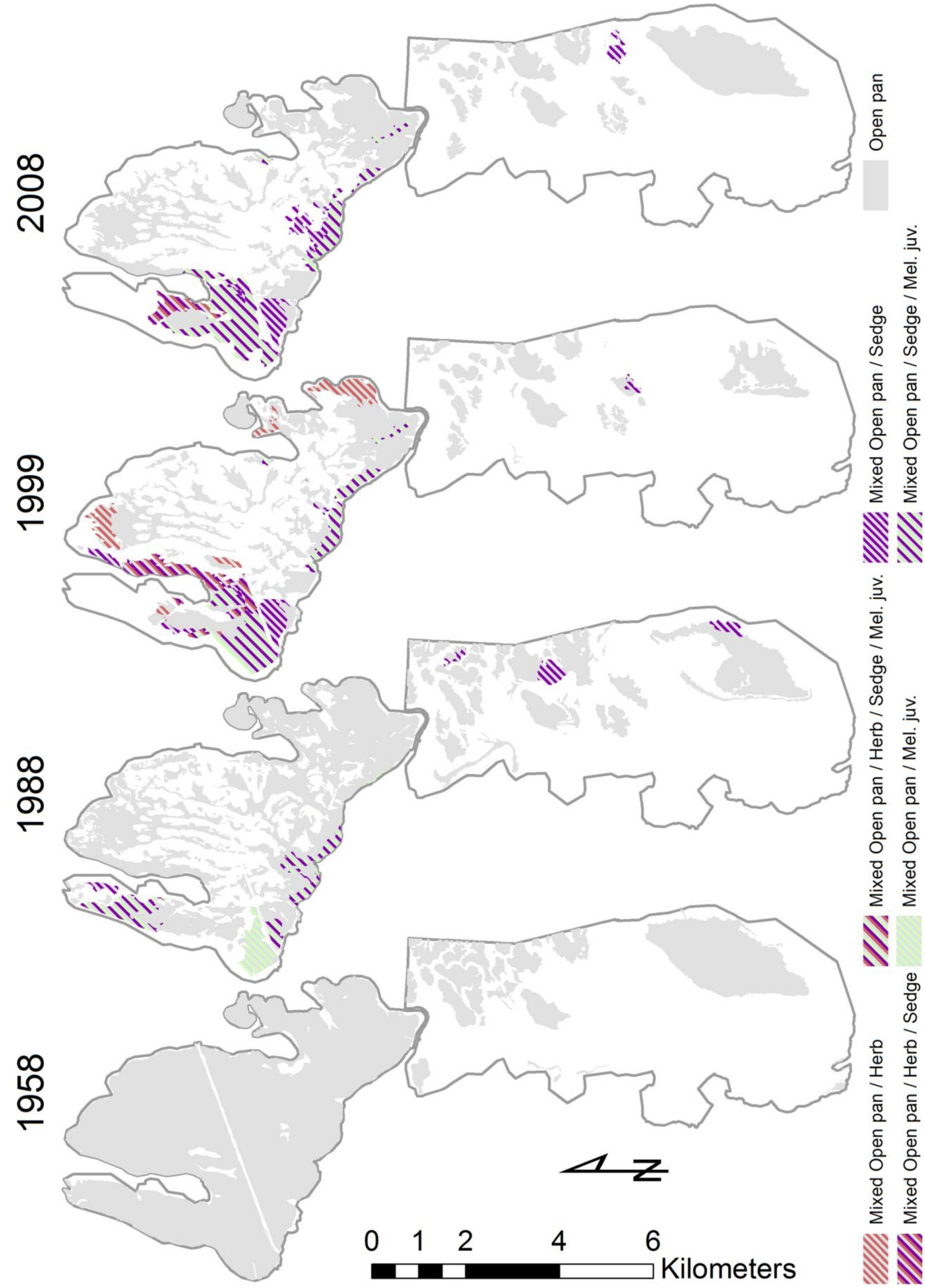


Figure 29. Change in distribution of Open pan in Lake Hawdon North and South derived by expert interpretation of 1958, 1988, 1999 and 2008 aerial photography.

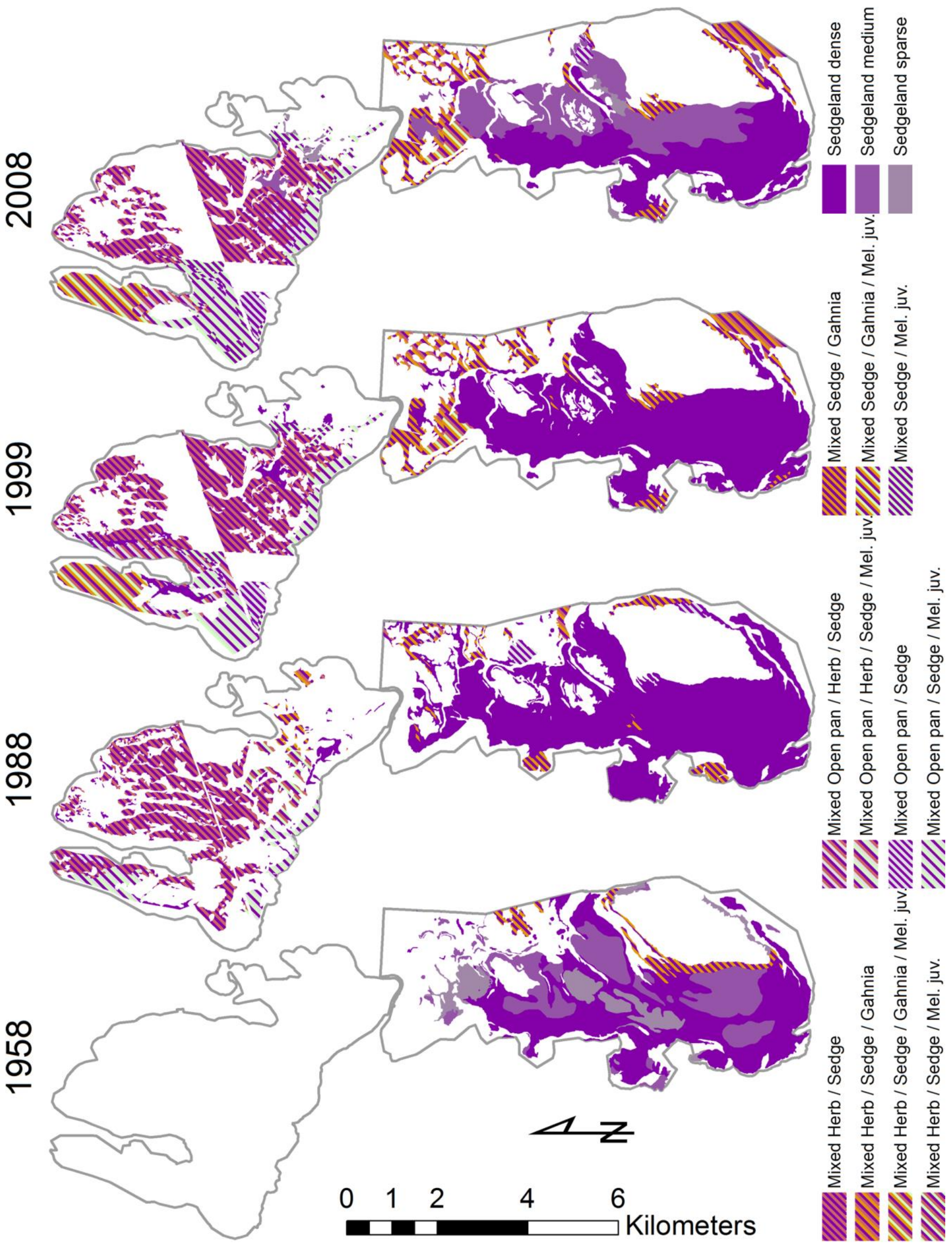


Figure 30. Change in distribution of Sedgeland in Lake Hawdon North and South derived by expert interpretation of 1958, 1988, 1999 and 2008 aerial photography.

3.5 Appendix 1: MODIS Composite Image Dates

Note that there is always some overlap between the final image in a year and the first image in the following year. In a non-leap year the final image covers 19 December to 3 January in the following year, resulting in three days overlap with the first image of the following year.

Appendix 1. Image start day for all MODIS MOD13Q1 image composites analysed in this project. *Image start date is listed as approximate to allow for the effect of leap years on post February 29 image start days.

Image start day	Approx date*	Year											
		00	01	02	03	04	05	06	07	08	09	10	11
1	1 Jan		x	x	x	x	x	x	x	x	x	x	x
17	17 Jan		x	x	x	x	x	x	x	x	x	x	x
33	2 Feb		x	x	x	x	x	x	x	x	x	x	x
49	18 Feb	x	x	x	x	x	x	x	x	x	x	x	x
65	6 Mar	x	x	x	x	x	x	x	x	x	x	x	x
81	22 Mar	x	x	x	x	x	x	x	x	x	x	x	x
97	7 Apr	x	x	x	x	x	x	x	x	x	x	x	x
113	23 Apr	x	x	x	x	x	x	x	x	x	x	x	x
129	9 May	x	x	x	x	x	x	x	x	x	x	x	x
145	25 May	x	x	x	x	x	x	x	x	x	x	x	x
161	10 Jun	x	x	x	x	x	x	x	x	x	x	x	x
177	26 Jun	x	x	x	x	x	x	x	x	x	x	x	x
193	12 Jul	x	x	x	x	x	x	x	x	x	x	x	x
209	28 Jul	x	x	x	x	x	x	x	x	x	x	x	x
225	13 Aug	x	x	x	x	x	x	x	x	x	x	x	x
241	29 Aug	x	x	x	x	x	x	x	x	x	x	x	x
257	14 Sep	x	x	x	x	x	x	x	x	x	x	x	x
273	30 Sep	x	x	x	x	x	x	x	x	x	x	x	x
289	16 Oct	x	x	x	x	x	x	x	x	x	x	x	x
305	1 Nov	x	x	x	x	x	x	x	x	x	x	x	x
321	17 Nov	x	x	x	x	x	x	x	x	x	x	x	x
337	3 Dec	x	x	x	x	x	x	x	x	x	x	x	x
353	19 Dec	x	x	x	x	x	x	x	x	x	x	x	

3.6 Appendix 2: Georectified Aerial Photograph Mosaics

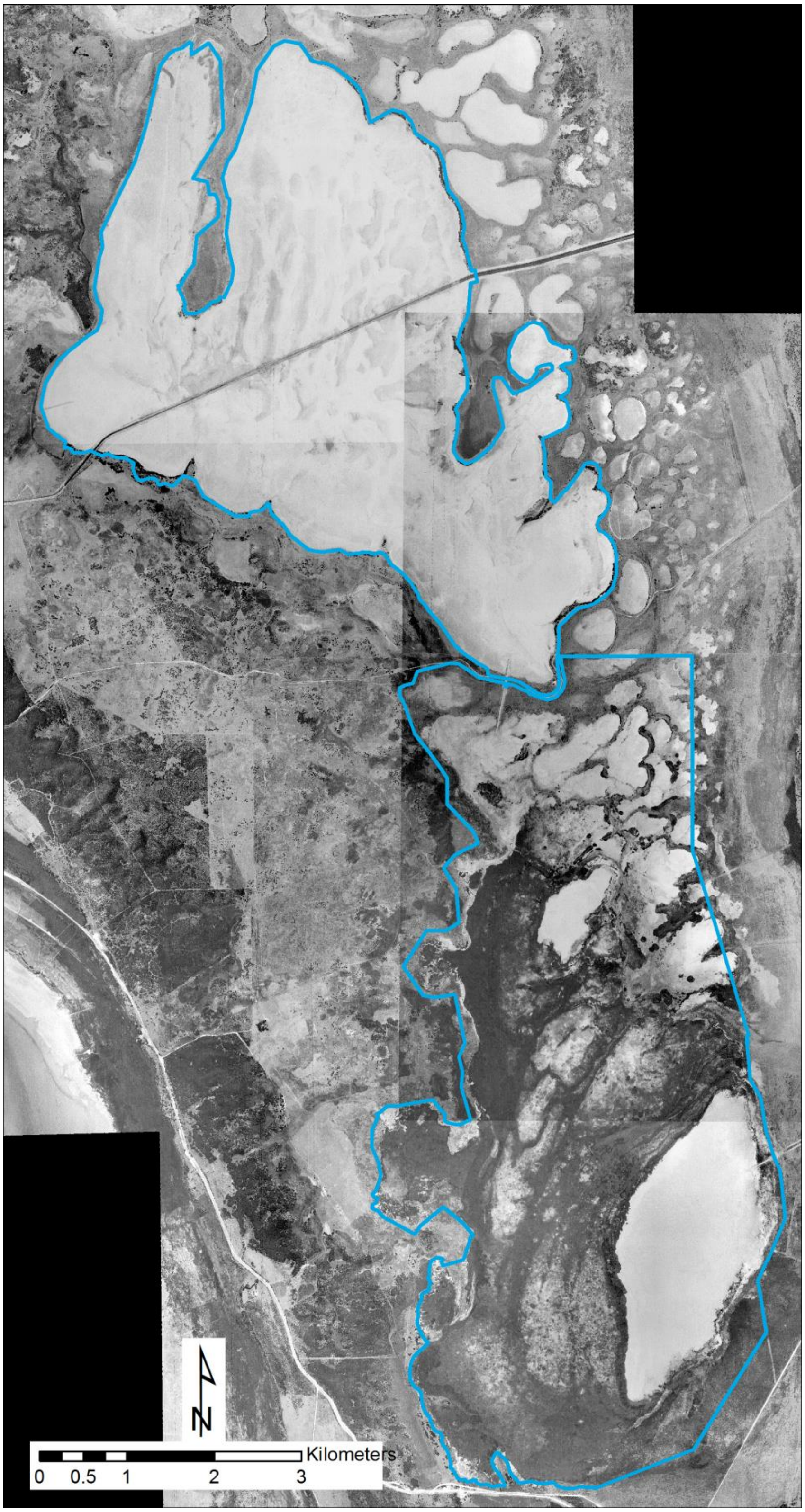


Figure 31. 1958 aerial photography mosaic.

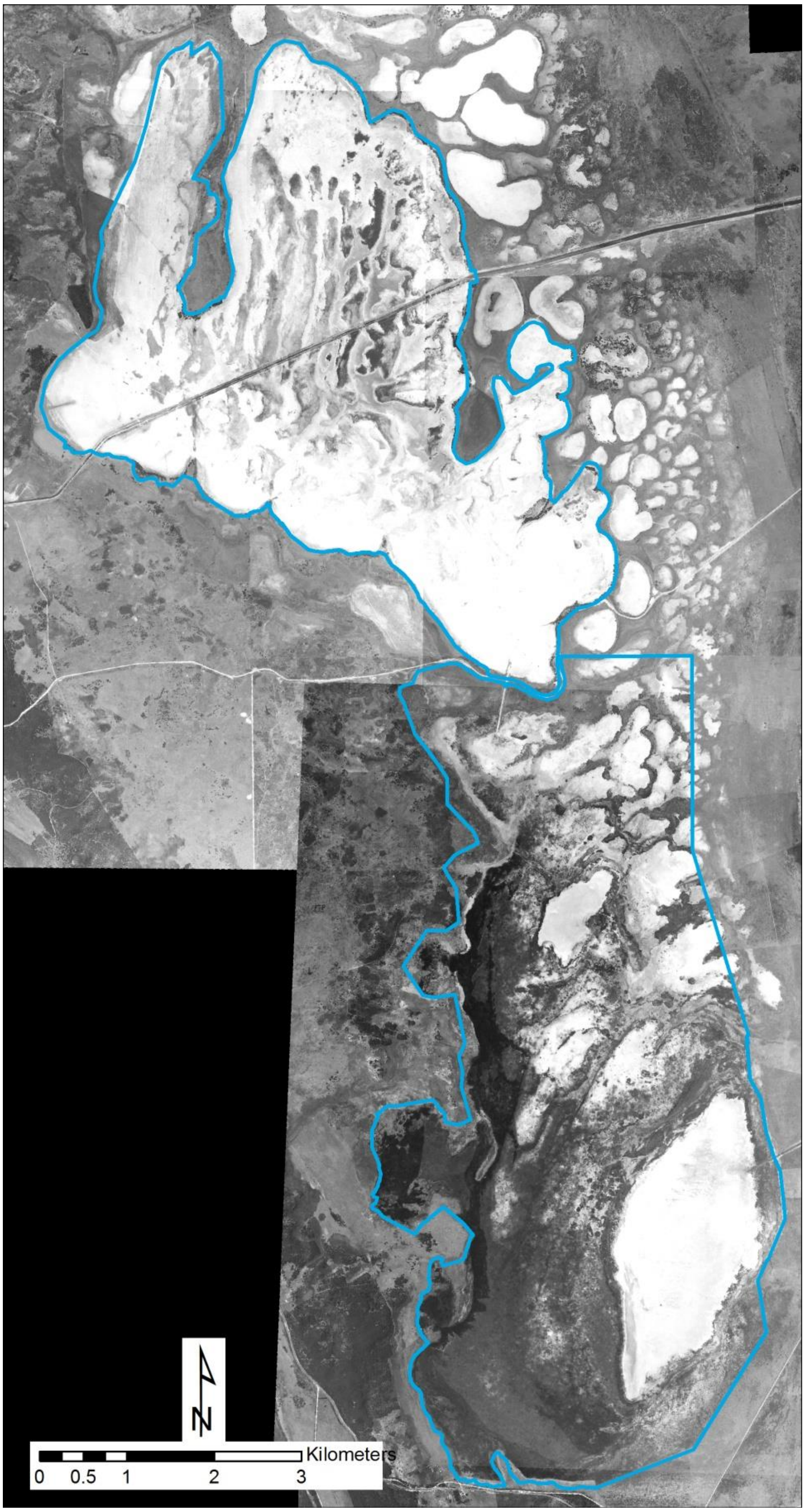


Figure 32. 1969 aerial photography mosaic.

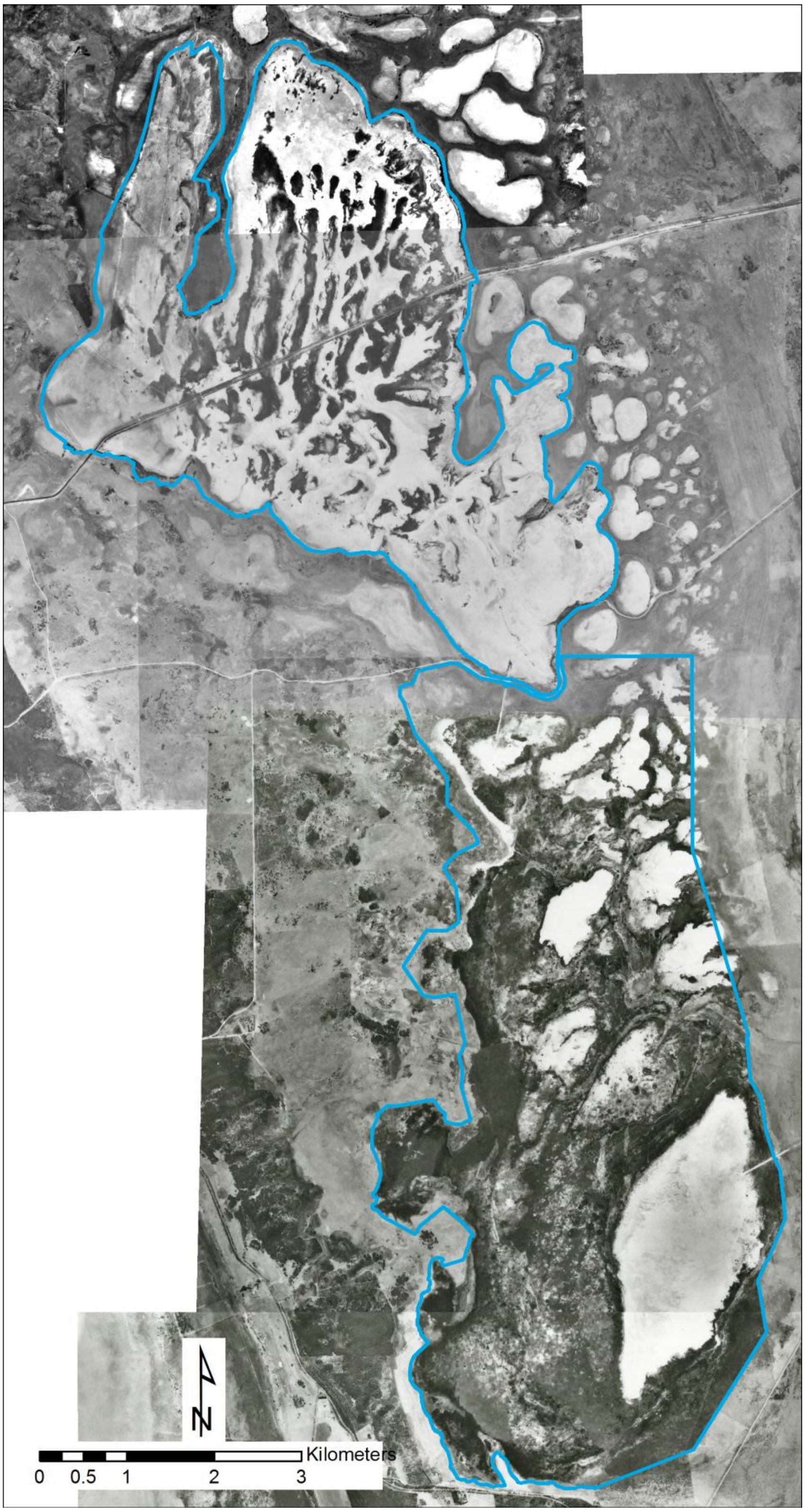


Figure 33. 1978 aerial photography mosaic.

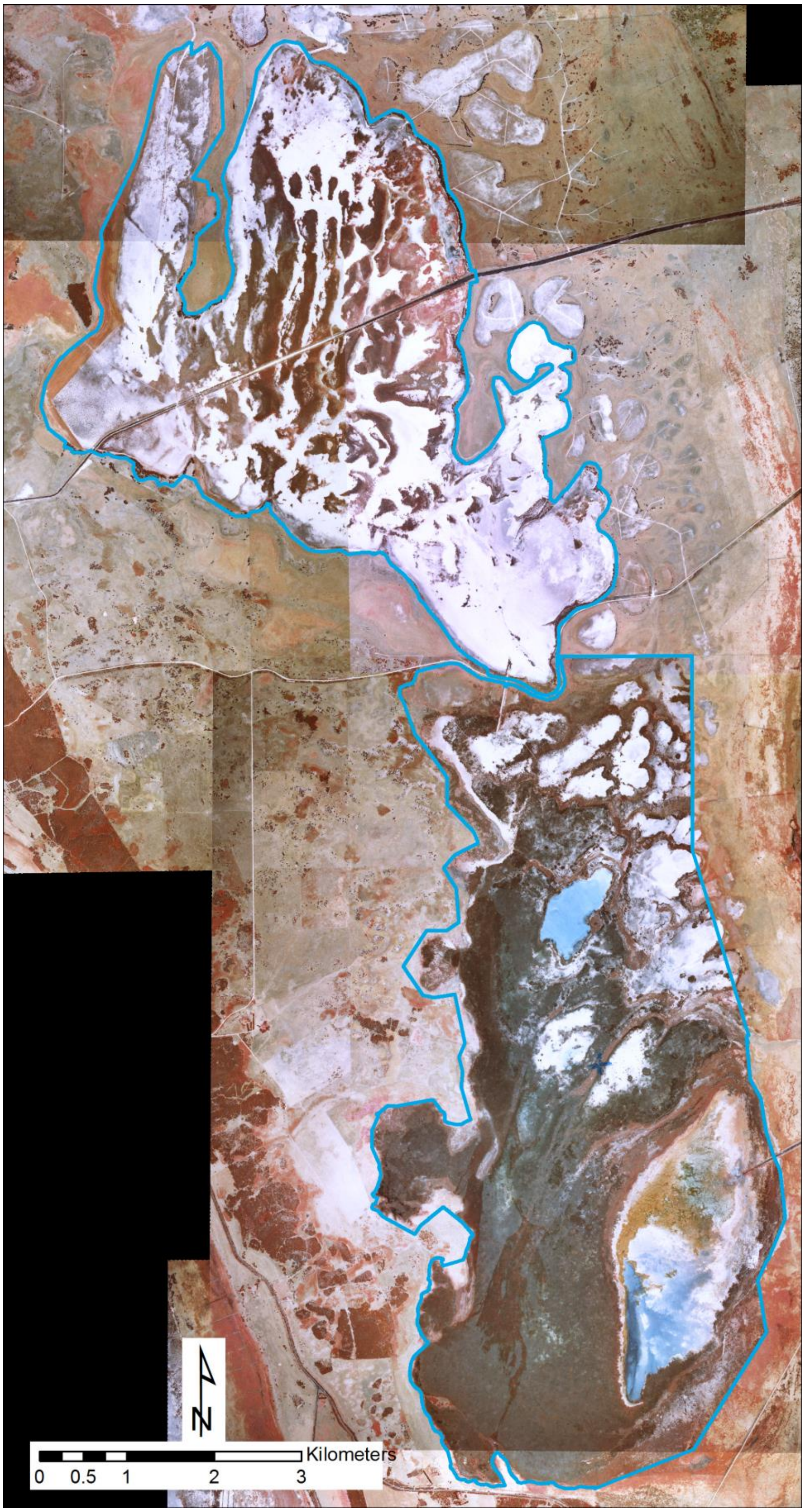


Figure 34. 1988 aerial photography mosaic.

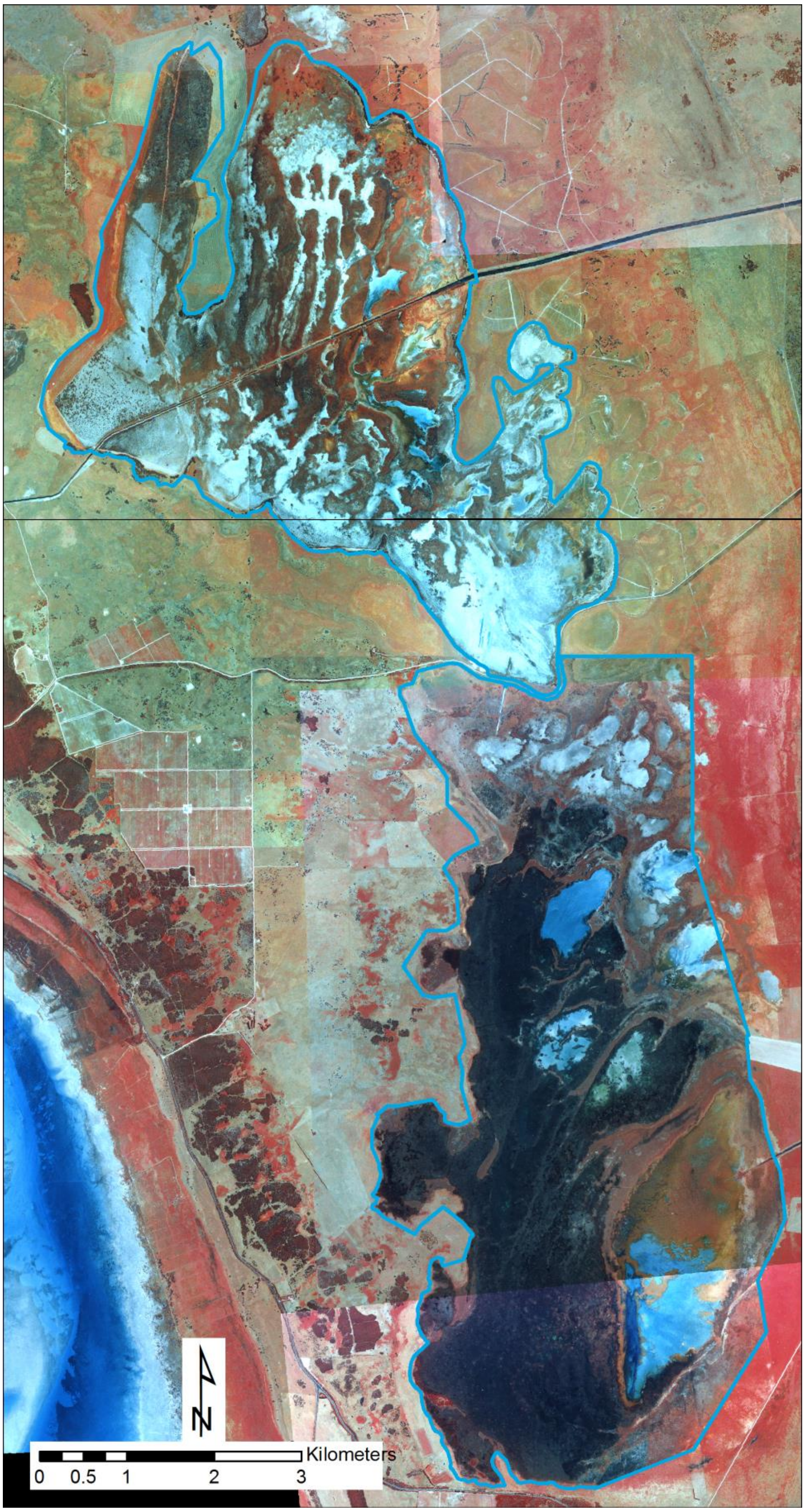


Figure 35. 1999 aerial photography mosaic.

Figure 36. 2008 aerial photography mosaic.

Chapter 4. Hydrodynamic Model for the Robe Lakes and the Implications of Upstream Diversion Rules on Lake Condition

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4.1 Acknowledgements

The authors acknowledge data supplied from Mark de Jong South East Water Conservation and Drainage Board for the Robe Lakes, and Dr. Paul Dalby of In Fusion Consulting for guidance in supporting the modelling and significant improvements to the report. We also acknowledge Brendan Busch from the UWA research team for support in DEM processing and model mesh development, and staff from BMTWBM for provision of the TUFLOW-FV modelling package.

4.2 Summary

The South East Flows Restoration Project (SEFRP) has been proposed as a long-term strategy for improving the ecological conditions of wetlands in the Upper South East, improving the marine environment of the South East and to maintain appropriate salinity levels in the South Lagoon of the Coorong. In particular, the SEFRP proposes to divert water from the Drain L catchment in the South East of South Australia towards the Coorong South Lagoon, potentially removing water from the Robe Lakes estuarine system.

It is hypothesised that inflows to the Robe Lakes under existing management arrangements exceed the environmental water requirement (EWR) of the Robe Lakes in most years. However, the EWR of the system has not been determined. This report describes the outputs from hydrodynamic modelling which can be used to assess the changes in water salinity and height in the lakes under a range of low, medium and high flow conditions. Furthermore, a range of diversion rules scenarios were then assessed to predict their impact on salinity and hydrodynamics.

The hydrodynamic model was built using the TUFLOW-FV platform and adopts a 3-D finite volume mesh of the system. The model was applied for four years, including dry (2007, 2008), medium flow (2010) and wet (2004) conditions. The model was validated against available monthly data from 2007-2008 and it is considered that the model captured the spatial and seasonal variability in the system reasonably well.

The range of salinities, salinity exceedance probabilities, and water levels experienced by different lake basins and sites within the estuary system was defined from existing information. This was used as a baseline to assess the significance of different flow diversion scenarios. The flow diversion scenarios were defined as:

- only allowing diversions during the winter months (Jun –Nov), and
- covered a range of lower and upper diversion limits, ranging from a 40 – 150 ML/day minimum to a 580 – 1500 ML/day.
- An additional final scenario was run where the estuary model was driven by the hydrological model output from the associated hydrology study for low, medium and wet years, and this included a more likely set of flow diversion rules (Chapter 5).

The scenario modelling suggests that diverting water between 80 – 580 ML/day or 100 – 600 ML/day was 80 – 580 ML/day (Scenario C) or 100 – 600 ML/day (Scenario D) was the optimum balance between limiting the impact to the general salinity structure of the Robes Lakes system, and providing the most volume of water for diversion. This information was built into the more complex diversion rules implemented in the catchment hydrology model, and used to generate the more realistic flow time-series with flow diversions considered (Chapter 5). For the dry years (2007, 2008) the forecast changes to the inflow were within the range of model uncertainty and so the assessment with the hydrodynamic model was unable to resolve impacts relative to the earlier assessment. For the medium and wet years, the impact of the diversion scenario was minor.

Other possible ecosystem impacts of flow diversion such as control of sand incursion and maintenance of an open estuary mouth, nutrient delivery to the estuary and flow cues for fish movement were not considered, but discussed in the context of the altered flow and salinity regime.

4.3 Background

The Coorong, Lower Lakes and Murray Mouth (CLLMM) Program is a program of the South Australian Government Department of Environment and Natural Resources. The South East Flows Restoration Project (SEFRP) is one of a suite of projects being investigated under the broader CLLMM Program. The SEFRP has been proposed as a long-term strategy for improving the ecological character of wetlands in the Upper South East, maintaining appropriate salinity levels in the Coorong South Lagoon and improving the ecological character of near shore marine environments affected by freshwater flows from the South East drainage system. In particular, SEFRP proposes to divert water from existing drains in the South East of South Australia, through wetlands in the Upper South East and terminating in the Coorong South Lagoon.

The Robe Lakes is an estuarine system of four interconnected lakes located at the terminus of "Drain L" within the township of Robe. The system consists of Lake Battye, Lake Nunan, The Pub Lake and Lake Fox. Inflows to the system are assumed to include:

- Freshwater inflows from Drain L;
- Inflows of seawater through the permanently open mouth;
- An unknown but potentially significant groundwater contribution;
- Local runoff; and
- Direct rainfall.

Proposed diversion points for the CSLFRP are located in the Drain L catchment upstream of the Robe Lakes, thus inflows to the Robe Lakes will be reduced by the CSLFRP project. It is assumed that Drain L inflows to the Robe Lakes under existing management arrangements greatly exceed the environmental water requirement (EWR) of the Robe Lakes in most years. However, the EWR of the system has not been determined.

It is an objective of the CSLFRP that the current ecological character and other values (e.g. amenity, recreation) of the Robe Lakes be maintained. The ecological character and values of the Robe Lakes are assumed to be strongly influenced by:

- Salinity, including both spatial and temporal variation;
- Water level regime; and
- Degree of mouth openness.

Thus, to ensure the ecological character of the Robe Lakes are maintained, salinity, water level and mouth openness need to be maintained close to their current range. This requirement may influence the amount of water than can be diverted away from the Robe Lakes by the SEFRP.

4.4 Objectives

The objectives of this project, *Hydrodynamic Model for the Robe Lakes and the Implications of Management Scenarios Upstream Diversion Rules on Lake Condition*, are:

- to further refine the salinity, water level and mouth morphology targets for the Robe Lakes; and
- to determine the Drain L inflows required to ensure those targets are achieved (i.e. to assess the EWR of the Robe Lakes).

Specifically, the aim of this study was to review the historical salinity and water level of the Robe Lakes, which would have shaped the character and extent of biological communities found there now. A spatially resolved hydrodynamic model was then used to simulate lake salinity and water level with different inflow hydrology and determine what flow could be diverted from the Robe Lakes without a significant change in water level or salinity.

The flow record was analysed to classify historical flow and determine levels of flow that might be recovered under different diversion limits and a range of diversion rule scenarios were then assessed. Finally, the model was used to assess the estuary condition under a likely diversion scenario, as predicted by the larger hydrological model of the system (Chapter 5).

4.5 Site Description

The Robe Lakes of interest in this study are the interconnected lakes; Lake Fox, Pub Lake, Lake Nunan and Lake Battye (Figure 37), which lie to the south-east of the Robe settlement in the Limestone Coast of South Australia. The lakes receive some water from a small local catchment but the majority of flow is from an extensive drainage network (Figure 38), which drains water from productive agricultural land and channels the water westwards into Drain L, through the Robe Lakes and into the ocean at Robe.

Figure 37. The Robe Lakes comprise a string of connected lakes receiving water from Drain L to the east and water flowing North-west to exit to the ocean north of Lake Fox.

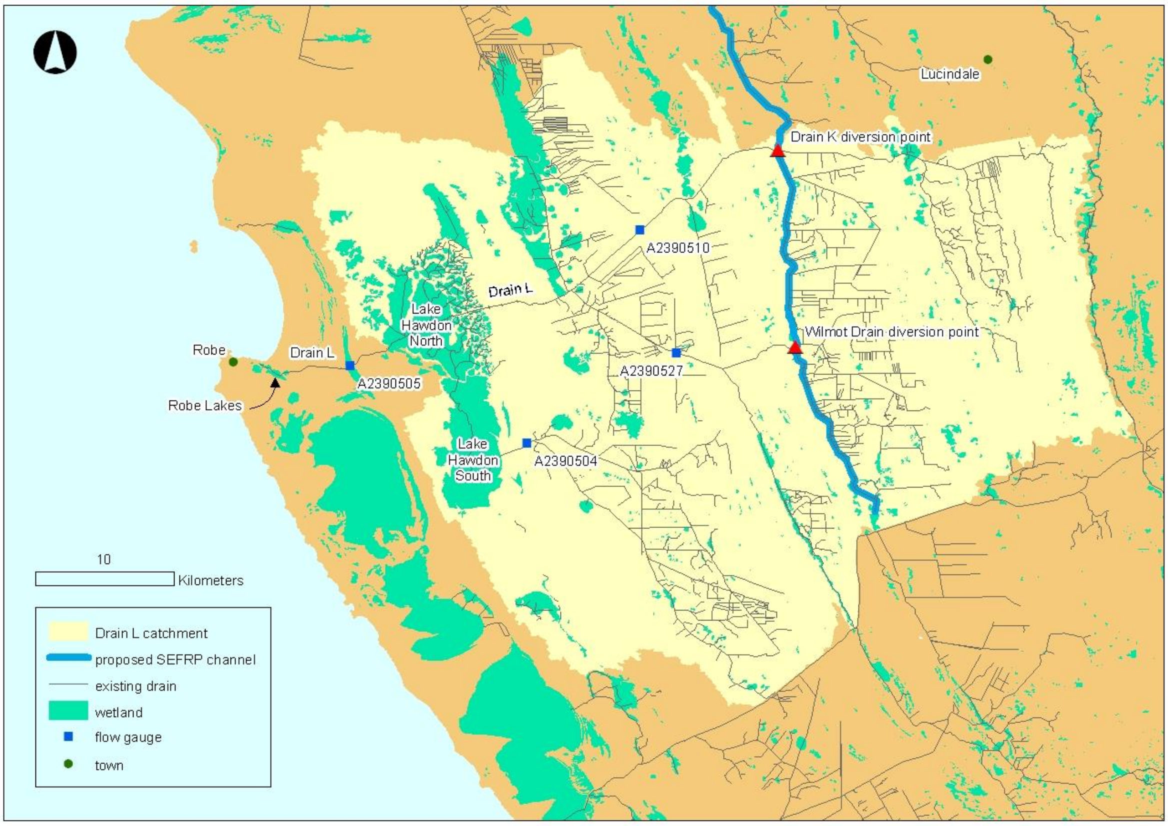


Figure 38. The catchment of Drain L is comprised of an extensive drainage network draining an area of 1642km^2.

4.6 Connectivity to the ocean

The connection to the ocean is an important feature of the Robe Lakes. The channel cut into the limestone defines the outer boundaries of the mouth (Figure 39). Note however that the hard base still supports a dynamic mouth as sand moves into and out of the estuary in response to different flow regimes.

Figure 39. The mouth of the Robe Lakes and the entrance to the Southern Ocean.

4.7 Lakes Bathymetry

For the purposes of hydrodynamic and hydrological modelling, a revised bathymetry of both the Robe Lakes and Lake Hawdon South was required. The existing South East regional digital elevation model (DEM) was inaccurate for these wetlands due to the presence of surface water and/or dense vegetation, which had influenced the LiDAR results used to create the DEM. To revise the DEM, the following procedure was followed:

1. The area of the Robe Lakes and Lake Hawdon South for which bathymetry was required was delineated.
2. Within the delineated water bodies, the areas where the existing DEM was accurate and inaccurate were determined.
3. Within the areas where the existing DEM was inaccurate, spot elevations of the lakebed were obtained by professional surveyors using differential GPS. This required the use of a boat for the Robe Lakes. The number of spot elevations obtained in this manner was:
    a. 894 for the Robe Lakes (Figure 40); and
    b. 622 for Lake Hawdon South.
4. For areas where the existing DEM was inaccurate and coverage of spot elevations was poor (due primarily to access difficulties), estimates of elevation were made based on aerial photography, i.e. where the vegetation or image colour in an area with poor coverage was similar to that in an area with good coverage, a similar lakebed elevation was estimated. The number of lakebed elevations estimated in this manner was:
    a. 223 for the Robe Lakes (Figure 40); and
    b. 1095 for Lake Hawdon South.
5. Using the combined data set of surveyed and estimated lakebed spot elevations (1117 for Robe Lakes, 1717 for Lake Hawdon South) a spatial data file of the xy (horizontal coordinates) and z (height values AHD) was generated. As well the

existing high resolution DEM was clipped to remove areas of suspect height data. The remaining good xyz values bounding the clipped area were updated into the spatial data file containing the surveyed and estimated point data.

6. From this data, a local area DEM was generated using an ESRI natural neighbour interpolation method (a process which respects the new measured data point values) at 10 metre grid cell size, this was merged and re-sampled at 2 metre grid cell size with the original South East 2 metre DEM.

As a result the known accuracy of the DEM used for hydrodynamic and hydrological modelling was improved by the incorporation of validated survey data, (even though the resolution of the DEM has been reduced over the inaccurate areas of the original high resolution DEM) by improving the alignment of the model with measured real world topography.

4.8 Hydrology: Drain L Flow

Flow was gauged at Boomaroo Park which is on Drain L (Site ID A2390505; UTM Zone 54 3988328, 5885867; elevation 3.7m). The catchment area for this site is 1,642.23 km^2. The data is available from the state government water data archive at:

http://e-nrims.dwlbc.sa.gov.au/SiteInfo/Default.aspx?site=A2390505#Historic%20Data

Flow records are available for the period April 1971- April 1975 and from May 1991 – Oct 2011. The daily discharge is shown in Figure 41 however, only the period from 1991-2011 was used for flow analysis.

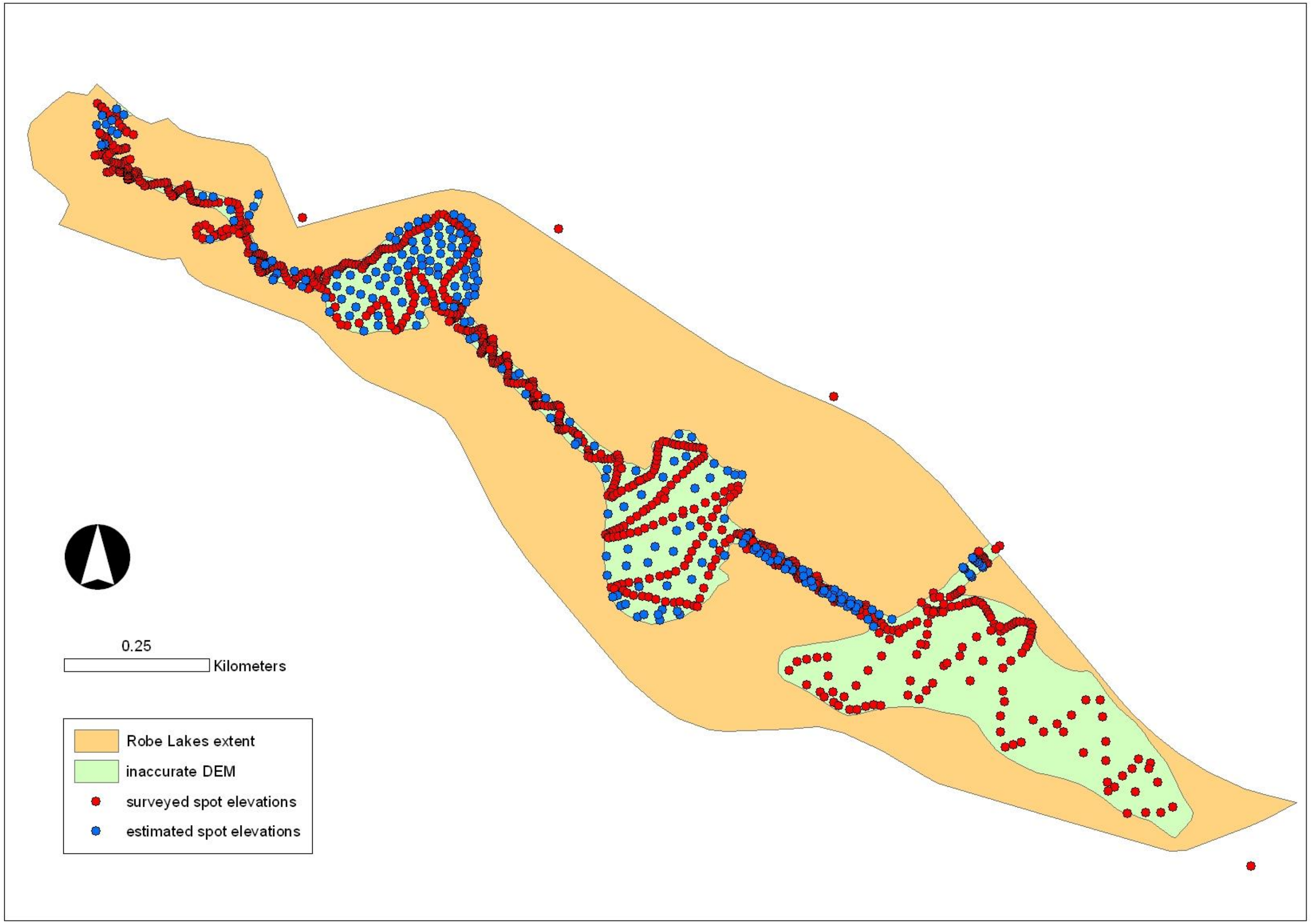


Figure 40. Map of Robe Lakes showing extent of inaccurate DEM and locations of surveyed and estimated spot elevations.

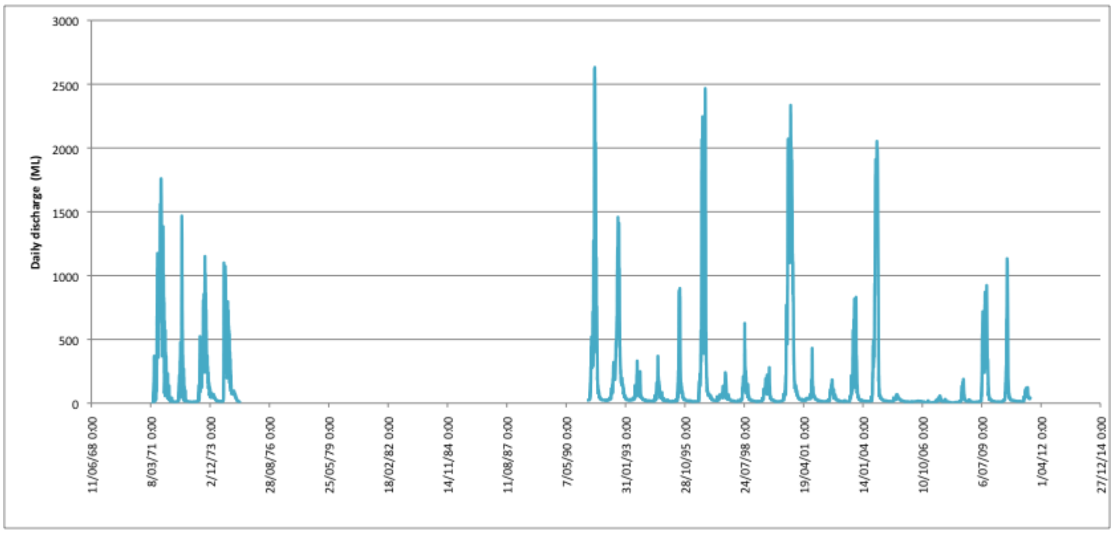


Figure 41. Daily flow at Boomoroo Park gauge in Drain L.

4.9 Flow Analysis

Annual flows for years between 1991 -2011 were assessed to define the probability of flow magnitudes, assuming a normal distribution (Figure 42). There is a notable increase in the number of low flow years (<10^4 ML/yr) in the period since 2001 relative to the previous decade from 1991.

Further, to analyse the hydrograph in terms of its ability to support diversion flows, it was classified into different flow bands for the years 1991-2011 (Table 16). This analysis enables a first assessment of how many days diversions may be available from any particular flow band. The analysis was then expanded to include the volume of water that would be available to the Robe Lakes if volumes exceeding particular volumes were diverted away from the lakes (Table 17). Finally the volume of water available for diversion under each of the diversion rules was calculated (Table 18). While this is a simple first-pass analysis it enabled refinement of what flow scenarios should be modeled in the more thorough modeling task.

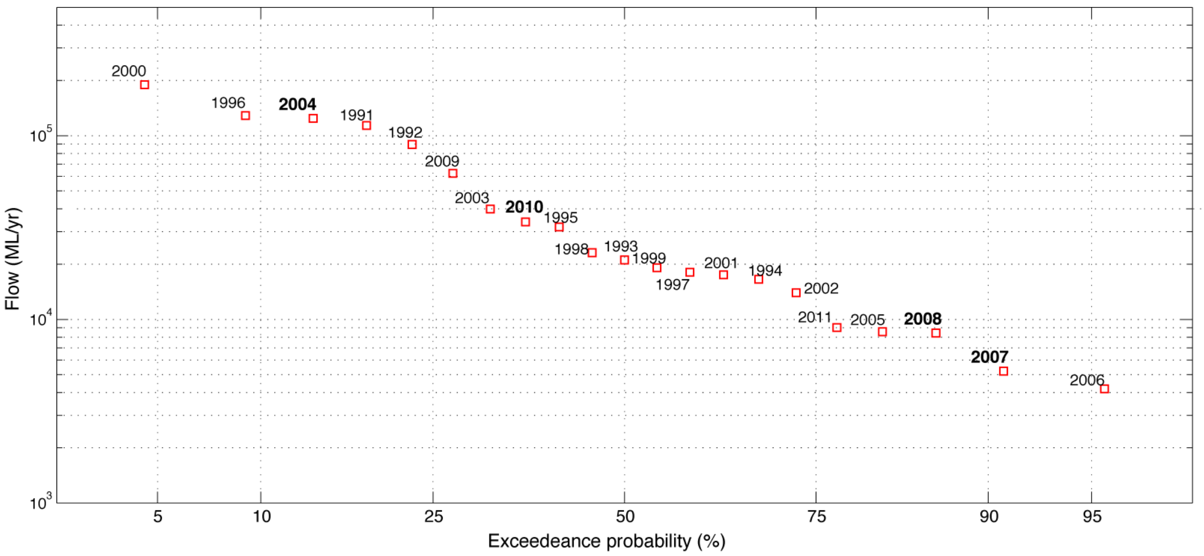


Figure 42. Annual flow exceedance probabilities for the period 1991 - 2011. Highlighted years are used later in the model analysis.

Table 16. Number of days in each year that flow is within flow bands.

Year	0-5 ML/day	5-10 ML/day	10-20 ML/day	20-40 ML/day	40-60 ML/day	60-80 ML/day	80-100 ML/da	100-200 ML/d	200-400 ML/d	400-800 ML/d	800-1600 ML (	>1600 ML.\/da
1991	0	0	0	53	24	10	13	18	27	44	16	24
1992	0	0	8	145	4	8	11	71	48	33	38	0
1993	0	0	0	202	56	36	24	33	14	0	0	0
1994	0	0	140	125	36	16	8	29	11	0	0	0
1995	0	1	167	96	25	7	10	23	9	17	10	0
1996	0	1	171	6	8	35	7	31	20	28	27	32
1997	0	0	41	162	79	40	13	20	10	0	0	0
1998	8	15	56	21	6	0	0	0	0	0	0	0
1999	0	9	154	77	14	14	33	55	9	0	0	0
2000	0	37	86	25	5	14	19	39	13	29	44	55
2001	0	0	9	238	58	20	11	23	4	2	0	0
2002	0	0	204	60	27	14	25	35	0	0	0	0
2003	0	2	156	70	20	7	7	39	30	32	2	0
2004	0	0	160	53	23	13	2	11	24	16	28	36
2005	0	1	204	129	24	7	0	0	0	0	0	0
2006	17	75	273	0	0	0	0	0	0	0	0	0
2007	101	47	137	64	16	0	0	0	0	0	0	0
2008	78	114	84	45	7	5	5	28	0	0	0	0
2009	0	125	63	43	8	11	1	10	26	70	8	0
2010	0	4	193	85	19	8	6	14	8	15	13	0
2011	0	0	170	25	38	24	11	10	0	0	0	0

Table 17. Volume of water available to the lakes if the diversion rules allow flow volumes exceeding 5, 10, 20, 40, 60, 80, 100, 200, 400, 800 or 1600 ML/day to be diverted northwards.

Year	>5 ML/day	>10 ML/day	>20 ML/day	>40 ML/day	>60 ML/day	>80 ML/day	>100 ML/day	>200 ML/day	>400 ML/day	>800 ML/day	>1600 ML/day
1991	1145	2290	4580	8607	11843	14762	17465	29373	50041	73654	98414
1992	1830	3660	7318	12415	16613	20739	24671	40554	58098	77967	89538
1993	1825	3650	7300	12111	14785	16490	17681	20361	21042	21042	21042
1994	1825	3650	6985	9738	11262	12378	13251	15687	16511	16511	16511
1995	1825	3650	6569	9096	10847	12285	13573	18091	24369	31343	31838
1996	1830	3660	6430	10224	13969	17139	19984	32329	51457	80163	115413
1997	1825	3650	7258	11645	14097	15221	15939	17850	18061	18061	18061
1998	1825	3650	6619	9444	11668	13713	15530	20104	22522	23067	23067
1999	1825	3640	6405	9427	11748	13843	15481	18834	19090	19090	19090
2000	1830	3638	6358	10821	15134	19258	23069	38563	65240	111068	172717
2001	1825	3650	7296	11783	13479	14420	15112	16549	17424	17462	17462
2002	1825	3650	6403	8827	10586	11873	12839	13946	13946	13946	13946
2003	1825	3650	6164	9450	12004	14245	16362	24467	34136	39826	39874
2004	1830	3660	6675	10179	12982	15421	17736	28487	47088	74416	114994
2005	1825	3650	6448	8156	8545	8567	8567	8567	8567	8567	8567
2006	1816	3423	4182	4182	4182	4182	4182	4182	4182	4182	4182
2007	1669	2850	4254	5096	5221	5221	5221	5221	5221	5221	5221
2008	1747	2812	4160	5350	6174	6892	7518	8418	8418	8418	8418
2009	1825	3406	5430	8465	11097	13446	15742	26521	44723	61834	62334
2010	1825	3648	5935	8033	9489	10695	11719	16017	22266	31066	33940
2011	1390	2780	4672	6720	7951	8579	8860	9015	9015	9015	9015

Table 18. Volume of water (ML) available for diversion if the diversion rules stipulate that flows greater than the X ML/day can be recovered for other systems. (X = 5, 10, 20, 40, 60, 80, 100, 200, 400, 800 or 1600 ML/day).

Year	>5 ML/day	>10 ML/day	>20 ML/day	>40 ML/day	>60 ML/day	>80 ML/day	>100 ML/day	>200 ML/day	>400 ML/day	>800 ML/day	>1600 ML/day
1991	112558	111413	109123	105096	101860	98941	96238	84331	63662	40049	15290
1992	87708	85878	82220	77123	72925	68799	64868	48984	31440	11571	0
1993	19217	17392	13742	8930	6257	4552	3360	681	0	0	0
1994	14686	12861	9526	6773	5249	4133	3260	824	0	0	0
1995	30013	28188	25269	22742	20991	19553	18265	13747	7469	495	0
1996	126756	124926	122156	118362	114617	111447	108602	96257	77129	48423	13173
1997	16236	14411	10803	6416	3964	2840	2122	211	0	0	0
1998	21242	19417	16448	13623	11399	9354	7536	2962	545	0	0
1999	17265	15451	12686	9663	7342	5247	3610	256	0	0	0
2000	187536	185729	183008	178545	174232	170108	166298	150803	124127	78298	16649
2001	15637	13812	10166	5679	3982	3042	2349	913	38	0	0
2002	12121	10296	7542	5119	3360	2072	1107	0	0	0	0
2003	38049	36225	33711	30425	27871	25629	23513	15408	5739	48	0
2004	122458	120628	117612	114108	111306	108867	106552	95801	77199	49872	9294
2005	6742	4917	2119	411	22	0	0	0	0	0	0
2006	2366	758	0	0	0	0	0	0	0	0	0
2007	3552	2372	967	125	0	0	0	0	0	0	0
2008	6670	5606	4257	3068	2243	1525	899	0	0	0	0
2009	60509	58928	56904	53869	51237	48887	46592	35813	17611	500	0
2010	32115	30292	28005	25907	24451	23245	22221	17923	11673	2874	0
2011	7625	6235	4343	2294	1063	436	155	0	0	0	0

4.10 Water Levels

Water level was reported by Mark de Jong, South East Water Conservation and Drainage Board, for both Pub Lake and Lake Battye during 2006-2009. Water level at the Pub Lake ranged between approximately 0.4 and 1.2 mAHD (Figure 43). Lake Battye showed a similar level range (Figure 43).

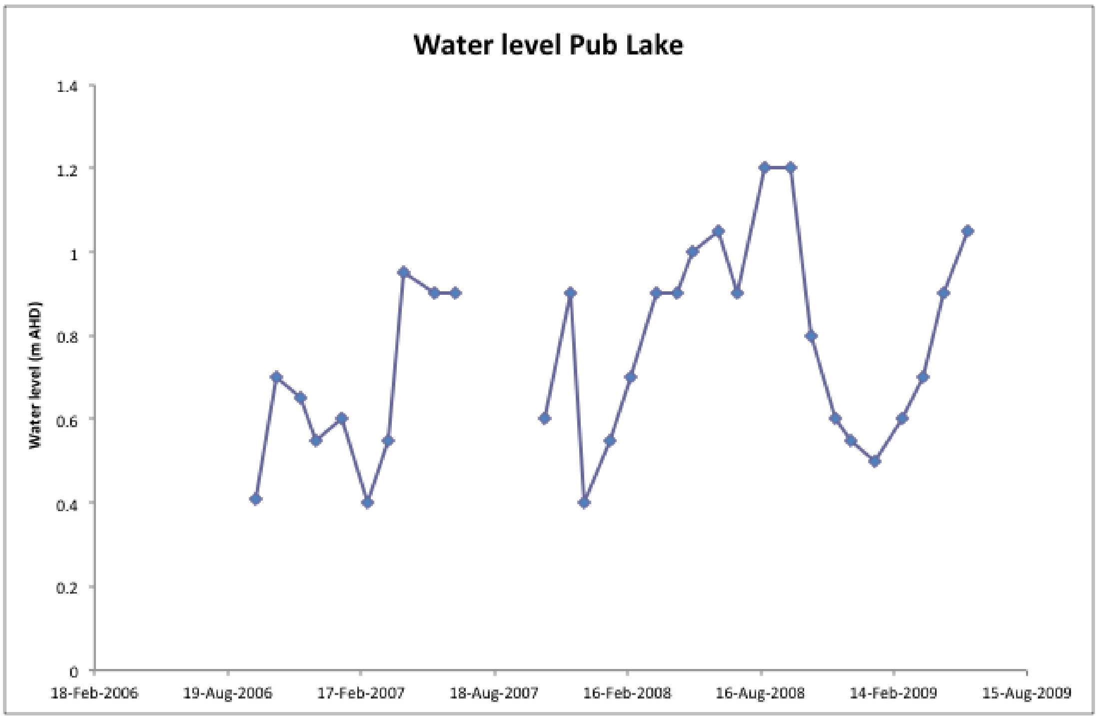


Figure 43. Water level in Pub Lake.

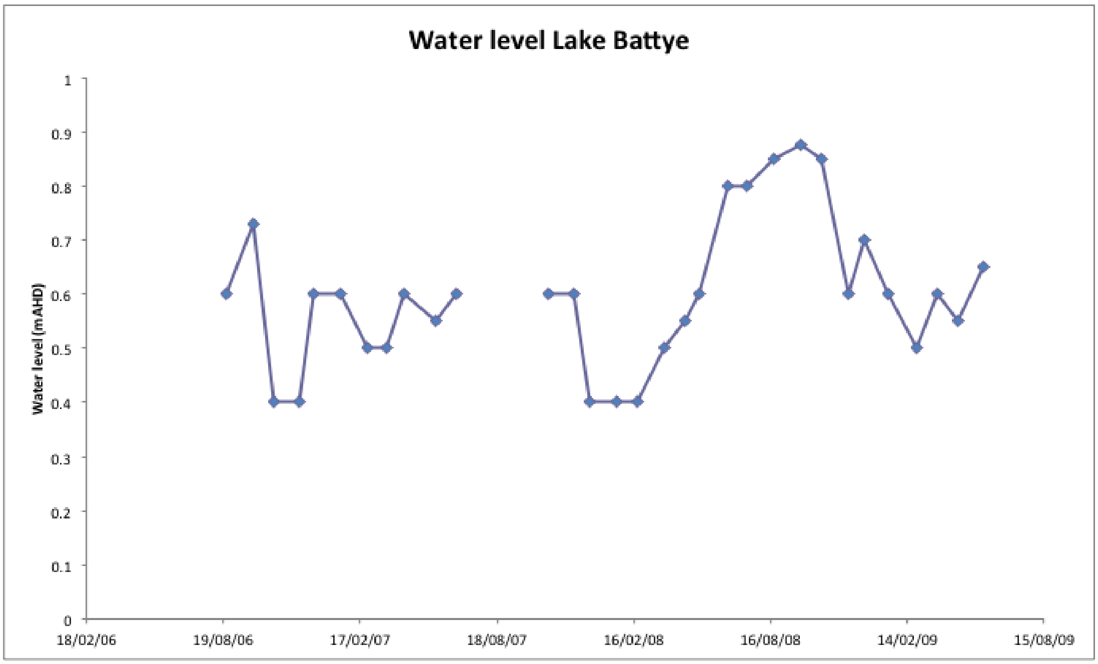


Figure 44. Water level at Lake Battye.

The tidal excursion was estimated based on data from Victor Harbour and varied between 0 mAHD and 1.6 mAHD, with an average level of approximately 0.4-0.7 m AHD. Based on bathymetric information, these depths relate to an observed excursion in Lake Battye similar to the tidal range of between 0.4-0.9 mAHD, suggesting the lake is hydraulically connected to the ocean at all times.

4.11 Water Quality

Salinity data was collected by Mark de Jong, South East Water Conservation and Drainage Board, during a monitoring program between 2006 and 2009. (Source data is contained in excel sheet *WQ and phytoplankton data 2006_2009 Mark de Jong.xls* Sheet 8 – is the metal footbridge between Lakes Fox and Pub; Sheet 9 is Lake Battye Jumbos Jetty).

4.12 Salinity

It is desirable that any diversions of water from the Robe Lakes do not alter the water level or salinity and understanding the base line salinity regime is important to assess the impacts of any changes to flow regimes. Some limited electrical conductivity measurements were made during the de Jong sampling which we used as the reference condition. Electrical conductivity is used as a measure of salinity, which varies with ocean salinity and temperature. Note that the conductivity of 35psu seawater at 25°C is approximately 54,000μS/cm (UNESCO, 1983).

Pub Lake salinity is influenced by both flows from Drain L and tidal inputs. The salinity ranged between 4,170 μS/cm and 54,100μS/cm over the three year period of monitoring (Figure 45). Lake Battye is further upstream and appears to be less influenced by tidal intrusions but still experiences salinity up to approximately half that of seawater (Figure 46).

Salinity in Drain L 1.1km upstream of Lake Battye in spring of 2011 was recorded on two occasions and was 3,510 and 4,490μS/cm.

4.13 Temperature

The historical temperature data for the Robe Lakes shows seasonal oscillation between approximately 12°C and 25°C (Figure 47 – 48). The monthly spot measurements do not provide any information on thermally-induced stratification and mixing behavior – risk factors for algal blooms. However it can be assumed that stratification behavior would be dominated by salinity and not change under a diversion strategy that does not alter summer inflow hydrology to the lakes.

4.14 Nutrients

Nutrients and changes to nutrient dynamics were not considered in the diversion scenario modelling but the nutrient concentrations in water destined for diversion is noteworthy. Nutrient data is available for Pub Lake and Lake Battye: Ammonia concentrations range from the minimum level of detection (0.01 mg/L) to 0.16 mg/L (Figure 49,54); Nitrate ranged from the minimum limit of detection to 0.08 mg/L (Figure 50,55); Total Nitrogen (TKN) had a maximum of 1.8 mg/L (Figure 51,56); Total Phosphorus (TP) ranged between 0.03 and 0.21 mg/L (Figure 52,57); and Filterable Reactive Phosphorus (FRP) ranged between the minimum level of detection and 0.068 mg/L (Figure 53,58). These concentrations are generally high: periods of Total Nitrogen above 1 mg/L and Total Phosphorus above 0.1 mg/L general considered eutrophic (Bricker *et al.*, 2003) and peaks in nutrient concentrations are likely to be a cause algal blooms in the lakes.

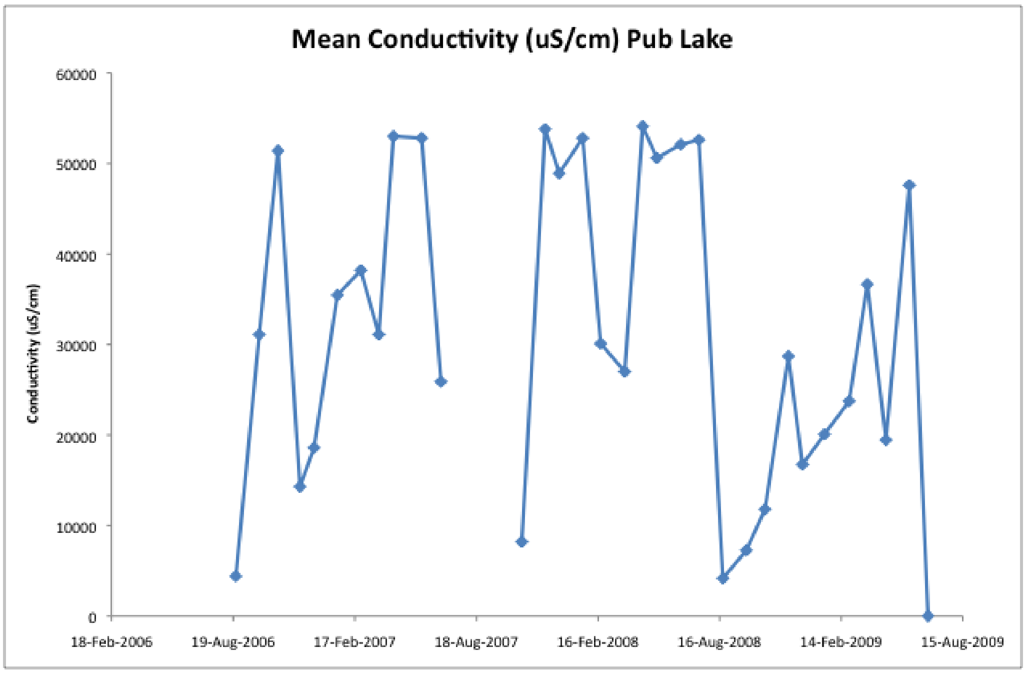


Figure 45. Conductivity at Footbridge between Fox and Pub Lakes.

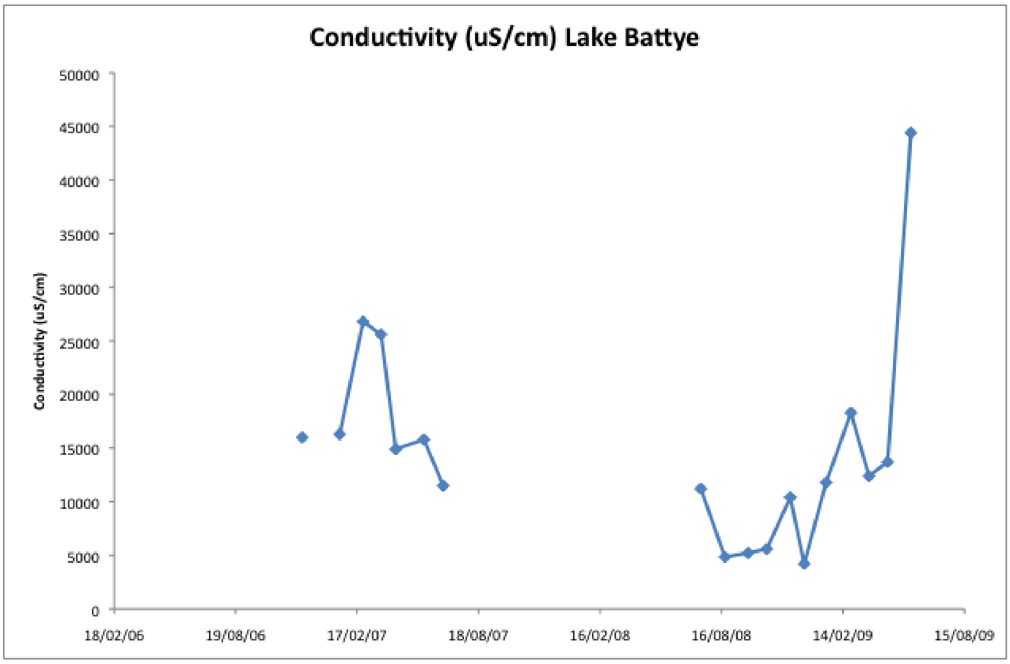


Figure 46. Conductivity in Lake Battye.

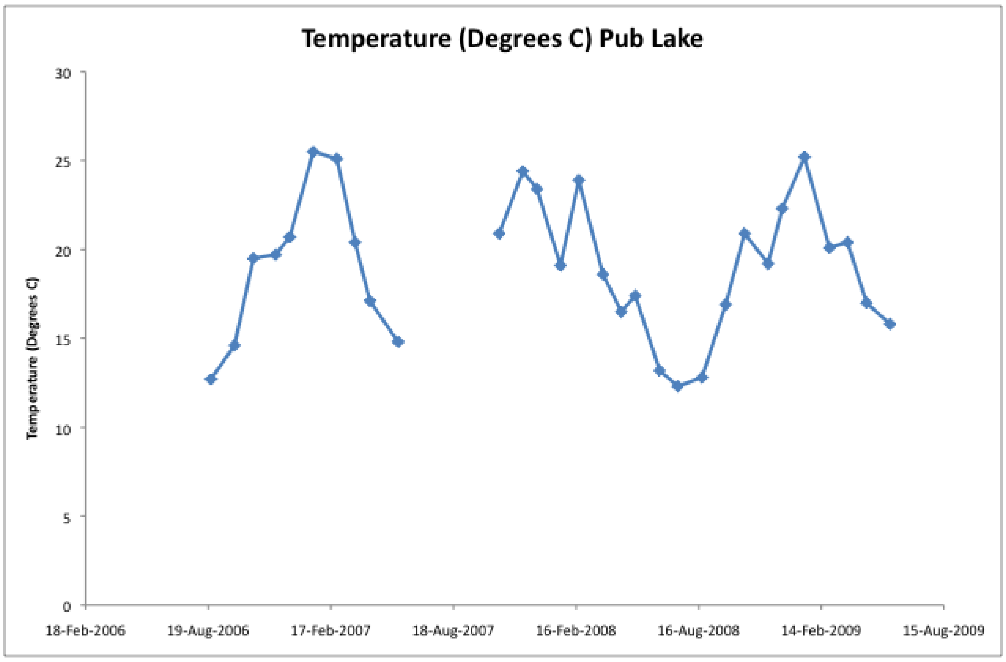


Figure 47. Conductivity in Lake Battye.

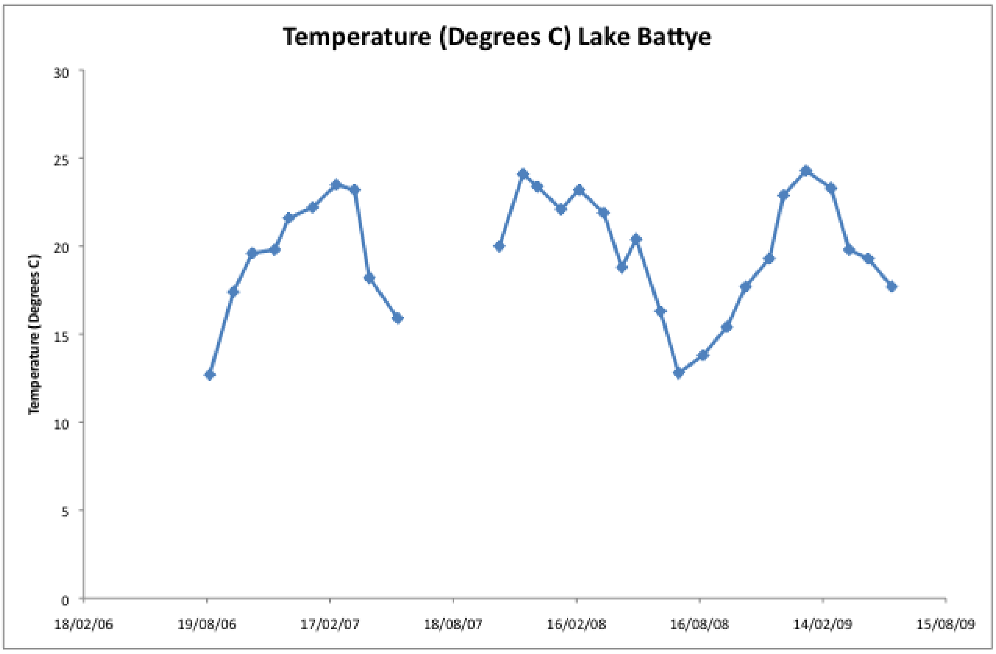


Figure 48. Temperature in Lake Battye.

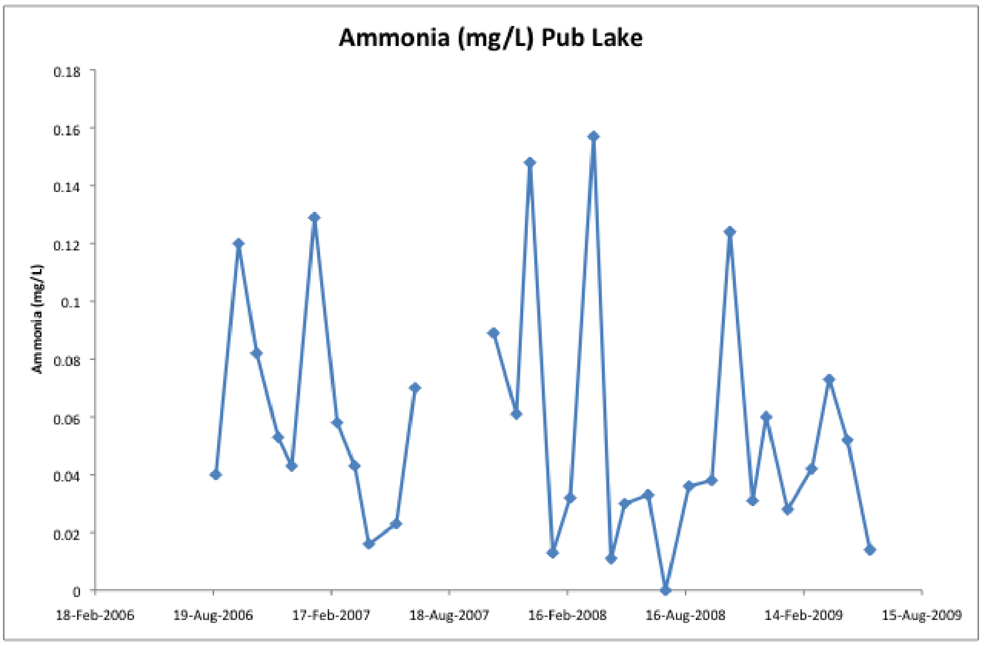


Figure 49. Ammonia concentration in Pub Lake.

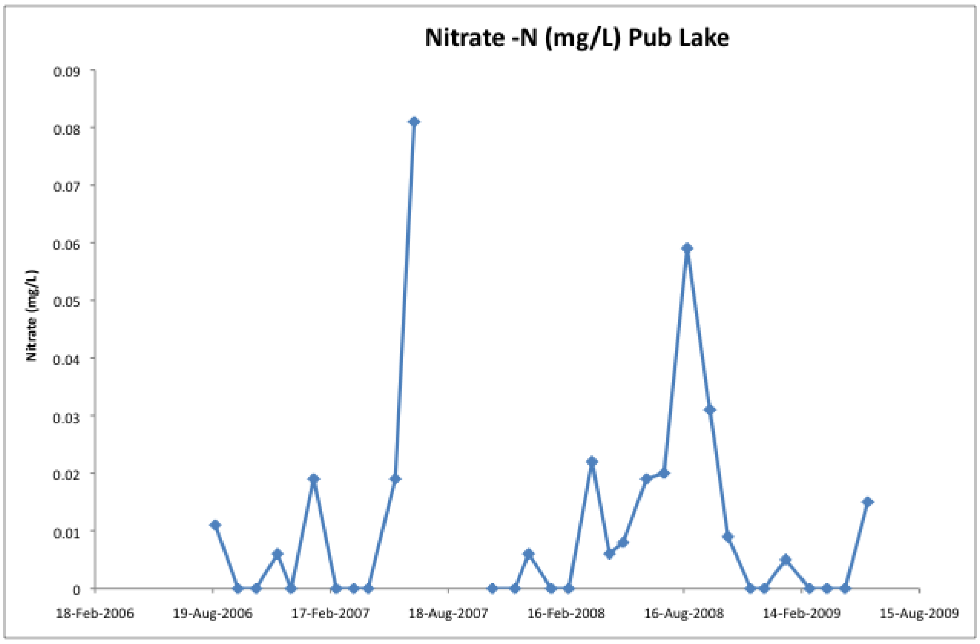


Figure 50. Nitrate concentration in Pub Lake.

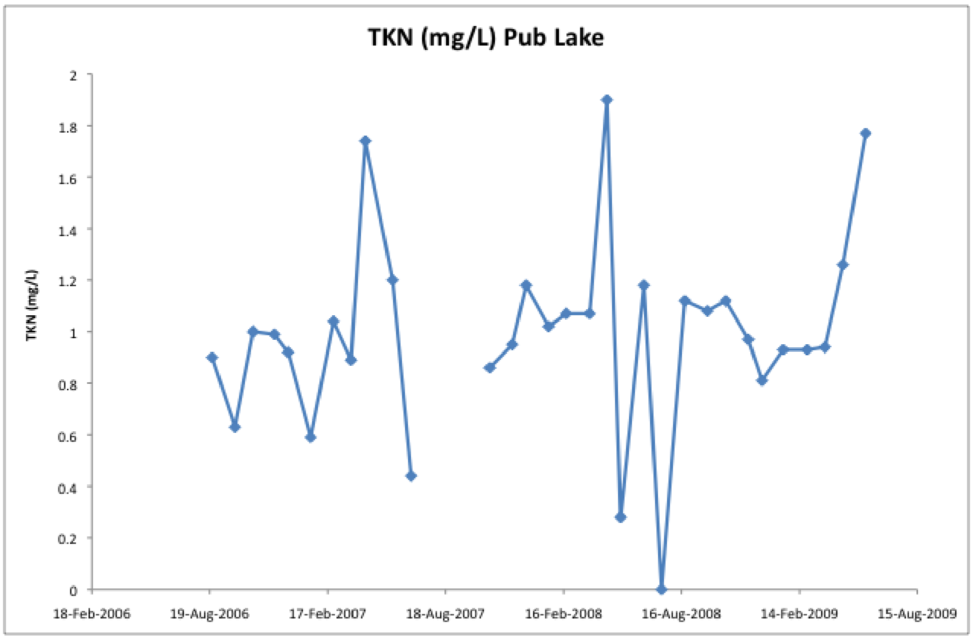


Figure 51. Total Kjeldahl Nitrogen in Pub Lake.

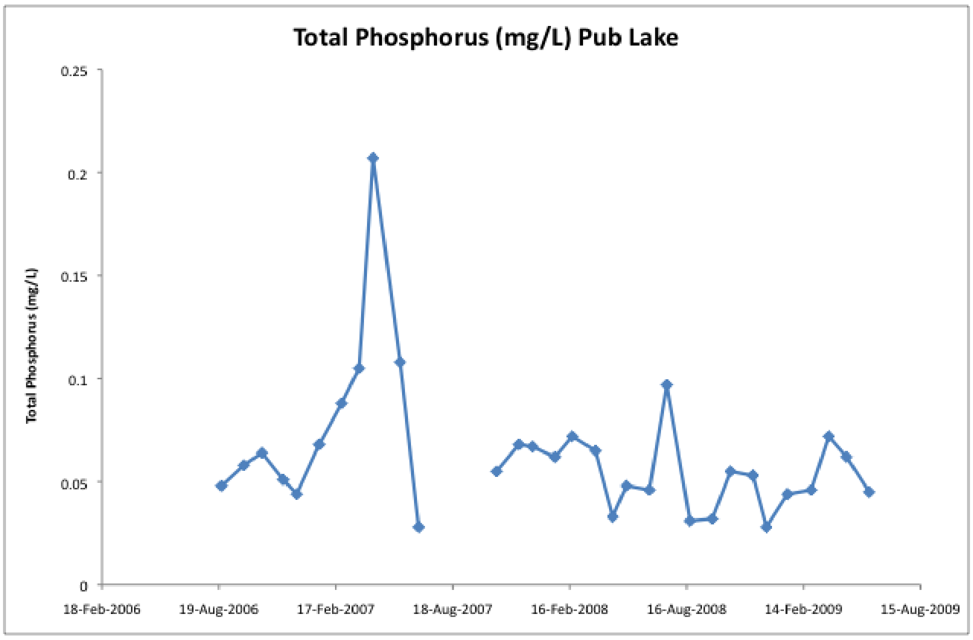


Figure 52. Total Phosphorus in Pub Lake.

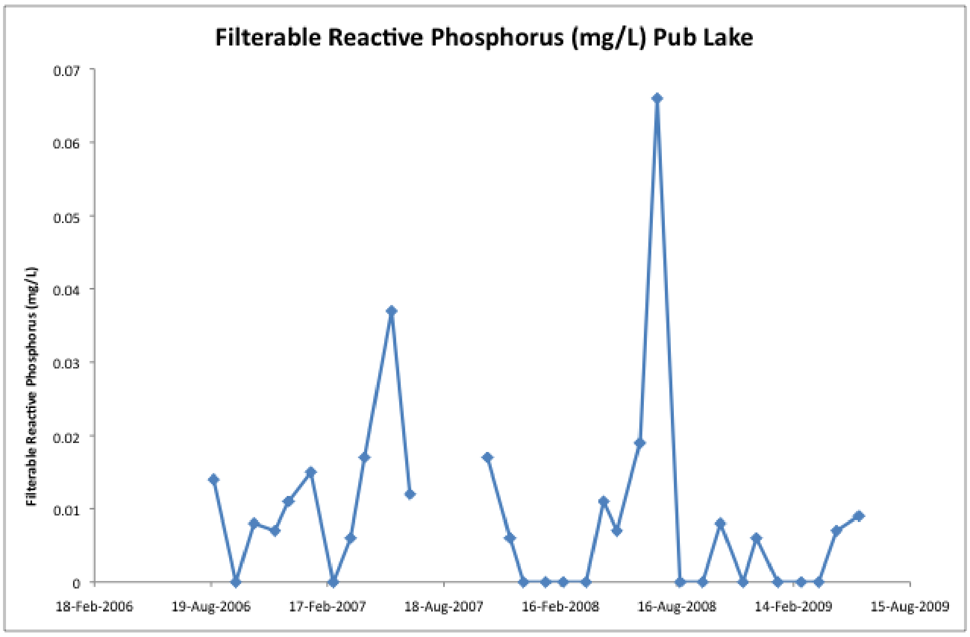


Figure 53. Filterable reactive phosphorus in Pub Lake.

4.15 Nutrients in Lake Battye

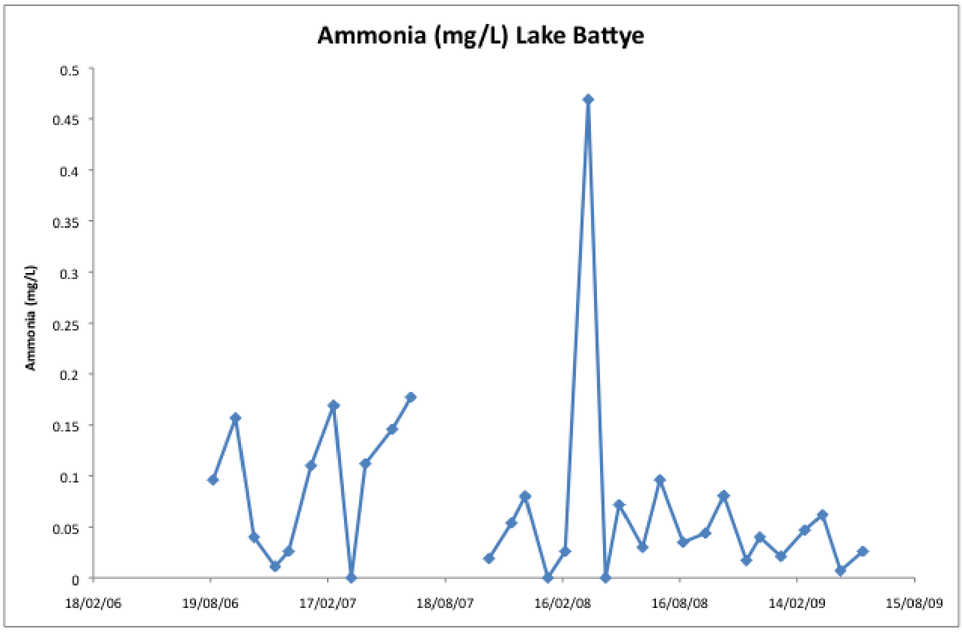


Figure 54. Ammonia concentration at Lake Battye.

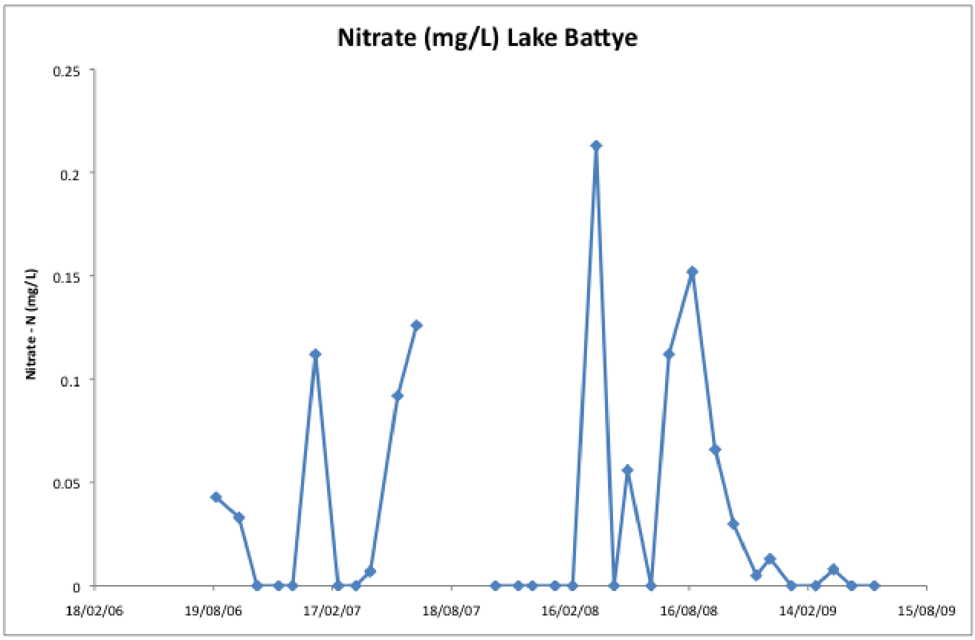


Figure 55. Nitrate concentration at Lake Battye.

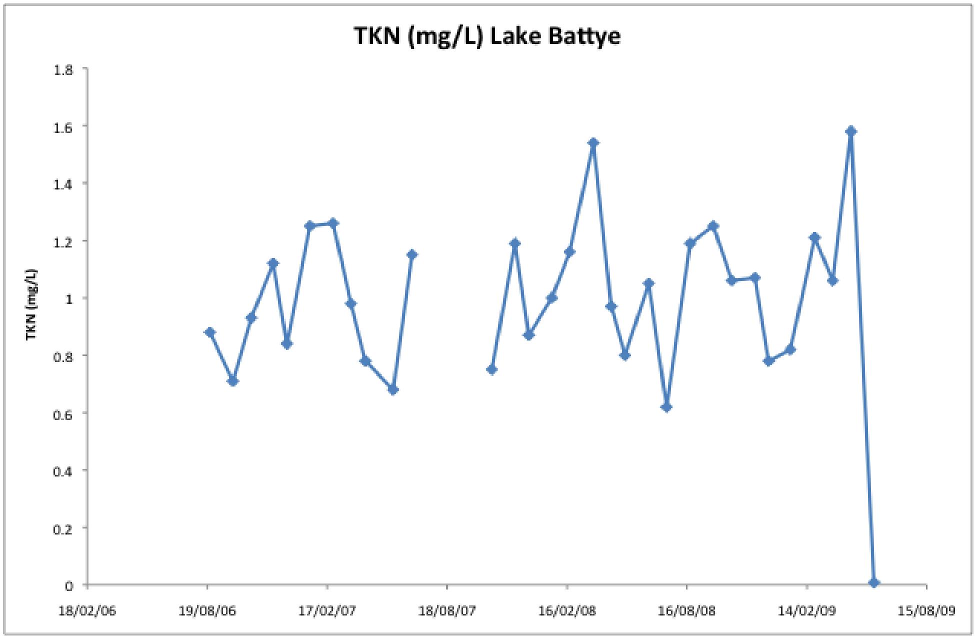


Figure 56. TKN concentrations at Lake Battye.

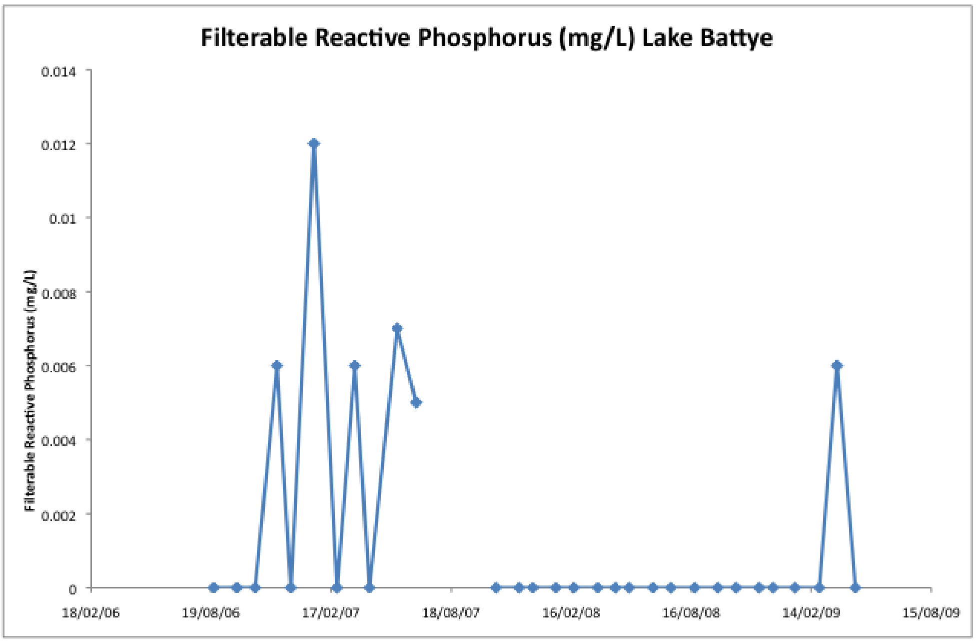


Figure 57. Filterable reactive phosphorus concentrations at Lake Battye.

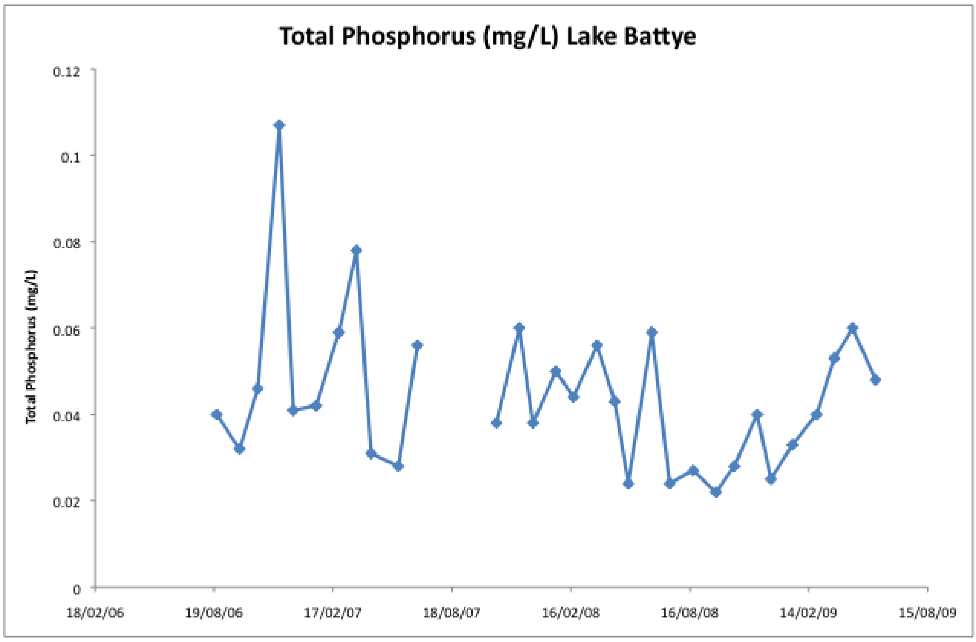


Figure 58. Total phosphorus concentrations at Lake Battye.

4.16 Hydrodynamic Model of the Robe Lakes

The TUFLOW-FV (www.tuflow.com, BMTWBM Pty. Ltd.) package is applied as a 3D flexible-mesh (finite volume) hydrodynamic model to simulate the water level, velocity and salinity distribution in the Robe Lakes system. It is applied in this study with a z-coordinate vertical grid scheme. The model accounts for variations in water level, the horizontal salinity distribution and vertical density stratification in response to inflows and surface thermodynamics.

The model is first applied to the Robe Lakes system from Drain L to the Ocean to assess the salinity structure during low, medium and wet years. We define the range of seasonal variation in salinity that the system experiences under these flow conditions as a proxy for EWR. The model is not configured to simulate the feedbacks between the hydrodynamics and morphometry and the mouth morphology is assumed constant in all these scenarios since there was insufficient information to be able to effectively model the behavior of the mouth.

In the next section, a description of how the model was run under different flow conditions is given and compared against available data where possible. The model is then used to assess a range of diversion rules scenarios: firstly by manipulating the observed flow data with idealized diversion rules to explore the range of responses possible; and secondly by inputting results from the specific diversion hydrological modelling conducted by Chapter 5. Since it was not explicitly simulated, our assessment of the effect of flow on mouth openness is simply linked to the water level and salinity at the mouth as a proxy for flow erosivity.

Model setup

The model is setup based on available bathymetric data for the region (Figure 59).

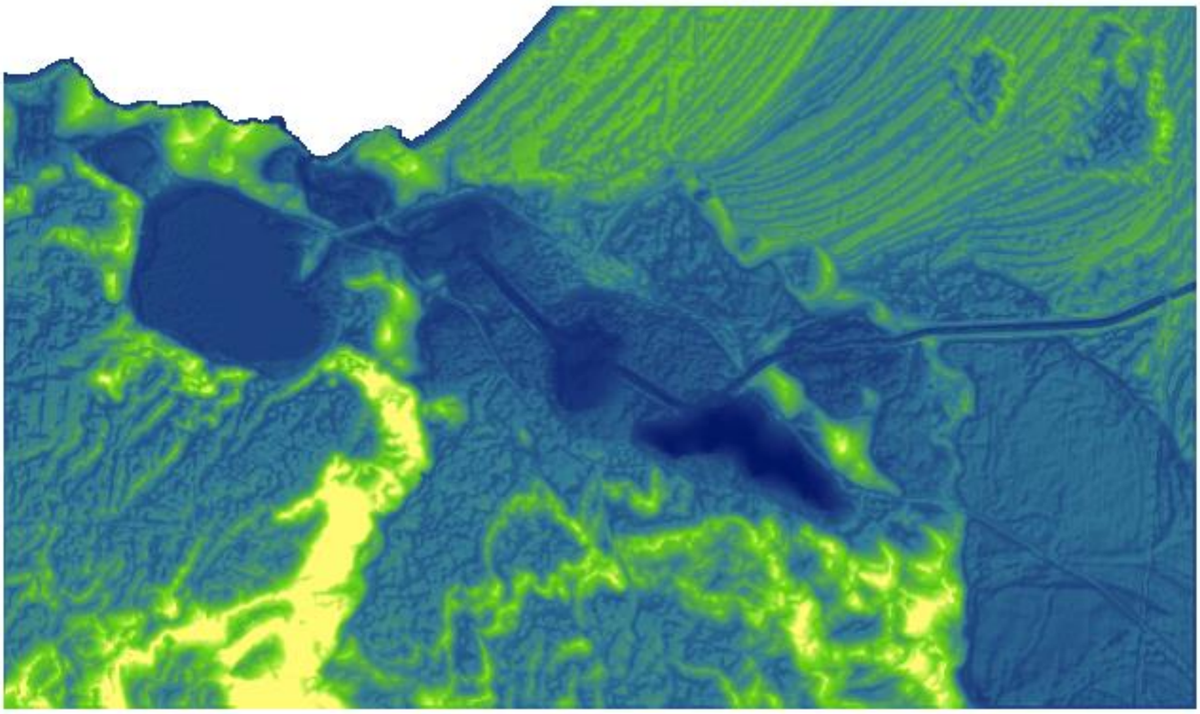
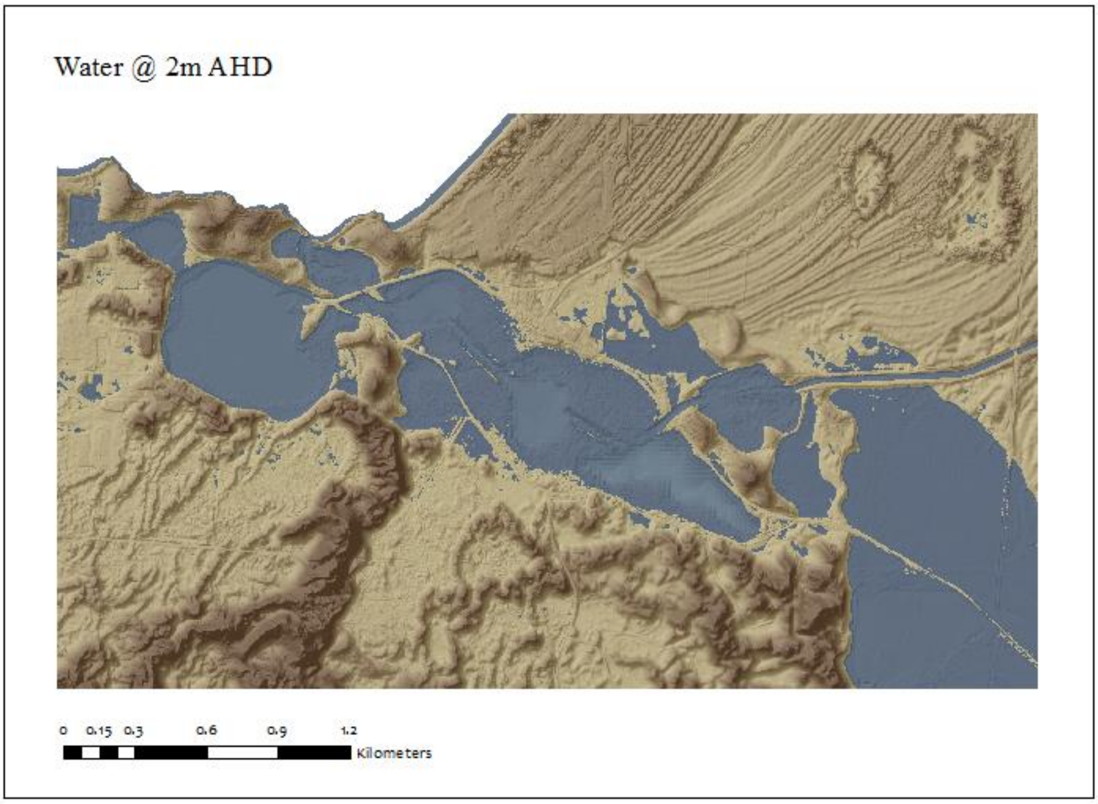


Figure 59. Map of the DEM for the Robe Lakes region including correction based on the survey presented in Figure 40.



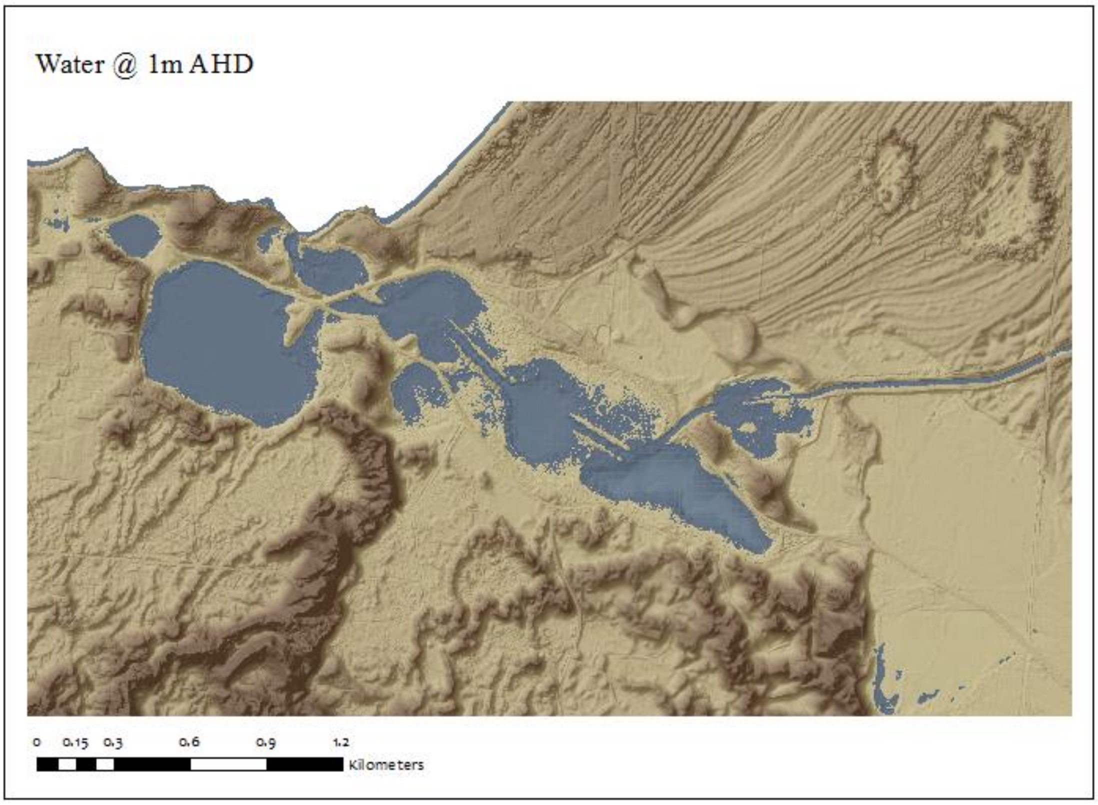


Figure 60. Extent of inundation at water levels of 1 and 2 mAHD.

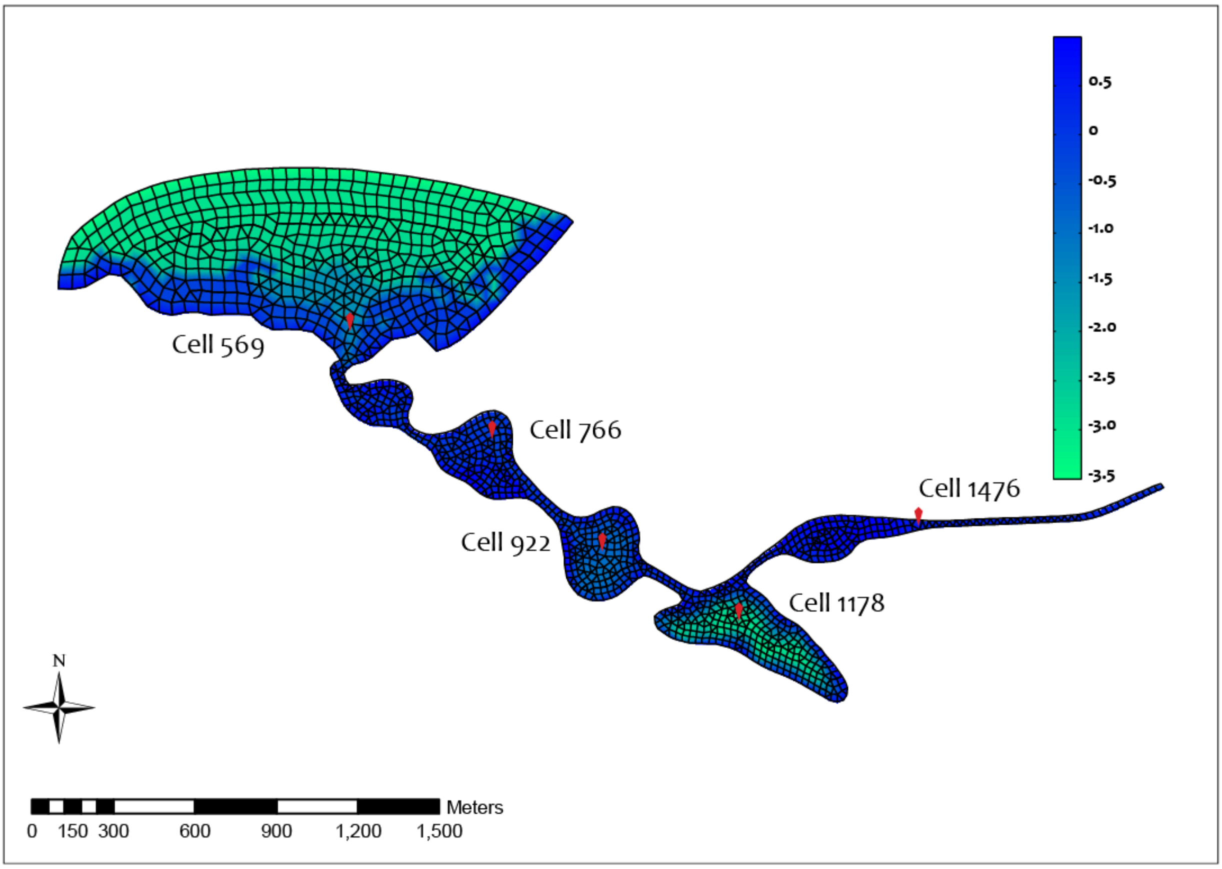


Figure 61. Model mesh of the Robe Lakes system showing key output cells used later in the analysis.

We assessed the extent of inundation at 1.0 and 2.0mAHD (Figure 61) and clipped data above 1.5mAHD out of the domain. This was used to build a variable mesh of quadrilateral and triangular elements (Figure 61). Note the extension of the mesh to the ocean beyond the available DEM data. Therefore depths were synthetically generated for this region assuming a gradual deepening of the water offshore.

Inputs to the model include tidal forcing data, meteorological conditions and inflows from Drain L. The tidal data was collected from Victor Harbour station (A4261039) and processed for the model for the period from 2004 - 2010. The raw 15min data was passed through a 1hr window smoothing filter. Temperature data for the site was also available and used directly. Salinity at the ocean boundary was set to 35psu for the entire simulation period. The entire ocean arc in the northern most reach of the domain was used as an open boundary condition by specifying the above water height data and temperature and salinity information.

The meteorological data was adapted from previous compilations done for the simulation period as part of the Lower Lakes water quality recovery modelling (Hipsey and Busch, 2012). Whilst this data was from stations significantly further north than the region of interest, such as the Narrung meteorological station, it was the closest available station with the necessary information at a fine temporal resolution. The model input included sub-hourly data for solar radiation, long wave radiation, air temperature, relative humidity, wind speed and rainfall.

Inflow data for the Drain was applied directly from the daily data from station A2390505 (Boomaroo Pk). This time-series covered a range of flow conditions (see above section, Figure 39) and a continuous time-series was derived for the period from 2004-2010. No outflows from the domain were simulated. Note also that inputs from groundwater were not considered in the model construction, though may be appreciable. Groundwater incursions are most likely to help maintain water height and salinity levels, rather than reduce them, so from a management perspective, ignoring groundwater effects has a low risk attached to it.

Model validation runs

It was our aim to initially understand the salinity distribution, degree of stratification and water level response under a range of conditions experienced by the estuary. Based on the above flow analysis (Figure 41) the following four simulation years were chosen:

- 2007 (5,221 ML): dry year (>90th percentile)
- 2008 (8,418 ML): dry year (80th percentile)
- 2010 (33,940 ML): medium year (30th percentile)
- 2004 (124,288 ML): wet year (<12th percentile)

Limited data was available for model validation and this mainly covered the years 2007 and 2008, and included monthly salinity and temperature information at the two key locations described in Figures 45-48. A validation plot for 2008 (Figure 62) shows the model was capturing the general seasonal trend in salinity at the two sites well, though it under-predicted a freshening of the water in that occurred in the Fox-Pub lake system in Feb-Mar. Datum referenced water level data was not available for this period, however some 2011 data collected by Ben Taylor of DFW suggest the model is over-predicting the Lake Battye level by ~0.3m, most likely due to inaccuracies in the DEM data in the channels creating an artificial sill.

The four flow years were also assessed to see how they compared to each other (Figure 63), at the main site of interest (Jumbo's Jetty in Lake Battye). Salinity variation between the years at four other sites ranging from the ocean mouth to within the drain was also compared (Figure 64). The salinity exceedance probabilities for each year at each of the five sites along the domain are also included and provide the range of expected salinity conditions under different dry (2007, 2008), medium (2010), and wet (2004) flow conditions. These values are used as a proxy of the EWR for the estuary, with the gap between the red and green lines (2008 and 2010) being the most likely expected salinity values (30-80th percentile) and the area between the red and black lines (2007 and 2004) covering the majority of the expected flow probability spectrum (12-90th percentile).

Note that the effect of different freshwater flow rates on the salinity structure can also be used as a simple proxy for mouth openness (e.g., top left hand plot of Figure 65), with the black and red lines indicating substantial seaward flow of freshwater with high erosive potential.

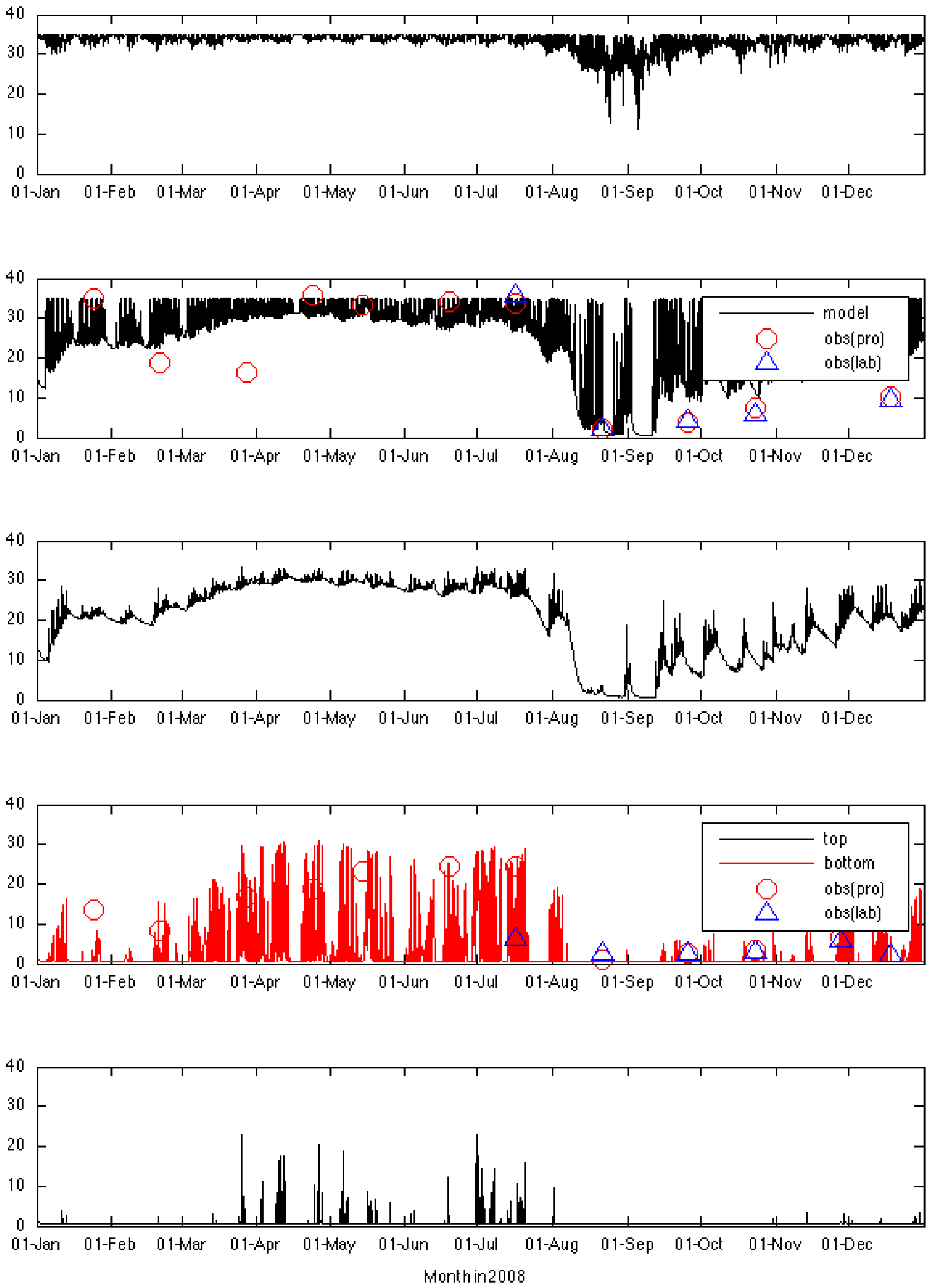


Figure 62. Time-series of salinity at 5 sites in the domain for the year 2008, showing available field data for the Fox-Pub Lake bridge (2nd plot) and Lake Battye jetty (4th plot).

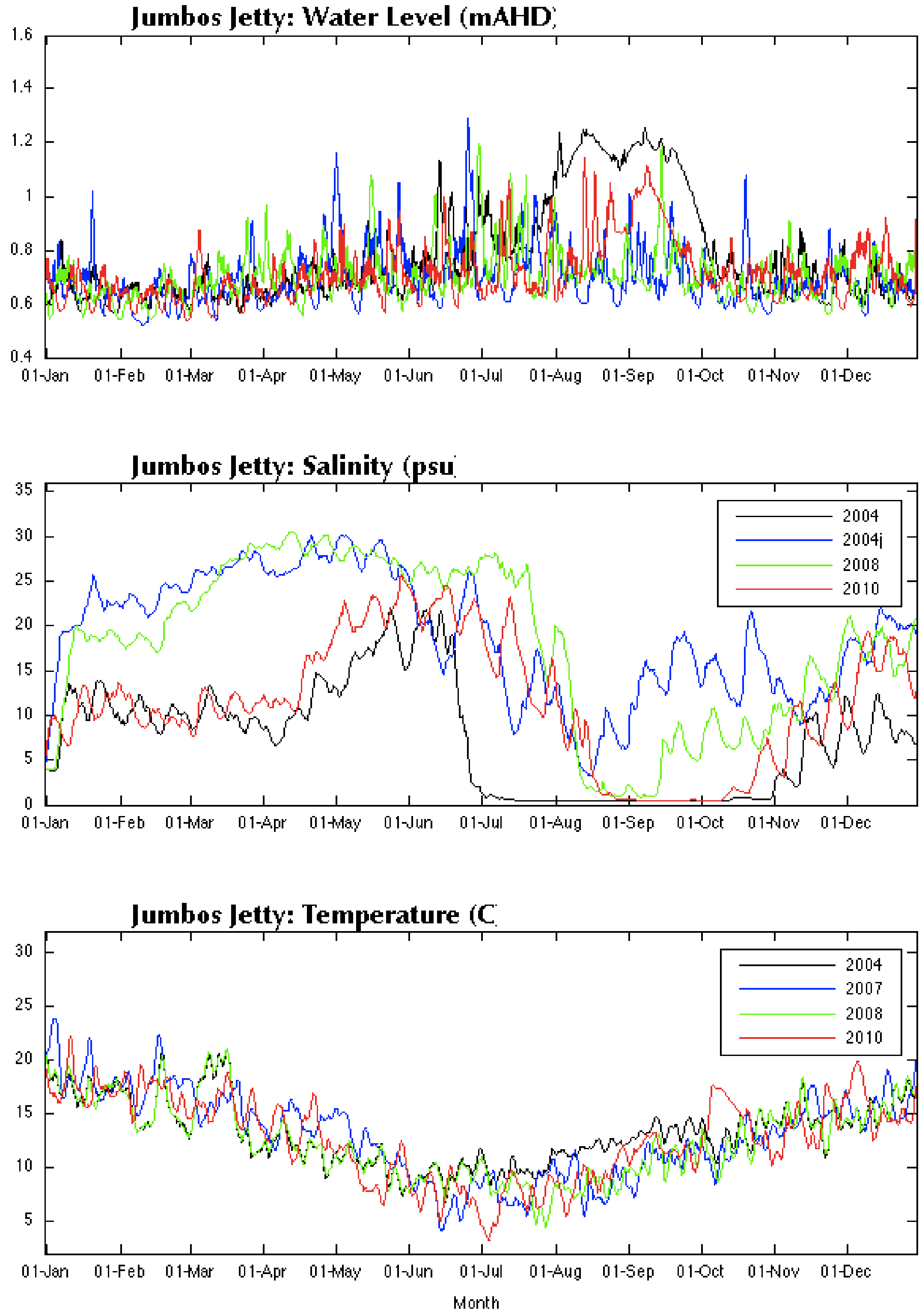


Figure 63. Time-series of level, salinity and temperature at Lake Battye site Jumbo's Jetty.

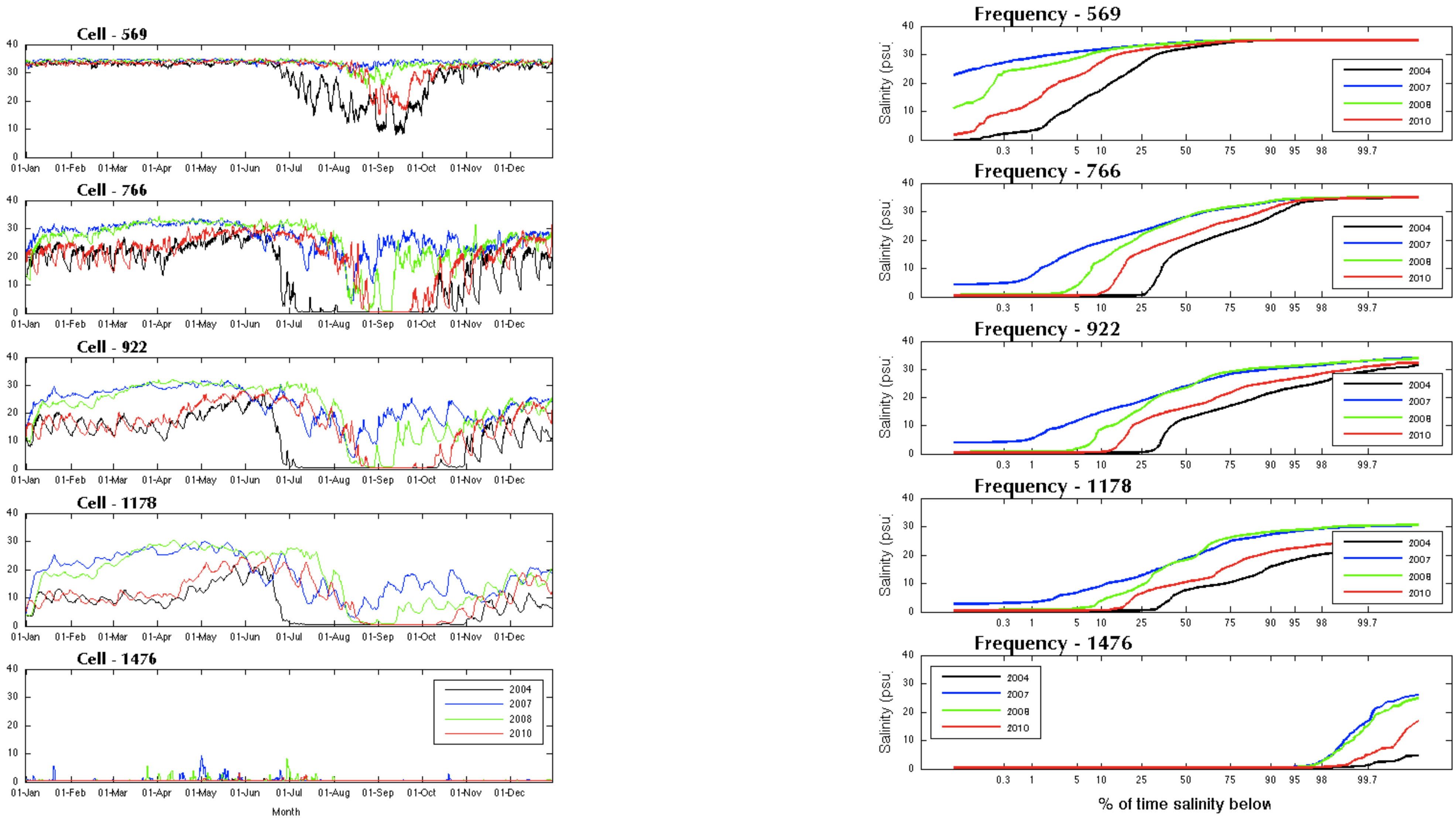


Figure 64. Salinity (left) and salinity frequency curves (right) for the for the four flow years (569=ocean; 766=foxpub; 922=nunan; 1178=battye; 1476=drain).

4.17 Environmental Flow Scenario Assessment

In this section, we take the above four validation simulations (which span the full range of flow conditions experienced by the estuary) and use the expected salinity reduction exceedance probabilities as a threshold by which to assess the effect of flow diversions on the salinity structure.

Considerations for scenarios

Peirson *et al.*, (2002) prepared a checklist to describe potential pathways by which reduced flows could impact on estuary ecological values. In principle, all manner of flow reductions could lead to reductions in survival and growth rates, abundance, biomass & diversity of the biota. As in Peirson *et al.*, (2002), the processes are grouped in relation to the freshwater inflow magnitudes where they are likely to have the greatest relevance.

Ideally when implementing diversions, the objective is to ensure that we do not alter the general salinity and water level regime of the Robe Lakes, and therefore take excess water over and above the estuary EWR. Since they have a mostly seawater salinity in summer, the diversion rules scenarios we assessed all allowed small flows that arrive during the summer period (Nov-May) to remain un-diverted. We also acknowledge the ecological significance of freshwater flows for nutrient delivery to the estuary and flow and salinity cues for fish migration are not considered in the model. However, we indirectly consider this need by considering the variability and number of days which certain salinity thresholds are crossed. Finally, we also do not consider in the model the amount of erosion and the dynamics of mouth morphometry. However, we consider that an important requirement is an occasional freshwater flood pulse, and so in most scenarios we have implemented an upper diversion limit so as to maintain the large peaks entering the lakes system, and use reduction in salinity at the ocean site as a proxy for the erosive potential of flood flows in regulating the mouth opening.

Table 19. Checklist of major ecological processes by which reduced estuary inflows may cause impacts on estuarine ecosystems and the adjacent marine environment1. From Peirson et al., (2002).

FLOW SIZE	IMPACTS
Across all inflow magnitudes (All)	All-1: altered variability in salinity structure altered variability of inflows to the estuary, and the consequent change in patterns of variation in the salinity structure of the estuary, is likely to disrupt life cycles as suitably-timed breeding and/or migration cues for fish and crustaceans are masked; can also have relevance to plants; growth/recruitment opportunities are lost because of a lack of synchronization with the temperature regime.
	All-2: dissipated salinity/chemical gradients used for animal navigation and transport reduced inflows which subsequently dissipate salinity & other chemical gradients out from the mouth of the estuary, and/or along the estuary; this is significant as there is evidence that some juvenile estuarine fish and invertebrates species use such gradients to navigate their way into and along estuaries (Grange et al., 2000). Salinity-gradient upstream transport mechanisms could also be inhibited.
	All-3: decreases in the availability of critical physical-habitat features, particularly the component associated with higher water-velocities reduced inflows lower water velocities thereby altering an important physical habitat component, particularly in the upper estuary where tide-induced water currents are less prevalent. Biota favouring higher velocity areas are disadvantaged; generally native biota are disadvantaged more than alien biota.
Low-magnitude inflows (Low)	Low-1: increased hostile water-quality conditions at depth reduced inflows, and concomitant reduced vertical mixing (turbulence), resulting in hostile water-quality conditions (e.g. low oxygen at depth) in deep sections within the upper-middle estuary where water retention times are protracted; higher salinity at depth would aggravate problems with oxygen; demersal eggs and large-size taxa are at most risk because they are found in deeper sections where water quality is likely to be most hostile
	Low-2: extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna reduced inflows resulting in extended durations of elevated salinity in the upper-middle estuary; fauna with low salinity tolerance (eggs, larvae, juveniles or adults) could be adversely affected through physiological stress and/or by competition and predation from colonising large fauna normally found in the lower estuary; increased parasitism may also be involved; avoidance response to salinity may cause occupation of suboptimal habitat and/or overcrowding; the low-salinity region of an estuary acts as an important nursery ground for juvenile fish and invertebrates

FLOW SIZE	IMPACTS
	Low-3: extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora reduced inflows resulting in extended durations of elevated salinity in the upper-middle estuary; instream and/or riparian plants with low salinity tolerance will be adversely affected through physiological stress; a considerable range of subsequent impacts could result: loss of shelter and foraging areas (riparian & instream plants) for fauna, reduced water quality as plants have diminished capacity to trap nutrients and sediments (riparian & instream), reduced bank stability if riparian plants die and subsequent water-quality deterioration if collapsed bank materials release nutrients to the water
	Low-4: extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota reduced inflows resulting in extended durations of elevated salinity in the lower estuary; marine biota thus able to colonise the lower portion of the estuary; sensitive biota either displaced through competition or predated upon, and may be additionally disadvantaged by high-salinity induced physiological stress
	Low-5: extended durations when flow-induced currents cannot suspend eggs or larvae reduced inflows resulting in extended durations when flow-induced currents cannot suspend eggs or larvae in the upper-middle estuary; eggs or larvae settle to the bottom and mortality results
	Low-6: extended durations when flow-induced currents cannot transport eggs or larvae reduced inflows resulting in extended durations when flow-induced currents cannot transport eggs or larvae in the upper-middle estuary to favourable habitats for later life-history stages (inhibition of advection); growth/recruitment opportunities are lost
	Low-7: aggravation of pollution problems reduced inflows aggravating pollution problems in the upper-middle estuary originating from either agricultural, industrial or urban pollution sources; may include consequent biological „pollution" (e.g. algal blooms, etc.); lowered dilution of pollutants and/or stratification-induced deoxygenation causing the releases of toxicants from estuary-bed sediments; higher salinity at depth would aggravate problems with DO; consequent lowered abundance of fish, shellfish and crustacea, and contamination of tissues; nutrients may also be released from sediments causing algal problems for example.
	Low-8: reduced longitudinal connectivity with upstream river systems decreased inflows can sever, or halt the establishment of, connectivity between the estuary and upstream river systems; this can have severe impacts on fauna with diadromous lifecycles (e.g. mobile fauna such as fish and crustaceans)

FLOW SIZE	IMPACTS
Middle- and high-magnitude inflows (M/H)	M/H-1: diminished frequency that the estuary bed is flushed fine sediments and organic material (physical-habitat quality reduction) reduced inflows greatly altering the frequency that the bed of the upper-middle estuary is flushed of fine sediments and organic material (i.e. high flows causing substrate turnover); this is significant as many fauna lay their eggs on or within hard substrates - the presence of sediment/organic matter will result in lowered reproductive success as suitable egg deposition/attachment sites will become limited
	M/H-2: diminished frequency that deep sections of the estuary are flushed of organic material (subsequent water quality reduction) reduced fresh water inflows greatly altering the frequency that organic material deposited on the bed of deep sections in the upper-middle estuary is flushed out; this is significant as a high organic load can result in hostile water-quality conditions (for example, low DO); again demersal eggs and poorly mobile taxa are at most risk
	M/H-3: reduced channel-maintenance processes reduced inflows greatly reducing channel-maintenance processes (mediated by flushing flows) in the upper-middle estuary with a result that major habitat contraction occurs in the long term; deep sections of the estuary are most vulnerable as very large flows are required to remove infilling material; again demersal eggs and large-sized taxa are at most risk; could be relevant to the lower estuary in respect to the closing of the estuary mouth through the deposition of transported marine sands; a range of impacts on migrating fauna may result from the reduced estuary-marine connectivity; water quality impacts could occur if tidal exchange flushing is substantially reduced
	M/H-4: reduced inputs of nutrients and organic material decreased inflows subsequently reducing the input of natural river-borne nutrients and organic material; reduced primary production followed by reduced zooplankton abundance along the length of the estuary and into adjacent coastal areas; fish and crustacean abundance diminishes in response to decreased food supply and sheltering areas (instream plants)
	M/H-5: reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to the estuary decreased inflows can sever, or halt the establishment of, connectivity between the estuary and adjacent water bodies (floodplain billabongs, wetlands, etc.) for mobile fauna; the loss of connecting flows may also result in ecological processes in the water bodies not being activated or maintained

Drain L inflow scenarios

In the context of the potential impacts of reduced environmental flows described above, our rationale in the modelling scenarios was to set a minimum and maximum flow diversion limit. A minimum diversion limit ensures that flow reductions are not exacerbated under naturally drought conditions. A maximum flow diversion limit was set to ensure higher flow peaks are still able to enter the system, as they are required for periodic flushing of the system, to prevent sedimentation of the mouth, and for inundation of riparian habitats.

The lowest minimum diversion rule tested was 40 ML/day, just below the peak of the dry year (2007). It was assumed continually subjecting the estuary to flows below this level would be undesirable over the medium- to long-term.

Note that all scenarios only divert water between Jun-Nov, as flows outside of this time are considered to be essential for the estuary to keep the inland reaches primed for autumn and the winter flow period, and to prevent hyper-salinity during periods of low connectivity with the ocean.

Since the 3D model run-times were of the order of 12-24 hours we were not able to assess all flow diversion permutations as outlined in the above flow analysis section. Instead, we defined five flow diversion scenarios (labeled A-E) and tested each, where relevant, on the four different flow years (Figure 65).

		Year:	**2004**	**2007**	**2008**	**2010**
		Indicative Flow:	>2000	40-50	150-180	1000-1100
			Wet	Dry	Dry	Medium
Scenario:	Diversion envelope (ML/day)	Maximum total diversions away from Robe Lakes (ML/day)	Able to run the computer simulations for this scenario?			
E	40-440	400	Y	Y	Y	Y
C	80- 580	500	Y	N	Y	Y
D	100-600	500	Y	N	Y	Y
A	100-1000	900	Y	N	N	Y
B	150-1000	850	Y	N	N	Y

Figure 65. Flow diversion scenarios able to be tested for different flow years, showing the diversion envelope and maximum daily diversions away from the Robe Lakes. The diversion envelope describes the lower and upper thresholds for flow rate in Drain L within which flows are diverted away from the Robe Lakes.

The effects of the diversion scenarios on the lake system were assessed by comparing changes in water level, changes in the salinity time-series, changes in the salinity exceedence probabilities each for the four sites used previously (Ocean entrance, Fox-Pub Lake, Lake Nunan and Lake Battye (Jumbo's Jetty) (Figures 65-71). In general the water level variation caused by the diversion rules scenarios was not significant, with the main impact seen in the wet year of 2004 under the higher diversion rates such as scenario A and B (Figure 73).

In addition we assessed the number of days where salinity was below an assumed salinity "threshold". This value was a subjectively chosen typical value for each of four main sites, set as:

1. *ocean* – 25psu mouth of estuary to ocean
2. *foxpub* – 15psu bridge between Fox and Pub Lakes
3. *nunan* – 10psu centre of Lake Nunan
4. *battye* – 5psu Jumbo's Jetty

This analysis counted days for each of the flow years where the salinity fell below these threshold values (Figure 73). Note that the treatment described as zero is the control: ie no water is removed from the flows to the system. For the 2007 case (dry year), only scenario E was had any impact on flows; the flow in this year was not high enough to trigger a diversion under the rules set for scenarios A-D.

The 2008 (dry) year was the most sensitive to diversions; scenario E caused a 50% reduction in the number of days in which the salinity value was above the 'metric', or boundary set for each location.

Salinity levels in medium and wet years of 2010 and 2004 were less sensitive to the diversion rules. For scenario C and D, the number of days that salinity exceeded the set boundary was reduced by a relatively small amount compared to the large variation seen between the years simulated.

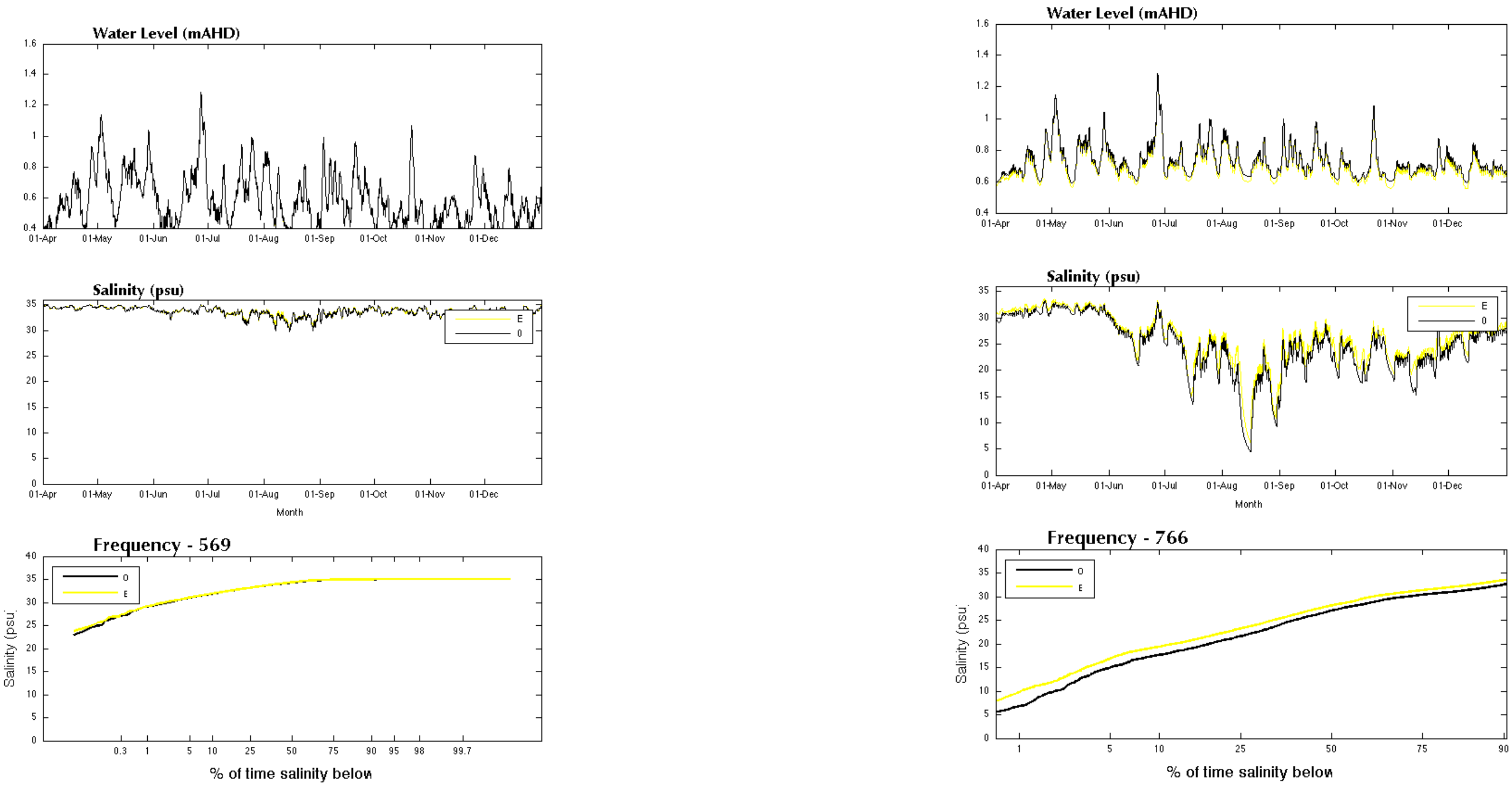


Figure 66. Water level, salinity, and salinity frequency curve for the year 2007 (dry), for the Ocean station (left) and Fox-Pub Lake station (right).

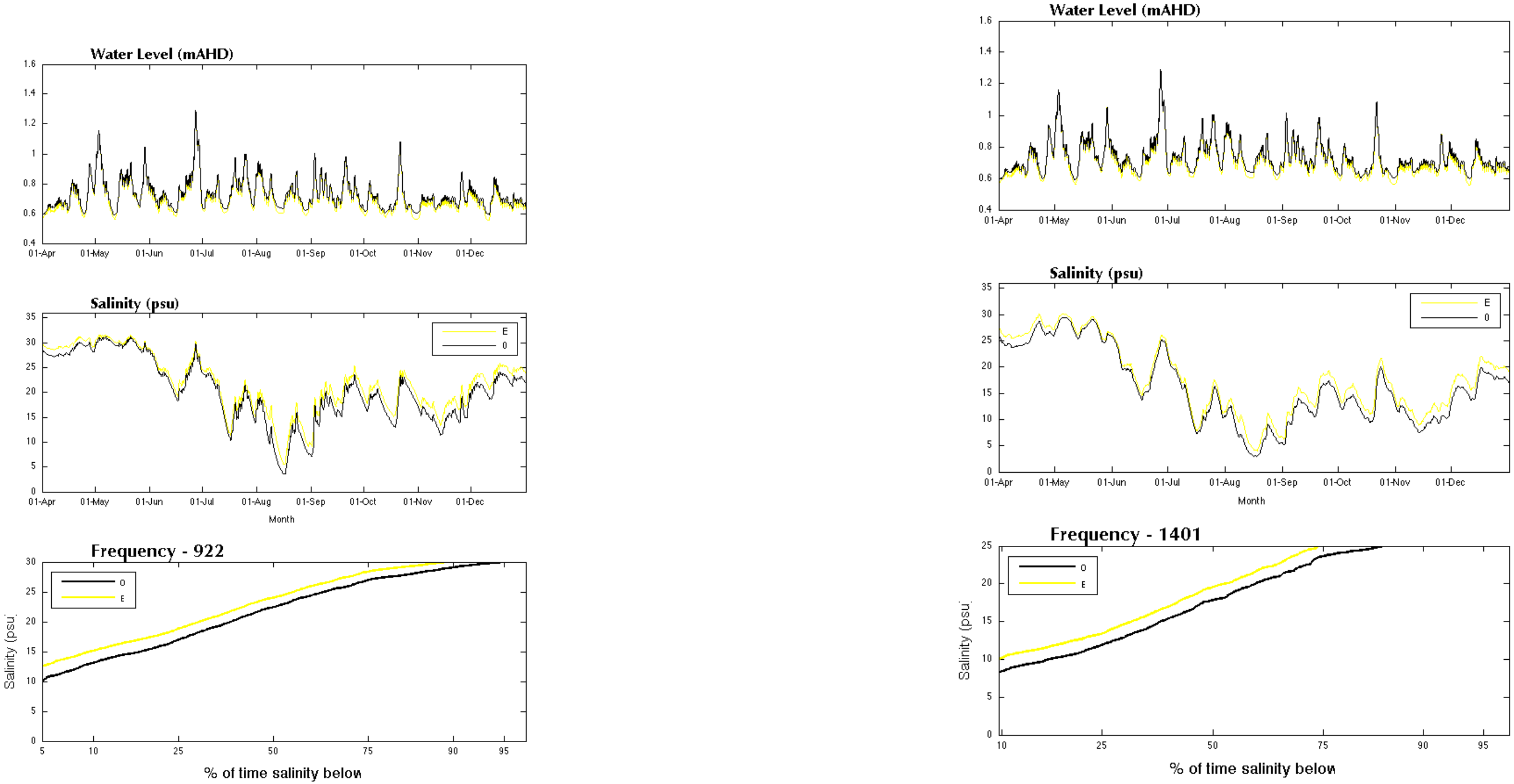


Figure 67. Water level, salinity, and salinity frequency curve for the year 2007 (dry), for the Lake Nunan station (left) and Lake Battye station (right).

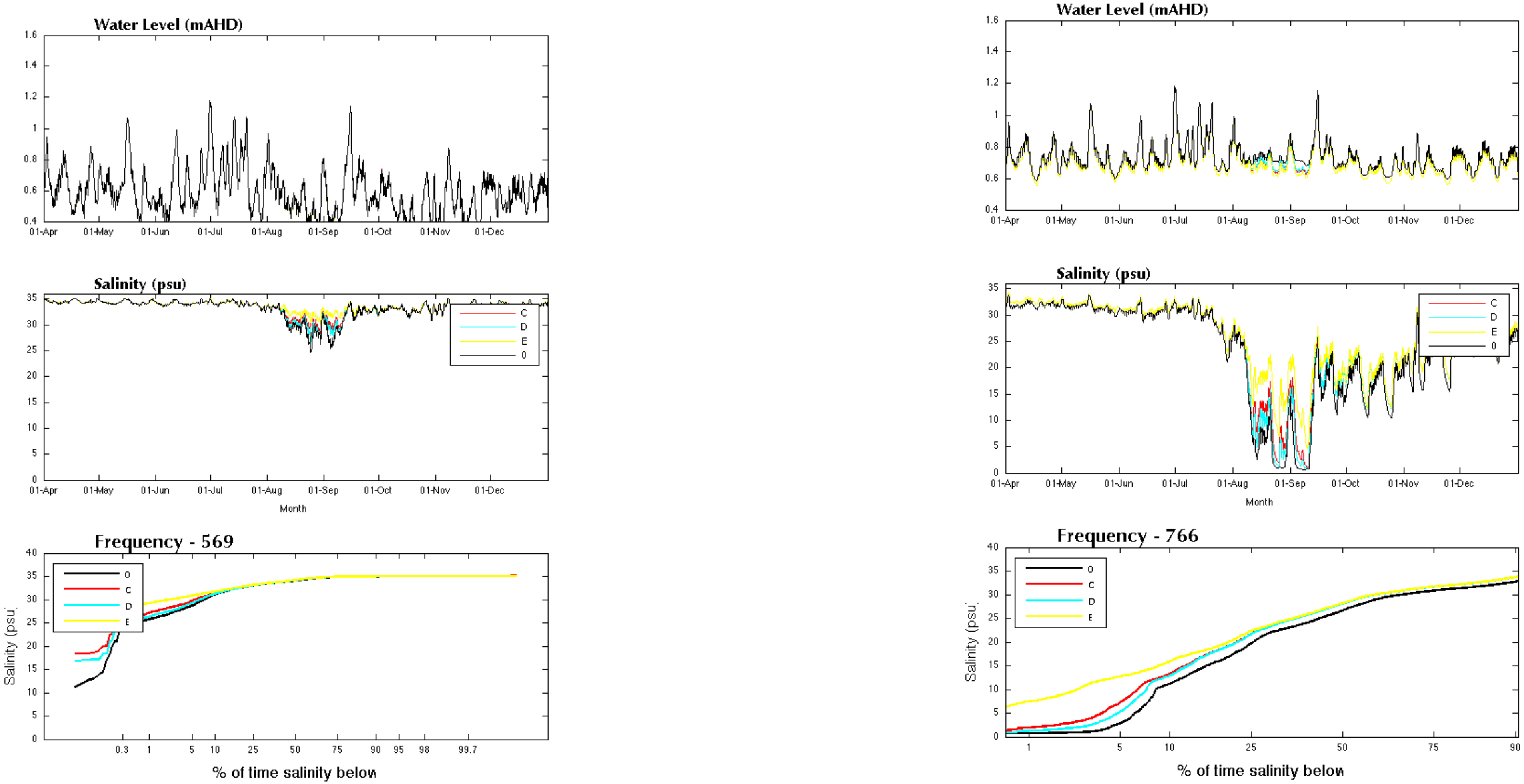


Figure 68. Water level, salinity, and salinity frequency curve for the year 2008 (dry), for the Ocean station (left) and Fox-Pub Lake station (right).

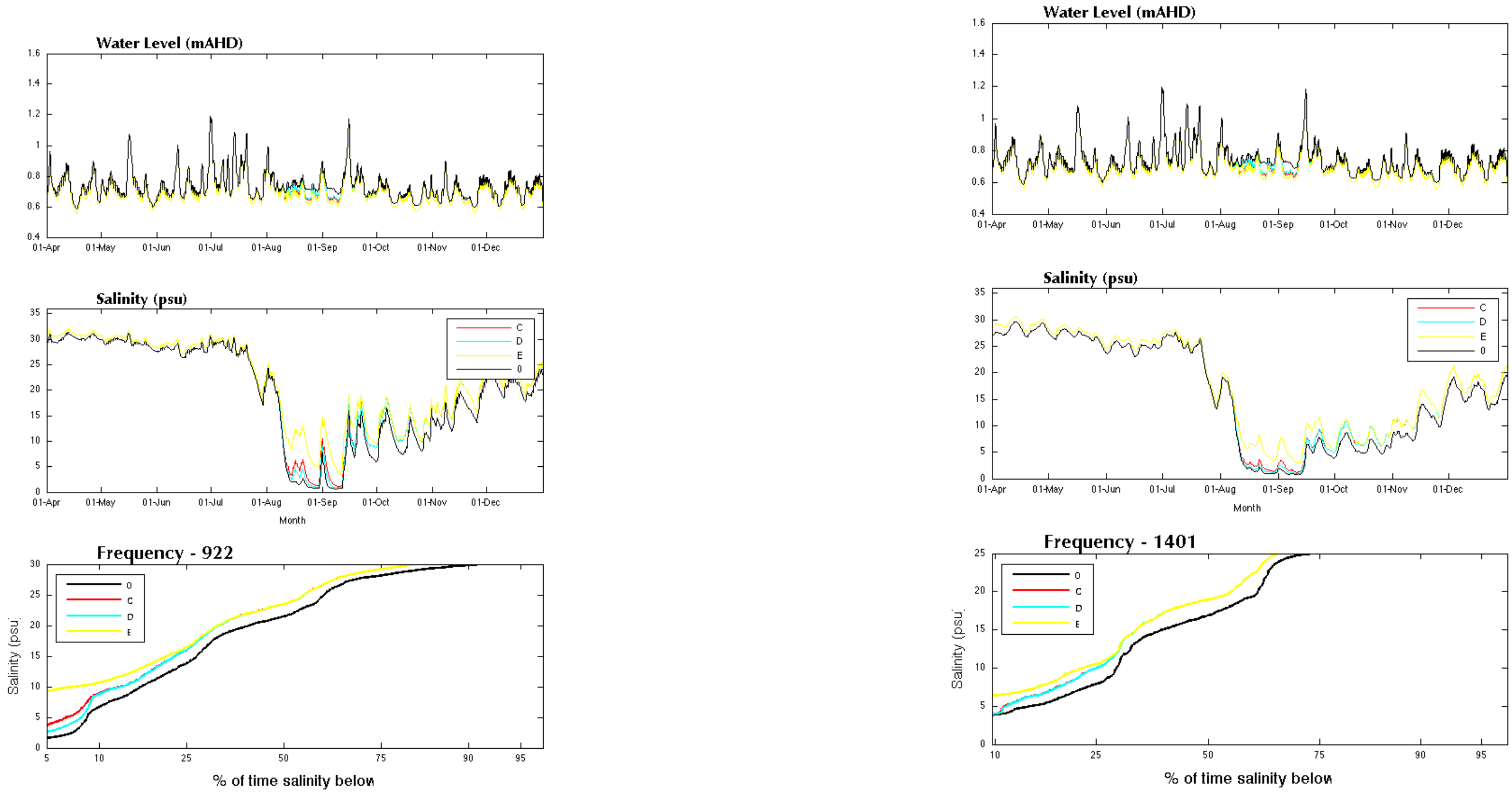


Figure 69. Water level, salinity, and salinity frequency curve for the year 2008 (dry), for the Lake Nunan station (left) and Lake Battye station (right).

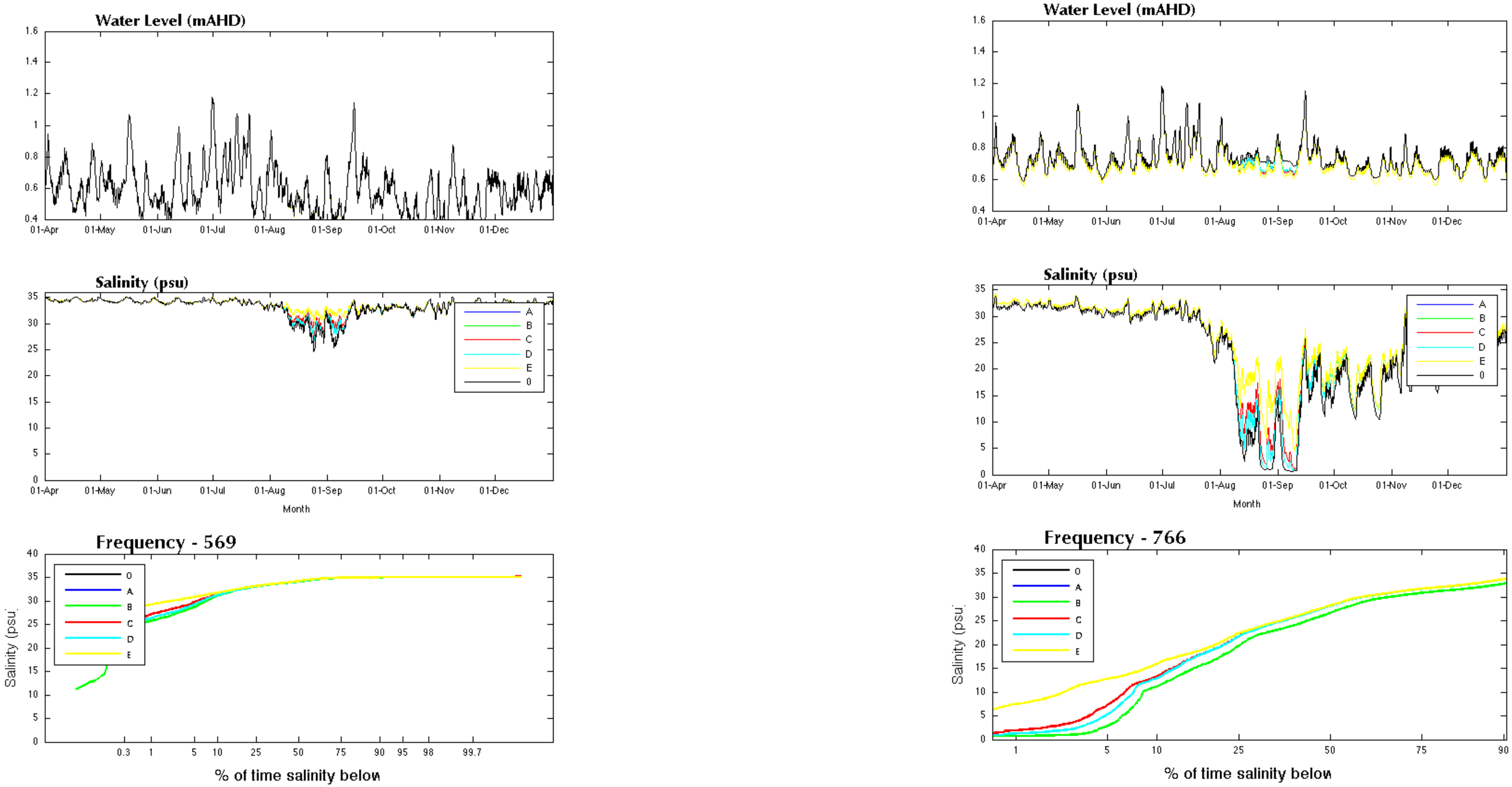


Figure 70. Water level, salinity, and salinity frequency curve for the year 2010 (medium), for the Ocean station (left) and Fox-Pub Lake station (right).

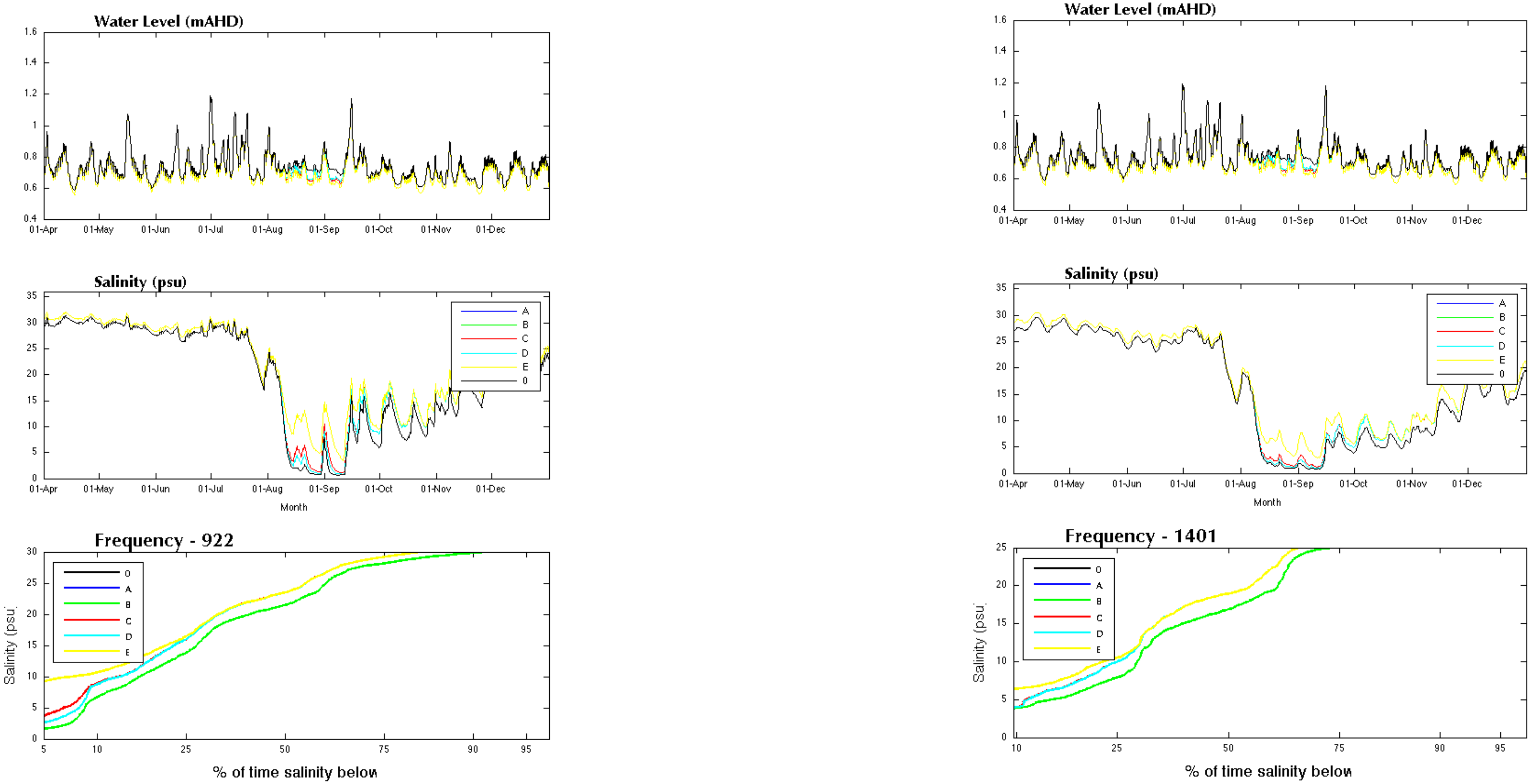


Figure 71. Water level, salinity, and salinity frequency curve for the year 2010 (medium), for the Lake Nunan station (left) and Lake Battye station (right).

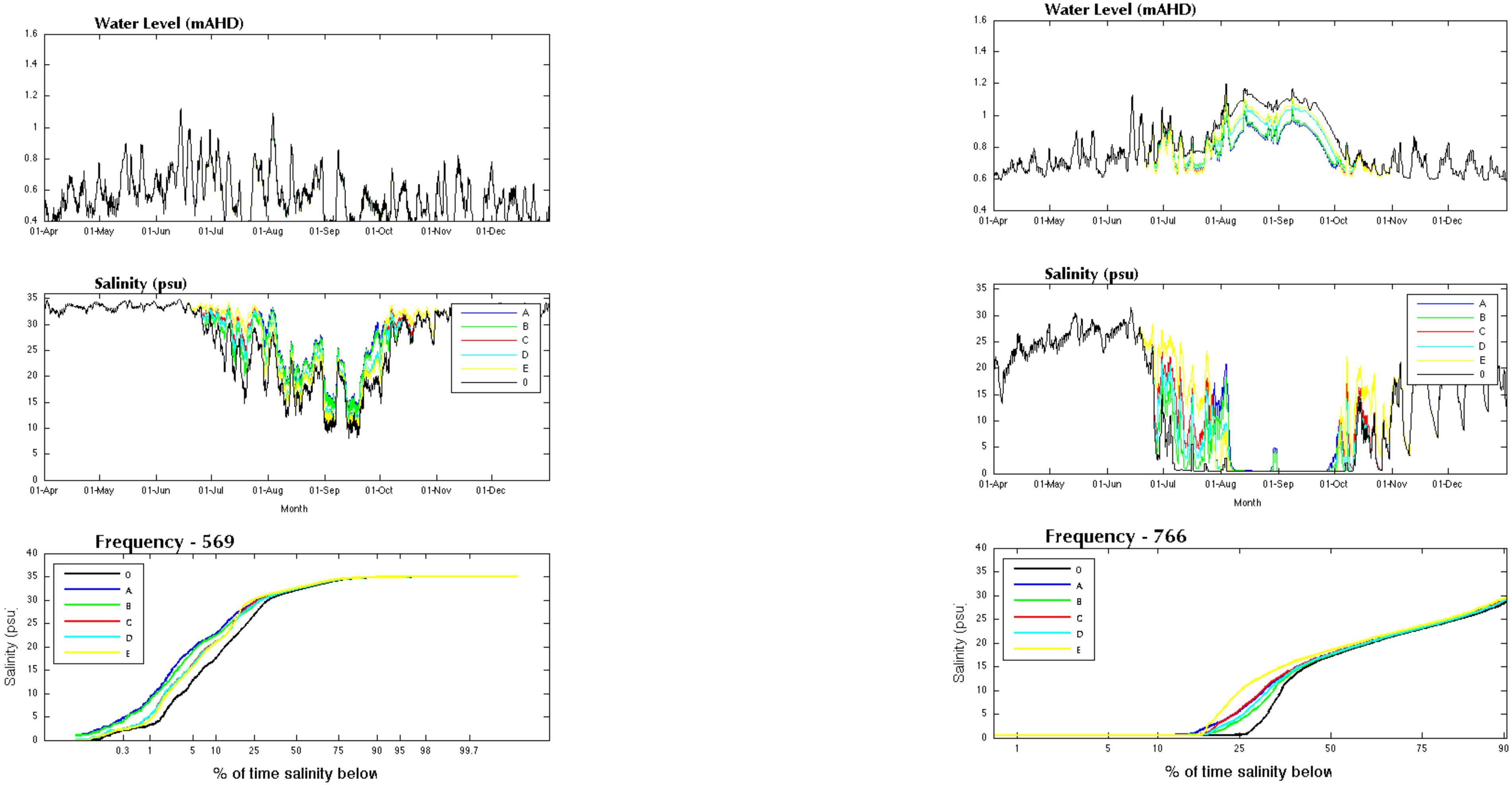


Figure 72. Water level, salinity, and salinity frequency curve for the year 2004 (wet), for the Ocean station (left) and Fox-Pub Lake station (right).

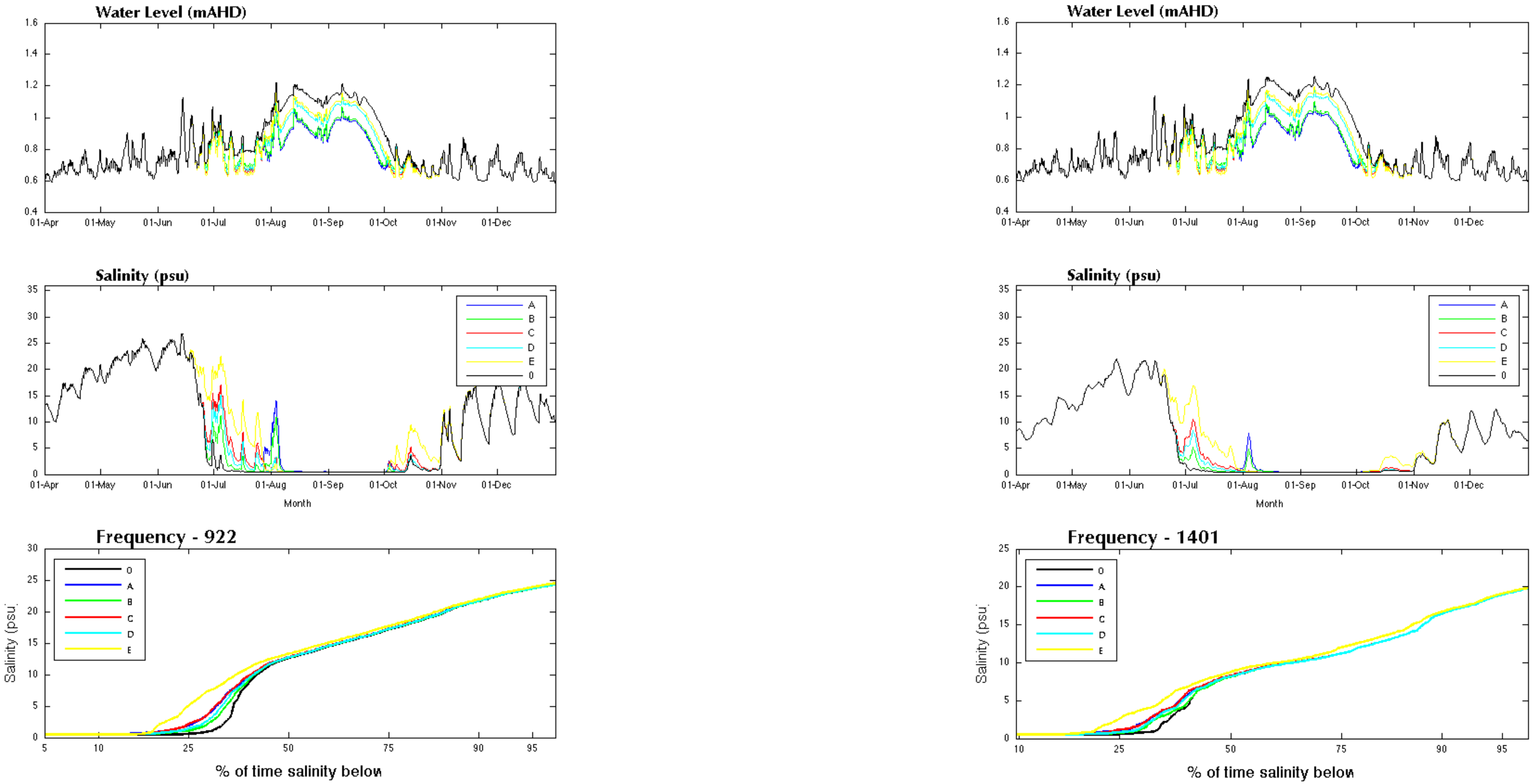


Figure 73. Water level, salinity, and salinity frequency curve for the year 2004 (wet), for the Lake Nunan (left) and Lake Battye station (right).

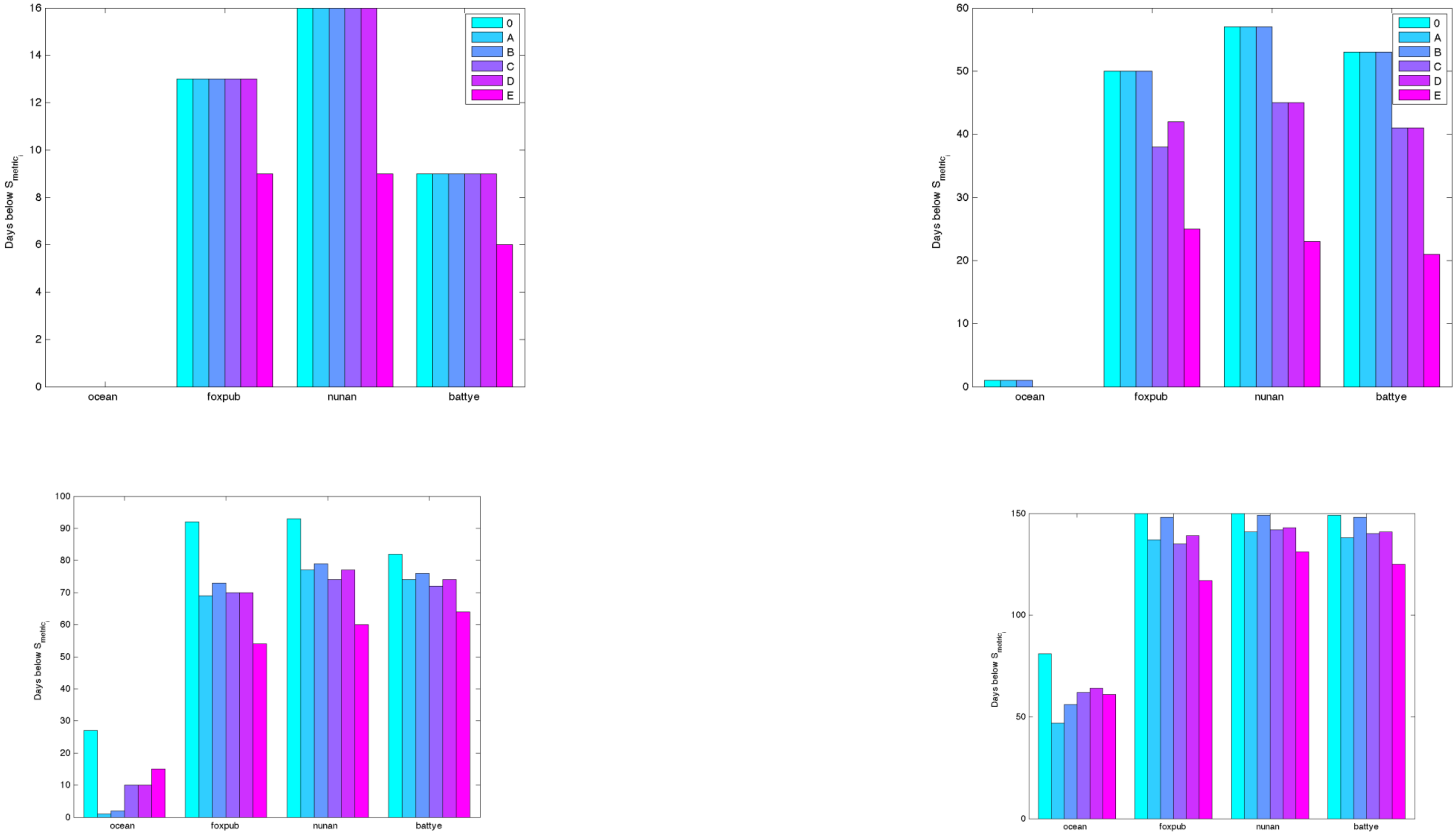


Figure 74. Number of days salinity is below Smetric (defined above) for 2007 (top left), 2008 (top right), 2010 (bottom left), and 2004 (bottom right).

Overall, scenario D (divert >100 and less than 600 ML/day) appears to be the optimum balance in meeting the estuary EWR and diverting water towards the wetlands of the Upper South East and the Southern Lagoon for the Coorong. In particular under this scenario:

- The reduction of number of freshwater days comparable to scenarios A-C for wet years;
- Maintaining the peak flows to estuary (>600 ML/day) ensures sufficient freshwater pushed through the mouth in wet years, and moderate degree of inundation and flooding of the lake system above average tidal values;
- Doesn't adversely impact dry (drought) years due to 100 ML lower threshold;
- Minimal effect in low-mid flow conditions.

However, with this in mind there was only a limited difference between D and C; therefore 80-580 GL diversion range has only slightly more impact.

The flow scenarios assessed here use idealized flow diversion rules and provide guidance on the setting of lower and upper limits and the daily flow diversion amounts. In a real situation the lakes can be accommodated through adaptive management of flow diversion volumes in response to decisions in the upper catchment. Therefore these results should be considered in this context. Below the response of the estuary to a model predictions with dynamic diversion rules included is assessed.

Assessment of integrated diversion scenario:

Here we describe the results from running the estuary model driven by flow outputs from the hydrological model for Drain L for the four flow years which integrates the effects of the various diversion and management rules occurring in the catchment (Chapter 5). We applied their "Scenario 1" (simulating *ColE* from the supplied spreadsheet). The results shown in Figure 74 and 75 compare the observed estuary response from the observed flows relative to the simulated flows with Scenario 1 diversions included.

Note that for 2007, and to a lesser extent for 2008 (ie. dry years), the modelled drain flows with the diversion rules in place in fact led to higher flows than the observed, undiverted flows. This result is because the diverted flow predictions were higher than the historical gauge data. In this case, the predictions are not reliable since at very low flows the effect of the diversion is small and masked by error in the hydrological model predictions typical under these extremely low flow rates. However, the volumes diverted during low flow years are small given the flow diversion thresholds used in that analysis, and the impact on the Robe Lakes in these years can be managed within the management framework and within the context of the results presented in the previous section so no further analysis was conducted here.

Under the medium (2010) and wet (2004) flow conditions, the input predictions are more reliable and outputs from the estuary model suggest the diverted flows fall within the range of conditions reported in the above scenarios, and are equivalent to similar scenarios reported in the above scenarios C and D. Therefore the operation of the integrated diversion and management rules across the catchment are similar to the idealised scenarios tested above, and changing the nature and complexity of the realistic diversion rules in place of the original idealized diversion rules made no significant difference to the estuary response.

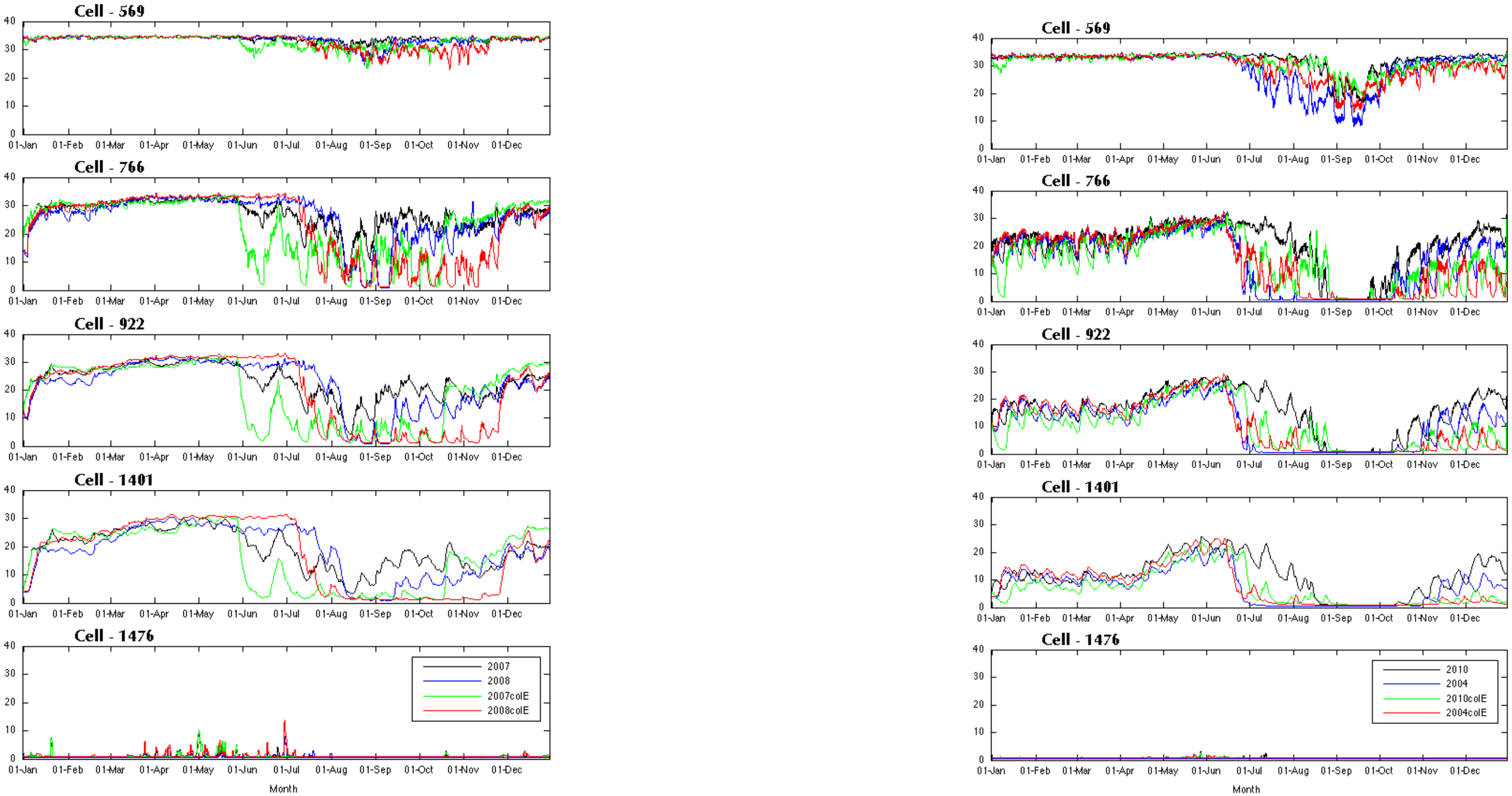


Figure 75. Comparison of historical and “Scenario 1” (colE) salinities for 2007 and 2008 (left) 2010 and 2004 (right).

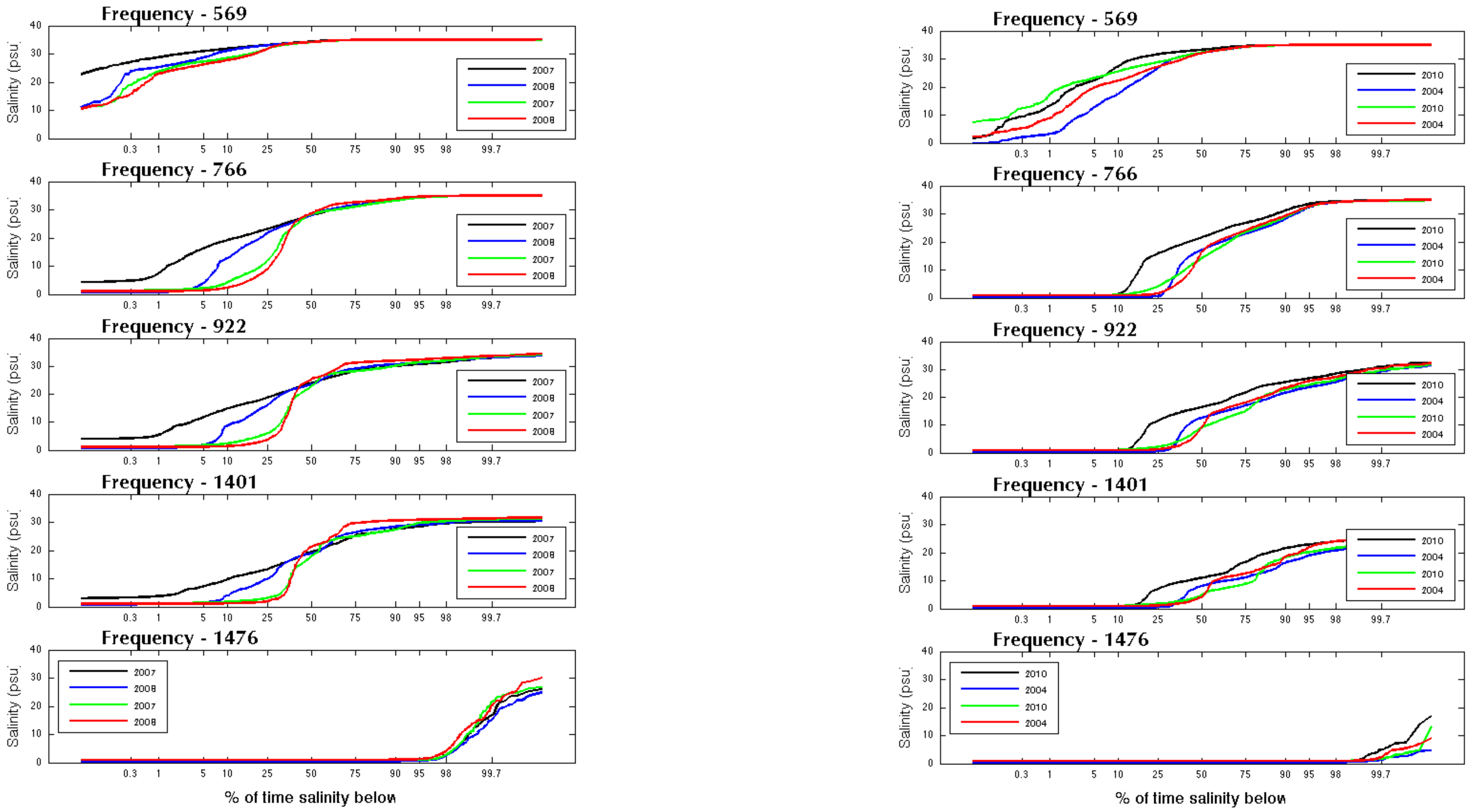


Figure 76. Comparison of historical and “Scenario 1” (colE) for 2007 and 2008 (left) 2010 and 2004 (right) salinity exceedance probabilities.

CHAPTER 5. Diversion Rules for the Drain L Catchment Subject to Downstream Environmental Water Requirements

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5.1 Executive Summary

The South East Flows Restoration Project (SEFRP) has to date investigated options for diverting volumes of water from the drainage network of the South East as a strategy for a number of reasons:

- improving the ecological conditions of wetlands in the Upper South East,
- improving the marine environment of the South East, and
- maintaining appropriate salinity levels in the South Lagoon of the Coorong.

However, there are further volumes that flow west and out to sea through the Lower South East constructed drainage network that could potentially be diverted north (Montezari et al., 2011). One of the most reliable drainage networks that flows west out to sea is the Drain L catchment, including Drain L, Wilmot Drain and Bray Drain. Before reaching the ocean at Robe, the drains support Lake Hawdon and Robe Lakes, both of which have environmental and social values that stakeholders wish to maintain.

The purpose of this project was to investigate diversion rules in the catchment upstream of Lake Hawdon and Robe Lakes, to maximise the volume that can be diverted towards the Coorong South Lagoon (CSL), subject to the downstream environmental water requirements (EWRs). A regulator on Drain L at the outlet of Lake Hawdon North has been considered necessary to meet these EWRs with less water. A low flow passage has been included to maintain a constant flow downstream to support water quality in the Robe Lakes and maintain a connection for possible fish migration. This project has assessed different scenarios at two upstream locations to identify suitable diversion rates that meet downstream EWRs: the frequency of meeting an Ecologically Ideal Hydrograph (EIH) in Lake Hawdon, as well as maintaining flows to maintain salinity and water levels in the Robe Lakes.

Two models were developed to investigate the impact of diverting flow from the Drain L catchment on the EWRs of Lake Hawdon and the Robe Lakes. Firstly, a rainfall – runoff model of the catchments contributing to Lake Hawdon was required to estimate inflows, and secondly, a lake – storage model to represent the interactions between the lakes, drains and proposed regulator. These models have been implemented in the eWater SourceIMS modelling framework (version 3.0.7). The rainfall – runoff model adopted a functional unit approach based on land use and soil type to represent the variability in the rainfall – runoff relationship across the catchment, and surface water – groundwater interactions were considered explicitly. The lake – storage model was used to assess water levels in Lake Hawdon North at a daily time step against the EIH.

The previously identified optimal maximum diversion rate of 250ML/day at both diversion points has been adopted in this work (Montezari et al., 2011). The modelling indicated a minimum flow rate before diversions occur was not necessary to support the downstream EWRs. The catchment area contributing to the two diversion points is 554km2, however there is still a catchment area of 1087km2 downstream of the diversion points that will continue flow unimpeded toward Lake Hawdon North and South. These results suggest that the unaffected downstream catchment area is sufficient to provide the low flow requirements of Lake Hawdon North that were targeted by the minimum diversion threshold in pervious SEFRP studies.

Both permanent and winter-only diversion scenarios were considered. Given that the majority of flow occurs over the winter period, the difference between the two diversion scenarios had little effect on the water levels of Lake Hawdon North. However, higher flows were simulated exiting Lake Hawdon North with winter-only diversions, as the summer low flows were approximately 40% lower with permanent diversions compared to the historical case, but only 8% lower than the historical case with winter only diversions.

The EIH was met at the same frequency as that occurred historically (without diversions or a regulator) for the most extreme case considered:

- permanent upstream diversions of up to 250 ML/d,
- a regulator on Drain L at the outlet of Lake Hawdon North, and
- a 100ML/day (20th percentile flow) bypass to support the Robe Lakes downstream.

Reduced bypass rates were also considered, where water levels in Lake Hawdon North were expected to be approximately 10 – 15 cm higher in the case of a bypass rate reduced to 20 ML/day, and the duration of inundation expected to extend for approximately two weeks for this case.

Based on the maximum divertible flow rate of 250ML/day, and no requirement for a minimum flow rate to pass the diversion points, the annual volume that can be diverted by the SEFRP toward the CSL has been estimated. For permanent diversions the average divertible volume from the Wilmot drain diversion point was 9.1GL/year, and 7.9GL/year from Drain K diversion. Median divertible volumes are 7.5GL/year and 6.4GL/year from the Wilmot and Drain K catchments, respectively.

The seasonal divertible volume has also been calculated, as not diverting flow to the north over the summer period would be expected to reduce the volume available to be diverted. For this case the average divertible volumes were 8.3GL/year and 7.0GL/year from the Wilmot and Drain L catchments, respectively. The divertible volumes were 6.7 and 5.7GL/year from the Wilmot and Drain L catchments, respectively. As such, not diverting for the summer period 6 months of the year is expected to reduce the total divertible volume by approximately 10%, or around 800 ML, at both diversion points.

Based on the modelling presented, the most extreme diversion case considered is expected to meet the EWRs for the region. However, the system is likely to be best managed in an adaptive way, with the ability to reduce the flow bypassing the Lake Hawdon North regulator when it is desirable to maintain the water level in Lake Hawdon North for longer periods of time (for example, after a number of sequential dry years). It may also be desirable at some times to allow summer baseflows to persist in the system from the upstream diversion points to reduce the salinity in Robe Lakes.

5.2 Introduction

The South East Flows Restoration Project (SEFRP) has to-date investigated options for diverting water from the drainage network of the South East to:

- improve the ecological conditions of wetlands in the Upper South East (USE),
- improve the marine environment of the South East by reducing fresh outflows, and
- maintain appropriate salinity levels in the South Lagoon of the Coorong.

However, there are still volumes that flow west and out to sea through the Lower South East drainage network that could be diverted north to further improve these objectives.

One of the most reliable drainage networks that flows west out to sea is the Drain L catchment, including Drain K, Wilmot Drain and Bray Drain. Before reaching the ocean at Robe, the drains contribute to Lake Hawdon and Robe Lakes, both of which have environmental and social values that should be maintained. The environmental water requirements of Lake Hawdon, in terms of an Ecological Ideal Hydrograph (EIH) for the ecosystems present in the wetland, have been defined as input to this work (Ecological Associates, 2009a; Chapter 2).

Drain L is a 20 – 30m wide open channel that flows through Lake Hawdon North. While there is a small local catchment contributing to the lake from the north, the wetland generally fills only when flow in Drain L is sufficient to cause spill out of the drain and into the lake. A regulator on Drain L at the outlet of Lake Hawdon North could possibly be used to hold water up in the drain, and result in filling of the lake more regularly. In this case, there may be the opportunity to divert flow from the upstream catchment as part of the SEFRP and still maintain the same frequency of inundating the lake through the use of a regulator.

The purpose of this project is to investigate the impact of a regulator on the water levels of Lake Hawdon. This regulator should allow for flows to pass downstream, to support water quality in the Robe Lakes (located at the end of Drain L in the town of Robe) and maintain a connection for fish migration. This project will also assess diversion rates that result in the same frequency of meeting the EIH for Lake Hawdon North as occurred historically with less water through the use of the regulator.

In the following section, the region and data available are outlined. This is followed by details on the development of the models that have been used to assess the diversion scenarios. The results from simulating different diversion scenarios through the models are then presented before a discussion of the results, assumptions and concluding remarks are made.

5.3 Catchment and Data

A map of the study region can be seen in Figure 77. The catchment area is approximately 1,641 km^2, containing Drain K which turns into Drain L, Wilmot Drain and the Bray Drain system. The point at which Drain K turns into Drain L has been taken at the gauging station on Drain L, A2390510. Toward the downstream end, Drain L can be seen to pass through the middle of Lake Hawdon North. There is a sill running along each side of the drain through the lake. The sill has a number of cut outs through the sill to facilitate flow out of the drain into the lake as flows in the drain increase, as well as water to drain back out of the lake into the drain as flow recedes. The Bray Drain system contributes flow to Lake Hawdon South, and flow occurs between Lake Hawdon North and South through a wide channel, the Lake Hawdon Connecting Drain, generally from the south lake to the north lake in most years. The rainfall gradient is from 580 mm/y in the north east of the area (at the start of drain K near Lucindale) to 700 mm/y in the south east of the area (at the start of the Bray drain network).

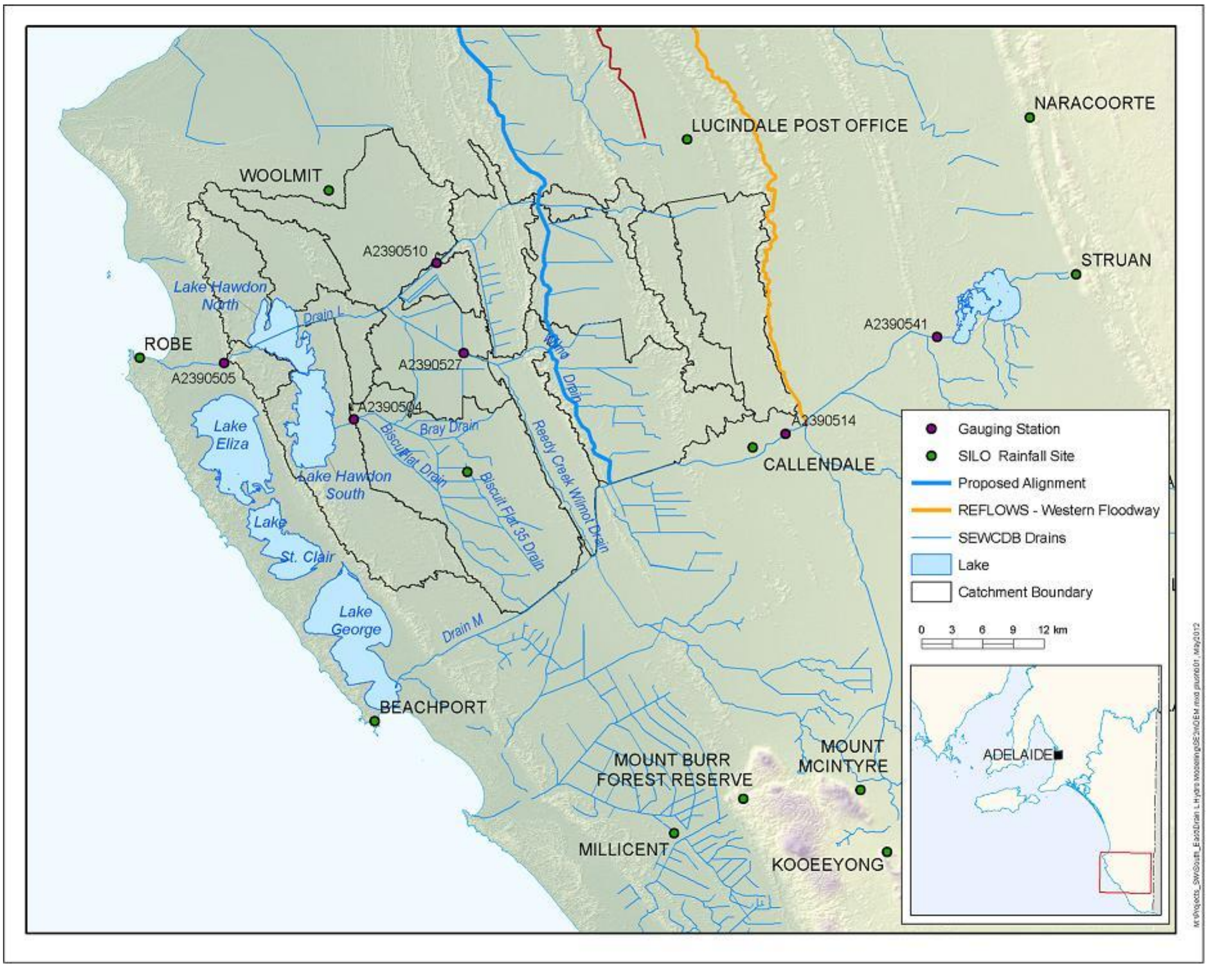
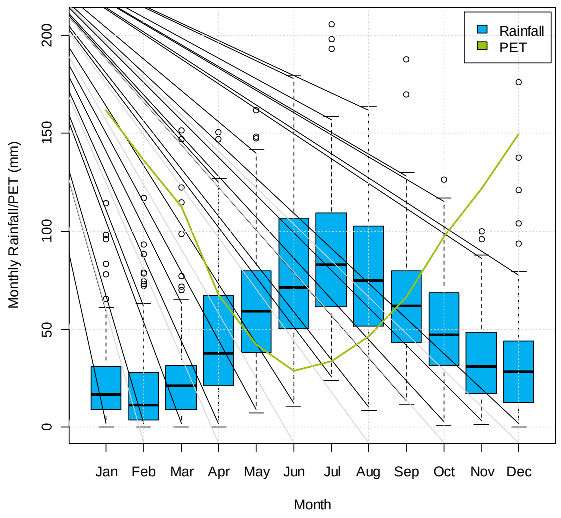


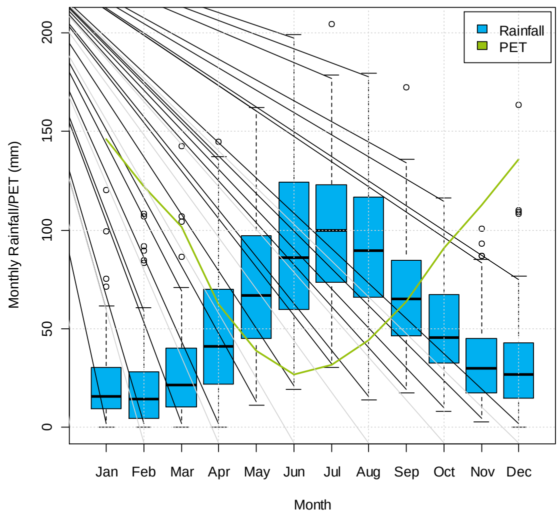
Figure 77. Map of the Lake Hawdon catchment, showing sub-catchments, rainfall and streamflow gauges.

5.4 Climate Data

The SILO stations (Jefferey et al., 2001) used in this study can be seen in Figure 77. Rainfall and FAO56 potential evapotranspiration (PET) data has been used from each site. The monthly rainfall and PET at Lucindale and the Konetta E&WS sites can be seen in Figure 78, to provide an indication of the climate variability across the catchment. The box plots represent the monthly rainfall and solid lines the average monthly PET. The whole period of the SILO rainfall record (1891–2011, inclusive) has been used to produce Figure 78. The black horizontal line within each box represents the median rainfall for each month and the lower and upper bounds of the box represents the 25th and 75th percentile monthly rainfall, respectively. The whiskers extending beyond each box represent 1.5 times the range of rainfall within the box and circles represent monthly rainfall totals that fall outside this range, which can be considered extreme events. The median monthly rainfall can be seen to exceed the average monthly PET from May to around September. It should be noted that the Konetta EW&S site was closed in 1982, however the SILO data uses an interpolation between adjacent sites to infill and extend the sites that are included in the network. A Thiessen polygon approach has been used to determine rainfall and PET data for each sub-catchment seen in Figure 77, based on a weighted average of the area in each sub-catchment that is closest to each of the adjacent SILO stations. This weighting approach has been considered appropriate for the region, due to the flat terrain being unlikely to lead to significant topographic effects on the spatial distribution of rainfall.



Lucindale Post Office (26016)



Konetta E&WS (26070)

Figure 78. Monthly average rainfall and PET at two sites in the Lake Hawdon catchment.

5.5 Streamflow Data

There are four flow gauges located in the Lake Hawdon catchments, all of which are currently operational. The locations of these are shown in in Figure 77, as A2390510 on Drain L, A2390527 on Wilmot Drain, A2390504 on Bray Drain and A2390505 at Boomaroo Park, on Drain L downstream of Lake Hawdon North. The sub-catchment boundaries contributing to each gauge derived from the 10m DEM produced as part of the regional Flow Management Strategy Project (Wood and Way, 2011) have been used, also seen in Figure 77. The streamflow data available at each station, including the area contributing to each gauge and when each station has been opened and closed is provided in Table 20.

Table 20. Summary of flow gauging station data in the Drain L catchment.

Station	Location	Area (km^2)	Opened	Closed	Opened
A2390510	Drain L (U/S of Princess Highway)	460.9	16/7/1971	Remained open	
A2390527	Wilmot Drain (9.2km from Drain L)	273.1	14/3/1973	10/4/1989	28/7/1999
A2390504	Bray drain (Site B)	275.6	4/9/1975	10/4/1989	6/7/2010
A2390505	Drain L (Boomaroo Park)	1661.5	16/4/1971	18/4/1975	16/5/1991

The annual flows recorded at each gauge can be seen in Figure 79. Figure 79 provides an indication of the flow contributions from each gauge as well to provide a visual representation of when gauges have opened and closed. Each year represented on the figure represents the water year from May 1 to April 30. Years with more than 30 days of data missing have not been plotted. Apart from 2008 for the gauge on Wilmot Drain (A2390527), the only time this occurs is when a gauge was closed. It should also be noted that a log scale has been used on the y-axis, which allows the flows from the full record to be interpreted, but should be taken into consideration when comparing across gauges and years (for example a bar that is twice the height of another represents much more than twice the flow).

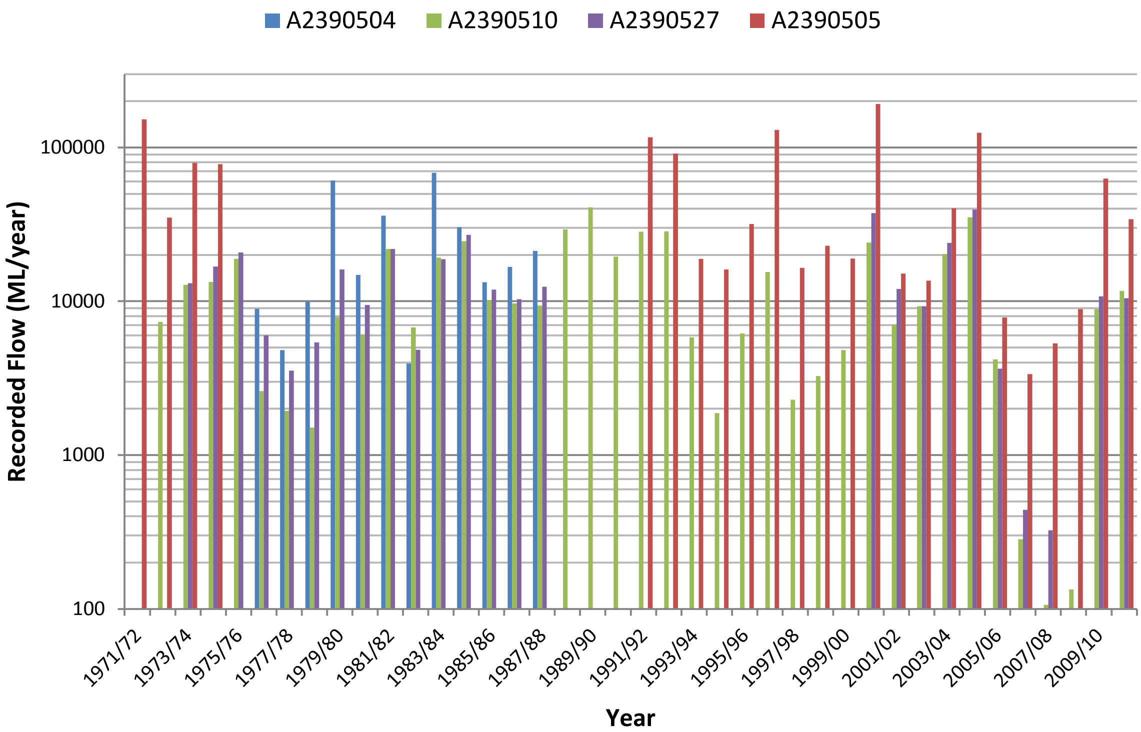


Figure 79. Annual flows recorded at each of the gauges located in the Drain L catchments.

5.6 Groundwater Data

A shallow unconfined aquifer is present in the region, and as such surface water – groundwater (SW-GW) interactions are of interest when representing the transmission of flow in the drains. In order to represent these interactions, groundwater data is required to represent the direction of this interaction (losing or gaining), as well as to quantify the flux involved. Observed data from groundwater wells CNM001, CNM018 and TNS014 have been used in the modelling of Drain L catchment.

In order to estimate the hydraulic conductivity of the drains, which is directly proportional to the SW-GW flux, two flow gauges have been identified that have limited influence from inflows or regulators in between the gauges, and as such the change in recorded flow between the gauges is likely to be largely due to the SW-GW interactions. The two gauges used were at the outlet of Bool Lagoon (A2390541), and along drain M to Callendale (A2390514), and the location of the two stations can be seen in Figure 77. Two releases from Bool Lagoon were undertaken in 2011, which allows for this comparison to be undertaken. Observed data from groundwater well CLS002, located at a distance of 166m from drain M, 13.5km downstream of Bool Lagoon and 5.6 km upstream of Callendale Regulator, was used to determine the amount of water lost or gained by the drain.

5.7 Model Development

Two models were required to consider the impact of diverting flow from the Drain L catchment on the environmental water requirements (EWRs) of Lake Hawdon and the Robe Lakes. Firstly, a rainfall – runoff model of the catchments contributing to Lake Hawdon is required to estimate inflows, and secondly, a lake – storage model to represent the interactions between the lakes, drains and proposed regulator. These models have been implemented in the eWater SourceIMS modelling framework (version 3.0.7), and details of the development and calibration of these models is provided in this section.

Rainfall - Runoff Model

There were a number of stages in the development of the model to simulate the rainfall – runoff relationship, and routing of this runoff through the drainage network, the critical ones being:

- Representation of SW-GW interaction,
- Identification of catchment functional units based on land use and soil type, and
- Calibration of models using a multi-response approach to the three gauges upstream of Lake Hawdon.

Each of these stages is outlined in more detail in this section.

Surface water – Groundwater Interactions

SW-GW interactions have been included in the model to represent the interaction between flow in the drains and the underlying shallow unconfined aquifer. A number of recent studies (Montezari et al., 2011, AWE, 2011) have attempted to quantify the transmission losses in the proposed drainage network for the SEFRP. These studies have considered different conceptual relationships between the surface and groundwater, and used typical soil properties to parameterise the relationships. These soil properties are highly variable and difficult to quantify at a reach scale, as identified in field studies along Reedy Creek (AWE, 2009b). To improve the estimates of suitable values at the reach scale for the relevant soil parameter (hydraulic conductivity) has been calibrated to observed flow events.

The previous studies have used analytical relationships such as the Dupuit equation and Darcy's Law to represent SW-GW interactions (Morgan et al., 2010). Similar analytical relationships have been integrated into the SourceIMS software, called the Groundwater – Surface Water Interaction Tool (GSWIT). For a head-based representation of interaction between the drain and groundwater system, the exchange flux is calculated as the product of the head difference between the groundwater table and the drain stage level, and the conductance of the river – aquifer interconnection (Kelley and O'Brien, 2012). The conductance can be specified directly, or in this work has been calculated based on the hydraulic conductivity and the bed thickness of the soil, as well as the drain length and width. Further details on the derivation of the GSWIT tool and underlying equations can be found in the Source Scientific Reference Guide (Kelley and O'Brien, 2012).

The drain length and width information have been calculated from the drain geometry. The required bed thickness has been determined using information available in the Soils of South Australia's Agricultural Lands database (DWLBC, 2007). This database was also used in previous SEFRP modelling studies to identify soil types and thicknesses (Montezari et al., 2011, AWE, 2011). To calculate a bed thickness, the length of drain crossing each soil type has been calculated, and the soil thickness for that soil type identified from the database. The length-weighted soil thickness for the reach has then been calculated to produce a representative bed thickness for the length of the reach.

The hydraulic conductivity has been calibrated to flow data between two gauging stations that were expected to have little influence from contributing catchments or regulators between the stations, and as such the main reason for changes in volume is likely to be the interaction with groundwater. The gauge downstream of the Bool lagoon regulator (A2390541) has been used as the upstream flow to input to the model. The gauge 18km downstream at Callendale (A2390514) has been used as the observed flow to calibrate the hydraulic conductivity in the model. Two releases from Bool Lagoon were undertaken in 2011, in May and again in July - August, to allow the losses along Drain M to be investigated. It is understood that the drains that contribute to Drain M between the two gauges were not flowing at the time of these releases, enabling this comparison to be made. While the flow record at Bool lagoon commenced in 1985, and there were a number of releases undertaken in the late 1980s and early 1990s, the drains between Bool Lagoon and Callendale are ungauged and as such information on if the drains were flowing is not available to allow these events to be used in the calibration process.

For this drain reach, the bed thickness was calculated to be 0.664 m from the Soils of South Australia's Agricultural Lands database (DWLBC, 2007). The model of the drain also required parameters to control the routing of flow along the reach. These routing parameters control the timing and attenuation of flow along the drain, where the hydraulic conductivity is the only parameter that influences a change in the downstream volume. Rainfall and evaporation from the drain surface was included in the model and would be expected to change the volume in the drain, but these processes are not considered model parameters as they have been derived directly from data at the SILO station at Callendale. The groundwater level for each event has been determined from well CLS002, and the rating curve at Callendale has been used to convert the modelled flow to a water level, to allow a head difference between the drain and groundwater level to be calculated.

The routing model used in SourceIMS can be described as follows:

$$S = K\,Q^{m}$$

Where: S is the storage volume in the reach (m3), K is a storage constant (seconds), Q is the discharge or outflow rate (m3/s), and m is a dimensional empirical exponent, measure of the non-linearity of the model. The value of m has been set to m = 0.74 to represent a trapezoidal channel (Laurenson et al., 2010). This value is based on a true trapezoid, where the length of the wetted sides of the channel is equal to the bottom width of the channel, and as such has been used an approximation in this work. The value of K has been manually adjusted to match the peaks between the modelled and observed downstream flow at Callendale. Following this, the hydraulic conductivity was manually adjusted to match the simulated and observed volumes. The result from this calibration was a value of K = 44,000 seconds (half a day) to represent the average travel time along the drain, and a hydraulic conductivity of 0.014 m/day. The value of K corresponds to an average velocity of 0.4 m/s, which was deemed appropriate for Drain M. The hydraulic conductivity value is representative of a clay loam soil. The resulting flows can be seen in Figure 80, including the upstream flow at Bool Lagoon, as well as the modelled and observed flows downstream at Callendale. The resulting flux, or loss from the drain, can be seen in Figure 81. The flux can be considered as the difference between the upstream and downstream flows, after accounting for the routing in the drain and net evaporation from the water surface.

From Figure 80, it can be seen that there is a substantial reduction in the recorded flows when comparing upstream flow to downstream flow in the first event, where the second event there is little change. This can be explained by the difference in groundwater level, where in May the groundwater is still relatively low, 6.3m below the surface level, and as such there is a large flux out of the drain. However, after recharge over the wetter months of June and July, the groundwater table increased to 3.3m below the surface. As such, for this second event there was little exchange between the drain and the unconfined aquifer, and hence little difference in the volume released from Bool Lagoon is similar to that observed at Callendale. While the model has generally slightly overestimated the loss (and as such lower flows at Callendale in Figure 80 for the July – August event), it is encouraging that the model can represent this change in the SW-GW processes.

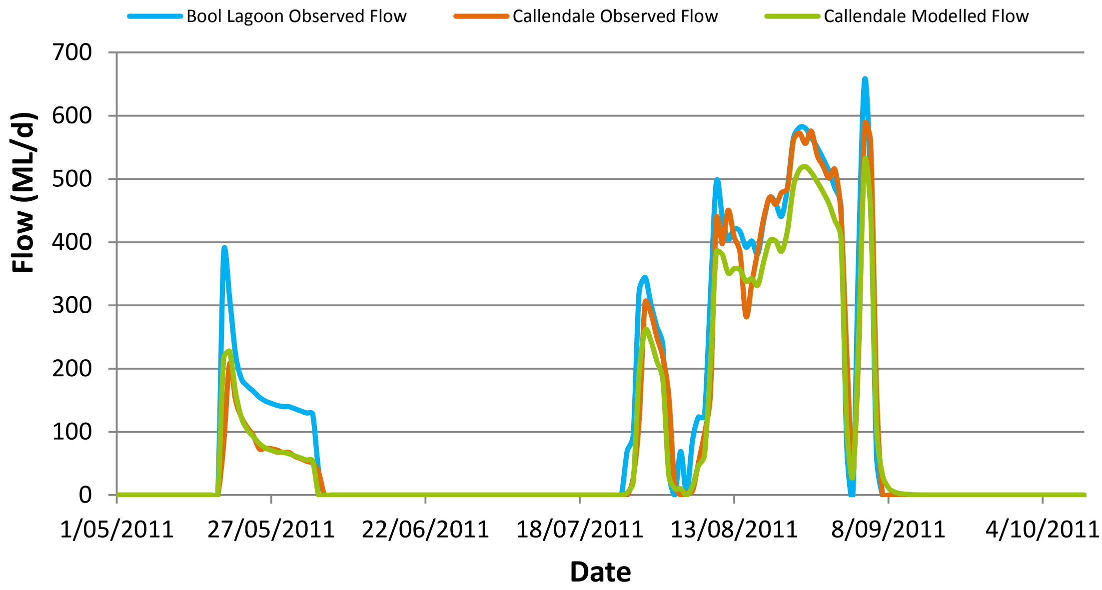


Figure 80. Stream flow comparison at Callendale gauging station for SW-GW model calibration.

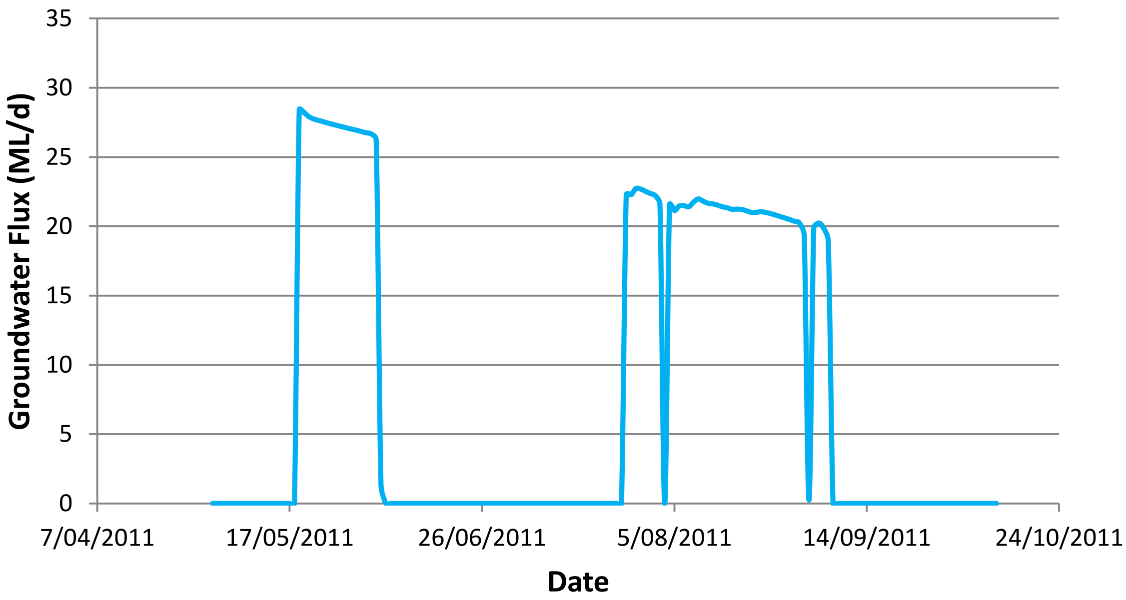


Figure 81. Groundwater flux along Drain M.

Due to limited further information, the calibrated value for the hydraulic conductivity of 0.014m/day has been adopted for all drains modelled in the Lake Hawdon catchments. It is acknowledged that this conductivity is likely to be a function of the local soil type, where a higher conductivity would be expected for sand compared to clay, for example. However, it is also likely that a clogging layer has developed in existing drains, which would be expected to reduce the conductivity when compared to the surrounding soil. As such, this conductivity has been used to represent an existing drain with an established clogging layer, and further work should consider the variations expected due to local soil properties. The approach used to determine the soil thickness has also been used for each reach in the Lake Hawdon rainfall – runoff model, and the routing exponent parameter value of m = 0.74 has also been used for all reaches. The remaining parameter, K, has been calibrated as part of the rainfall – runoff model calibration, as outlined in the following section.

Model configuration

Catchment sub - boundaries for the rainfall – runoff model were derived using the Arc Hydro GIS extension based on the 10 m digital elevation model (DEM) of the region by Wood and Way (2011). The catchment boundaries (shown in Figure 77) cover an area of 1641km2. Sub – boundaries were delineated based on a number of factors, including locations of streamflow gauges, diversion points and substantial contributing catchments where it was expected routing of upstream flows was required.

A multi-response approach has been adopted to calibrate the model, where the model parameters have been calibrated to the three gauges available concurrently, A2390510 located on Drain L, A2390527 located on Wilmot Drain and A2390504 located on Bray Drain. A number of "functional units" have been implemented to provide a mechanism to represent the variations in runoff generation processes expected across the catchments, where each functional unit has its own model parameters, and each sub – catchment is represented by a proportion of each functional unit. A number of different options for the delineation of functional units were trialled, and it was found that a combination of land use information and soil type information was required to provide a suitable representation of the variable runoff response across the three gauges.

The land use dataset used was collated as part of the South East Water Science Review (DFW, 2010), where existing datasets were interrogated to produce a spatial representation of land use by water use. These data can be seen in Figure 82, with the different classifications outlined in the legend. For this work, land uses with a low and moderate water use were grouped together into a low water use land use functional unit, and the high water use land uses were represented by a high water use land use functional unit.

This layer provides the most up to date representation of land use for the region. However, data since the 1970s have been used in this work, and there is the possibility that land uses have changed over this time. To investigate if the functional units should be varied over time, the Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences (ABARE–BRS) land use dataset (ABARES, 2012) has been investigated. These datasets provide land use classes at a national scale (1:2,500,000) using Australian Bureau of Statistics agricultural commodity data and satellite imagery. While these data are at a coarse scale, they are updated every few years and as such provide an indication of changes in land use over time at this broad scale. Figures 83 - 85 provide a summary of these data for the catchments contributing to each gauge considered in this work. It can be seen that grazing of pasture represented over 90% of the catchments in the earliest dataset in 1992. The proportion of grazing can be seen to slightly decrease over time, with the proportion of cropping increasing slightly over the 13 year period considered. It is unclear what represented the increase in the "other" category for the 2005 data, and if this is considered as grazing, the variation in land uses over time is within the accuracy of the data at this coarse scale. Therefore, while there is some variation in land use over time, given the scale and accuracy of the BRS dataset it had been deemed appropriate to adopt constant functional unit fractions over time for each catchment for the purposes of this study.

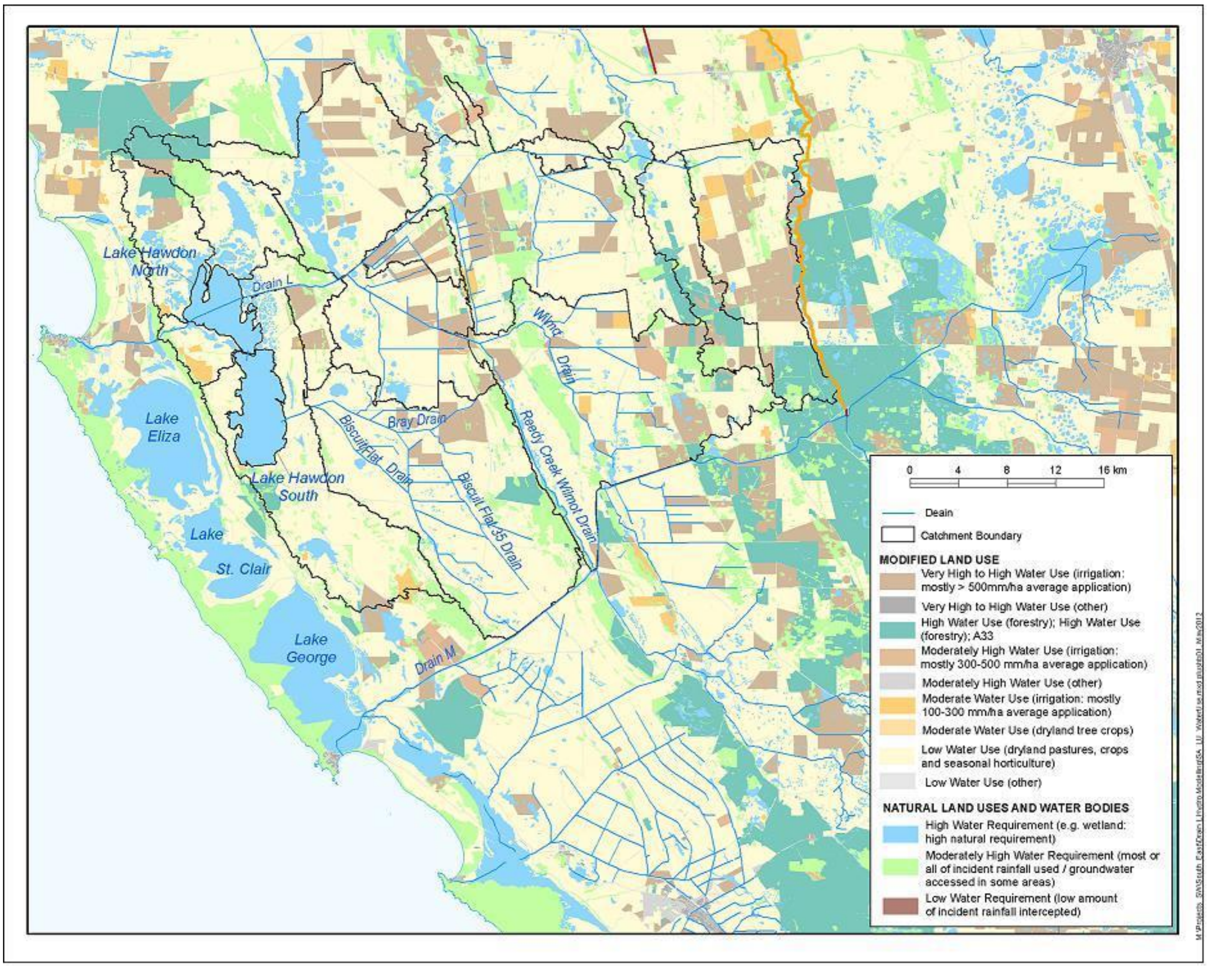


Figure 82. Land use by water use.

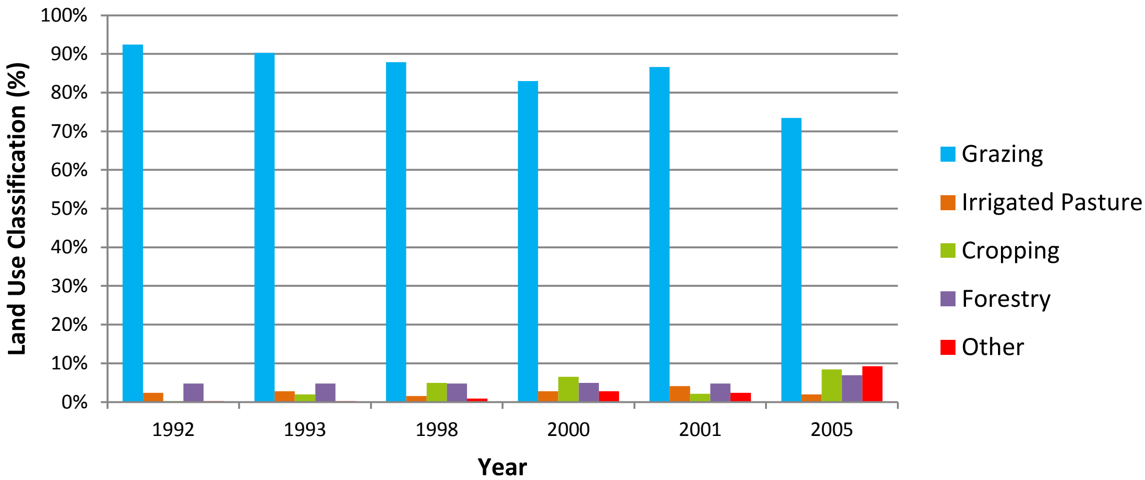


Figure 83. Land use change in the Drain L catchment (A2390510).

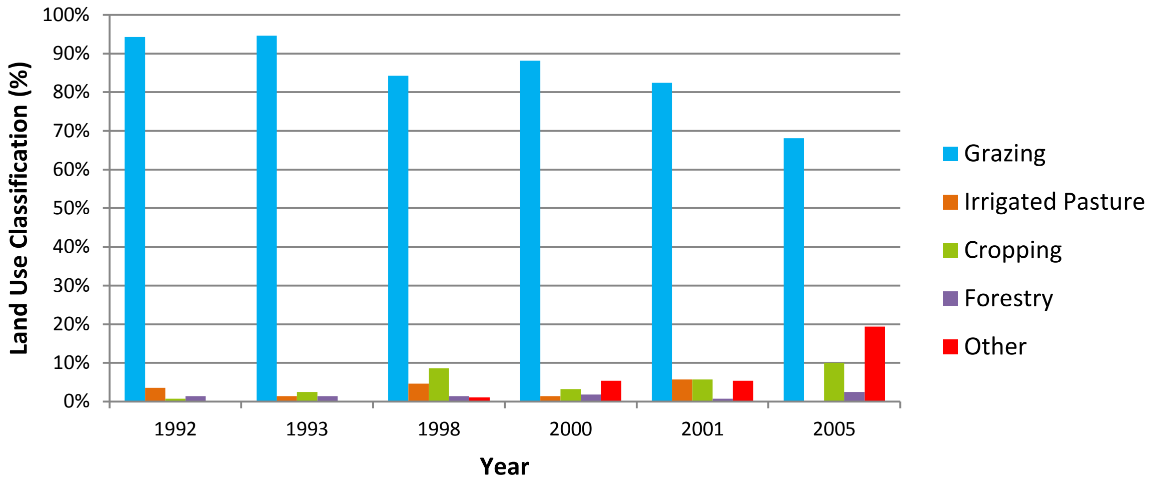


Figure 84. Land use change in the Wilmot Drain catchment (A2390527).

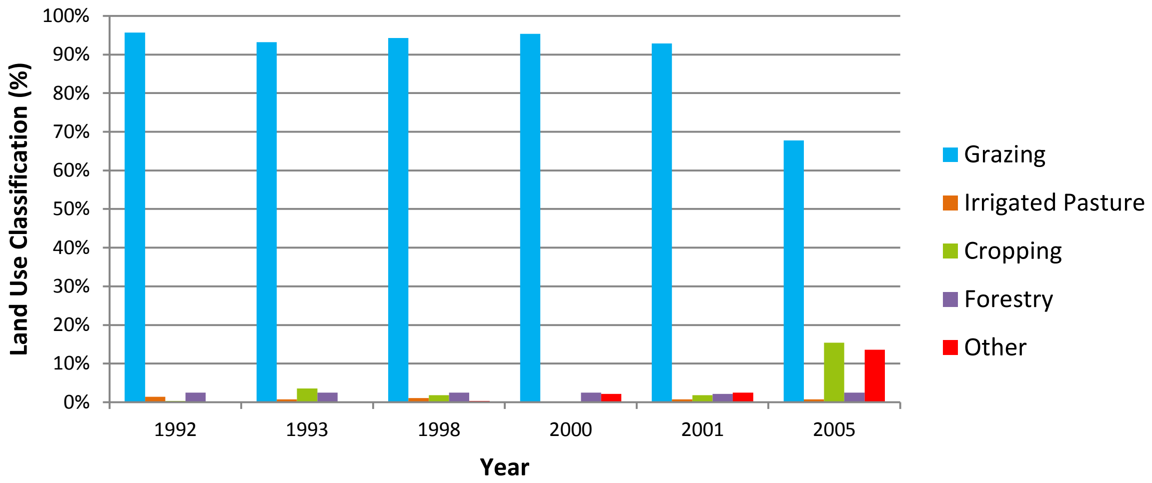


Figure 85. Land use change in the Bray Drain catchment (A22390504).

It was found that land use alone was not sufficient to represent the observed runoff response at all three gauges. Soil type would also be expected to influence the runoff generated from a catchment, and as such has been factored into the functional unit classifications. The water holding capacity was selected as the soil parameter to delineate the functional units, as high water holding capacity would be expected to retain more rainfall and result in less runoff, and vice versa. The plant water holding capacity for the region from the Land and Soil Spatial Data for Southern South Australia (DWLBC, 2007) can be seen in Figure 86. The soils classified to have a moderate or high available water holding capacity were grouped to have a high water holding capacity for the purposes of the functional units, with the remaining moderately low, low and very low soils represented by a low classification for the functional unit delineation.

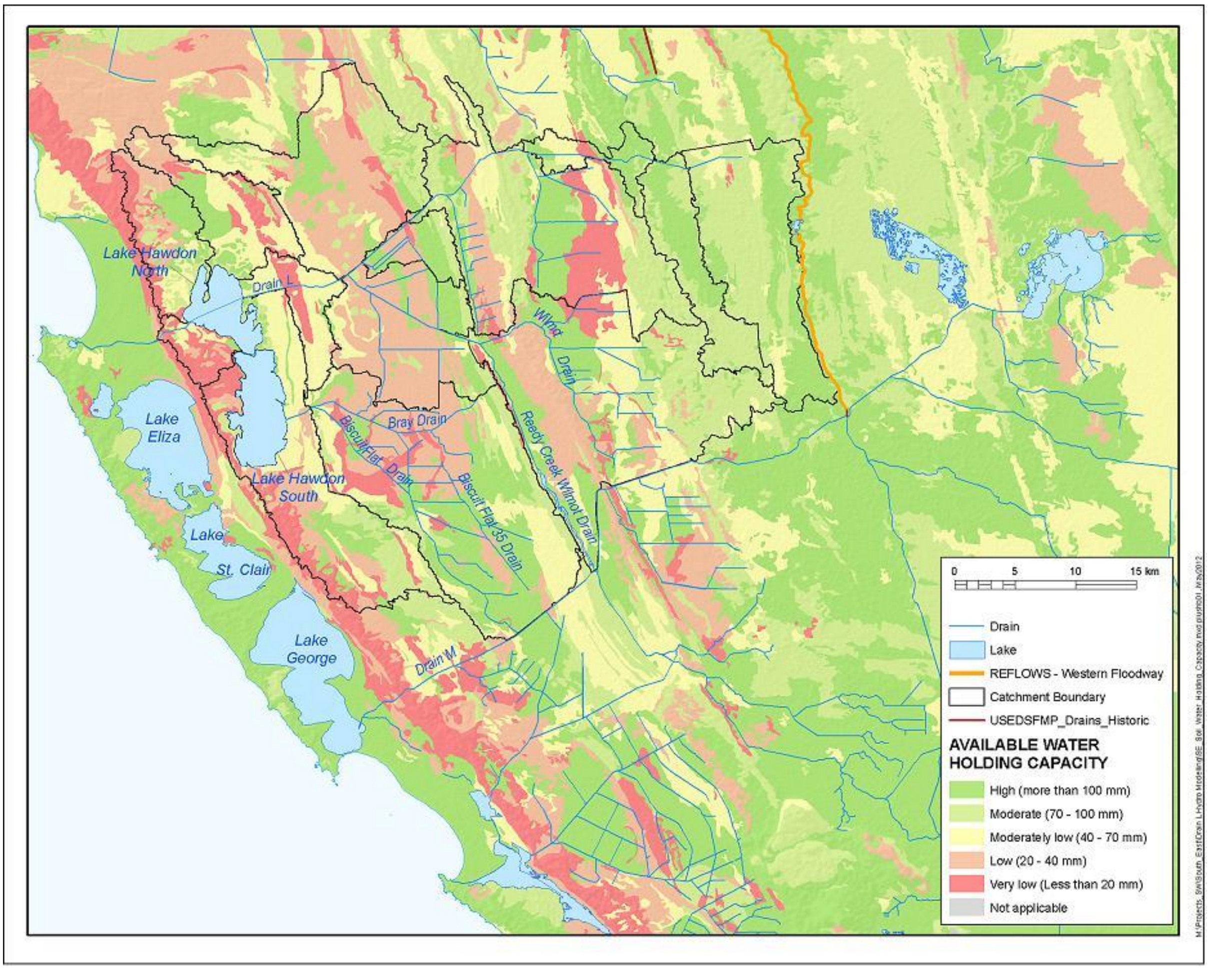


Figure 86. Soil available water holding capacity for the Lake Hawdon catchments.

As a result, four functional units were identified for the catchment modelling, for each combination of a high and low water use, and high and low soil water holding capacity. The proportion of each sub-catchment represented by each of the four functional units has been calculated, and is provided in Appendix 4.1 (catchment identification numbers can be seen in Figure 90). These fractions of the total area for each sub-catchment was used in SourceIMS to determine the total runoff for each sub-catchment, based on the model parameters calibrated in the next section for each of the four functional units. While these four functional units were found to provide a reasonable representation of the runoff variability across the catchments, there are other factors that could also be considered, such as the rainfall gradient, slope of the contributing areas, or depth to groundwater.

Rainfall – Runoff Model Calibration

Each of the four functional units identified had its own set of model parameters to represent the rainfall – runoff relationship expected for that unit. The same set of parameter values were used for the fraction of each functional unit in each sub – catchment, and then calibrated to minimise the error when compared to data at the three gauges available concurrently. This approach is not expected to maximise the performance of the model in terms of these error metrics compared to allowing different parameter values for each gauged catchment. However, it is expected to produce model parameters that are more representative of the runoff response of the different components of the catchments, and as such increase the confidence when these values were applied to the ungauged regions in the study area, where the model performance cannot be tested.

Three commonly used rainfall runoff models were compared, to allow the best performing model for the region to be selected. Each model has between four and nine parameters to be calibrated, and a schematic of each model is presented in Appendix B. The models considered were:

- AWBM (Boughton, 2004)
- GR4J (Perrin et al., 2003)
- IHACRES (Croke et al., 2005)

The minimum and maximum ranges used for each parameter in the calibration process were varied to ensure the calibration process did not produce values at the limit, while still maintaining hydrologically sensible values. Appendix C provides a list of the parameters for each of the models, including the minimum and maximum ranges, and the initial values used if necessary for the calibration approach. The objective function used was the Nash-Sutcliffe Efficiency (NSE) on a daily time step minus the bias in the estimated volume over the simulation period. Different weightings were applied to combine the error measures from the three gauges into one objective function value, based on the length of the record available, and the quality of the data record, as outlined in Table 21.

Table 21. Calibration and Validation period of historical flows at gauging sites.

Site	Weighting	Calibration Period		Validation Period	
		Start Date	End Date	Start Date	End Date
A2390510 – Drain L	2.0	01/01/1990	04/10/2011	05/09/1975	31/12/1989
A2390527 – Wilmot Drain	1.5	07/11/1999	04/10/2011	05/09/1975	1/12/1989
A2390504 – Bray Drain	0.5	14/04/1979	21/04/1988	08/12/1975	13/04/1979

The available data was split into calibration and validation periods, also indicated in Table 21. The calibration period was used to fit the parameters for each model in each functional unit. The validation period was used to assess the calibrated parameters on an independent set of data, to test the ability of the parameters to generalise the rainfall – runoff relationship, to ensure that the model parameters were over-fitted to the calibration period. The most recent data was used for calibration to provide a better representation of the current state of the catchments, and also it was found that using the most recent data for the validation period resulted in substantial over estimation of the observed runoff by the model for the recent dry period. A one year warm up period was used to remove the influence of initial state variables in the model on the objective function values.

A number of optimisation runs were undertaken in an attempt to identify the best model parameters for each runoff model considered, using a local optimisation method (Rosenbrock's Method), a global optimisation method (Shuffled Complex Evaluation, SCE), and a combination of the two by using the local optimisation method to fine tune the values found by the global search algorithm. The storage constant for each reach has also been included in the optimisation, along with the parameter for the rainfall – runoff model for each of the four functional units. The calibration using the SCE optimisation algorithm was performed using 25 shuffles and default parameters for the remainder of the algorithm parameters, which generally resulted in approximately 10,000 model runs per calibration trial. The Rosenbrock algorithm was run for 600 iterations, and both stopping criteria were found to be sufficient for the objective function value to converge to a single value. The optimised parameter values obtained from the calibration exercise for each model are provided in Appendix 4.1.

The model calibration and validation results for the AWBM, GR4J and IHACRES can be seen in Table 22, Table 23 and Table 24, respectively. From the tables, it can be seen that all the models perform poorly for the data recorded at the Bray Drain (A2390504). However, the data at this site is not expected to be very reliable, as the gauging station can be influenced by backwater effects when Lake Hawdon South is close to full, and as such recorded higher water levels, which are interpreted as higher flows than would be caused by unimpaired flow. As such, all the models can be seen to underestimate the recorded flow (negative bias value) due to these backwater effects. To minimise the effect of this phenomenon on the model calibration, and also because of the shorter data record compared to the other two gauges, the error calculated against the Bray Drain data has been given a low weighting in the overall objective function, as seen in Table 21.

The overall calibrated objective function value for each model can be seen as the NSE Bias value in Tables 22 - 24. The IHACRES model can be seen to perform poorly compared to the other models considered, by underestimating the runoff volumes by a large amount (large negative bias values in Table 24). This is expected to be a problem with the calibration methodology for this model, and further investigation of the model parameter bounds used and the parameters of the SCE algorithm may be required to improve this performance.

Table 22. AWBM calibration and validation results.

	Calibration			Validation	
	Efficiency	**Bias**	**NSE Bias**	**Efficiency**	**Bias**
A2390510	0.81	-4.45	0.82	0.86	-2.74
A2390527	0.85	-7.47		0.88	-0.74
A2390504	0.59	-33.28		0.89	-23.42

Table 23. GR4J calibration and validation results.

	Calibration			Validation	
	Efficiency	**Bias**	**NSE Bias**	**Efficiency**	**Bias**
A2390510	0.8	15.19	0.8	0.84	10.49
A2390527	0.86	8.4		0.88	9.36
A2390504	0.55	-28.19		0.83	21.49

Table 24. IHACRES calibration and validation results.

	Calibration			Validation	
	Efficiency	**Bias**	**NSE Bias**	**Efficiency**	**Bias**
A2390510	0.31	-30.89	0.45	0.36	-72.05
A2390527	0.51	-67.93		0.45	-68.22
A2390504	0.24	-75.13		0.38	-69.77

The AWBM and GR4J models can be seen to perform very similarly, with overall NSE Bias values of 0.82 and 0.8, respectively. If model performance was similar, the GR4J model would be the more desirable model, as it has half the number of parameters to calibrate (four compared to eight), and as such there is less margin for over fitting of the model. Ignoring the Bray Drain (A2390504) results for the reasons outlined above, it can be seen that the AWBM model performs better than the GR4J model in both the Nash Sutcliffe Efficiency value and the volume bias for both the calibration and validation periods at both the Drain L (A2390510) and Wilmot Drain (A2390527) gauges in all but one case. For this case, the difference is not expected to represent a significantly better model, with the Nash Sutcliffe Efficiency value for the Wilmot Drain for the calibration period a value of 0.86 for the GR4J model, compared to 0.85 for the AWBM model.

The Nash Sutcliffe Efficiency value is based on a sum of squared differences, and as such has a bias toward matching the highest flow peaks, often at the expense of accurate simulation of lower flows. The bias value represents the error in the total runoff simulated over the whole period. To further investigate the performance of the models over the range of flows, the flow duration curves for each model at each gauge over both the calibration and validation periods can be seen in Figures 87 – 89. The underestimation of flow by the IHACRES model can be seen in the flow duration curves, as well as the overestimation of low flows by the GR4J model. For most cases the calibrated AWBM model can be seen to represent the distribution of flows more accurately than the GR4J model. Based on these results, AWBM has been selected as the most suitable runoff model for the Lake Hawdon rainfall - runoff model.

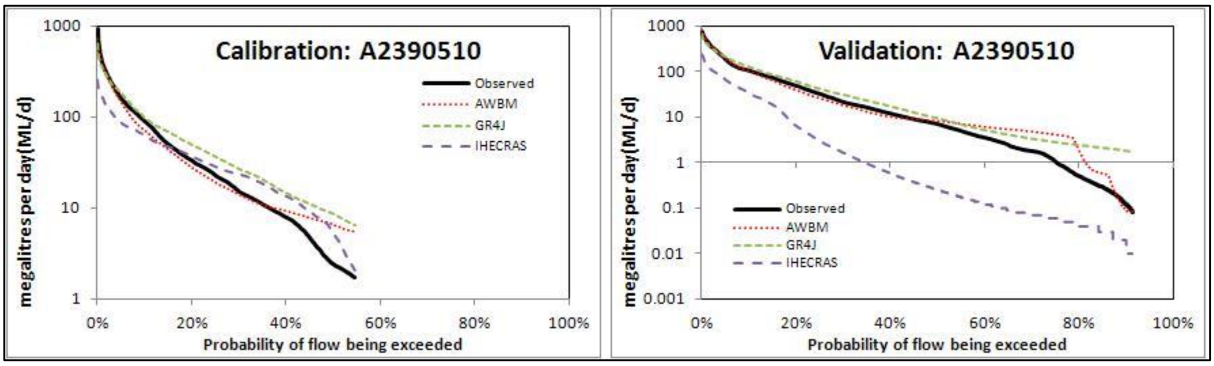


Figure 87. Flow duration curve for calibration and validation at gauging station A2390510.

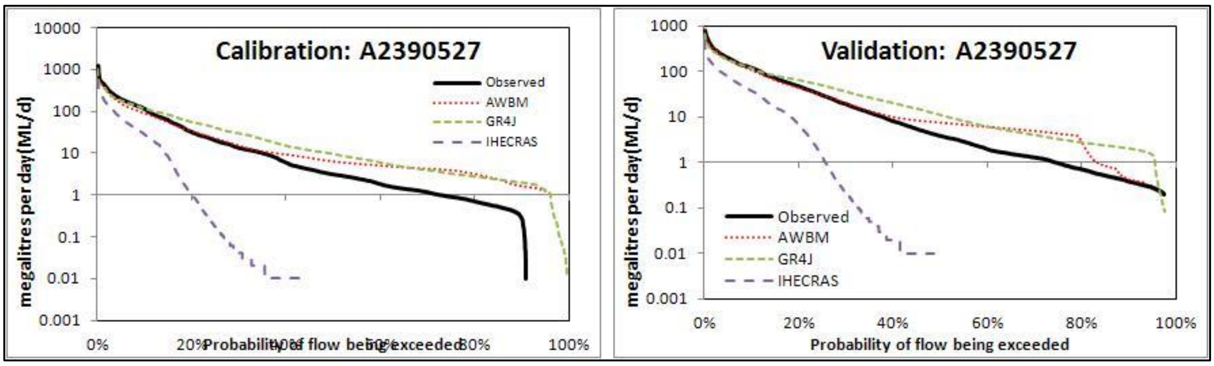


Figure 88. Flow duration curve for calibration and validation at gauging station A2390527.

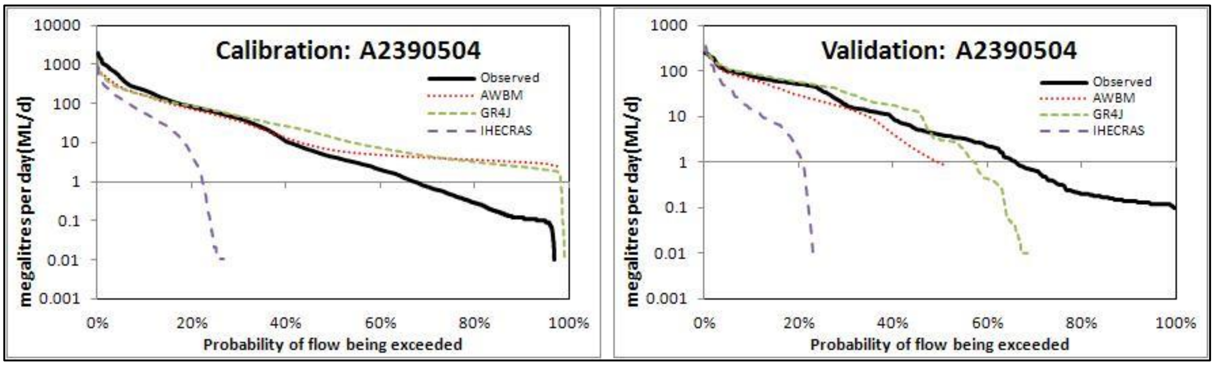


Figure 89. Flow duration curve for calibration and validation at gauging station A2390504.

The final schematic of the rainfall – runoff model can be seen in Figure 90. The three nodes that provide inflow to Lake Hawdon North can be seen, from "Drain L – Inflow", the "Local Catchment" to Lake Hawdon North, and the "Bray Drain" flow to Lake Hawdon South. The physical location of the proposed South East Flows drain alignment relative to the catchment boundaries can be seen as the thick blue line in Figure 90. Water user nodes (blue waves with yellow circle) are used to extract water from the diversion points north toward the CSL. The green diamonds represent "supply points", which can control the maximum daily flow extracted from the model. While the green diamonds appear downstream of the proposed alignment, they represent only the catchments that can contribute to the proposed drain alignment.

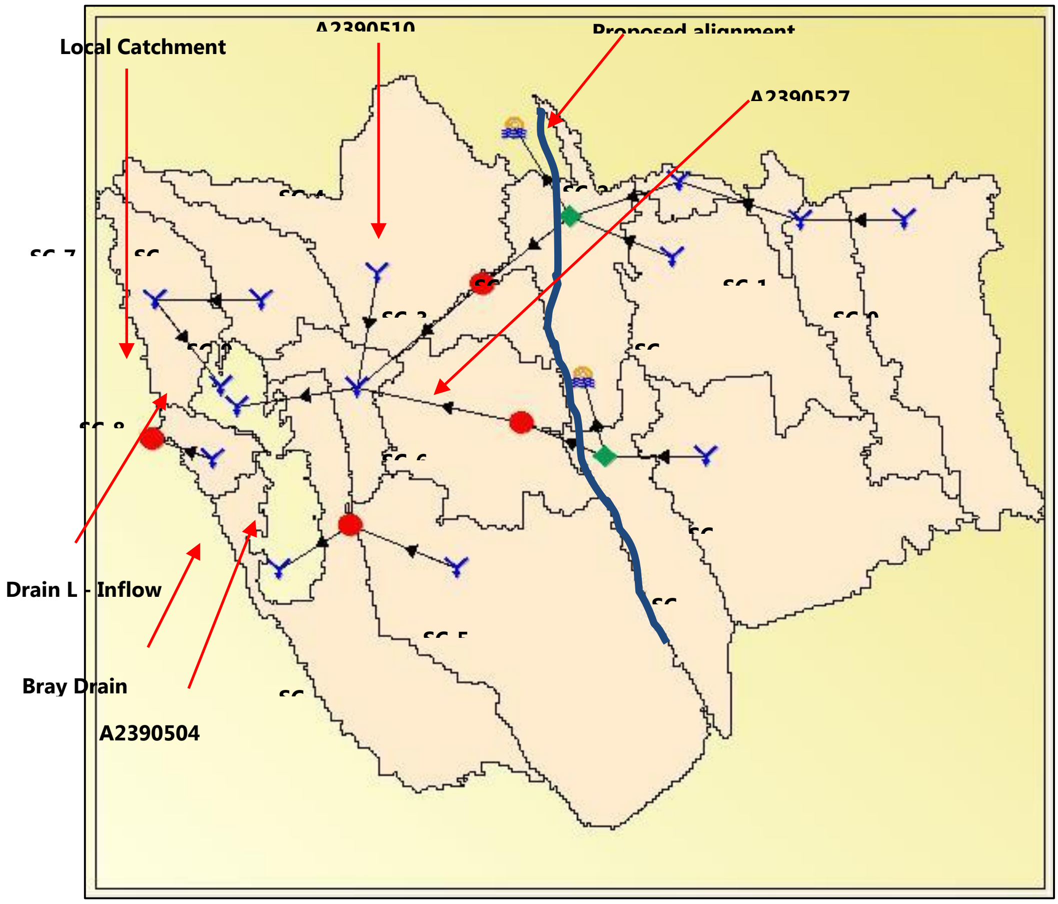


Figure 90. Catchment model schematic of proposed alignment and diversion points.

Lake Hawdon Storage Model

The runoff models calibrated above allow the inflows to Lake Hawdon North and South to be simulated. A second model was required to take these inflows as inputs and represent the resulting water level in the lakes, and allow the effects of a regulator to be investigated. A water balance storage model in SourceIMS was developed, including the necessary storages for the lakes, and the hydraulic connections between them. A number of steps were undertaken to develop this model, including:

- defining the model structure,
- determining the relationships between depth, area and volume for each storage, and
- calibrating the hydraulic connections between the storages.

Each step is outlined in more detail below.

Model Schematic

The initial model schematic developed can be seen in Figure 91. The inflow nodes (blue circle with an arrow) correspond to flow time series derived from the runoff model. The Bray Drain inflow has been split between Lake Hawdon South and Lake Hawdon North based on the area contributing to each lake.

To capture the dynamics of the interaction between Drain L and Lake Hawdon North, the lake has been split into three storages, one to represent the drain passing through the lake, and one to represent each of the areas of the lake on the north and south side of the drain. The resulting model schematic representation of the drain and Lake Hawdon North can be seen in Figure 91, with from the left the storage for Lake Hawdon North on the North side of the drain, Drain L itself, and then Drain L on the South side of the drain. When flow in Drain L is above the connection with Lake Hawdon North, simulated to occur at 3.9m AHD, the three storages are connected. The final storage seen in Figure 91 (on the right) represents Lake Hawdon South.

The green lines in Figure 91 represent hydraulic connector links, which contain the conveyance relationship to drive flow between storages based on the water level in each of the storages linked together. Along the length of Drain L within Lake Hawdon North there are a number of cut outs in the sill to allow water to flow in or out of the drain. Due to data and modelling limitations these cutouts have not been modelled individually, instead one representative link between the drain and the lake on each side of the drain has been used to simulate the overall interaction between the water bodies.

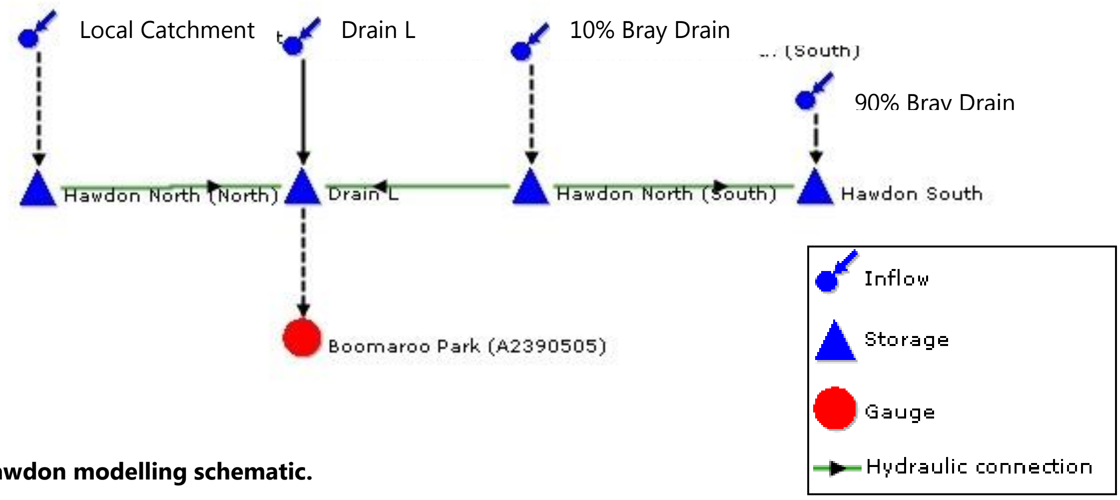


Figure 91. Lake Hawdon modelling schematic.

Storage Relationships

Each storage in Figure 91 requires a depth – area – volume relationship to allow the volume in storage to be converted into a depth (the variable of interest for the EIH of Lake Hawdon) as well as an area (to allow the net effect of rainfall and evaporation from the water surface to be taken into account). The 2m DEM and 3D analyst tool in ArcGIS has been used to derive the relationships for the lake storages.

For the Drain L storage relationship, the cross section as the drain enters Lake Hawdon North has been extracted from the DEM to provide a representative cross section. The slope of the drain through the lake means that the bottom elevation according to the DEM drops from 4m as the drain enters the lake, to 2.6 m as the drain exits again, however a representative bottom depth is required for the modelling. It was determined that for water levels above 3.9m AHD there should be hydrological connectivity between drain and wetland, and based on interrogating a number of locations in the DEM a representative bottom depth of the drain has been assumed to be 3.64m. The cross section has been multiplied by the 4.8km length of drain through the lake to provide the necessary depth – area – volume relationship to represent the drain in the storage model. This approach is likely to result in an overestimation of the actual volume, as the drain gets narrower and deeper as it progresses through Lake Hawdon North. However, the volume is still much smaller than the Lake Hawdon North storages and a sensitivity analysis indicated that the Drain L volume has very little impact on the simulated results.

For Lake Hawdon South, a revised bathymetry was required due to inaccuracies in the existing DEM due to dense vegetation or the presence of surface water when the data were collected. The area where the DEM was expected to be inaccurate was identified, as outlined in Figure 92. A total of 622 spot elevations of the lakebed were obtained by professional surveyors using differential GPS to determine a more accurate estimate of the bed elevation at each location, seen as the red dots in Figure 92. For locations that spot elevations were not able to be taken (due primarily to access difficulties), estimates of elevation were made based on aerial photography, i.e. where the vegetation or image colour in an area with poor coverage was similar to that in an area with good coverage, a similar lakebed elevation was estimated. A total of 1095 points were updated using this method, seen as the blue dots in Figure 92. Using these points a local area DEM was generated using an ESRI natural neighbour interpolation method (a process which respects the new measured data point values) at 10 metre grid cell size for the area with suspect accuracy, and this was then merged and re-sampled at 2 metre grid cell size with the original South East 2 metre DEM. As a result the known accuracy of the DEM used for hydrodynamic and hydrological modelling was improved by the incorporation of validated survey data (Ben Taylor, pers. comm., 22/6/12).

The corrected DEM was then used as the basis to derive the depth – area – volume relationship for Lake Hawdon South to be used in the storage modelling. The relationships for Drain L, the north and south sides of Lake Hawdon North and Lake Hawdon South, and can be seen in Tables 25 – 28, respectively.

Table 25. Drain L storage dimensions.

Level (m)	Volume (ML)	Surface Area (ha)
3.64	0	0
3.7	0.97	0.81
3.85	5.85	4.89
3.86	6.26	5.23
3.94	11.43	9.55
4.03	20.61	17.23
6.12	308.67	257.93
6.13	310.38	259.35
6.22	327.51	273.67
7.24	544.14	454.69

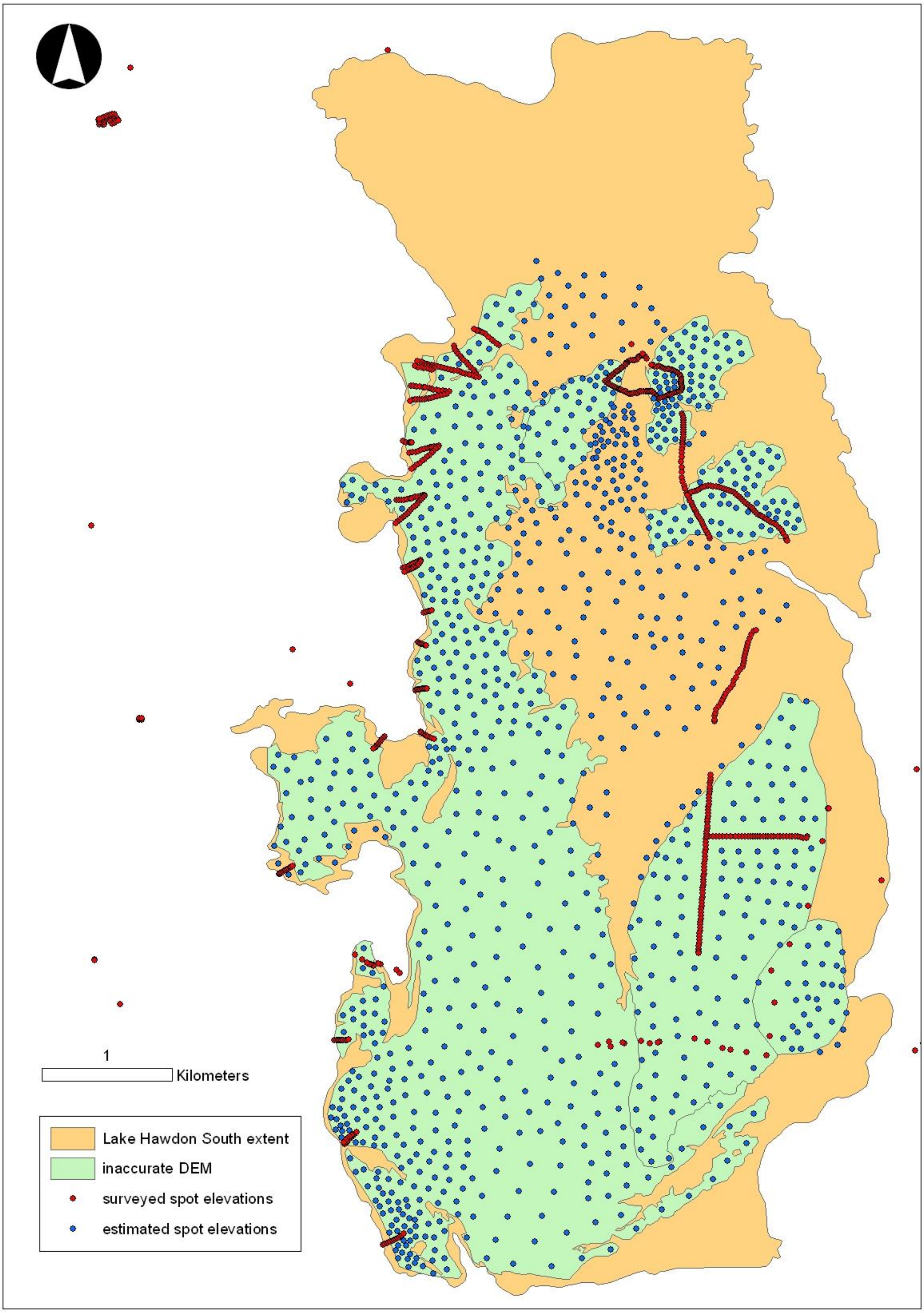


Figure 92. Map of Lake Hawdon South showing extent of inaccurate DEM and locations of surveyed and estimated spot elevations.

Table 26. Hawdon North (North) dimensions.

Level (m)	Volume (ML)	Surface Area (ha)
2.6	0	0
2.8	0.5	0.3
3	1.2	0.5
3.2	2.7	1
3.4	5.2	1.6
3.5	6.8	1.8
3.8	58.4	72.9
4.2	1684	832.6
4.4	3634.4	1085.9
4.6	5900.8	1164.8
5	10634.1	1191.8
5.2	13022.9	1196.5
5.4	15419.2	1199.5
5.6	17820.5	1201.7
5.8	20225.6	1203.3
6	22633.3	1204.4
6.2	25042.8	1205

Table 27. Hawdon North (South) dimensions.

Level (m)	Volume (ML)	Surface Area (ha)
2.6	0	0
2.8	0	0
3	0.1	0
3.2	0.2	0.1
3.4	0.7	0.4
3.5	1.1	0.5
3.8	14.5	32.2
4.2	2030.1	973.8
4.4	4184.8	1152.1
4.6	6542.7	1195.1
5	11387.8	1223.7
5.2	13844.7	1232.6
5.5	17556.7	1241.3
5.6	18799	1243.3
5.8	21288.8	1246.2
6	23783.4	1248.3
6.2	26281.9	1249.9

Table 28. Hawdon South dimensions.

Level (m)	Volume (ML)	Surface Area (ha)
3.66	0	0
3.8	2.3	4.12
4	453.92	675.28
4.2	2745.72	1677.82
4.5	8555.81	2161.86
4.6	10830.37	2400.1
4.8	16105.04	2852.67
5	22091.97	3100
5.2	28424.75	3213.89
5.4	34891.87	3247.29
5.5	38143.57	3255.42
5.6	41402.18	3261.25
5.8	47933.68	3269.22
6.4	67586.58	3278.47

Conveyance Relationships

Channel conveyance is a measure of the carrying capacity of a channel. Tables of differences in water level and the corresponding conveyance are required to represent the flow between storages in SourceIMS. This is analogous to a standard stage – discharge curve, with the difference being that the former is more appropriate for when the downstream water level will influence the upstream flow, and as such the flow is driven by the difference in the water levels, as opposed to only the water depth (stage). Conceptually this is desirable, as a scenario can be conceived where the water level of two linked storages is high but at the same level, and as such there would be expected to be no flow across the link. The conveyance value is multiplied by the square root of the difference in water level, and as such has units of m2.5/s, as opposed to m3/s for flow.

In SourceIMS, the conveyance relationship is entered into a hydraulic connection link to represent the flow between storages based on the difference in water level in the storages. This way, flow can occur in both directions across the link, and the flow can change (generally increase) as the head difference between the water levels increases. Preliminary hydraulic modelling was used to inform the conveyance relationships, followed by calibration to the flow and water level data available.

The downstream flow at Boomaroo Park has been used to calibrate the conveyance relationships out of Drain L into the two Lake Hawdon North storages, and the link between Lake Hawdon North and South. The effect of errors in the simulated inflows were reduced by replacing the simulated flows by the recorded flows at Drain L (A2390510), on Wilmot drain (A2390527) and Bray drain (A2390504) where possible.

The conveyance relationship between Lake Hawdon North and South was manually calibrated to flow in most years, with a maximum flow rate (in 2000) of approximately 150ML/day. While the channel between North and South is wide (around 20m), this rate should be reassessed based on the capacity of the culverts under Old Naracoorte Road that runs between the two lakes. However, this is likely to have little impact on the results of this study, as the wetlands will balance their levels; it is just over how many days it takes for this volume to transfer.

Similar calibration of conveyance relationships out of Drain L was performed to represent the filling of the wetland as flow commences and draining of the wetland over the summer period. The sill for spill out or into Drain L from Hawdon North was set at 3.9 m and the bottom of the drain was set at 3.64 m as shown in Table 21. Setting a deeper drain only connected the drain flows to the lake in very wet years, which is much rarer than expected from anecdotal evidence. Seepage rates on the Hawdon North and South storages were calibrated to achieve the drying out of the wetlands during the dry periods, once flow between the drain and Lake Hawdon North ceased, after water levels dropped below 3.9 m. The calibrated model was able to adequately replicate the historical flow at Boomaroo Park, downstream of Lake Hawdon, for the period of data since 1991, as seen in Figure 93, with a Nash Sutcliffe Efficiency value of 0.7, and volume bias of 3.12%.

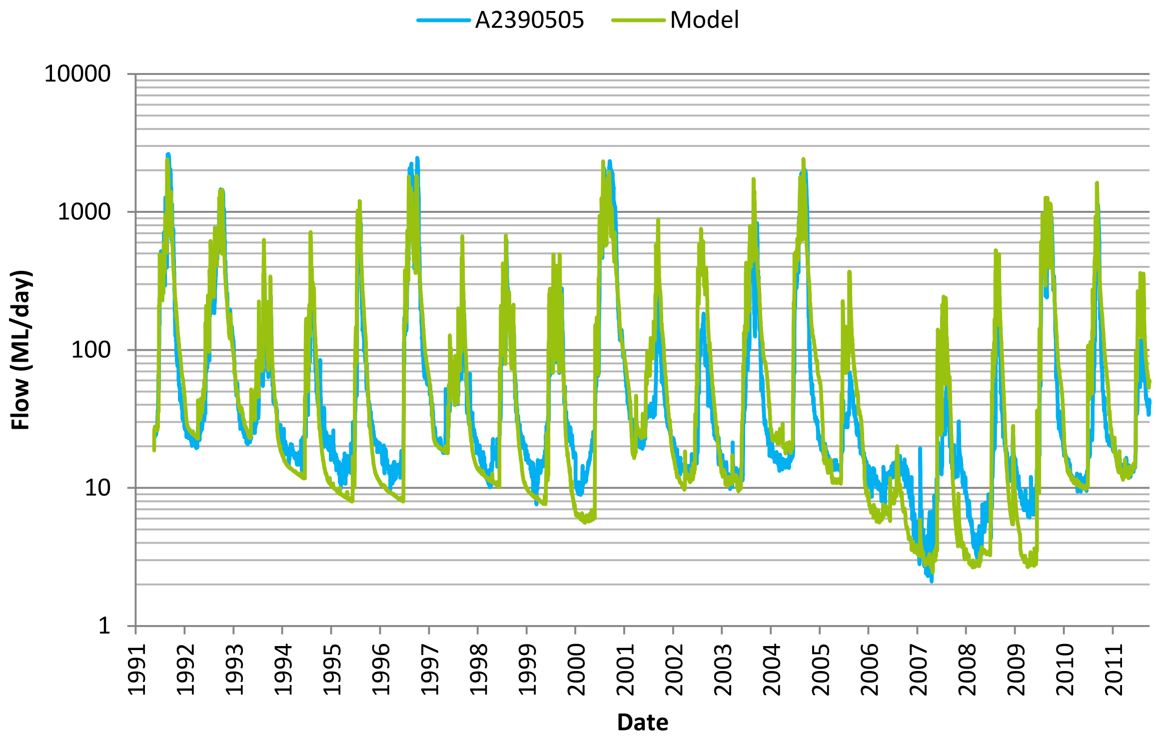


Figure 93. Comparison of modelled and historical flow at Boomaroo Park.

Model Validation

Water level observations have been used to validate the model, in a process separate to the calibration of the model. In Chapter 2, Landsat imagery was used to identify areas of inundation in Lake Hawdon North and South since the data archive commenced in 1989. As inundation was expected to result from significant drain flow, the drain flow records were examined to determine periods of major drain flow within each year. A search was conducted for Landsat imagery within the month of peak drain flow, or one month either side of major drain flow and all cloud-free images were acquired. Where no cloud-free imagery was available within the three months around peak drain flow a search was conducted for any cloud-free imagery within that year. In some years no cloud-free imagery was available (see Chapter 2).

The area of the wetland inundated identified in Chapter 2 was converted to storage volume based on the depth – area – volume relationships presented in Tables 22 - 24. As shown in Figure 94, the modelled volume in Lake Hawdon North represents the volume derived from landsat imagery reasonably well. The underestimation of the storage volume from the remote sensing imagery may be attributed to the vegetation in the wetland, or differences in the way that the hydraulics in the lake fill on the eastern side and spill into the drain again on the western side, compared to the simple "bucket" type relationship adopted in the water balance model. The overestimation of the volume during the period 2009-2010 compared to 2002-2003 may be attributed to the strong vegetation growth during the former period as indicated by a maximum of 0.6 mean NDVI (Normalised Difference Vegetation Index) compared to a maximum of 0.5 mean NDVI during the latter period. Extensive inundation, which could result in strong floating and anchored vegetation growth physically reduces the visible water area and hence overwhelm the water effect on NDVI.

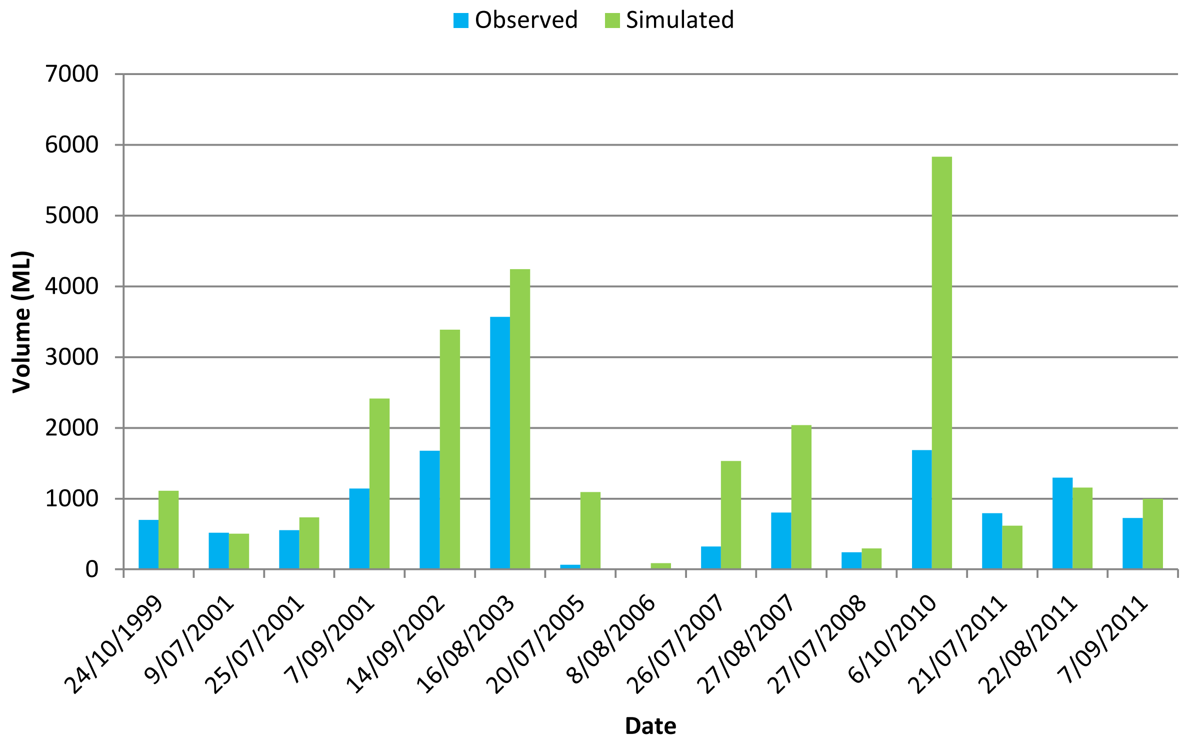


Figure 94. Comparison between remote sensing imagery of Lake Hawdon North volume and simulated volume.

For Lake Hawdon South, the model overestimates the area inundated (as converted to volume) derived from the Landsat imagery, as seen in Figure 95. There are large stands of dense vegetation in Lake Hawdon South located in the deepest part of the wetland on the western side (Figure 95). It is expected that this vegetation might have led to an underestimation of the area inundated derived from Landsat imagery, and in part may be the cause for the discrepancy between the modelled and observed volumes presented in Figure 95. Nonetheless, it is encouraging that the pattern of wet and dry periods is similar between the observed and modelled volumes, with a correlation between the two series in Figure 95 of R=0.65.

A network of water level loggers was installed in Lake Hawdon South in 2009, and the location of sites can be seen in Figure 97. The data available at two of these stations has also been used as a validation of the water balance model developed. One logger located near the Bray Drain entrance to the lake was selected for comparison (BRA036), as well as one logger near the middle of the lake (BRA038). The recorded water levels at these two locations, as well as the simulated water level, can be seen in Figure 96. The model was found to closely follow the filling and draining pattern recorded at the BRA036 station, with the main difference being the initial water level lower in the model compared to the observed data. There are some differences between the two observed water levels, indicating the level of accuracy of the water level loggers as well as local effects at the lake, such as wind setup and vegetation impeding south-to-north flow (Ben Taylor, pers. Comm., 13/07/12). Given the variation in the observed data, and also the general agreement between the filling and draining rates between the observed and modelled water level, the lake storage water balance model has been deemed a suitable representation of the dynamics of the Lake Hawdon system.

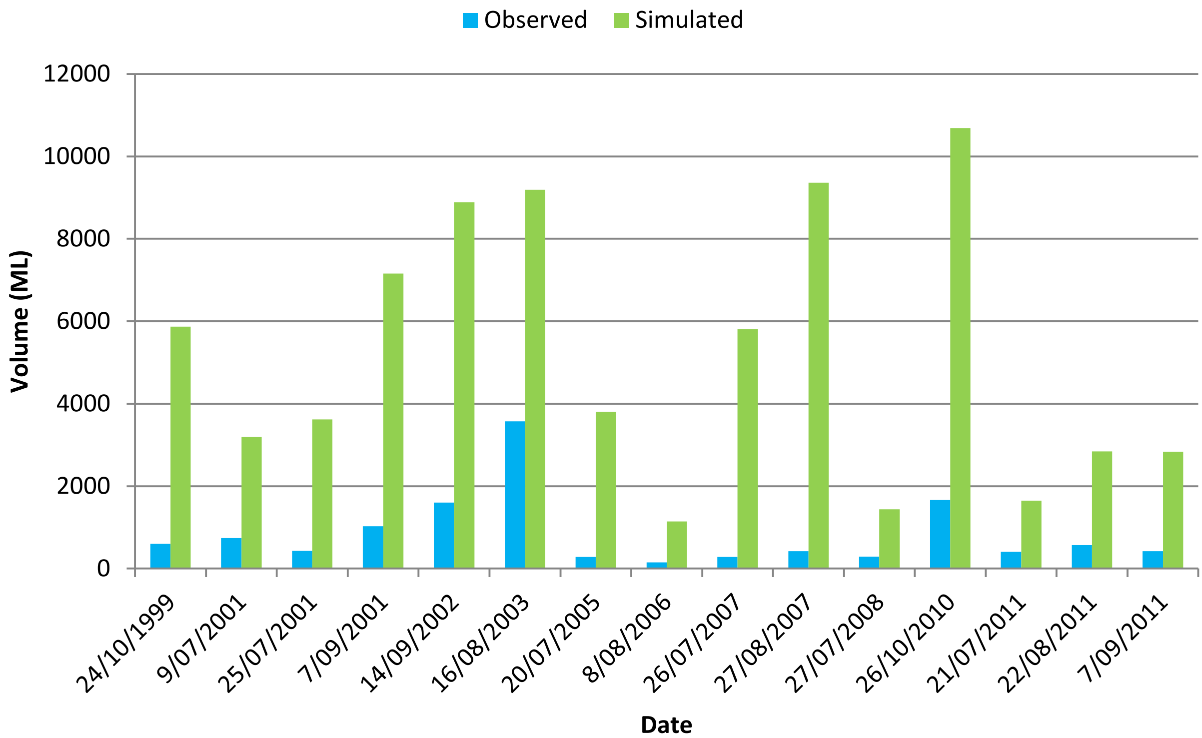


Figure 95. Comparison between remote sensing imagery of Lake Hawdon South volume and simulated volume.

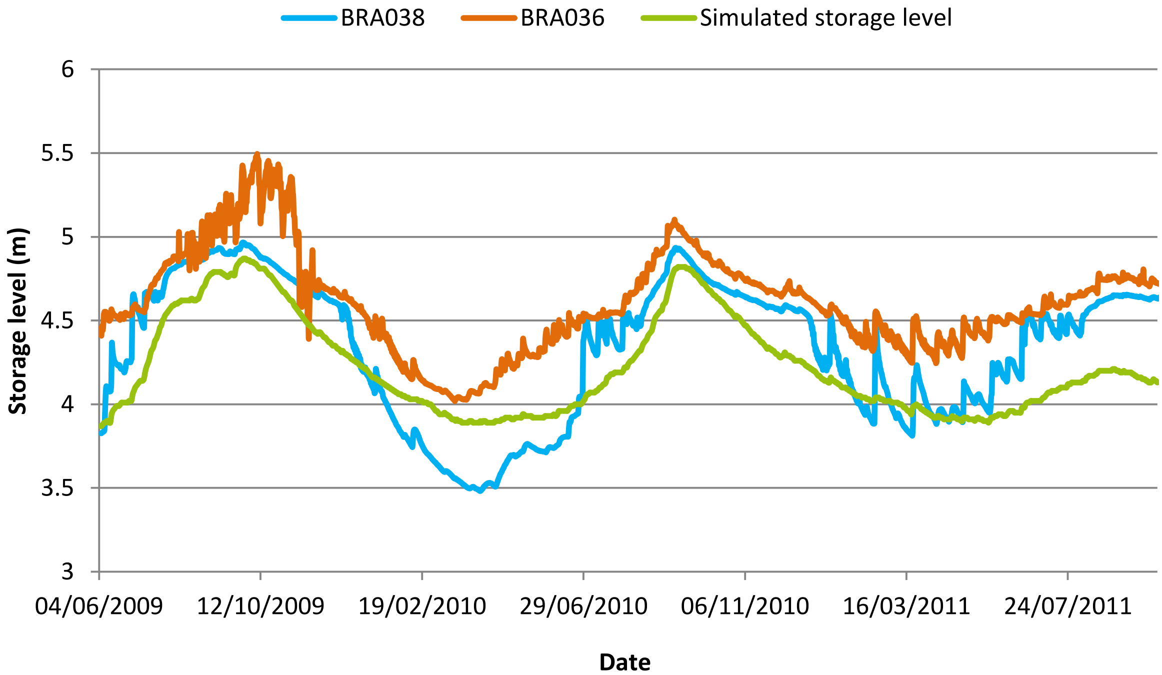


Figure 96. Modelled water level at Hawdon South (green line) compared to two logger stations (orange and blue lines).

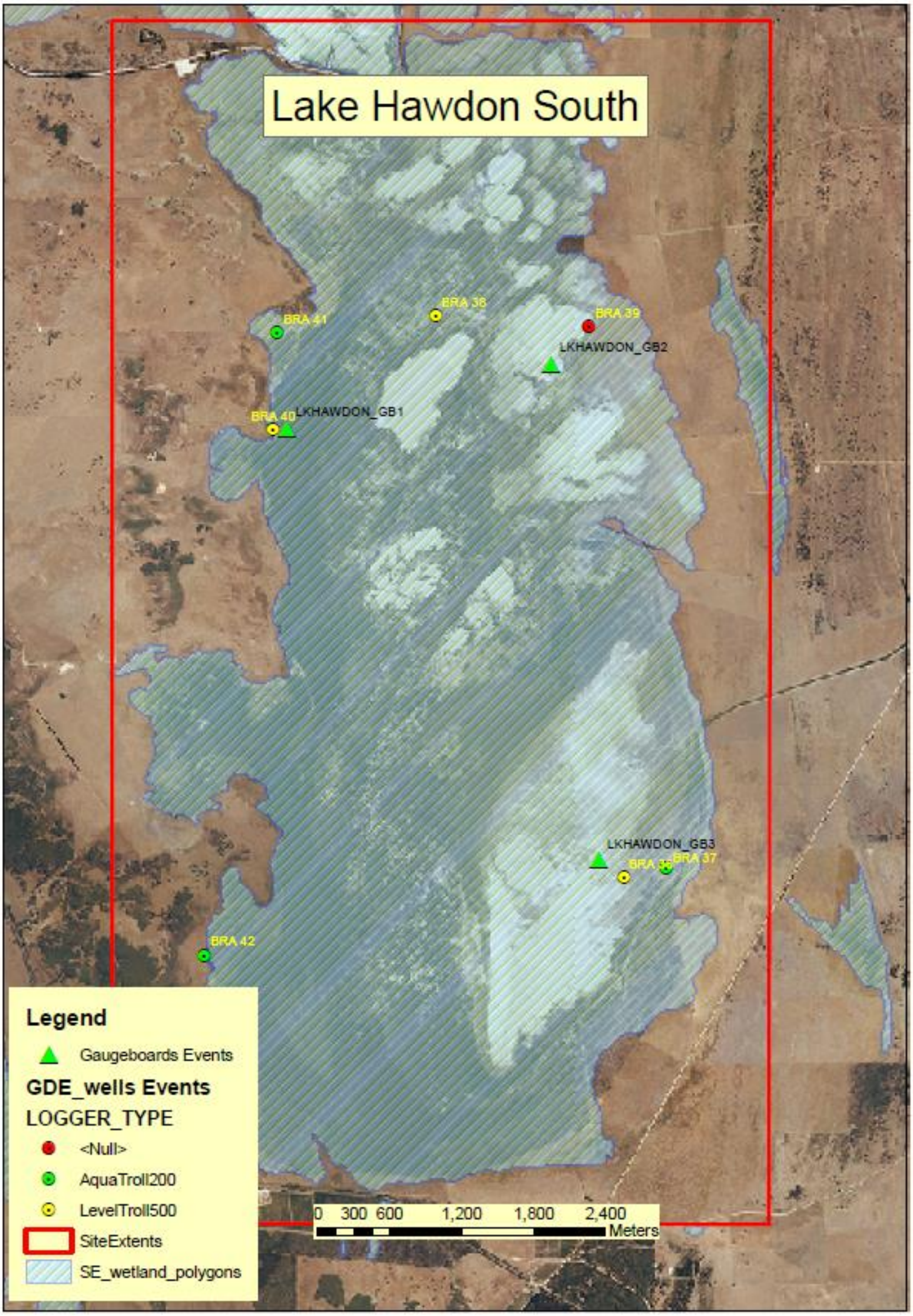


Figure 97. Location of water level loggers in Lake Hawdon South.

Storage Model Including a Regulator

With some confidence in the ability of the water balance model to represent the observed flows and water levels around Lake Hawdon, the model was adjusted to simulate the impact of a regulator located on Drain L at the exit of Lake Hawdon North. It is expected that a regulator at this location could be used to hold water in Lake Hawdon and maintain water levels, compared to requiring a high flow in Drain L for this to occur.

The Robe Lakes are downstream of the proposed regulator location, and also have an Environmental Water Requirement (EWR) that should be maintained. In a Chapter 5, hydrodynamic modelling has been undertaken to assess the fresh inflow required into the Robe Lakes at the end of the system to maintain salinity and water levels. As such, a minimum flow rate has also been considered through or around the regulator, to maintain a minimum flow to the Robe Lakes to support their EWR, as well as allow for fish migration in and out of Lake Hawdon. This minimum flow rate only applies to flows greater than the minimum flow rate, and lower flows are unaffected by the operation of the regulator. Different flow rates have been considered to investigate the resulting impact on water levels in Lake Hawdon North.

To represent flow overtopping the regulator (Q), flow over a broad-crested weir has been calculated using the equation:

$$Q = C \times b \times H_1^{\frac{3}{2}}$$

Where b with the width of the weir (m), H_1 is the head of water above the weir (m) and C a weir constant ($\sqrt{m}/s$). A value of C = 1.6 has been used for the constant, within the commonly used range of 1.44 – 1.8, and a weir width of b= 20m was used based on a surveyed cross section of Drain L at the exit of Lake Hawdon North (Ben Taylor, pers. Comm. 20/04/12). A cease to flow level of 4.3m has been adopted, to provide a trade-off between meeting the 4.4 m level of the EIH (Table 26), and reducing the number of very high levels of inundation. As such H_1 has been increased in step of 0.1 m above the zero flow level of 4.3 m to produce the discharge relationship required to represent flow overtopping the regulator. The bypass flow to Robe Lakes under the regulator was represented in the model as a culvert with a constant flow, irrespective of the depth of water behind the regulator. This bypass flow has been referred to as a culvert in the remainder of this work.

Initially, the discharge relationship out of the Drain L storage, seen in Figure 91, was modified to represent the regulator, as described above. However, due to the relatively small volume in the Drain L storage compared to that flowing into the storage from the Drain L inflow node, the outflows to the two Lake Hawdon North storages, as well as overtopping the regulator, instabilities occurred in the numerical solver in the version of SourceIMS used for this project (3.0.7). In order to overcome these instabilities, the three Lake Hawdon North storages were combined into one storage node, so that there was only one inflow into and two outflows from the Lake Hawdon North system. The spill out of Drain L into Lake Hawdon North is implicitly represented by the depth – area – volume relationship derived from the 2m DEM for the whole extent of Lake Hawdon North, as is presented in Table 29. This allowed SourceIMS to suitably represent the flow dynamics within Lake Hawdon North, as well as overtopping of a regulator. The resulting model schematic can be seen in Figure 98.

Table 29. Lake Hawdon North storage dimension.

Level (m)	Volume (ML)	Surface area (ha)
2.6	0	0.04
2.7	0.2	0.34
2.8	0.6	0.42
3	1.5	0.59
3.1	2.3	1.02
3.2	3.5	1.36
3.3	5	1.76
3.4	7.1	2.35
3.5	9.6	2.77
3.6	12.6	3.44
3.7	20.7	21.95
3.8	76.4	105.79
3.9	279.7	339.15
4	885.9	926.97
4.2	3743.6	1826.99
4.3	5713.9	2099.41
4.4	7920.5	2306.37
4.5	10336.9	2528.18
4.6	12968	2731.69
4.7	15792.6	2902.81

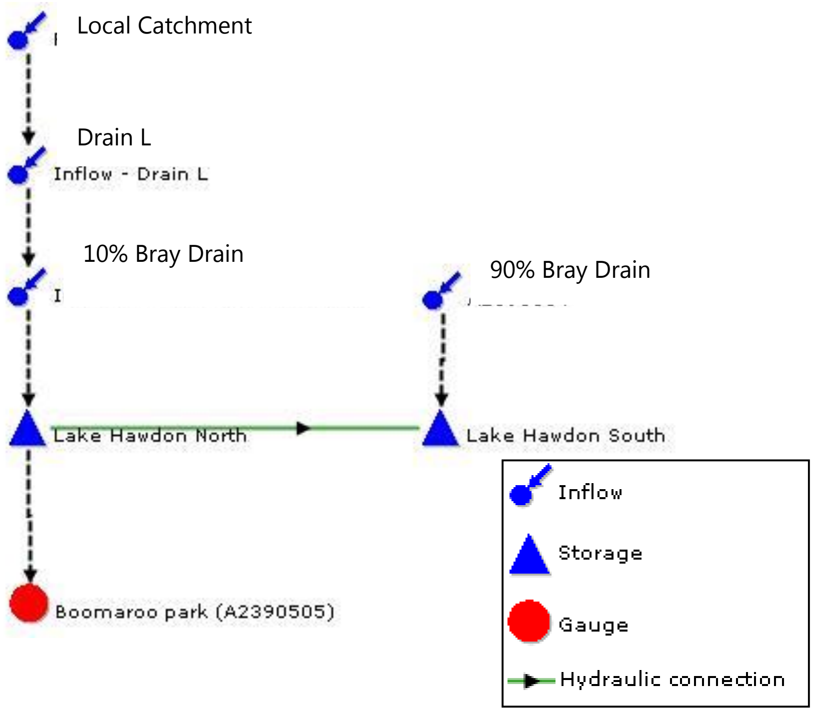


Figure 98. Lake Hawdon model schematic for diversion scenarios.

Diversion Scenarios

The models outlined in the previous section have been developed to assess the degree to which flows can be diverted at the Wilmot and Drain K diversion points northward toward the CSL while still meeting the EWRs for Lake Hawdon and the Robe Lakes. It has been assumed that the regulator on Drain L at the outlet of Lake Hawdon North is required to maintain the EWRs of Lake Hawdon North with less water than historically available from the upstream catchments.

The Lake Hawdon North EIH is outlined in Table 30 (Ecological Associates, 2009a; Chapter 2). It is not desirable to meet this hydrograph every year, and as such the aim is to meet the EIH with the same frequency as expected historically, based on the Lake Hawdon storage model. For the months from February to May flows are generally not sufficient to overflow the Drain L banks into Lake Hawdon North. The EIH assumes that the bed level is at 3.7 m, and the connection with the drain is at 3.9 m.

Table 30. Hawdon North level ideal hydrograph.

Month	Minimum Hawdon North Level (mAHD)
June	3.70
July	3.90
August	4.20
September	4.40
October	4.40
November	4.20
December	4.00
January	3.80
February	Dry
March	Dry
April	Dry
May	Dry

Montezari et al. (2011) and AWE (2011) have previously estimated the maximum diversion rate from the diversion points on Wilmot and Drain K (green diamonds on Figure 90), based on the yield expected at the CSL based on increasing the maximum capacity of the downstream channel. These studies have concluded that 250 ML/day is the optimal maximum diversion rate at both locations. As such, any flows above this were assumed to overtop the diversion structure and continue toward Lake Hawdon North, after the 250ML/day has been diverted.

These previous studies also considered a minimum flow rate that must pass downstream before diversions can occur, to maintain the downstream environmental assets. As such, a minimum flow rate that should pass the diversion points before diversion can occur has also been assessed in this work. Previously, values of 22 ML/day at Wilmot Drain and 10 ML/day at Drain K have been assumed for the previously considered Reedy Creek alignment, which is downstream of the Blackford alignment considered in this work.

Two operational scenarios have been tested at the diversion points on the Blackford alignment, to:

- divert flows all year around, and
- divert flows only between June and November inclusive, to allow summer baseflow to remain in the system to support the downstream EWRs.

Different flow rates through the culvert under the regulator at the outlet of Lake Hawdon North have also been considered. Initially, 100 ML/day was estimated to be necessary to maintain salinity targets in the Robe Lakes. However, the representation of diversions from the upstream catchment used in the hydrodynamic modelling (see Chapter 5) was different to that used in this work, and as such a range of values have been assessed to provide an indication of the effect of different flow rates out of Lake Hawdon North to support the Robe Lakes. The 100 ML/day identified has been tested, along with 20ML/day steps down to 20ML/day.

In summary, the 10 diversion scenarios were considered:

- Implement culvert at the Lake Hawdon North regulator with the capacity for a 100ML/day bypass. Adopt a maximum diversion rate of 250ML/day at each of the Wilmot and Drain K diversion points. Maintain a minimum flow in each drain before diversion occurs, with the flow identified to maintain the same frequency of meeting the EIH as the case with no diversion and no regulator at Lake Hawdon North.
- 2 – 5) as outlined in 1) but reduce the culvert flow rate to 80, 60, 40 and 20 ML/day.
- 6) As in 1) but only divert flow from June 1 to November 30 each year. For the dry period, allow all flows to pass from the upstream diversion points toward Lake Hawdon.
- 7 – 10) as outlined in 6) but reduce the low flow pass to 80, 60, 40 and 20 ML/day.

5.8 Results

The results are presented in three sections:

1. The minimum diversion rules at the Wilmot and Drain K diversion points to maintain water levels in Lake Hawdon,
2. Volumes that can be diverted from the Wilmot Drain and Drain K diversion points based on the minimum diversion rate identified,
3. A sensitivity analysis on the impact of the low flow pass culvert on the regulator on Drain K located at the outlet of Lake Hawdon North.

Minimum Diversion Rate

Previous studies on the South East Flow Restoration Project (AWE, 2009a; Montazeri et al., 2011) estimated the minimum flow to pass along each drain to maintain the downstream environment of Lake Hawdon before diversions to the north should occur. These minimum flow rates were estimated to be 22 ML/day at Wilmot Drain and 10 ML/day at Drain K for the previously considered drain alignment further downstream. The purpose of this analysis is to provide further confidence in the values that have been assumed. The maximum diversion rate of 250 ML/day, determined based on the yield achieved at the Coorong South Lagoon (AWE, 2011), has also been adopted in this work.

To achieve a similar frequency of meeting the EIH with less flow than occurred historically, a regulator on Drain L located at the outlet of Lake Hawdon North has been assumed to be necessary. Hydrodynamic modelling in the following chapter has suggested that maintaining flows up to 100ML/day into Robe Lakes, downstream of the regulator, is necessary to ensure EWRs in terms of maximum salinity and minimum water level targets are maintained. As such, a culvert has been included under the regulator on Drain L, to ensure this flow rate is preserved downstream of Lake Hawdon North toward the Robe Lakes.

As an initial extreme case, all flow less than the maximum 250ML/day at both the Wilmot Drain and Drain K diversion points has been considered. For flows greater than this, the first 250ML/day are diverted to the north, with the remaining volume spilling downstream toward Lake Hawdon North. This diversion scenario has also been considered to be occurring only in the months June to November (inclusive), with the dry season baseflows remaining in the system. The resulting water levels in Lake Hawdon North for diversions permanently (all year) and seasonally, as well as historically with no diversions or regulator, can be seen in Figure 99. To provide comparable results, the historical simulation has been derived by removing the regulator and culvert from the model with the combined Lake Hawdon North storage (Figure 98), as opposed to the model with the separate storages for Drain L as well as each side of Lake Hawdon North (Figure 91). The EIH, as outlined in Table 30, is also presented on Figure 99. The simulated bottom of the drain was at 3.64 m which is below the assumed bed level of the Lake at 3.7 m, and is the reason for the water levels in Figure 99 below the EIH.

The simulated historical water levels in Figure 99 suggest that the EIH was met in approximately 8 out of 20 years since 1991. It may not be desirable to exceed this frequency of inundating the lake, as the ecosystems in the wetland are conditioned to this frequency of wetting and drying periods (see Chapter 2 or Ecological Associates 2009b), and the grazing practices of local landholders may not be conducive to increased frequency of inundation of the lake. Even for this extreme case of no minimum diversion rate at the upstream diversion points and a 100 ML/day low flow pass culvert under the regulator at the outlet of Lake Hawdon North, the same frequency of inundation of Lake Hawdon North historically is expected to be achieved through the use of a regulator. From Figure 99, it can be seen that seasonal or permanent diversions are not expected to result in a significant difference in water levels in Lake Hawdon North. However, the water level does recede more slowly in some years due to low flows persisting through the system over the drier months with seasonal diversions and a regulator in place.

As such, according to the model, no minimum flow rate is required to pass either the Wilmot Drain or Drain K diversion points to support the downstream EWRs before diversions to the north occur. The catchment area contributing to the two diversion points is 554 km^2, however there is still a catchment area 1087 km^2 downstream of the diversion points that will continue flow unimpeded toward Lake Hawdon North and South (the area stated includes the Bray Drain). These results suggest that the unaffected downstream catchment area is sufficient to provide the lower flow requirements of Lake Hawdon North that were targeted by the minimum diversion threshold in previous SEFRP studies.

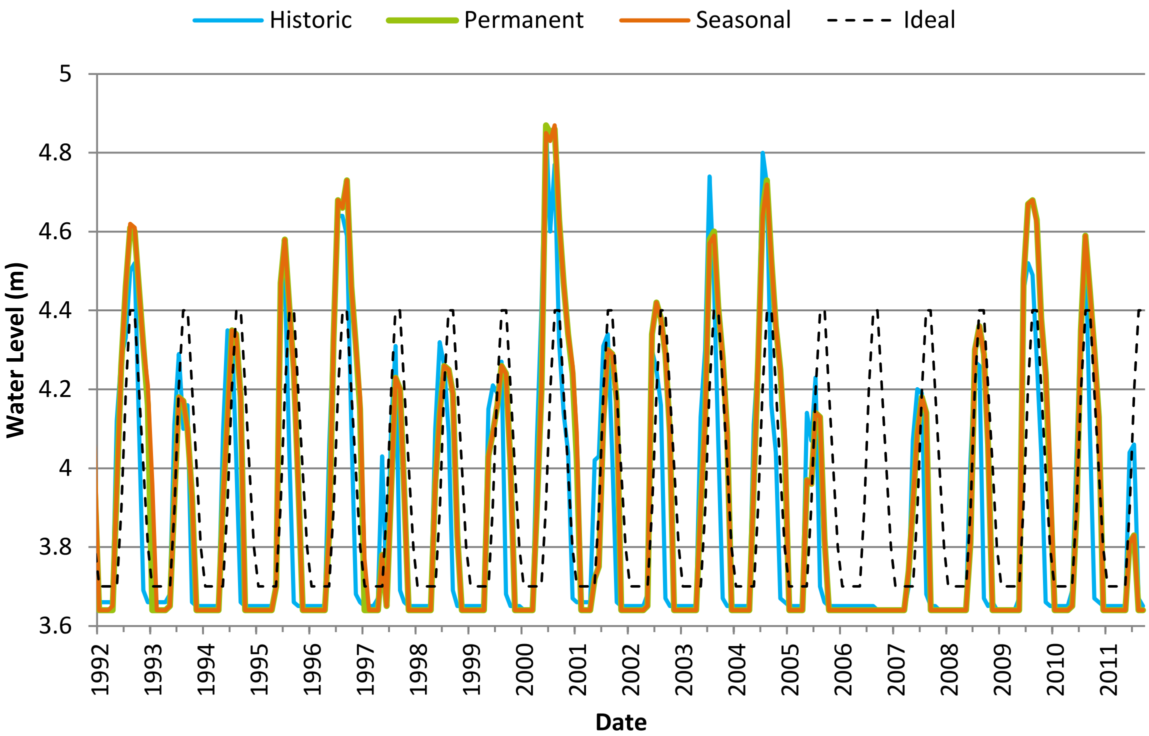


Figure 99. Simulated water levels in lake Hawdon North for the historic case (blue line), as well as seasonal (red line) and permanent (green line) upstream diversions using a regulator, compared to the ideal hydrograph.

The resulting flows at the Boomaroo Park gauge (A2390505, Figure 77) are presented in Figure 100. The impact of the regulator can be seen, with a flat 100 ML/day simulated for much of the winter season, and some spilling over the regulator in wet years. This spilling and the resulting high flows of up to 1000 ML/day are necessary to flush salt in the Robe Lakes. However, given the log scale used in Figure 100 the peak flows are significantly reduced, in part by the upstream diversions, but mostly by the peak flows being attenuated by the regulator and storage time in Lake Hawdon North and South.

The impact of diverting flow from the upstream catchments on the summer low flows can be seen in Figure 100, with the average flow between January and May 40% less than the historical case with permanent diversions upstream, but only 8% less than the historical case when seasonal diversions are in place. The sharp rises and falls in the low flows for seasonal diversions (green line) in Figure 100 correspond with when diversions commence or conclude based on the seasonality (i.e. start of June or end of November). In summary, winter only diversions are likely to maintain the historical summer low flows observed in Drain L downstream of Lake Hawdon. However, little difference in the water levels in Lake Hawdon North is expected compared to permanent diversions, due to the smaller volumes over the dry period compared to the large winter flows.

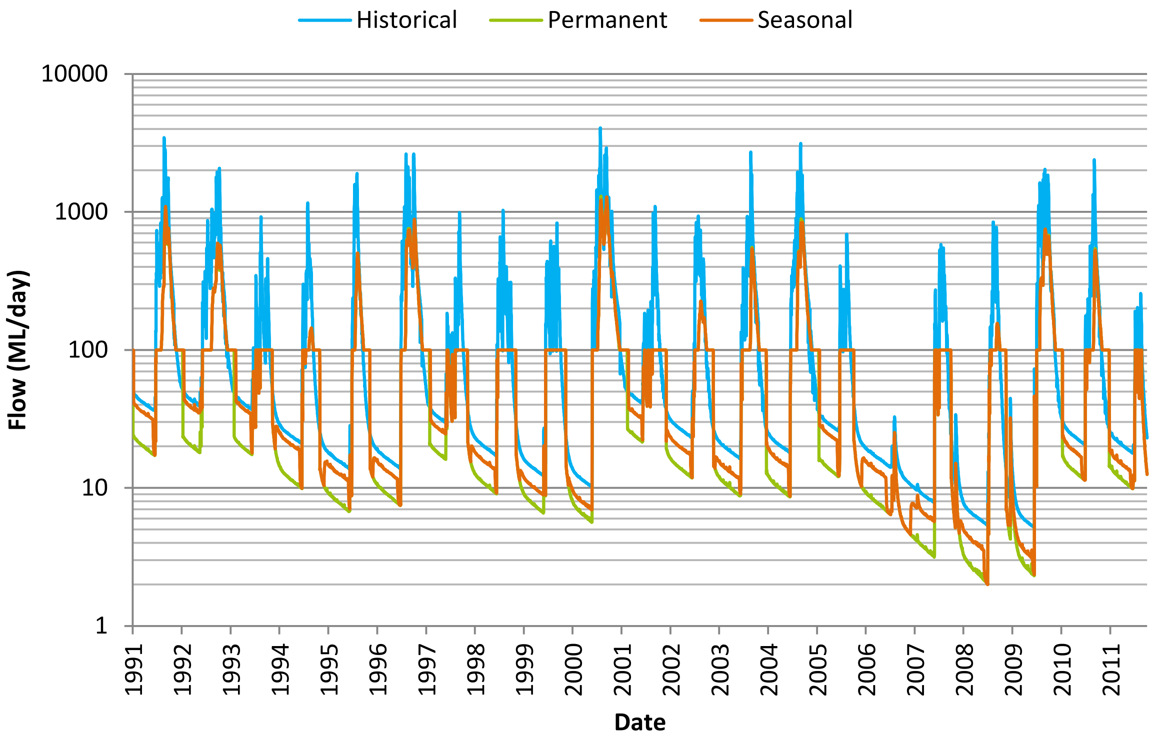


Figure 100. Simulated Flows downstream of Lake Hawdon North historically (green line) with and without upstream diversions (both seasonal and permanent) and a regulator.

Divertible Volumes to Proposed Drain Alignment

Based on the above results, no minimum flow rate has been used to estimate the volume that is expected be able to be diverted from the two upstream catchments to the north toward the CSL. The maximum diversion threshold of 250ML/day permanently (all year) has also been considered, where any flow above this is assumed to spill downstream toward Lake Hawdon North. Using these diversion rules, the divertible volumes at both diversion points have been estimated.

The annual volumes expected based on modelled flows at the diversion points (intersection of the proposed alignment and SEWCDB drains in Figure 39) are presented in Figure 101. The same annual volumes are presented as an exceedance curve in Figure 102. Annual volumes have been calculated based on the water year starting in May, and as such “1971” in Figure 101 corresponds to the period 01/05/1971 to 30/04/1972. On average, the divertible volume from the Wilmot drain diversion point was found to be 9.1 GL/year, and 7.9 GL/year from Drain K diversion point. Median divertible volumes, seen at the 50th percentile in Figure 102, were 7.5 GL/year and 6.4 GL/year from the Wilmot and Drain K catchments, respectively.

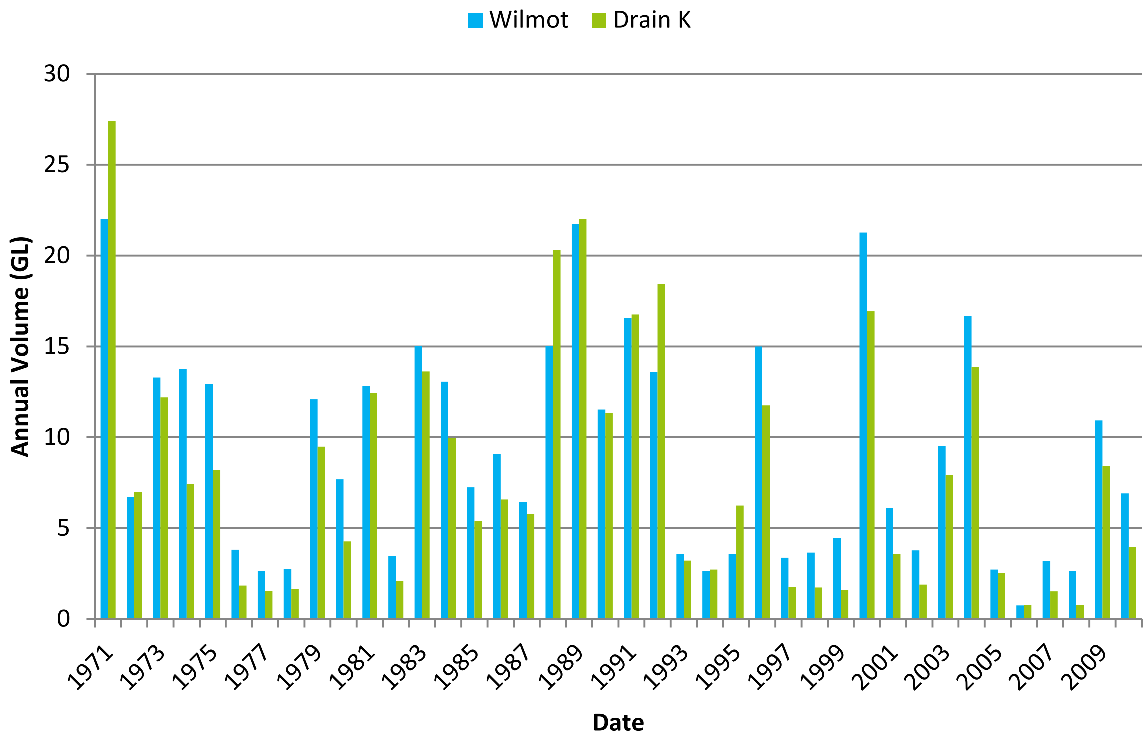


Figure 101. Annual divertible volumes at diversion points on Drain K and Wilmot Drain.

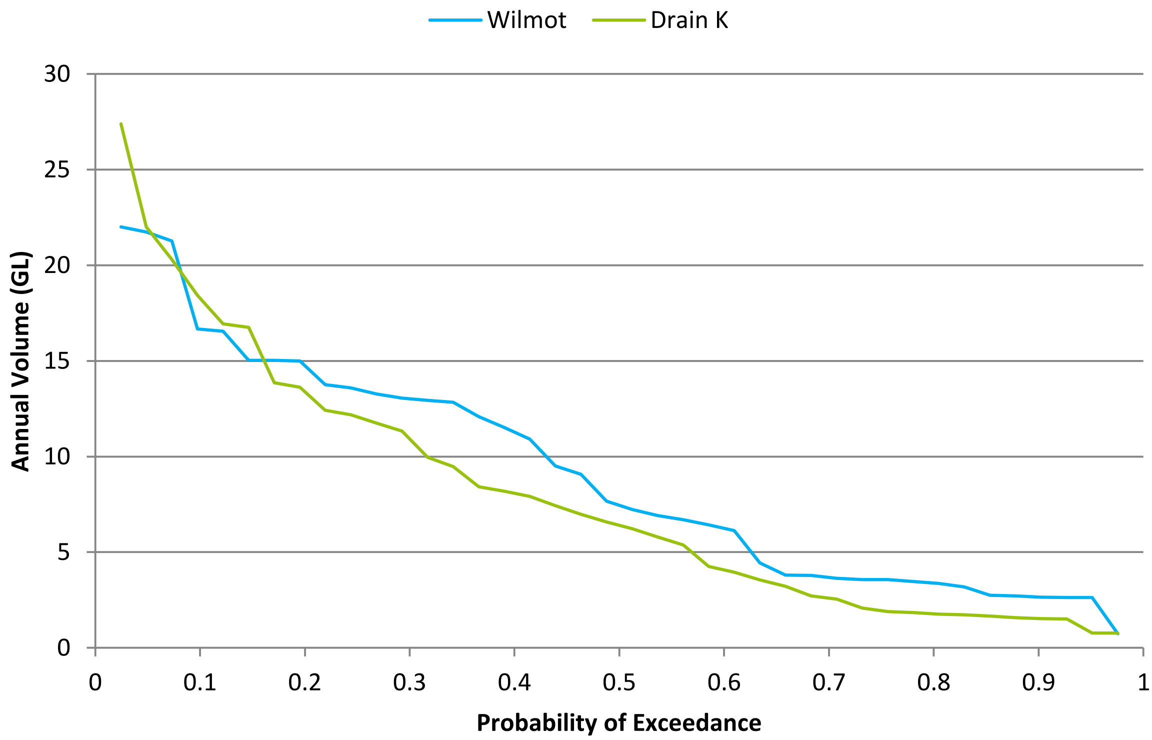


Figure 102. Probability of exceeding a given annual volume to divert from the Wilmot and Drain K catchments.

To check the results presented above, the flows recorded at Drain K and Wilmot Drain have been scaled by the area contributing to the diversion point to estimate the divertible volumes. This fraction was estimated to be 79% and 68% for Drain K and Wilmot Drain, respectively. After scaling the daily recorded flows by this amount, and then applying a maximum daily diversion rate of 250 ML/day at each location, the average annual divertible volume for Drain K over the period 1972 to 2011 was 9.0 GL/year, and for Wilmot Drain 8.7 GL/year over the period 1974 to 1988 and 2000 to 2011 (the gauge was closed for the period in between, Figure 79). Median values are 7.2 GL/year for Drain K, and 7.3 GL/year for Wilmot Drain, respectively.

These values correspond closely with those derived from the rainfall – runoff modelling, with the Wilmot Drain average and median numbers within 5% of those values derived from the recorded data, and the Drain K values all within 14% of each other. It is expected that the larger difference in the Drain K values is due to the high water holding capacity of the soil and high water use land uses in these catchments (used in the calibration of the model), which are not taken into account when simply scaling the observed flow by contributing areas.

The seasonal divertible volume has also been calculated, as not diverting flow over the period December to May (inclusive) would be expected to reduce the volume available to be diverted. Annual volumes represented as a time series and exceedance curve are shown in Figure 103 and Figure 104, respectively, and for this case the average divertible volume is 8.3 GL/year and 7.0 GL/year from the Wilmot and Drain K catchments, respectively. The median flows, seen as the 50th percentile in Figure 104, are 6.7 and 5.7 GL/year from the Wilmot and Drain K catchments, respectively. As such, not diverting for the summer period 6 months of the year is expected to reduce the total divertible volume by approximately 10%, or around 800 ML, at both diversion points.

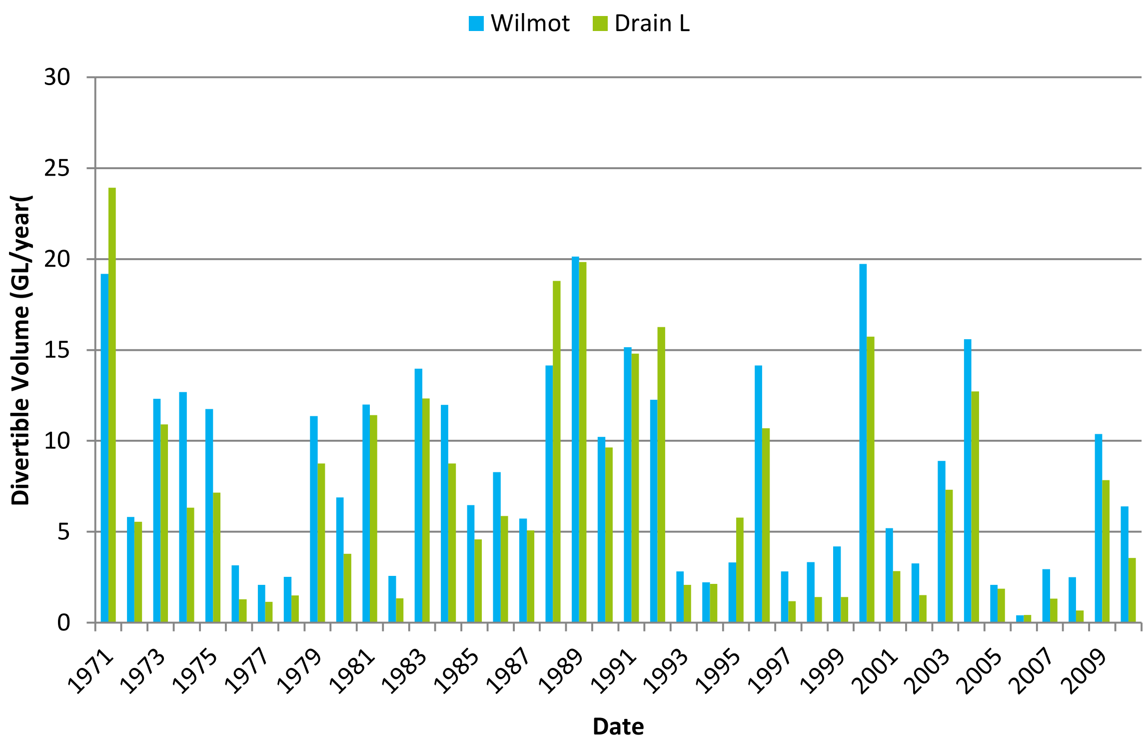


Figure 103. Annual divertible volume from a seasonal period only.

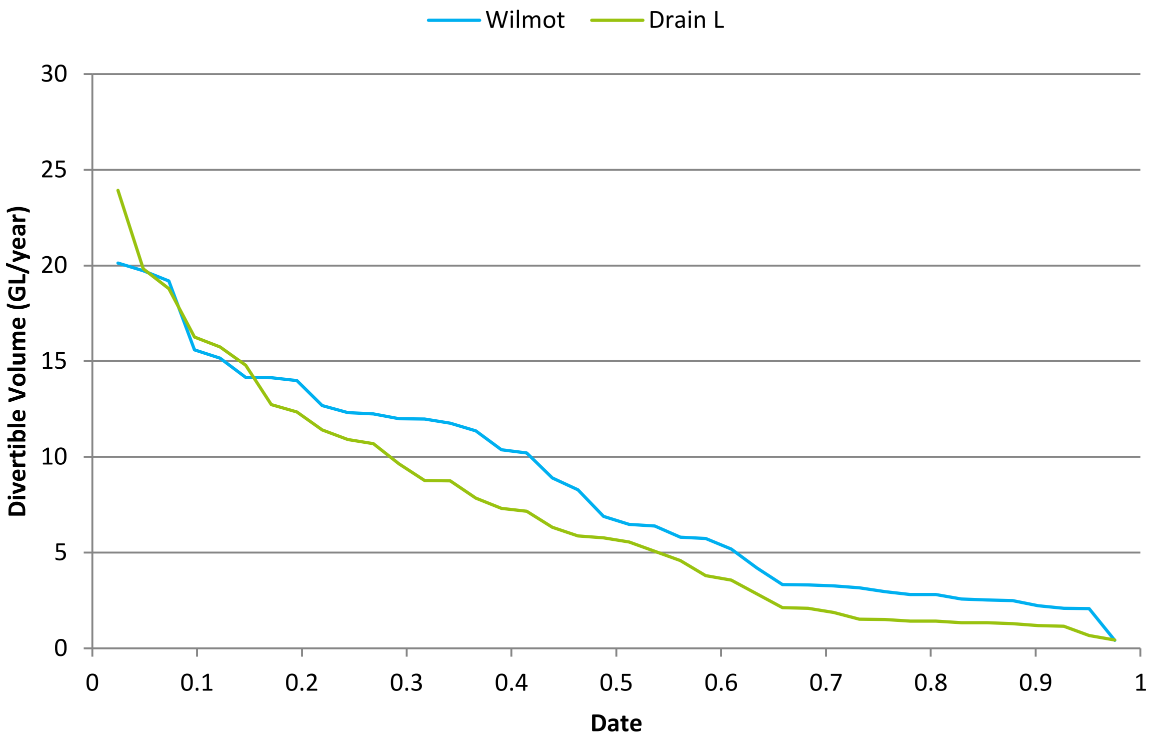


Figure 104. Probability of exceeding seasonable divertible volumes.

Regulator Low Flow Pass Sensitivity

The requirement for a 100 ML/day culvert under the regulator proposed for the outlet of Lake Hawdon North was identified through hydrodynamic modelling of the Robe Lakes to maintain salinity and water levels (see Chapter 5). The Drain L inflows used in the hydrodynamic model of Robe Lakes was produced by processing the flow record at Boomaroo Park downstream of Lake Hawdon North, and therefore does not directly represent diversions occurring at the upstream locations on the Blackford alignment. Therefore, there is some uncertainty in the 100 ML/day flow rate identified, and a sensitivity analysis has been undertaken to investigate the impact of lower flow rate under the Lake Hawdon North regulator (the 100 ML/day identified was assumed to be an upper limit). Both permanent and seasonal upstream diversion rules have been considered, along with a range of culvert flow rates.

Permanent Diversions

The effect of the size of a culvert, represented as a constant flow rate under the regulator, on water level in Lake Hawdon North can be seen in Figure 105, and downstream flows in Figure 106. The maximum water level in Lake Hawdon North can be seen to increase as the culvert flow rate decreases, but this difference is generally only 10-15 cm when compared the 20 to 100 ML/day cases, and only in the region of interest, for example increasing the water level from 4.2 or 4.3 m to the desired 4.4 m in the EIH. For the wet years when the wetland fills above the 4.3 m level and the regulator spills, the different culvert flow rates resulted in little difference in water levels. As outlined above, the frequency of meeting the EIH historically is already matched with a 100 ML/day culvert, and as such it may not be desirable to increase this frequency by reducing the size of the culvert (for example adding successful events in 1999, 2002 and 2009).

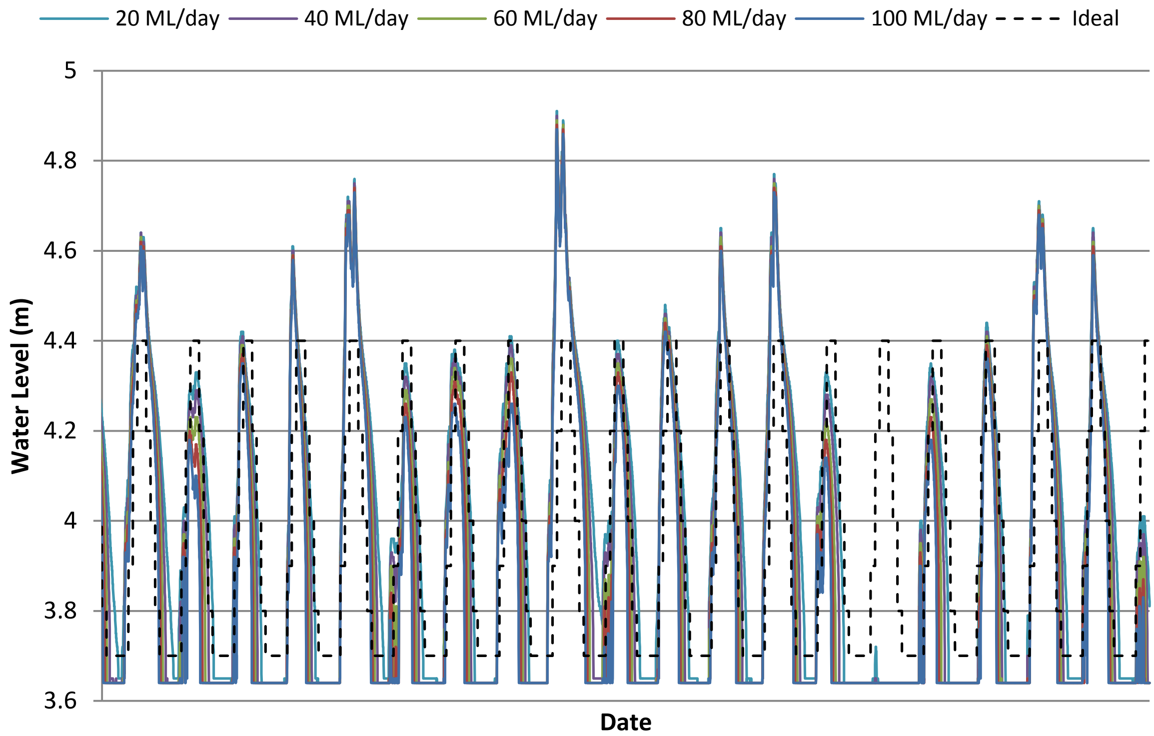


Figure 105. Impact of culvert flow rate and permanent diversions on Lake Hawdon North water levels.

The flows downstream of the regulator resulting from the different culvert sizes can be seen in Figure 106. The peak flows for the lower flow culverts are higher than the peak flow for a higher flow culvert for the same day, and as such they are all very similar, as opposed to being hidden by the blue line in the foreground in Figure 106. The impact of the culvert and upstream diversion can be seen, with the constant flow at the relevant flow rate for much of the winter season, with some larger flow events when spilling over the regulator is expected to occur. The duration of flow at the rate of flow of the culvert can also be seen to extend as the flow rate reduces, as the same volume in the lake is released over a longer period of time.

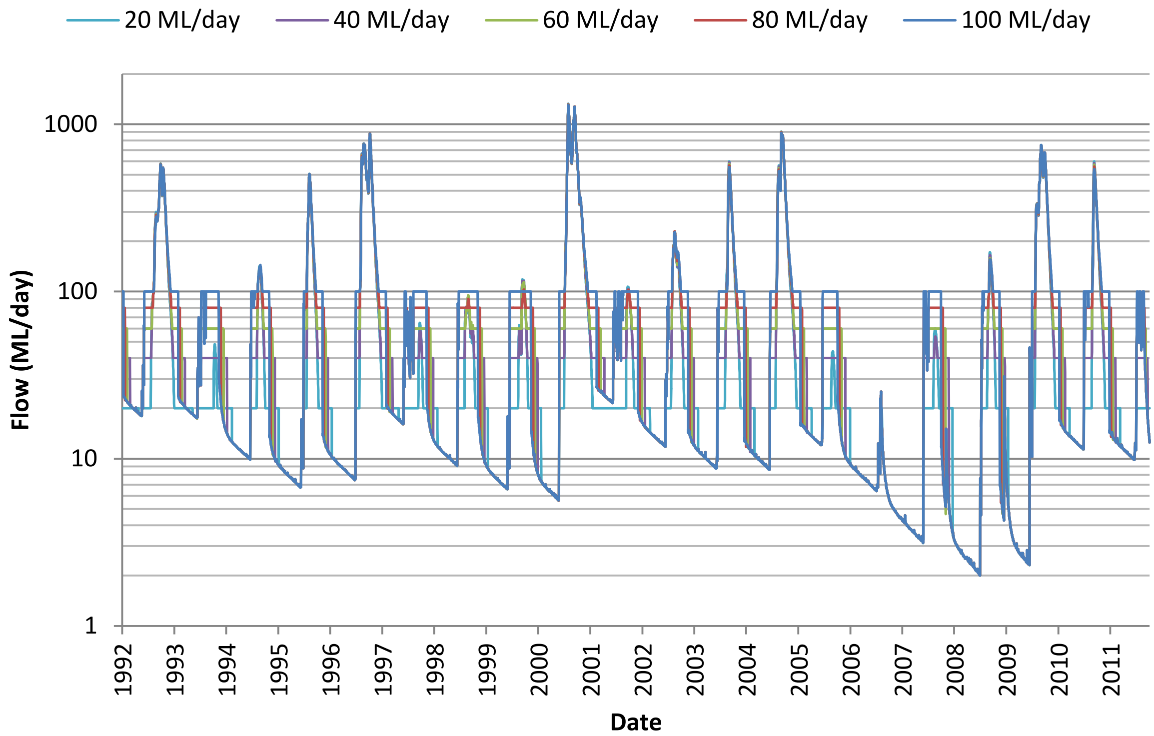


Figure 106. Impact of culvert flow rate and permanent diversions on flows downstream of Lake Hawdon North.

It is difficult to interpret the detail in Figure 105 and Figure 106 over the 20 year period shown. To allow the impact of the different culvert flow rates on the simulated water levels and flow rates to be seen in more detail, a one year period of water levels is presented in Figure 107, and flows in Figure 108. The year 1999 was selected, as from Figure 105 it can be seen that that reducing the size of the culvert results in the simulated water level approaching closer to the EIH. As would be expected, for larger culvert size the water level goes down quicker, and also the water level does not reach the higher maximum water level over the year compared to the lower flow culverts. The 20 ML/day culvert can be seen to provide a very close drawdown rate to the EIH, however this will also be a function of the inflows to both Lake Hawdon North and South, and as such is not a general result.

The flows for the five culvert scenarios for the 1999 water year can be seen in Figure 108. The regulator can be seen to start operating in June, with the specified culvert flow rate commencing, and then the flow dropping to be equal to the inflow to Drain L over the summer period, with the timing of this later in the year for the lower culvert sizes at the regulator holds the same volume of water for longer. The regulator is spilling when the water level is above the regulator height of 4.3 m in Figure 107, and can be seen to correspond to flows greater than the specified culvert flow rate in Figure 108. It can be seen from Figure 108 that a peak flow of over 100ML/day is achieved in 1999 for all scenarios considered, but only for around one month for the low flow culvert scenarios, compared to around 5 months with the 100 ML/day culvert.

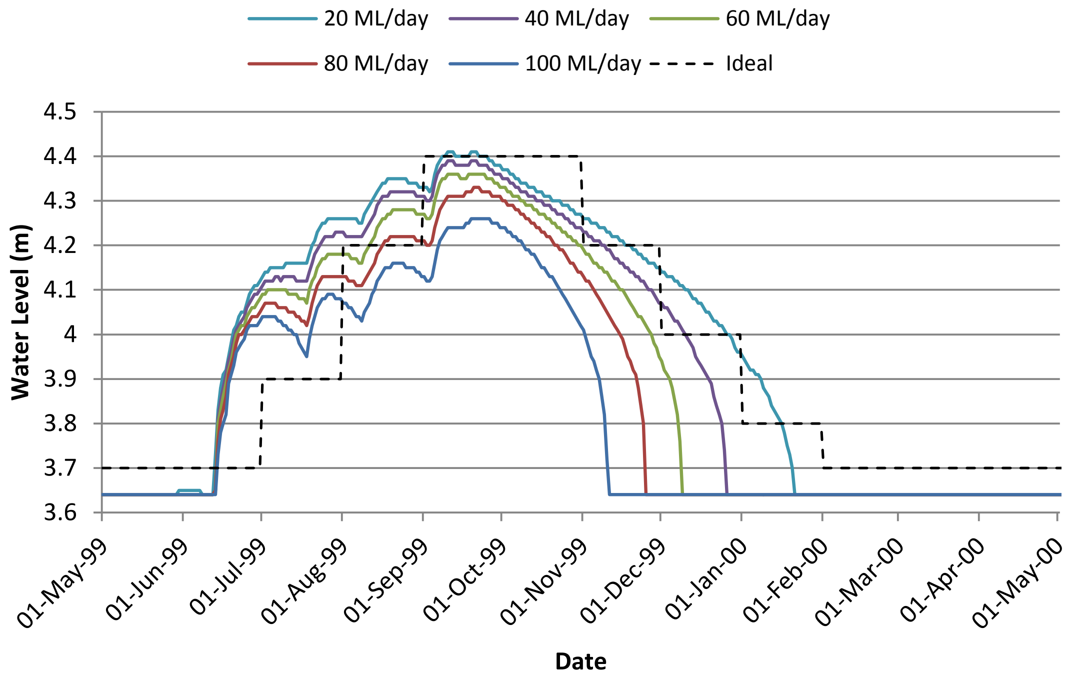


Figure 107. Impact of culvert flow rate and permanent diversions on Lake Hawdon North water levels for the year 1999.

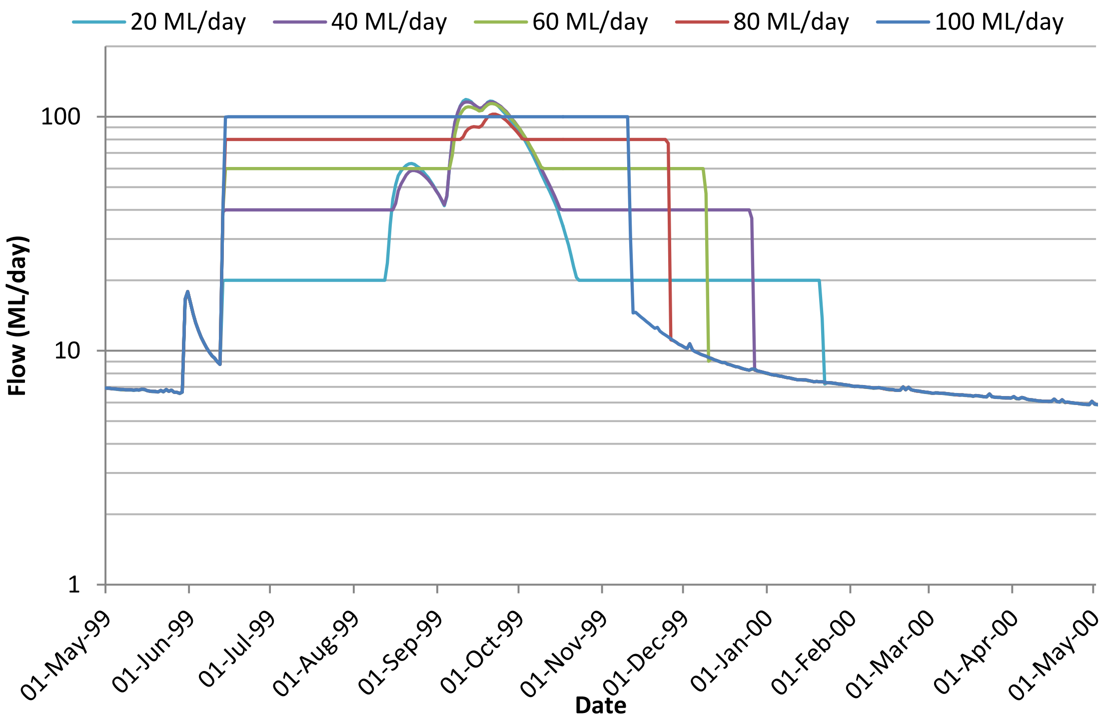


Figure 108. Impact of culvert flow rate and permanent diversions on flows downstream of Lake Hawdon North for the year 1999.

Seasonal Diversions

The same sensitivity analysis on culvert size has been undertaken for the case with seasonal diversions only at the upstream diversion points. The water levels can be seen in Figure 109, with the flow rates in Figure 110. With seasonal diversions, in some years the summer low flow is greater than 20 ML/day (e.g. 1992, 1993, 1994, 2002) and as such the water level is maintained slightly higher in Lake Hawdon North, however this is lower than the 3.9 m level where Drain L is simulated to spill out to the lake. The increase in the summer baseflows can again be seen by allowing these flows to remain in the system through seasonal diversions, with the flow only dropping to below 10 ML/day on a few occasions in Figure 110, compared to the case with permanent diversions in Figure 106. However, the peak flow scan also been slightly higher for this case, for example the regulator spilling in 1997, 1998 and 1999 in Figure 110, where this did not occur for the permanent diversion case in Figure 106.

To show the detail on the impact of the different culvert size on the simulated water levels and flows, again the water year of 1999 is presented for the seasonal only diversion case in Figure 111 and Figure 112, respectively. The seasonal diversions can be seen to extend the period that the regulator holds water in the lake, but only by around two weeks, looking at the time when the lake returns to the 3.64 m elevation (empty) for each of the culvert sizes considered. While the summer baseflows can be seen to be higher, as expected due to diversions no longer occurring over this period, the winter peak flows are also higher in Figure 112 compared to Figure 108. This is expected to be due to the extra volume flowing into the system where the flows at the start of the period can be seen to be higher, a well as the small peak in flow around the start of June is also higher due to the summer baseflows remaining in the system.

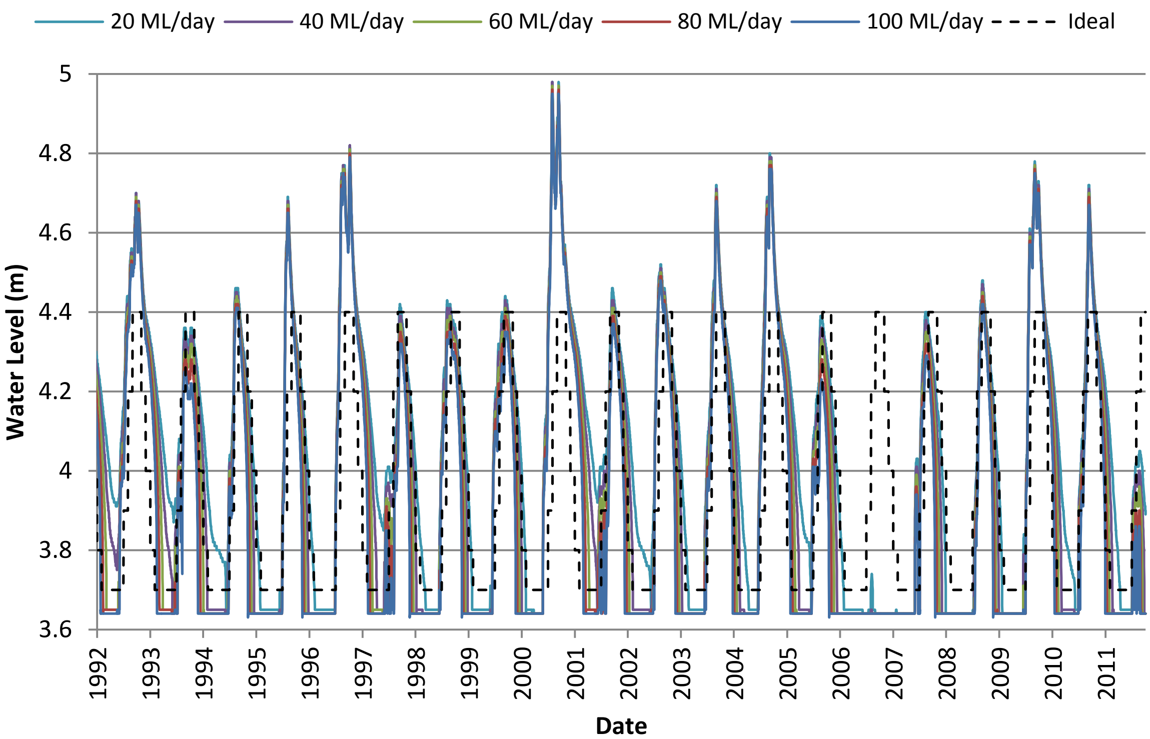


Figure 109. Impact of culvert flow rate and seasonal diversions on Lake Hawdon North water levels.

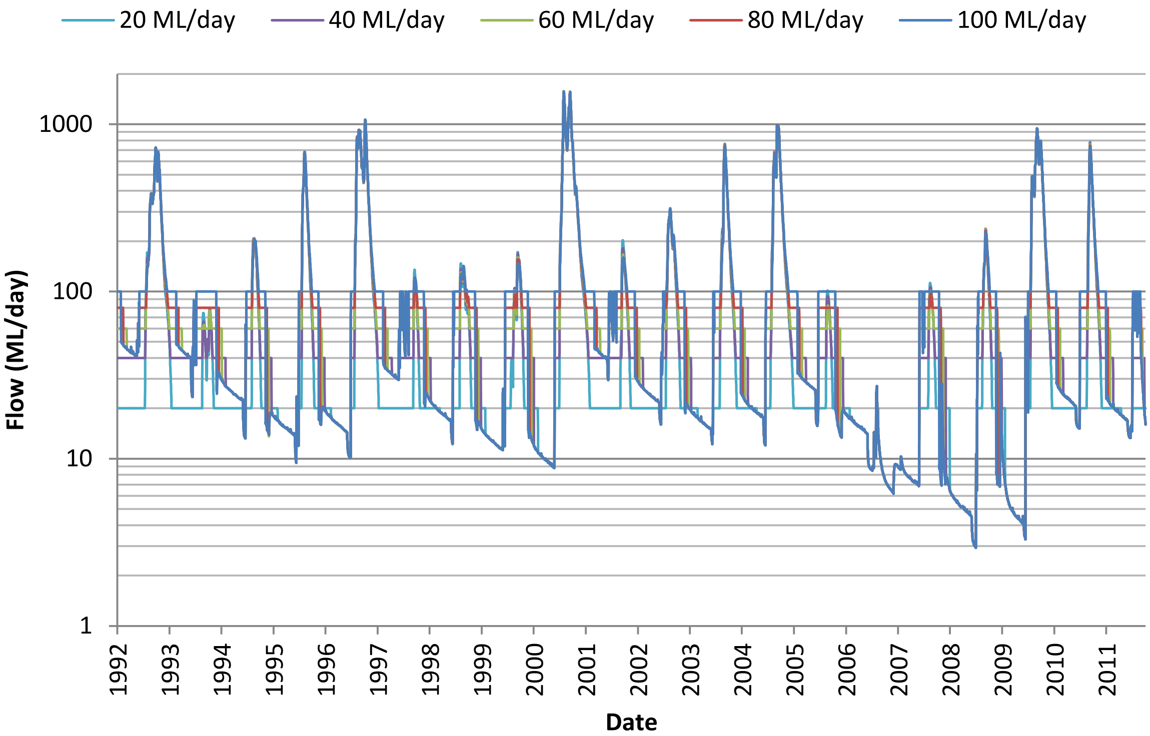


Figure 110. Impact of culvert flow rate and seasonal diversions on flows downstream of Lake Hawdon North.

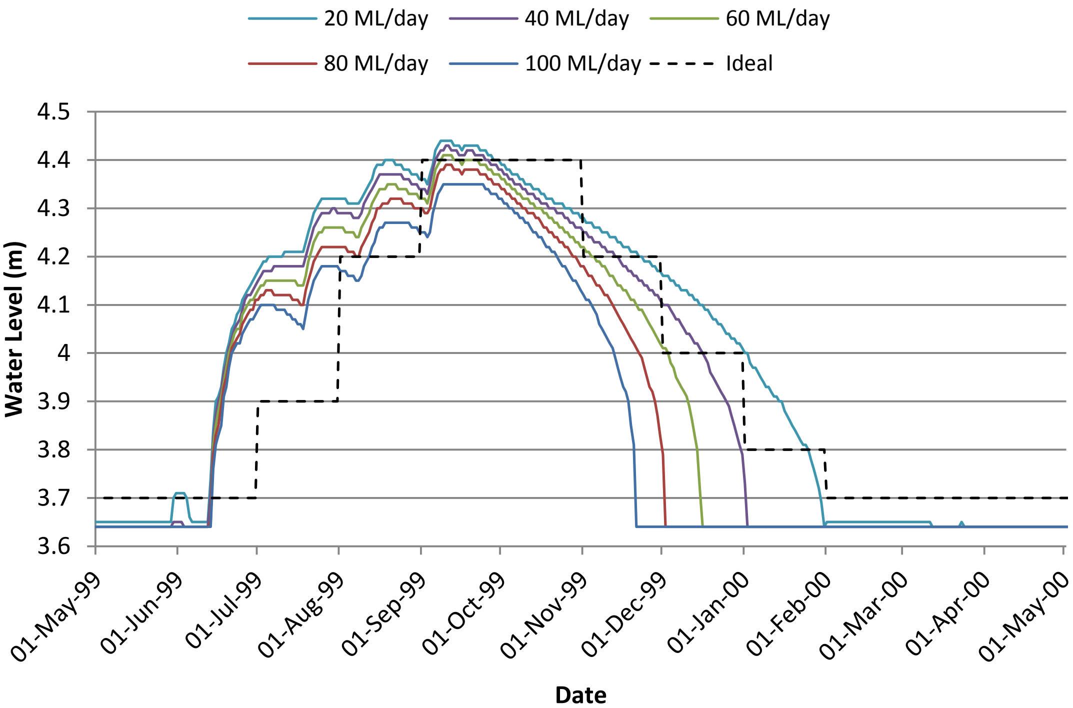


Figure 111. Impact of culvert flow rate and seasonal diversions on Lake Hawdon North water levels for the year 1999.

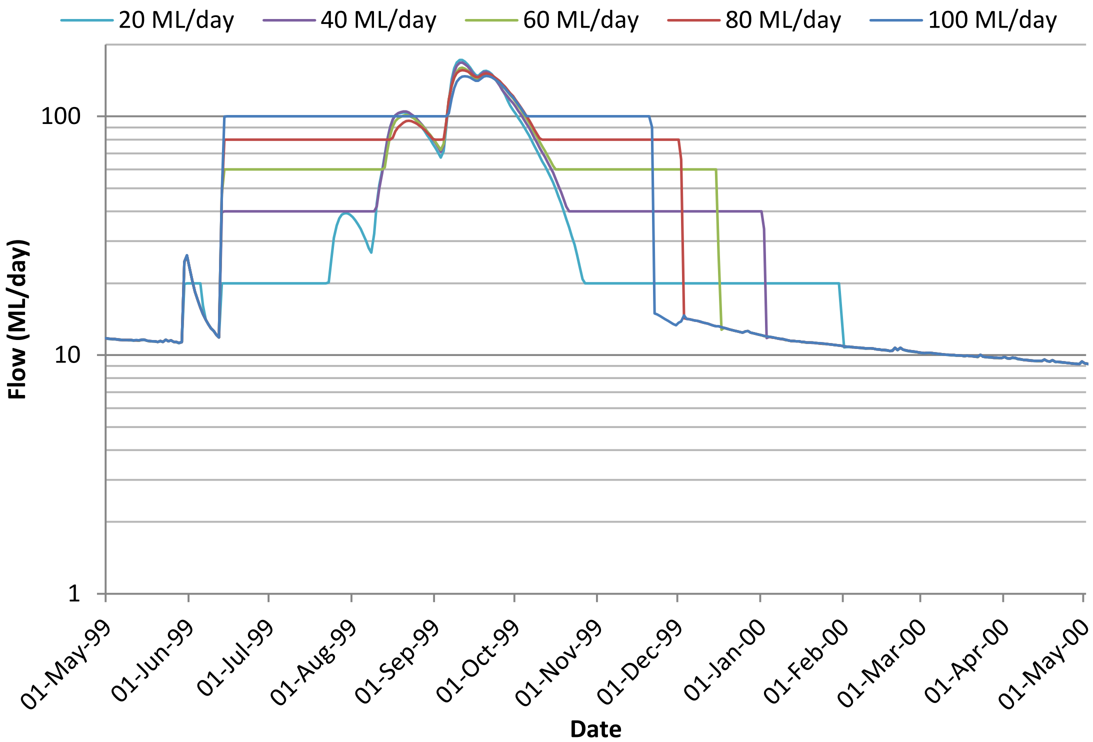


Figure 112. Impact of culvert flow rate and seasonal diversions on flows downstream of Lake Hawdon North for the year 1999.

5.9 Discussion and Key Messages

The main purpose for this work has been to increase the confidence in the SEFRP diversion rules on Drain K and Wilmot Drain, with the object to maximise the volume diverted while maintaining the downstream EWRs of Lake Hawdon and the Robe Lakes. The maximum diversion rate has been previously optimised based on the yield to the Coorong South Lagoon (CSL), and has been adopted in this work. There were a number of questions that remained to be answered by this modelling study:

- What is the minimum flow rate that should pass the diversion points before diversions to the CSL occur?
- Should the summer low flows remain in the system to maintain the downstream ecosystems?
- What flow rate past a regulator on Drain L at the outlet of Lake Hawdon North is feasible to still meet the EIH of Lake Hawdon North?

Given these considerations, what is the volume that can be expected to be diverted toward the CSL?

Minimum Flow Rate Before Diversions Occur

The modelling results presented suggest that a minimum flow to pass downstream before diversions occur is not necessary to meet the downstream EWRs. This is expected to be due to the large downstream catchment (1087 km^2) that will continue to generate flow toward Lake Hawdon North and South, irrespective of diversions. This area is expected to be sufficient to provide the lower flow requirements of Lake Hawdon North that were targeted by the minimum diversion threshold in previous SEFRP studies. While these low flows bypassing the diversion points are not expected to be required to maintain the EWRs of Lake Hawdon and Robe Lakes, the drain immediately downstream of the diversion point has not been considered in this work. As such, it may be desirable to maintain a small flow in the drain to support local habitats. A small flow such as this is not expected to alter the yield at the diversion points significantly, and is likely to be within the accuracy of the models.

Suitable Period for Diversions

The impact of seasonal only diversions (June to November inclusive) was compared to the diversion scenario where the catchments upstream of the diversion points were completely cut off from the downstream environment, apart from flows over 250 ML/day spilling downstream. The two approaches were not expected to result in large differences in water level in Lake Hawdon North, however the water level did recede slower in some years due to these low flows persisting through the system over the drier months. The difference in the two diversion scenarios was more apparent on the flows simulated downstream of the regulator, with the average flow between January and May 40% less than the historical case with permanent diversions upstream, but only 8% less than the historical case when seasonal diversions are in place.

In summary, seasonal diversions are expected to result in little difference in the water levels in Lake Hawdon North compared to permanent diversions, due to the smaller volumes over the dry period compared to the large winter flows. However, as might be expected, the summer low flows are largely maintained by not diverting these flows upstream. Further analysis of the hydrodynamic modelling undertaken for Robe Lakes may be necessary to determine if an average reduction of 40% in the summer baseflows is acceptable, or if it is necessary to maintain these low flows over the summer period. However, this question may be best managed in an adaptive approach, where low flows can be maintained in the catchment if the water quality conditions in Robe Lakes require all available flows in dry years, and in wetter years it is likely that all flows can be diverted at the two upstream diversion points. There may also be an advantage in adopting a permanent diversion scenario in that it may help protect the downstream environment of Lake Hawdon and Robe Lakes from pest or invasive species that may invade from outside the Drain L catchment. However, this advantage may be negated by overtopping of the diversion points, effectively reconnecting the downstream environment.

Low Flow Passed Drain L Regulator

The requirement for a 100 ML/day culvert under the regulator proposed for the outlet of Lake Hawdon North was identified through hydrodynamic modelling of the Robe Lakes to maintain salinity and water levels (see Chapter 5). A sensitivity analysis has been undertaken to investigate the impact of lower flow rate under the regulator on Drain L on the ability to meet the EIH at Lake Hawdon North. The modelling suggests that the same frequency of meeting the EIH historically is also met in the extreme case of permanent diversions upstream and a 100 ML/day culvert under the regulator on Drain L, and as such it may not be desirable to further increase this frequency of meeting the EIH with a lower culvert flow rate. Increases in water level of around 10 – 15 cm were simulated in some years, which may be significant when attempting to meet the EIH, for example an analysis of the year 1999 showed that a lower culvert flow rate (20 ML/day) resulted in the EIH being met, which was not the case for higher culvert flow rates. As with the minimum flow rate at the upstream diversion points, the culvert flow rate at the regulator on Drain L downstream of Lake Hawdon North may be best managed in an adaptive process, where a sluice gate type setup with a capacity of up to 100 ML/day will provide the flexibility to deliver the expected flows necessary to maintain water quality in Robe Lakes, but also potentially reduce the flow rate to extend the period of inundation and more closely match the EIH for Lake Hawdon North in some years.

Expected Divertible Yield

Based on the above findings, the average divertible volume from the Wilmot Drain diversion point was found to be 9.1 GL/year, and 7.9 GL/year from Drain K diversion point. Median divertible volumes were found to be 7.5 GL/year and 6.4 GL/year from the Wilmot and Drain K catchments, respectively. Seasonal only diversions were found to reduce the average and median divertible volumes by approximately 10%, or 800 ML. The volumes presented here are at the diversion points, and further analysis would be required to estimate how this volume translates into a volume at the CSL, after incorporating losses en route.

These volumes for the new proposed alignment (Blackford) are comparable to those reported in Montezari et al. (2011) for the previous alignment considered (Reedy Creek) in Table 31. It is understood that AWE (2011) did not change the volume estimates from Montezari et al. (2011), and this more recent work (e.g Montezari et al., 2011) provides more robust estimate of the divertible volume compared to AWE (2009a), as outlined in AWE (2011). It should be noted that the volumes presented in Table 31 for the Reedy Creek alignment are currently being revised by AWE.

Table 31. Comparison between estimated yields for different SEFRP alignments.

	Average Volume			**Median Volume**		
	Reedy Creek (GL)	Blackford (GL)	Change (%)	Reedy Creek (GL)	Blackford (GL)	Change (%)
Drain K	10.8	7.9	27	10.4	6.4	38
Wilmot	11.2	9.1	19	11.7	7.5	36

The estimated yield from the Blackford alignment considered in this work would be expected to be smaller than previous studies, due to the smaller catchment area upstream of the diversion points. This reduction in area was 79% of the original Reedy Creek alignment diversion point catchment area for Drain K, and 68% for Wilmot Drain. The reduction in flow can be seen to be comparable to this reduction in area, however the yield from the Wilmot Drain catchment is higher than might be expected based on a simple area proportioning alone. This is likely to be due to the maximum diversion rate of 250 ML/day, and in most years this flow may be reached even at the diversion point further upstream, and the difference in yield between the two diversion point locations may become greater if this maximum diversion rate was increased. The results for the yield expected from the two drain alignments presented in Table 16 are not directly comparable, as different modelling packages were used to produce the results, as well as different diversion rules for the minimum diversion threshold. This difference may be the cause for the larger decline in the median volumes compared to the average.

Due to limited further information, the calibrated value for the hydraulic conductivity of 0.014m/day to represent SW-GW interactions has been adopted for all drains modelled in the Lake Hawdon catchments. It is acknowledged that this conductivity is likely to be a function of the local soil type, where a higher conductivity would be expected for sand compared to clay, for example. Given that the transmission loss calculated is directly proportional to the value adopted for the hydraulic conductivity, the uncertainty in this value is likely to have a large bearing on any losses calculated. For example, observed values of hydraulic conductivity are often estimated to within one to three orders of magnitude.

However, it is also likely that a clogging layer has developed in existing drains, which would be expected to reduce the conductivity when compared to the surrounding soil. As such, this calibrated value for the hydraulic conductivity has been used to represent an existing drain with an established clogging layer, and further work should consider the variations expected due to local soil properties, as well as recalibrating the value adopted as further data become available.

The design of the regulator structure in Lake Hawdon North should be further investigated if this project is to be implemented. The spill over the regulator has been calculated using a simple flow over broad-crested weir relationship, and these assumptions should be reassessed at the design stage. Also the culvert under the regulator has been assumed to operate at a constant flow rate, however in practice this rate will be dependant of the head of water behind the regulator driving the flow, and as such is likely to reduce as the water level reduces, which has not been considered in this work. For the water balance undertaken in this work these considerations are unlikely to change the outcomes from the results, as the total volume after diversions has been found to be sufficient to maintain the downstream EWRs, and it is only the timing of the drawdown and filling rates, and resulting downstream flows that will be refined by these design considerations. Another design consideration may be considered is the size and location of the cut outs in the sill along Drain L in Lake Hawdon North, which may be able to be modified to alter the filling and drawdown rates in the lake to more closely match the EIH.

5.10 Conclusion

Drain L, including Wilmot Drain and Drain K, are two of the most reliable drains that still flow out to the ocean in the South East of South Australia. As such, a number of studies have previously assessed the feasibility of diverting some of this flow to support the EWRs of ecosystems to the north of these drains, including the Coorong South Lagoon. However, there are also water bodies that have their own EWRs at the terminus of these drains, that should be maintained before any diversions of surplus flows occur. This project has expanded on these previous studies to explicitly consider the downstream EWRs and provide more confidence in the sustainable diversion rules, and ultimately expected yield, from the Wilmot and Drain K systems.

The downstream EWRs considered was the EIH for Lake Hawdon North, which was also assumed to maintain the EWRs of Lake Hawdon South, as well as supplying a minimum flow to Robe Lakes at the terminus of Drain L to maintain salinity and water level targets. Two models were developed to allow this to be assessed, one to simulate the inflows to the system to estimate the flows available, and a second model to represent the water balance in the lakes to simulate water levels. A regulator on Drain L at the outlet of Lake Hawdon North was considered to maintain water levels. This regulator is expected to be required to maintain water levels in the lake at similar frequencies to that occurred historically but with less water.

The maximum divertible flow of 250 ML/day at each of the diversion points on Wilmot Drain and Drain K identified in previous studies has also been adopted in this work. These previous studies have considered minimum flow rates to continue downstream before diversions occur to meet the downstream EWRs, which have been reassessed in this work. The modelling results presented here indicate that this minimum flow rate requirement is not necessary to meet the downstream EWRs. This result is expected to be due to the catchment area of 1087 km2 downstream of the diversion points that will continue to flow unimpeded toward Lake Hawdon North and South and is sufficient to provide the lower flow requirements of Lake Hawdon North that were targeted by the minimum diversion threshold in previous SEFRP studies.

Seasonal (June to November only) and permanent diversions were considered, where little difference was found on water levels in Lake Hawdon North for the different diversion scenarios, provided a regulator was in place at the outlet of Lake Hawdon North. The difference in the two diversion scenarios was more apparent on the flows simulated downstream of the regulator, with the average flow between January and May 40% less than the historical case with permanent diversions upstream, but only 8% less than the historical case when seasonal diversions are in place.

A culvert under the regulator at the outlet of Lake Hawdon North was considered necessary to provide flows to Robe Lakes, as well as allow for fish migration in Lake Hawdon North. The modelling suggests that the frequency of meeting the EIH in Lake Hawdon North in the extreme case of permanent diversions upstream and a 100 ML/day culvert under the regulator on Drain L is the same as the historic frequency (no diversion and no regulator). Reducing the flow rate through the culvert lead to increases in water level of around 10 – 15 cm in some years, which may be significant when attempting to meet the EIH. For example, an analysis of the year 1999 showed that a lower culvert flow rate (20 ML/day) resulted in the EIH being met, which was not the case for higher culvert flow rates.

Based on the above findings, the average divertible volume from the Wilmot Drain diversion point was found to be 9.1 GL/year, and 7.9 GL/year from Drain K diversion point. Median divertible volumes were found to be 7.5 GL/year and 6.4 GL/year from the Wilmot and Drain K catchments, respectively. Considering seasonal only diversions was found to reduce the average and median divertible volumes by approximately 10%, or 800 ML. Compared to previous SEFRP studies that considered diversion points further downstream (Montazeri et al., 2011), these annual average flows are 27% lower for Drain K, and 19% lower for Wilmot Drain.

Based on the modelling presented in this report, the most extreme case considered is expected to meet the specified EIH at the same frequency as occurred historically, without diversions or a regulator. However, the system is likely to be best managed in an adaptive way, with the ability to reduce the flow bypassing the Lake Hawdon North regulator when it is desirable to maintain the water level in Lake Hawdon North for longer periods of time (for example, after a number of sequential dry years), as well as allow summer baseflows to persist in the system from the upstream diversion points when these flows may to be desirable to reduce the salinity in Robe Lakes.

5.11 Appendix 1: Sub Catchment Functional Units

Sub-catchment	Functional Unit	Area (ha)	Area Percentage (%)
SC-0	WHH-LUH	7045.53	49.00%
	WHH-LUL	5929.75	41.24%
	WHL-LUH	655.67	4.56%
	WHL-LUL	746.25	5.19%
SC-1	WHH-LUH	3507.81	51.99%
	WHH-LUL	3217.01	47.68%
	WHL-LUH	18.89	0.28%
	WHL-LUL	3.37	0.05%
SC-2	WHH-LUH	745.91	27.44%
	WHH-LUL	1138.71	41.89%
	WHL-LUH	169.35	6.23%
	WHL-LUL	664.36	24.44%
SC-12	WHH-LUH	1558.9	18.29%
	WHH-LUL	2717.2	31.88%
	WHL-LUH	1620.26	19.01%
	WHL-LUL	2625.15	30.8%
SC-13	WHH-LUH	4624.33	24.61%
	WHH-LUL	5678.35	30.22%
	WHL-LUH	2450.22	13.04%
	WHL-LUL	6033.49	32.11%
SC-5	WHH-LUH	2767.11	10.05%
	WHH-LUL	10385.62	37.72%
	WHL-LUH	2915.79	10.59%
	WHL-LUL	11464.94	41.64%
SC-15	WHH-LUH	2445.75	25.77%
	WHH-LUL	2520.73	26.56%
	WHL-LUH	1646.63	17.35%
	WHL-LUL	2874.73	30.29%
SC-16	WHH-LUH	1888.35	14.81%
	WHH-LUL	5459.77	42.82%
	WHL-LUH	1289.08	10.11%
	WHL-LUL	4112.04	32.25%
SC-3	WHH-LUH	963.72	34.58%
	WHH-LUL	909.37	32.63%
	WHL-LUH	374.84	13.45%
	WHL-LUL	538.71	19.33%

Sub-catchment	Functional Unit	Area (ha)	Area Percentage (%)
SC-4	WHH-LUH	2572.57	15.70%
	WHH-LUL	3334.51	20.35%
	WHL-LUH	3916.2	23.90%
	WHL-LUL	6564.15	40.06%
SC-6	WHH-LUH	1268.87	11.06%
	WHH-LUL	1835.61	16.00%
	WHL-LUH	1494.88	13.03%
	WHL-LUL	6873.22	59.91%
SC-9	WHH-LUH	77.06	2.01%
	WHH-LUL	111.18	2.90%
	WHL-LUH	1503.62	39.22%
	WHL-LUL	2141.96	55.87%
SC-10	WHH-LUH	959.9	14.10%
	WHH-LUL	944.53	13.87%
	WHL-LUH	2487.43	36.53%
	WHL-LUL	2413.1	35.44%
SC-7	WHH-LUH	1452.65	24.27%
	WHH-LUL	885.84	14.80%
	WHL-LUH	1177.32	19.67%
	WHL-LUL	2469.57	41.26%
SC-11	WHH-LUH	1185.96	7.48%
	WHH-LUL	3925.73	24.76%
	WHL-LUH	2295.82	14.48%
	WHL-LUL	8447.61	53.28%
SC-8	WHH-LUH	156.08	7.48%
	WHH-LUL	516.64	24.76%
	WHL-LUH	302.14	14.48%
	WHL-LUL	1111.73	53.28%

*WHH-LUH →WaterHoldingHigh-LandUseHigh

*WHH-LUL→ WaterHoldingHigh-LandUseLow

*WHL-LUH→ WaterHoldingLow-LandUseHigh

*WHL-LUL→ WaterHoldingLow-LandUseLow

5.12 Appendix 2: Schematics of Rainfall – runoff models investigated

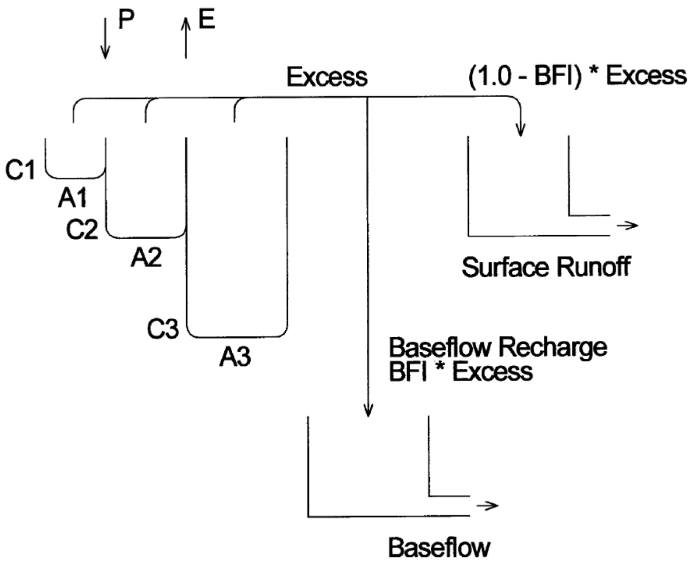


Figure 113. Schematic of the AWBM rainfall-runoff model (Boughton, 2004).

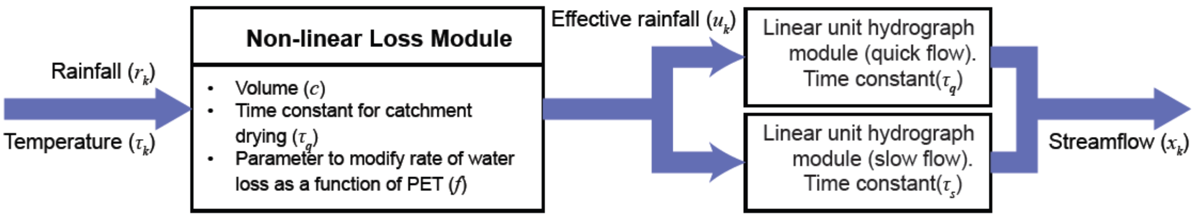


Figure 114. Schematic of the IHACRES rainfall-runoff model (Kelley and O'Brien, 2012).

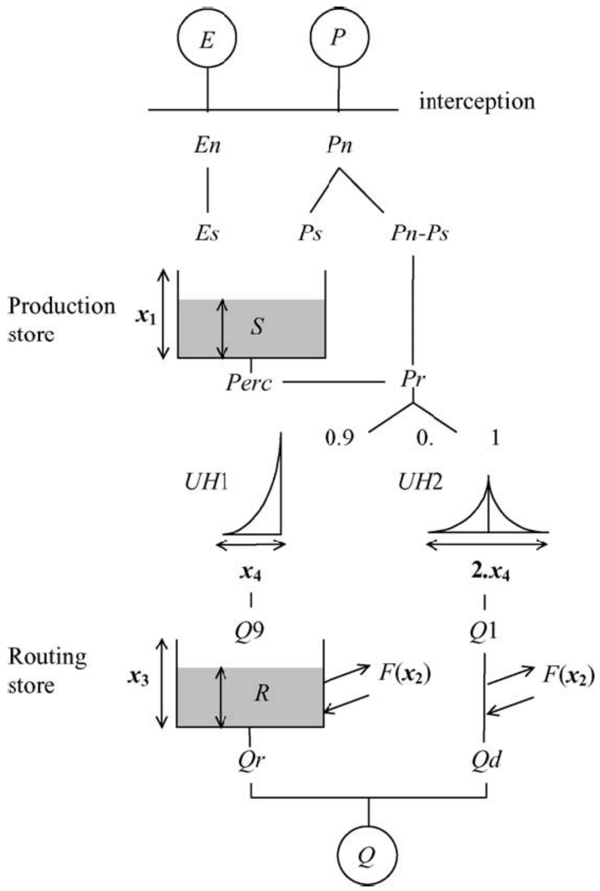


Figure 115. Schematic of the GR4J rainfall - runoff model (Perrin et al., 2003).

5.13 Appendix 3: Model Parameters Ranges

Table 32. AWBM initial, minimum, maximum and fixed parameter values.

Name	Description	Initial	Min	Max
A1	Area of the first surface store	0.134	0	0.3
A2	Area of the second surface store	0.433	0	0.6
BFI	Base flow Index	0.35	0	1
C1	Capacity of the first surface store (mm)	7	0	200
C2	Capacity of the second surface store (mm)	70	50	500
C3	Capacity of the third surface store (mm)	150	100	1000
KBase	Recession constant for the base flow store	0.95	0	1
KSurf	Recession constant for the surface store	0.35	0	1

Table 33. GR4J initial, minimum, maximum and fixed parameter values.

Name	Description	Initial	Min	Max
x1	Soil reservoir capacity (mm)	1	1	1500
x2	Groundwater exchange coefficient	0	-80	5
x3	Routing reservoir capacity (mm)	1	1	500
x4	Time base of unit hydrograph (days)	0.5	0.5	10

Table 34. IHACRES initial, minimum, maximum and fixed parameter values.

Name	Description	Initial	Min	Max
F	Temperature modulation factor	1	0	30
InverseC	Volume-forcing constant	10	10	14000
L	Moisture threshold for producing	100	0	5000
P	Power on Soil Moisture	1	0	10
Tq	Quick flow reservoir time constant	1	0	10
Tref	Reference Temperature	3.4	0	40
Ts	Slow flow reservoir time constant	5	5	1000
Tw	Catchment drying time constant	2	1	1000
Vs	Vs	0.5	0	1

5.14 Appendix 4: Optimised Parameter Values

Table 35. Optimised parameter set for AWBM obtained from calibration.

AWBM (Rosenbrock) E Bias = 0.82				
Parameter	WHHLUH	WHHLUL	WHLLUH	WHLLUL
A1	0.02	0.19	0.30	0.30
A2	0.57	0.17	0.01	0.60
BFI	1	0.01	0.08	0.47
C1	130.72	199.37	131.85	41.32
C2	324.28	247.82	499.48	148.72
C3	1000	790.04	1000	184.31
KBase	0.97	1	0.65	0.94
KSurf	1	0.73	0.65	0.97
Reach 1523	63138.87			
Reach 1528	337766.11			
Reach 1543	95618.05			
Reach 1591	129823.38			

Table 36. Optimised parameter set for GR4J obtained from calibration.

GR4J (SCE with Rosenbrock) NSE Bias = 0.8				
Parameter	WHHLUH	WHHLUL	WHLLUH	WHLLUL
x1	377.26	338.27	327.33	258.16
x2	-55.46	-6.22	-4.76	-1.45
x3	97.53	46.69	52.43	60.05
x4	7.1	2.3	4.92	0.91

Table 37. Optimised parameter set for IHECRAS obtained from calibration.

IHECRAS (Rosenbrock) NSE Bias = 0.45				
Parameter	WHHLUH	WHHLUL	WHLLUH	WHLLUL
F	0	22.80	1.11	29.99
InverseC	1786.09	1485.94	14000	419.08
L	283.91	3558.70	5563.6	257.09
p	4.29	3.54	0.03	0.85
Tq	0.39	0.9	10	1.69
Tref	40	5.23	26.85	1.53
Ts	573.77	520.32	24.78	402.54
Tw	220.11	995.66	965.09	521.02
Vs	0	0	1	0
Reach 1523	863889.31			
Reach 1528	863912.62			
Reach 1543	863225.43			
Reach 1591	266070.86			

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