Lake Innes hydrologic isolation study

Author:
Rayner, D. S.; Glamore, W. C.

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WRL Technical Report 2012/24
December 2012

by
D S Rayner and W C Glamore

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

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Client Address	PO Box 114 King Lake Vic
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Water Research Laboratory
110 King Street, Manly Vale, NSW, 2093, Australia
Tel: +61 (2) 8071 9800 Fax: +61 (2) 9949 4188
ABN: 57 195 873 179
www.wrl.unsw.edu.au
Quality System certified to AS/NZS ISO 9001:2008

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1. Introduction

Located on the mid-north coast of NSW approximately 8 km south of Port Macquarie, Lake Innes is a large coastal lake connected to Lake Cathie via Cathie Creek (Figure 1.1). The lake system is intermittently connected to the ocean providing tidal flushing of the waterway.

Lake Innes was historically the largest freshwater coastal lake in NSW providing important habitat for freshwater species. In 1933 Lake Innes was connected to Lake Cathie in an attempt to drain the surrounding land and expand local agriculture practices. The hydrological connection of the two lakes resulted in Lake Innes becoming a brackish system.

The Water Research Laboratory (WRL) at the University of New South Wales was commissioned to assess the potential of returning Lake Innes to its historical freshwater state. WRL developed an advection-dispersion model of Lake Innes to assess the hydrology following construction of a levee with a crest elevation of +1.6 m AHD (Australian Height Datum). This proposed levee height aims to limit the potential for saline intrusion from Lake Cathie to Lake Innes. Currently, Port Macquarie Hastings Council (PMHC) manually opens the ocean entrance of Lake Cathie when water levels in Lake Cathie reach +1.6 m AHD (BMT WBM, 2011).

This study focuses on the hydrologic implications of reinstating a levee to isolate Lake Innes from Lake Cathie (Figure 1.2). The implications of isolating Lake Innes from Lake Cathie on entrance opening, sediment transport and flooding have been previously discussed (Webb McKeown, 1994; BMT WBM, 2011). While previous studies have focused on the impacts to Lake Cathie, limited investigation has been undertaken into salinity levels in the lake following the closure of Lake Innes, and how long the lake would take to reach freshwater concentrations. Freshwater is classified as salinity concentrations less than 3 parts per thousand (ppt) (AETG, 2012).

This hydrological investigation provides an assessment of Lake Innes salinity and water levels following levee construction. The results will support ecological, geomorphological, and socio-economic assessments of closing Lake Innes. This study was undertaken by updating Lake Innes bathymetry, collating relevant climatic data and constructing a one-dimensional advection-dispersion model using the MIKE software packages.

This study is broken into five key sections detailing:

- Relevant hydrological background (Section 2);
- Bathymetric survey of Lake Innes (Section 3);
- Model methodology (Section 4);
- Hydrological model scenarios (Section 5); and
- Recommendations (Section 6).

2. Relevant Historical Hydrologic Information

This section provides a literature review focused on hydrological information relevant to returning Lake Innes to a freshwater system. Reviewing relevant information before and after the opening of Lake Innes is crucial to determine the processes required to restore Lake Innes to a freshwater system. The ecological history of the site will be reviewed separately by appropriate experts and is not within the scope of works of this hydrological study.

2.1 Pre-1933 Lake Innes Opening

Prior to 1933, Lake Innes was isolated from Lake Cathie and Cathie Creek via a natural peat levee at the south-eastern end of Lake Cathie (see Figure 1.2). In the early 1900s, the Public Works Department (PWD) undertook investigations to drain Lake Innes with the aim of creating potential agricultural land. Recommendations from the 1905 PWD report detailed that the lake should be drained either; north to the Hasting River, north through Innes Swamp, or east to the ocean. At no stage during the report was drainage south to Cathie Creek recommended (Armstrong, 2002).

Due to the cost involved in the required drainage works and the onset of World War I, Lake Innes drainage options were not again reviewed until 1925 when a former NSW Parliament Minister set about gathering investor funds to drain Lake Innes and sell the resulting arable land. Over the following 8 years, local private and local government support for the drainage scheme increased, culminating in 1933 when the Mayor of Port Macquarie announced that Lake Innes would be drained via a connection to Cathie Creek. This announcement, and subsequent drainage plan, disregarded the PWD recommendations.

2.2 Post-Opening Connection to Lake Cathie

Construction of a drainage canal began in March 1933 and was noted to be 300 yards long, 2 feet deep and 10 feet wide (Armstrong, 2002). Although the intent to protect the drain from scour was noted, no scour protection was installed. This resulted in a sudden and significant expansion of the drain following connection of Lake Innes to Cathie Creek. PWD recommended tidal floodgates to maintain freshwater conditions in the lake but this was ignored, resulting in saline water intruding into Lake Innes.

The pre-1933 height of the levee is not accurately known, however anecdotal evidence suggests that the levee elevation could have been at least +1.7 m AHD (Armstrong, 2002). The natural levee bank that historically separated Lake Innes and Cathie was noted to be largely composed of peat that promptly dried out and was burnt during a bushfire (Webb McKeown, 1994). This resulted in a lowering of the natural levee to its current elevation of between +0.5 m AHD to +0.8 m AHD (Webb McKeown, 1994).

Following the connection of Lake Innes to Lake Cathie, deterioration of the waterways and lakes were observed and suggestions of returning Lake Innes to a freshwater system were made as early as 1954 (Armstrong, 2002). A decline of fish and bird numbers was observed by local residents, coupled with a change in fringing vegetation (Armstrong, 2002). The formation of a 'reverse delta' in Lake Innes was observed, caused by the transport of sediment into Lake Innes. This has resulted in the gradual infilling of Lake Innes. Although anecdotal evidence suggests that Lake Innes was "up 30 feet deep in some places" prior to construction of the drain, recent surveys observed depths rarely in excess of 2.0 m (Armstrong, 2002). Initial investigations into isolating Lake Innes were dispelled by the NSW Department of Lands and no further significant hydrological investigations were undertaken on Lake Innes until 1994.

The 1994 Estuary Management Plan made the recommendation, amongst others, that Lake Innes be closed and further investigations into the implications of closure on hydrodynamics, water quality and aquatic ecosystems be undertaken (Webb McKeown, 1994). Since release of the 1994 Estuary Management Plan, significant investigation and works have been invested in the Lake Innes/Lake Cathie system. A range of hydrological, ecological and geomorphological studies have been undertaken to characterise key processes, driving factors and sensitive/threatened areas of the Lake Cathie/Lake Innes system (Webb McKeown (1994), BMT WBM (2011)). These investigations have assessed the potential closure of Lake Innes, the entrance opening dynamics of Lake Cathie and the sedimentation/shoaling dynamics in the waterways.

The Lake Innes/Cathie system is intermittently connected to the ocean. Due to the small catchment and significant longshore sediment transport along the coast, the lake system naturally connects to the ocean when a lake water level exceeds the height of the sand entrance berm, usually above 2.0 m AHD. This results in tidal exchange in the lakes and intrusion of saline water. The connection persist until sediment infills the channel and inhibits tidal exchange. Due to a number of factors, the opening of the Lake Cathie to the ocean is artificially managed by the local Council, who manually open the entrance using earth-moving equipment. This trigger level is currently set to +1.6 m AHD to mitigate potential flooding (BMT WBM, 2011). The entrance is also occasionally opened during summer months for water quality reasons.

The 1994 Estuary Management Plan (Webb McKeown, 1994) indicated that the closure of Lake Innes provided possible long-term benefits. A levee elevation of +1.5 m AHD was suggested with a low flow channel of +1.3 m AHD, however no justification for such elevations was provided. A constructed levee located at the original peat levee location was also recommended, with other locations deemed to have potential impacts on Innes Swamp (Figure 1.1). The 1994 EMP listed a number of aims for the minimum levee elevation, stating that the levee elevation should seek to:

- Create a lake of adequate depth and size to restore the basic ecological conditions that existed pre-1933;
- Provide a levee of sufficient height to prevent any possible ingress of tidal salt water;
- Maintain (or more desirably increase and improve) ecotourism opportunities;
- Eliminate any possible overflow of floodwaters from Cathie Creek into Lake Innes when floods occur and the estuary entrance berm is closed; and,
- Maximise the hydrodynamic force available to scour Cathie Creek and berm opening when the entrance is opened and the floodwaters are released.

2.3 Lake Innes Existing Conditions

Lake Innes is currently connected to Lake Cathie receiving tidal exchange from the ocean when the Lake Cathie entrance is open. Webb McKeown (1994) lists the annual water balance components for the Lake Innes/Lake Cathie system as:

- Tidal flows;
- Flood flows;
- Breakout prism;
- Surface water/groundwater runoff;
- Direct precipitation;
- Evaporation;
- Wave overtopping; and
- Seepage.

Webb McKeown (1994) outlined the following inflow sources of the existing system:

- Cowarra Creek;
- Karikeree Creek;
- Lake Cathie;
- Lake Innes;
- Direct runoff areas.

Lake Cathie water level statistics from August 1992 to July 2012 are presented in Table 2.1.

Table 2.1: Lake Cathie Water Level Statistics (1992 – 2012)

Statistic	Water Level (m AHD)
Minimum	-0.67
Lower Quartile	0.30
Mean	0.65
Median	0.52
Upper Quartile	1.08
Maximum	1.85

2.4 Summary of Available Data

Climate data was available online from the Bureau of Meteorology (BoM). Daily rainfall and monthly evaporation averages were used for this study.

A detailed Airborne Laser Scanning Survey (ALS or LIDAR) was undertaken by AAMHATCH for Hastings Shire Council in 2005. Raw and processed LIDAR data was supplied by Council. A bathymetric survey of the Lake Cathie/Lake Innes waterway was undertaken in 1993 by the NSW Department of Public Works and Services (DPWS). BMT WBM (2011) provided a summary of available hydrodynamic data available for the Lake Innes/Lake Cathie system (Table 2.2).

Table 2.2: Summary of Available Hydrodynamic Data (WBM BMT, 2011)

Data Source	Data Duration	Data Collected	Location of Data Collection
NSW PWD (1982)	22nd April 1982 Approx. 25 hours	Water level, velocity, discharge, salinity, water temperature and suspended sediment	Current metering at Ocean Drive Bridge, culvert at Lake Cathie and channel near entrance to Lake Innes. Water level readings at 8 locations in entrance channel, Ocean Drive, Kenwood Drive culvert, Lake Cathie, Cathie Creek and Lake Innes
MHL (1994)	August 1993 – September 1994	Water level, water temperature, salinity	Lake Cathie and Lake Innes
MHL (2012)	August 1992 – ongoing	Water level	Lake Cathie and Ocean Drive Bridge
MHL (2012)	August 1993-September 1994	Water level	Lake Innes

2.5 Previous Predictions of Lake Innes Closure Impacts

2.5.1 Impact on Lake Cathie

Webb McKeown (1994) identified that closing Lake Innes would have a substantial impact on tidal response within Lake Cathie. The effect in the upper reaches of Cathie Creek would be an increase in tidal response from 0.3 m to 0.5 m for a 1.0 m ocean tide. The tidal prism that flows through the entrance during normal tides was found to be unchanged due to the response of Cathie Creek (Webb McKeown, 1994). Conversely, WBM BMT (2011) found that the tidal prism would increase and decrease depending on tidal direction (flood/ebb) and tidal amplitude (spring or neap cycle). WBM BMT (2011) found that the magnitude of bed load sediment transport in and out of the estuary would be reduced.

Webb McKeown (1994) also highlighted the implications of isolating Lake Innes on estuary entrance dynamics. Webb McKeown (1994) suggested that the subsequent breakout prism would be significantly reduced from 13.0 Mm^3 to 3.4 Mm^3 resulting in reduced scouring of the estuary entrance. This reduced scour would lower the average entrance opening time from 3.5 months to 1.5 months. However, due to the reduced volume in the Cathie system, the breakout elevation would be reached more quickly and connect to the ocean more often. Potential discharge from Lake Innes was not included. Webb McKeown (1994) found that the net result would be more frequent and smaller entrance openings occurring at an average rate of 2.5 to 3 per year, compared to a single annual breakout event.

Neither WBM BMT (2011) nor Webb McKeown (1994) investigated salinity changes in Lake Cathie or Lake Innes. Confirmation or reproduction of these prediction was outside the scope of works for this study.

2.5.2 Impact on Lake Innes

Limited investigations into the impacts of closure on Lake Innes have been undertaken. Webb McKeown (1994) indicated a potential for an increase in direct precipitation and evaporation due to the sustained larger surface area of Lake Innes.

The 1994 Estuary Management Plan provided some quantification of the impact of a levee on Lake Innes peak flood levels. An overall increase in flood levels in Lake Innes and Lake Cathie from +2.4 m AHD to +2.6 m AHD was predicted during a 100 year ARI flood event (Webb McKeown, 1994).

NPWS (1999) indicated that reversion of Lake Innes to a freshwater system would enhance waterbird habitats and provide a significant increase in coastal freshwater habitat on the mid-north coast, with current freshwater extents expanded from 40 hectares to 700 hectares.

Although Webb McKeown (1994) outlined a number of issues that should be addressed in the 1994 EMP, potential impacts of closure were focused on Lake Cathie and Cathie Creek. Similarly, WBM BMT (2011) focused on impacts to Lake Cathie and entrance opening dynamics.

2.6 Climate

The Lake Innes climate is dominated by coastal processes. Rainfall at Port Macquarie is significantly different compared to nearby inland sites. The average yearly rainfall for Wauchope is 1290 mm (1890-2012) compared to Port Macquarie with 1535 mm (1840-2010). Yearly rainfall distribution is lowest during the end of winter into the start of spring with the highest monthly rainfall occurring in summer (February). Rainfall statistics for Port Macquarie (BoM station number 060026) are presented in Table 2.3.

Evaporation in Lake Innes is dominated by coastal processes. Subsequently, the nearest inland evaporation stations near Tamworth were not used. An average of the nearest north and south coastally located evaporation stations; Coffs Harbour and Taree (**Table 2.4**), were used to provide representative coastal evaporation rates.

Table 2.3: Monthly Rainfall (mm) Statistics for Port Macquarie (060026) for 1840 to 2010 (Source: BoM)

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	152.3	178.1	175.2	167.3	144.3	133.2	97.6	81.3	81.4	94.0	104.1	126.5	1534.5
5th %ile	35.3	51.3	60.2	40.4	23.1	16.5	10.7	8.1	14.1	23.1	28.4	29.9	1042.4
95th %ile	259.2	324.9	306.5	351.9	283.8	285.2	207.5	189.4	186.2	193.2	195.0	233.4	2111.0
Median	112.4	158.8	155.4	130.8	112.8	104.6	72.6	53.4	63.7	72.6	87.8	105.7	1407.6

Table 2.4: Mean Daily Evaporation (mm) (Source: BoM)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Period
Coffs Harbour (059040)	6.4	5.7	4.9	4.0	2.8	2.4	2.5	3.5	4.6	5.3	5.8	6.4	4.5	1968-2007
Taree (060030)	5.7	5.2	4.3	3.3	2.1	1.8	2.0	2.7	3.7	4.7	5.3	6.1	3.9	1970-1999
Lake Innes Adopted	6.1	5.5	4.6	3.7	2.5	2.1	2.3	3.1	4.2	5.0	5.6	6.3	4.2	-

2.7 Climate Change

The NSW Department of Climate Change and Water (DECCW) (currently NSW Office of Environment and Heritage (OEH)) (2010) outlined quantitative changes in rainfall, evaporation and sea levels due to climate change in 2050. These predicted changes are likely to influence Lake Innes hydrology (i.e. inflows and evaporation) into the future. However, the impact of climate change on the following is unknown and not considered as part of this hydrological assessment:

- Groundwater;
- Sedimentation;
- Ecological feedback.

2.7.1 2050 Rainfall and Evaporation

DECCW (2010) outlined regional changes in temperature, rainfall and evaporation for the North Coast of NSW (Table 2.5). Predicted changes are likely to have an impact on the hydrology of Lake Innes.

Table 2.5: Summary of Predicted Temperature and Rainfall Changes in the North Coast NSW Region to 2050 (DECCW, 2010)

Season	Minimum Temperatures	Maximum Temperatures	Precipitation	Evaporation
Spring	2.0 – 3.0^{O}C warmer	1.5 – 2.0^{O}C warmer	No change	10 – 20% increase
Summer	2.0 – 3.0^{O}C warmer	1.0 – 1.5^{O}C warmer	5 – 20% increase	10 – 20% increase
Autumn	2.0 – 3.0^{O}C warmer	1.5 – 2.0^{O}C warmer	5 – 10% increase	10 – 20% increase
Winter	2.0 – 3.0^{O}C warmer	2.0 – 3.0^{O}C warmer	5 – 10% decrease	5 – 20% increase

2.7.2 2050 Sea Level Rise

DECCW (2010) detailed a predicted 2050 sea level rise (SLR) of +0.4 m. The current highest astronomical tide (HAT) for Sydney Fort Denison tide gauge is +1.175 m AHD. Therefore, HAT in 2050 will be +1.575 m AHD which is below the +1.6 m AHD crest elevation of the proposed levee. As such, sea level rise is unlikely to directly impact water levels and salinity in Lake Innes for the period up to 2050.

3. Bathymetric Survey

3.1 Existing Topographic and Bathymetric Data

An Airborne Laser Scanning Survey (ALS or LIDAR) was undertaken by AAMHATCH for Hastings Shire Council in 2005. The raw ground point cloud was supplied to WRL and interpolated to a 1 m x 1 m grid using a spline function (Figure 3.1). This LIDAR data was used to infill elevations and areas not covered by the WRL survey detailed in Section 3.2.

The 2005 LIDAR data had a vertical accuracy of 0.2 m. The resulting point cloud was validated by AAMHATCH to have a standard deviation of ± 0.071 m. The accuracy of the LIDAR was checked by WRL against a number of points taken using an RTK GPS. The points were located on open ground to the west of Lake Innes. WRL found that the variation of measured RTK GPS points when compared to LIDAR points varied between 0.03 m to 0.3 m (Table 3.1).

Table 3.1: LIDAR Verification

Easting GDA94 MGA56	Northing GDA94 MGA56	LIDAR Elevation (m AHD)	RTK GPS Elevation (m AHD)	Difference (m)
482905	6514371	5.84	6.14	+0.30
482876	6514348	6.65	6.68	+0.03
482910	6514350	5.48	5.67	+0.19
482898	6514340	5.92	5.99	+0.07

A bathymetric survey of the Lake Cathie/Lake Innes waterway was undertaken in 1993 by the NSW Department of Public Works and Services (DPWS) (Figure 3.2). Figure 3.2 shows various contouring artefacts resulting from the interpolation method. These artefacts are particularly apparent in areas outside of the survey boundary, and around the edges of Lake Innes. This survey consisted of transverse and longitudinal profiles of the waterway bathymetry, with land levels on the edge of the lakes approximated using photogrammetry from 1989. This dataset was compared to the 2012 survey undertaken by WRL to determine sedimentation rates and geomorphological changes to Lake Innes since 1993.

3.2 August 2012 Bathymetric Survey

Armstrong (2002) identified potential sedimentation of Lake Innes from tidal inflows. As such, pre-existing bathymetric data of Lake Innes was identified to be potentially unrepresentative of current conditions due to sedimentation and geomorphological changes. To provide an updated bathymetric dataset, WRL undertook a fit-for-purpose bathymetric survey of Lake Innes in August 2012. The raw and interpolated data is presented in Figure 3.3.

The survey was undertaken using a Ceescope echosounder mounted to a small boat, and Trimble R6 RTK GPS corrected using the CORSNET base station network (Figure 3.4a). Soundings were taken with reference to water surface then offset using water surface elevations regularly obtained with RTK GPS. The water level on 15th August was 1.64 m AHD due to a closed entrance condition at Lake Cathie (Figure 3.4b). The echosounder data was processed and smoothed to eliminate boat roll/pitch effects and to reference all depths to AHD.

The processed bathymetric points were imported into ArcGIS 10 and interpolated to a 1 m x 1 m grid using a spline (with boundaries) algorithm. The interpolated bathymetry was incorporated into the 2005 LIDAR DEM (Digital Elevation Model) with 2012 bathymetry points used in preference to LIDAR where overlapping occurred. Elevation for some areas of open water on Lake Innes were not included in the supplied dataset.

The 1993 and 2012 bathymetric surveys were compared by plotting similar transverse and longitudinal sections against each other using raw survey data points. Indicative section locations used for comparisons are presented in Figure 3.5 with resulting data plotted in Figures 3.6 and 3.7. The interpolated data from each survey was also compared to assess gross accretion/erosion rates since the 1993 survey (Figure 3.8).

Overall, accretion is the dominant geomorphological processes in Lake Innes. Lake cross-sections indicate an increase in lakebed elevation of 0.05 m to 0.1 m in some areas. This equates to approximately 2 mm to 4 mm of accretion per year since the 1993 survey. This increase in bed elevation is likely due to a combination of catchment inflows, tidal inflows and biota breakdown. The rate of sedimentation is in line with Haworth's (2001) estimation of 3 mm/year (Armstrong, 2001). Sedimentation of Lake Innes has had minimal impact on the overall storage volumes (Figure 3.9).

Figure 3.10 presents Lake Innes stage versus inundation area based on the 2012 survey. Stage-volume and stage-area relationships are also presented in Table 3.2.

Table 3.2: Existing Lake Innes 2012 Stage-Area and Stage-Volume Relationships

LIDAR Elevation (m AHD)	Plan Area (m^2)	Volume (m^3)
-3	500	500
-2.5	4,000	1,500
-2	11,000	4,500
-1.75	16,500	7,500
-1.5	30,000	12,500
-1.25	36,500	21,000
-1	41,000	30,500
-0.75	1,509,000	181,000
-0.5	2,954,500	747,000
-0.25	4,367,000	1,679,000
0	5,418,500	2,904,000
0.25	6,561,500	4,391,000
0.5	9,224,500	6,299,000
0.75	13,511,500	9,161,000
1	16,346,500	12,928,000
1.25	17,581,500	17,197,500
1.5	18,037,000	21,658,000
1.6	18,160,500	23,468,500
1.7	18,271,500	25,290,000
2	18,555,500	30,816,000
2.5	18,869,000	40,180,500
3	19,037,500	49,661,500

3.3 Event Required to Fill Lake Innes

To understand the magnitude of a rainfall event that would be required to fill Lake Innes, a simple desktop assessment was undertaken. Annual Recurrence Interval (ARI) rainfall for Lake Innes was utilised to assess the filling of Lake Innes from a level of 0.0 m AHD to 1.6 m AHD, a volume of approximately 20,000,000 m^3. The ARI rainfall for Lake Innes (Table 3.3) were combined with a catchment area of 51 km^2 and open water area of 7 km^2 to characterise rainfall events with respect to Lake Innes volume (Table 3.4). It was assumed losses would be 2 mm/hour.

Table 3.3: Rainfall ARI Curves for Lake Innes

Duration	Hours	ARI Event Rainfall (mm/hr)					
		2 Years	5 Years	10 Years	20 Years	50 Years	100 Years
5Mins	0.08	131.0	168.0	189.0	217.0	254.0	282.0
6Mins	0.10	123.0	157.0	177.0	204.0	239.0	266.0
10Mins	0.17	101.0	130.0	147.0	170.0	199.0	222.0
20Mins	0.33	73.7	96.5	110.0	128.0	151.0	169.0
30Mins	0.5	60.0	79.2	90.7	106.0	126.0	141.0
1Hr	1	41.0	54.5	62.7	73.3	87.5	98.4
2Hrs	2	27.4	36.4	41.8	48.9	58.2	65.5
3Hrs	3	21.6	28.5	32.7	38.1	45.2	50.8
6Hrs	6	14.3	18.7	21.3	24.7	29.2	32.7
12Hrs	12	9.4	12.2	13.9	16.1	19.0	21.2
24Hrs	24	6.0	8.0	9.1	10.6	12.6	14.1
48Hrs	48	3.7	5.0	5.8	6.9	8.2	9.3
72Hrs	72	2.8	3.7	4.4	5.1	6.2	7.0

Table 3.4: Event Inflow as a Percentage of Lake Innes Volume (From 0.0 m to 1.6 m AHD)

Duration	Hours	ARI Event					
		2 Years	5 Years	10 Years	20 Years	50 Years	100 Years
5Mins	0.08	3%	4%	5%	5%	6%	7%
6Mins	0.10	4%	4%	5%	6%	7%	8%
10Mins	0.17	5%	6%	7%	8%	10%	11%
20Mins	0.33	7%	9%	10%	12%	14%	16%
30Mins	0.5	8%	11%	13%	15%	18%	20%
1Hr	1	11%	15%	18%	21%	25%	28%
2Hrs	2	15%	20%	23%	27%	33%	37%
3Hrs	3	17%	23%	27%	31%	38%	42%
6Hrs	6	21%	29%	34%	39%	47%	53%
12Hrs	12	26%	35%	41%	49%	59%	67%
24Hrs	24	28%	41%	49%	60%	74%	84%
48Hrs	48	24%	42%	53%	68%	87%	101%
72Hrs	72	16%	36%	49%	65%	87%	105%

4. Hydrologic Assessment Methodology

4.1 Model Inflows

There was no flow gauging data available for the Lake Innes catchment. Subsequently an AWBM catchment model was developed to generate catchment runoff volumes. AWBM is a catchment water balance model that calculates runoff from rainfall and has been extensively tested on Australian catchments (Boughton and Chiew, 2007). Nighty-nine (99) years of daily rainfall data was used from Port Macquarie (BoM station 060026) and combined with averaged Coffs Harbour and Taree evaporation data (Table 2.4). Daily averaged inflows from the surrounding 51 km^2 catchment were output from the AWBM model as input into the hydrodynamic MIKE model. Catchment areas were sourced from the 1994 Estuary Management Plan (Webb McKeown, 1994).

Rainfall and evaporation were totalled daily to provide a single environmental input for open water in the MIKE model. If daily rainfall exceeded evaporation then a positive input occurred, otherwise evaporation (mm/m^2/day) was applied to the open surface area (approximately 7 km^2) of Lake Innes. The 99-year timeseries of rainfall, evaporation and catchment runoff is presented in Figure 4.1.

4.2 Modelling Process

MIKE 11 was utilised to undertake long-term simulations of Lake Innes closure scenarios. MIKE 11 is a one-dimensional (1D) unsteady finite difference model used for numerical modelling of rivers, lakes and estuaries. Lake Innes bathymetry, inflows and evaporation were input into MIKE 11 and coupled with a levee at the south-eastern boundary of Lake Innes. The levee crest was set to an elevation of +1.6 m AHD.

A 1D MIKE model was used in preference to a 2D model as:

- A fully mixed system was assumed as Lake Innes is a shallow water body and consistent wind providing mixing;
- 2D did not provide additional required information;
- Mixing data to calibrate a 2D model; and
- Any gradient in water levels or salinity was assumed to be insignificant.

4.2.1 Bathymetry

To determine the extent of Lake Innes included in the model, an elevation of +1.6 m AHD was applied to the combined 2012 bathymetry and 2005 LIDAR DEM. The extent of water surface coverage at +1.6 m AHD can be seen in Figure 4.2. Cross-sections were extracted from the combined 2012 bathymetry and 2005 LIDAR DEM. One-dimensional cross-section locations are also presented in Figure 4.2 with cross-sections detailed in Figures 4.3 to 4.5.

4.2.2 Boundary Conditions

Inflow timeseries were created using AWBM in conjunction with Port Macquarie daily rainfall data and a 51 km^2 catchment size. A weir/levee at +1.6 m AHD was applied at the downstream extent of the model domain spanning 1,500 m. An outflow boundary was applied on the Lake Cathie side of the weir with overtopping water being removed from the model domain. No interaction of water from Lake Cathie (i.e. downstream) to Lake Innes was modelled as it was assumed that the current Council policy of opening Lake Cathie at the water level of +1.6 m AHD would be maintained.

4.2.3 Salinity Modelling

Salinity was modelled using the outputs from MIKE 11 from the hydrodynamic model in combination with an analytical salt mass balance. A constant initial salinity was applied to the lake. When coupled with an initial water level, the mass of salinity in the model domain was determined. This mass is removed from the model via advection from the model domain as water is discharged over the levee. At water levels below +1.6 m AHD, inflows and rainfall dilute the salinity concentration and evaporation increases the concentration.

To accurately simulate the range of conditions likely to be encountered, scenario modelling was undertaken using various starting water levels and salinities. The results were assessed to determine the time taken until the lake reaches freshwater concentrations (< 3 ppt) as per AETG (2012). A description of Scenarios is provided in Section 5.

4.3 Climate Change

Changes in precipitation and evaporation due to climate change were modelled using predictions supplied by DECCW (2010) (Table 2.5). To cover the full range of likely climatic scenarios and assess the potential impact on Lake Innes; precipitation and evaporation were combined to produce the driest and wettest climate prediction scenarios (Table 4.1). Increases in temperature were not directly considered.

The 99-year daily rainfall timeseries and evaporation averages were adjusting by the percentage increase or decrease outlined in Table 4.1 to create new rainfall and evaporation timeseries. The modified timeseries were then used to create daily catchment runoff flows using the AWBM catchment water balance model. The modified rainfall and evaporation timeseries were applied to the lake surface area during model runs.

Table 4.1: 2050 Climate Change Scenarios

Season	2050 Wettest Climate Change		2050 Driest Climate Change	
	Precipitation	Evaporation	Precipitation	Evaporation
Spring	No change	10% increase	No change	20% increase
Summer	20% increase	10% increase	5% increase	20% increase
Autumn	10% increase	10% increase	5% increase	20% increase
Winter	5% decrease	5% increase	10% decrease	20% increase

4.4 Model Assumptions

The following assumptions need to be considered when reviewing the model results:

- A catchment inflow salinity concentration of 0 ppt was assumed for all modelling scenarios;
- Full mixing of salinity and catchment inflows was assumed;
- No wind was applied to the model, however ongoing mixing due to wind was assumed;
- Backwater effects from Cathie Creek were not considered;
- No secondary source of salt was assumed. Remnant salinity remaining in the soil matrix, or flux of salt from sea spay was considered to be zero;
- Model influx was applied at a single location in Lake Innes and were assumed to be representative of global Lake Innes salinity and water level.

5. Hydrological Modelling

5.1 Scenarios

The transition of Lake Innes from a saline to freshwater ecosystem is dependent on the export of salt from Lake Innes. Export occurs as mass flux over the levee at the southern boundary. At water levels below 1.6 m AHD, salt remains in Lake Innes with the concentration dependent on water level/volume. The time required to flush Lake Innes below 3 ppt is largely dependent on two factors:

1. The initial mass of salt when Lake Innes is closed; and,
2. The rate and frequency of runoff events.

The initial salt mass is a function of the starting water level (or volume) and concentration. For example, a combination of high salinity and high water levels results in an initial high mass of salt compared to an initial condition of low water levels with low salinity.

A combination of initial salt mass (water level and concentration) and hydrological period (wet or dry) scenarios were selected to provide a range of possible Lake Innes saline transition times (Table 5.1). Catchment inflows and rainfall determines how often water levels exceed 1.6 m AHD, resulting in salt export from the system. Historical wet and dry periods were chosen to determine indicative maximum and minimum periods until freshwater conditions are achieved (Figure 5.1). For instance, from 1939, eastern Australia experienced a prolonged drought with below average rainfall. Conversely, in the mid to late-1980s the east coast experienced frequent rainfall events. While the entire 99-year time period was run, these periods were chosen to represent extended 'dry' and 'wet' periods thus enabling extreme climatic variables to be considered.

An initial lake salinity of 35 ppt was selected, as the levee is likely to be constructed when Lake Cathie and Lake Innes have been connected to the ocean. BMT WBM (2011) showed that the southern extent of Lake Innes salinity reaches ocean salinity approximately 1.5 months following an entrance-opening event with the northern boundary reaching 13 ppt due to intruding salinity from downstream. Given the average entrance opening time is approximately 3.5 months (Webb McKeown, 1994), it was conservatively assumed that the global Lake Innes salinity concentration at the time of lake closure was 35 ppt and long-term salinity gradients would be negligible.

Table 5.1: Lake Innes Closure Scenarios

Scenario	Hydrological Period	Initial Lake Water Level (m AHD)	Levee Elevation (m AHD)	Initial Salinity (ppt)
1	Dry	0.0	+1.60	35.0
2	Wet	0.0	+1.60	35.0
3 (Fast Transition)	Wet	-0.5	+1.60	10.0
4 (Slow Transition)	Dry	+0.75	+1.60	35.0

5.2 Scenario Results

Scenario 1 featured a starting water elevation of mean sea level and ocean salinity. These initial conditions combined with dry hydrological conditions resulted in high salinity levels (i.e. > 3 ppt) for 10.75 years (Figure 5.2). Periods of extreme salinity resulting from evapoconcentration were also predicted to occur during extended periods of low inflow. This demonstrates the adverse conditions possible if even a short dry period is experienced.

Scenario 2 assessed the impact of the rainfall frequency/volume on the time until freshwater concentrations are reached. The same initial conditions as Scenario 1 were combined with increased rainfall frequency/intensity. Due to the increased runoff, the time until freshwater concentrations are achieved decreased to 30 months (Figure 5.3).

Scenario 3 tested a fast transition from saline to fresh. A low water level combined with low salinity concentrations produced a lower initial mass of salt to be exported from Lake Innes. Low initial salt mass combined with active hydrological conditions resulted in a four (4) months transition from brackish to freshwater (Figure 5.4). Note that this rapid transition is purely due to a large dilution of the initial salt mass. Scenario 3 may occur if the saline transition were to be artificially progressed using hydraulic manipulation (i.e. pumping or floodgates) of lake levels following construction of a levee. Allowing initial saline concentrations to dilute prior to draining Lake Innes (i.e. via a floodgate) would dramatically decrease the time until freshwater conditions are achieved. This approach has potential implications on the ecological and biochemical response rate of Lake Innes (i.e. ecosystem shock).

Scenario 4 represents a conservative saline transition scenario. A high initial water level and salinity, combined with dry hydrological conditions resulted in persistent high salinity concentrations (Figure 5.5). Under these conditions, periods of extreme hyper salinity were predicted as evaporation combined with below average inflows increased concentrations. It is not until average to above average rainfall returns that salinity concentrations were reduced to freshwater conditions. This period was predicted to be approximately 11.5 years (Table 5.2).

Table 5.2: Lake Innes Modelling Results

Scenario	Time Until Fresh (3 ppt) (approx. months)	Time Until Fresh (3 ppt) (approx. years)
1	129	10.75
2	30	2.5
3	4	0.3
4	138	11.5

5.3 Long-term Water Level Statistics

The Lake Innes hydrodynamic model was run for the complete 99-years of boundary data using historical climatic conditions. The 99-years of rainfall and evaporation data was also modified to account for climate change (see Table 2.5 for climatic variables applied). Wettest and driest climate change scenarios for 2050 were modelled.

Monthly water level statistics were extracted from the model and are presented in Tables 5.3, 5.4 and 5.5. Statistical plots of the three climate scenarios are presented in Figure 5.6. Long-term water level statistics are also graphically presented in Figure 5.7.

Table 5.3: Water Level (m AHD) Statistics for Historical Climatic Conditions

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	-0.15	-0.15	0.00	-0.01	-0.01	0.12	0.22	0.28	0.17	0.14	0.10	0.00
Lower Quartile	0.98	0.93	0.93	1.00	1.06	1.17	1.24	1.25	1.20	1.16	1.11	1.05
Mean	1.13	1.13	1.18	1.23	1.29	1.36	1.39	1.39	1.35	1.30	1.25	1.20
Median	1.18	1.15	1.21	1.33	1.46	1.54	1.57	1.55	1.50	1.43	1.34	1.26
Upper Quartile	1.41	1.45	1.54	1.57	1.60	1.60	1.60	1.59	1.56	1.53	1.50	1.45
Maximum	1.67	1.67	1.77	1.78	1.71	1.73	1.69	1.66	1.65	1.69	1.68	1.62

Table 5.4: Water Level (m AHD) Statistics for Wettest 2050 Climate Change Prediction

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	-0.29	-0.28	-0.14	-0.15	-0.13	0.02	0.18	0.21	0.10	0.06	-0.03	-0.13
Lower Quartile	0.91	0.89	0.90	0.97	1.06	1.21	1.23	1.21	1.15	1.09	1.04	0.98
Mean	1.09	1.10	1.16	1.23	1.29	1.36	1.38	1.38	1.33	1.27	1.21	1.15
Median	1.15	1.12	1.22	1.34	1.48	1.58	1.58	1.55	1.49	1.41	1.31	1.22
Upper Quartile	1.38	1.46	1.55	1.58	1.60	1.60	1.60	1.59	1.56	1.51	1.46	1.41
Maximum	1.69	1.70	1.79	1.81	1.72	1.72	1.68	1.66	1.65	1.69	1.68	1.63

Table 5.5: Water Level (m AHD) Statistics for Driest 2050 Climate Change Prediction

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	-0.82	-0.82	-0.65	-0.67	-0.65	-0.45	-0.23	-0.24	-0.35	-0.51	-0.65	-0.77
Lower Quartile	0.45	0.41	0.44	0.55	0.67	0.84	0.88	0.86	0.78	0.69	0.62	0.55
Mean	0.83	0.82	0.87	0.95	1.03	1.12	1.17	1.17	1.13	1.06	0.99	0.91
Median	0.91	0.90	0.93	1.08	1.13	1.22	1.25	1.31	1.31	1.23	1.13	1.02
Upper Quartile	1.25	1.26	1.36	1.46	1.52	1.59	1.59	1.57	1.53	1.46	1.41	1.31
Maximum	1.63	1.67	1.77	1.78	1.71	1.72	1.68	1.66	1.65	1.68	1.68	1.62

6. Summary and Recommendations

Since the connection of Lake Innes to Lake Cathie in 1933, debate as to the benefits of reverting Lake Innes to a freshwater system has been ongoing. Webb McKeown (1994) and BMT WBM (2011) have previously investigated the impact of closing Lake Innes on flooding and Lake Cathie entrance dynamics. Limited investigations into the ecological impact on Lake Innes and the transition to freshwater conditions have been undertaken to date.

WRL was commissioned to undertake a hydrologic assessment of Lake Innes following construction of a levee bank that isolates Lake Innes from tidal flushing with Lake Cathie. A levee bank with a crest elevation at +1.6 m AHD would hydrologically isolate Lake Innes, inhibiting the potential for saline intrusion from Lake Cathie. This is dependent on Council maintaining a +1.6 m AHD trigger level for opening Lake Cathie. The levee crest elevation and location are based on pre-1933 levee historical information and ensures no direct impact to Innes Swamp.

For this study, WRL undertook a bathymetric survey of Lake Innes to update previous bathymetry, determining sedimentation rates and a stage-volume relationship. Updated bathymetric data was combined with surrounding LIDAR data to create a DEM. The DEM was used to create a hydraulic model of Lake Innes using the MIKE modelling software. An AWBM catchment model was used to predict runoff based on daily rainfall data collected at Port Macquarie.

Four (4) scenarios were selected to determine the impact of initial salinity and hydrologic period (rainfall intensity and frequency) on the salinity transition of Lake Innes. Under favourable conditions, freshwater conditions are achievable within 30 months. With worst-case initial and hydrologic conditions, over eleven (11) years of persistent salinity occurs prior to freshwater concentrations (3 ppt) being achieved.

Evaporation of Lake Innes during dry hydrological periods was found to produce brief periods of extreme hyper-salinity. Salinity concentrations were found to potentially exceed 200 ppt (mg/L) under the slowest transition conditions. To combat these events, WRL recommends that some form of hydraulic connection between Cathie Creek and Lake Innes be maintained to permit manually flushing of Lake Innes during hyper saline events and reduce salinity to at least ocean salinity (35 ppt).

The transition from saline to fresh could be progressed artificially by hydraulic manipulation of Lake Innes water levels. Draining Lake Innes to a level below the levee crest would result in the export of salt mass and provide lower salinity concentrations which could then be diluted by catchment runoff. When combined with a period of increased rainfall, this could result in a rapid transformation from saline to freshwater conditions. This approach would require consideration of the ecological repercussions from rapidly manipulating the rate of change of a brackish ecosystem.

Water level statistics were also calculated based on 99-years of rainfall and evaporation data. The mean predicted water level was approximately 1.4 m AHD, with levels predicted to drop below 0.81 m AHD and equal or exceed 1.6 m AHD approximately 10% of the time.

Based on the current topography surrounding Lake Innes, a levee of approximately 1,500 m length would be required to isolate Lake Innes. The cross-sectional area below +1.6 m AHD is approximately 1,235 m^2. Alternative locations were originally proposed by Webb McKeown

(1994), however these locations were not assessed as part of this study due to potential impacts on Innes Swamp. Figure 6.1 shows an alternative levee location further south that would result in a significantly shorter levee, approximately 425 m in length. This levee would require significantly less earthen fill to construct, with a cross-sectional area (below +1.6 m AHD) of approximately 385 m^2. Three dimensional fill volume calculations required for levee construction have not been considered as part of this study, however the cross-sectional area calculations provide an indication of relative levee sizes. Levee location and design should be optimised to protect from scour and maintain levee crest elevations.

Filling the Lake Cathie/Innes system to a water level of 1.6 m AHD showed no connection between Lake Innes and Innes Swamp however, flood modelling undertaken by Webb McKeown (1994) indicated that interaction is likely to occur during large rainfall events. An assessment of an alternative levee location would require consideration of:

- Direction of runoff from Lake Innes;
- Upland flow path from Innes Swamp and potential deadspot concerns;
- Impact of any Innes Swamp catchment runoff on Lake Innes; and,
- Ecological impacts of joining a relatively pristine ecosystem (Innes Swamp) with a modified system (Lake Innes).

This investigation indicated that reversion of Lake Innes to freshwater is hydrologically feasible. Although Lake Innes has a small catchment, transformation to a freshwater system is likely to occur in approximately 10 years. The modelling undertaken for this study highlighted the impact of rainfall frequency/intensity on transforming Lake Innes to a freshwater system. A significant difference in transformation times was predicted when simulating Lake Innes isolation during wet versus dry periods. The mass of salt stored in Lake Innes at the time of levee construction was also identified as a determining factor. Limiting the initial mass stored in Lake Innes by having a low initial water level and low salinity concentration enables Lake Innes to approach freshwater concentrations sooner. Modelling undertaken predicted periods of extreme hyper salinity may occur under dry conditions. Some form of manual hydraulic connection between Lake Cathie and Lake Innes is recommended to reduce the impact of extreme salinity events.

Other issues to be considered that were not included in this hydrological study are:

- Salinity diffusion from soil;
- Ecological transformation responses;
- Biochemical processes;
- System feedback mechanisms; and
- Incomplete mixing responses.

7. References

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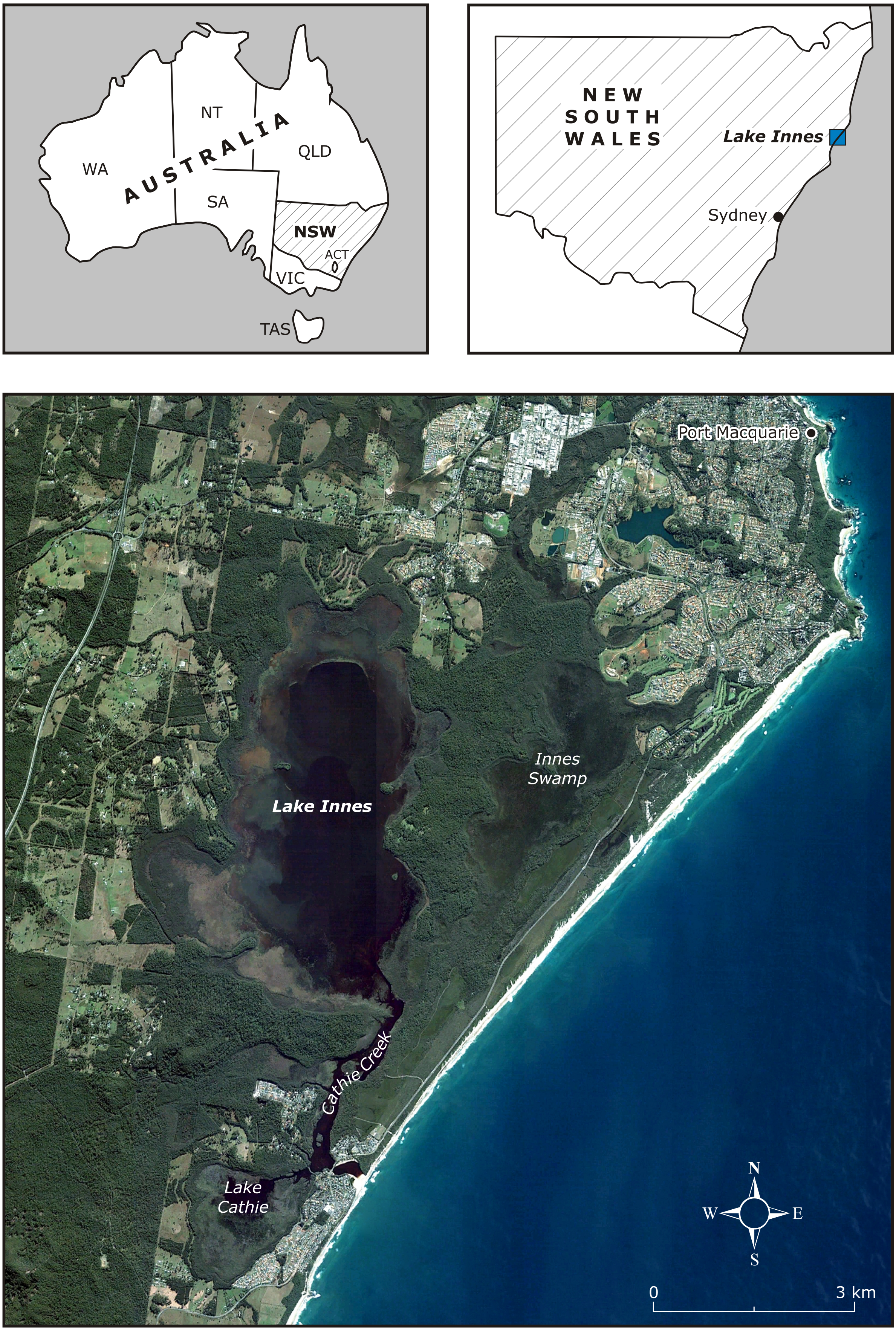
Webb McKeown & Associates (1994) "Appendix A – Physical Processes Lake Cathie/Lake Innes Management Study"


AUSTRALIA
WA
NT
SA
QLD
NSW
ACT
VIC
TAS
NEW SOUTH WALES
Lake Innes
Sydney
Port Macquarie
Innes Swamp
Lake Innes
Cathie Creek
Lake Cathie
N
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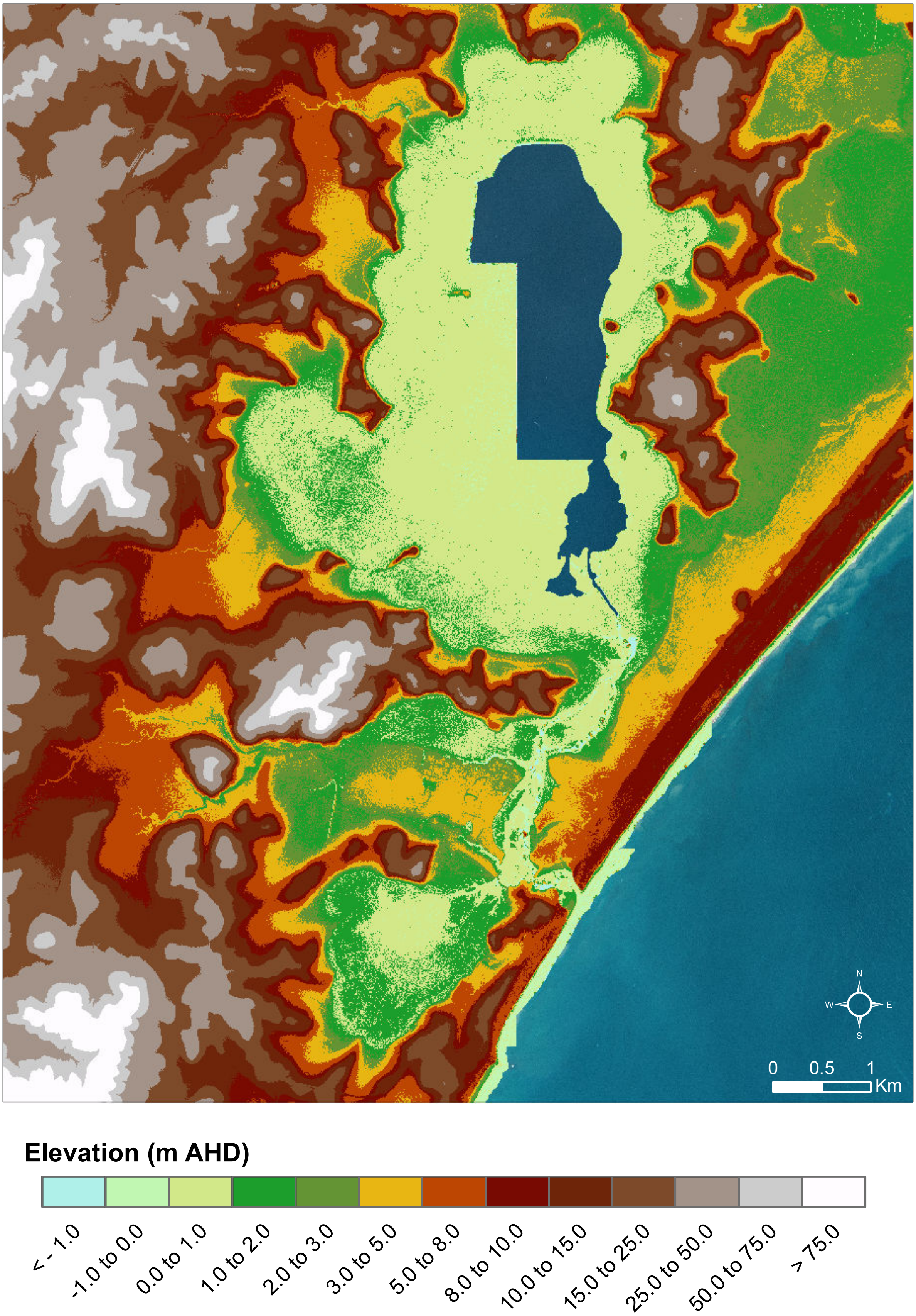
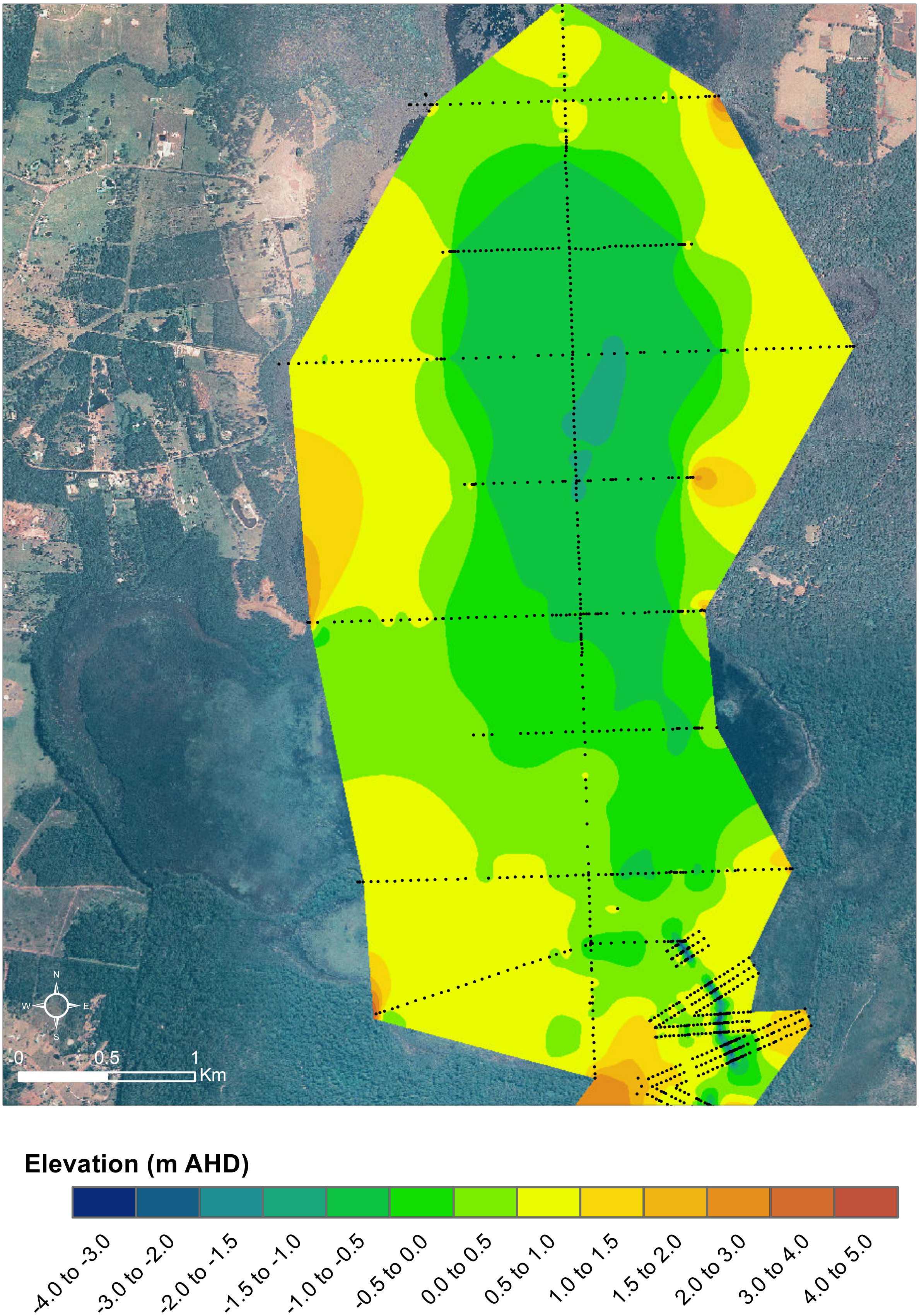
E
S
0
3 km

Location

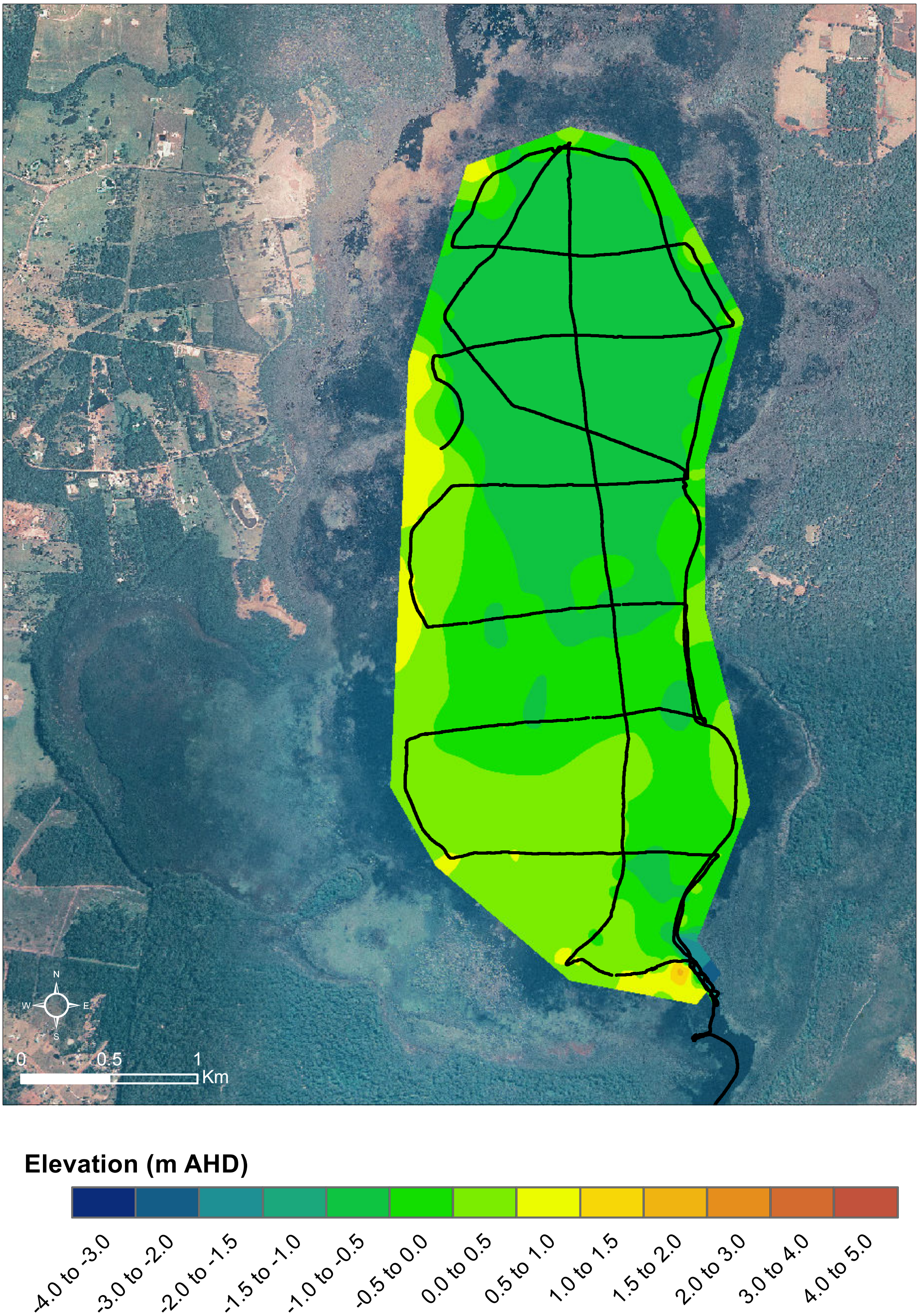
Location of Historical Levee and Proposed Levee



LIDAR Survey of Lake Cathie and Lake Innes Area
(AAMHATCH for Hastings Shire Council, 2005)



NSW Department of Public Works and Services (DPWS) 1993 Survey

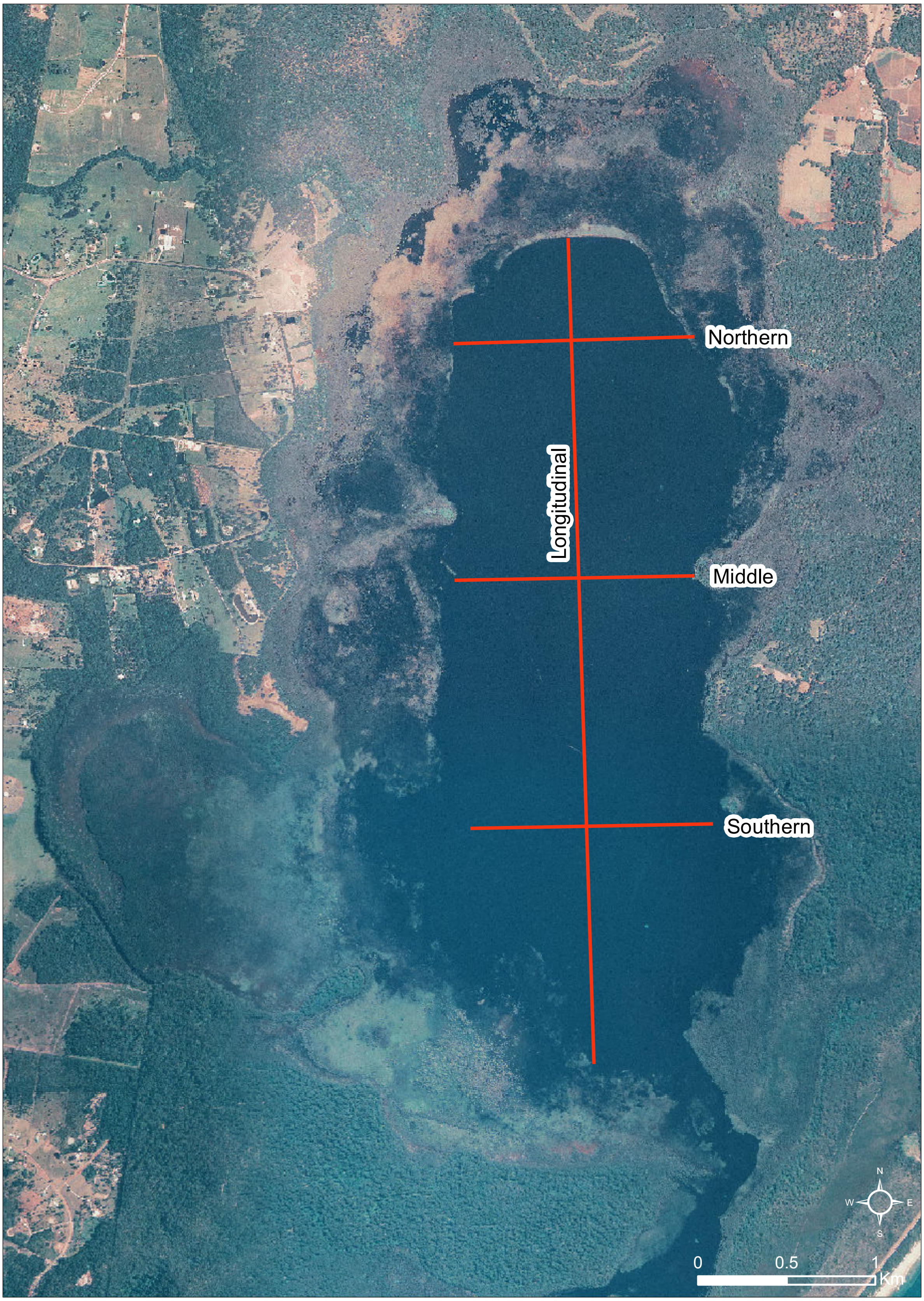


Water Research Laboratory (WRL) 2012 Survey

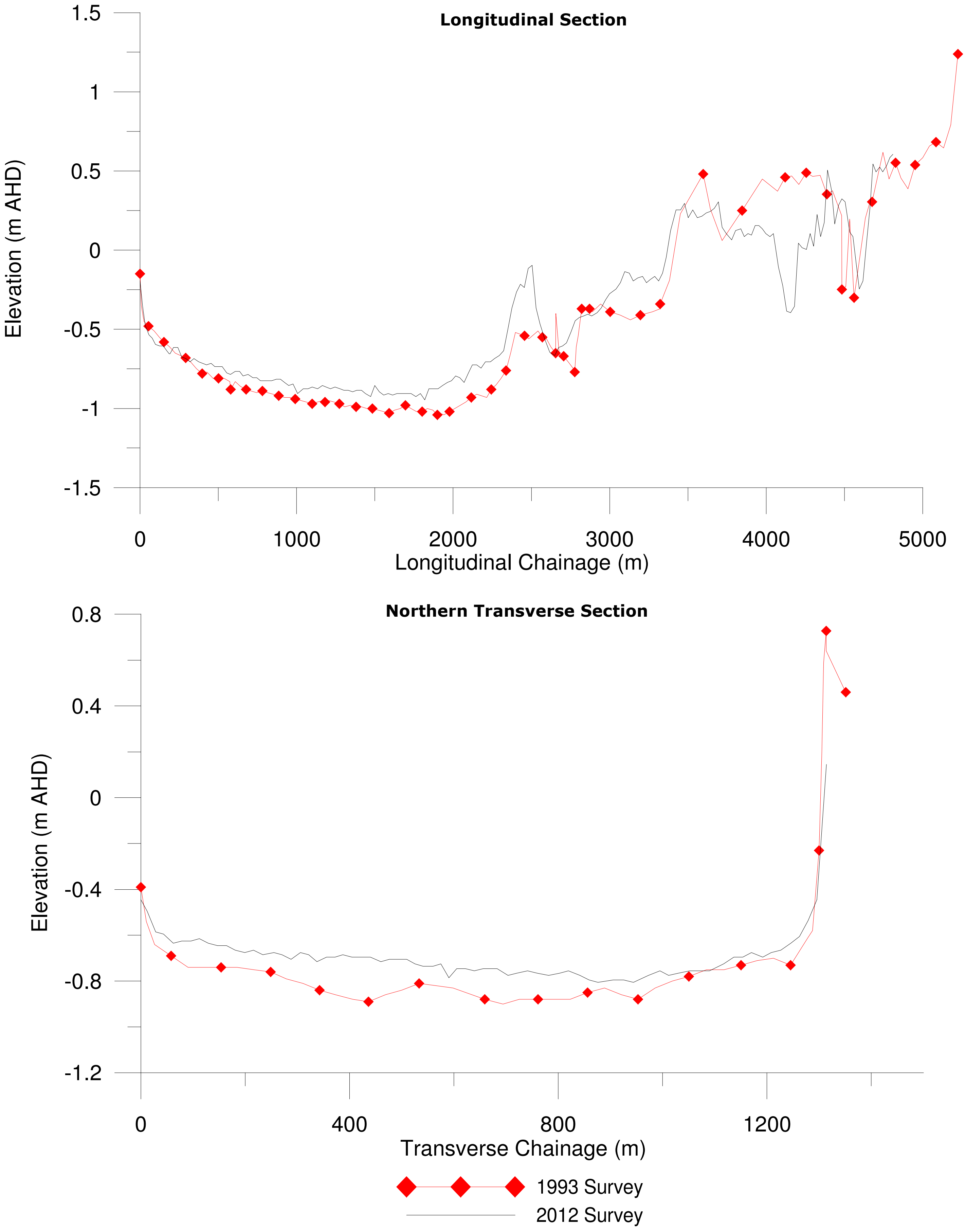
3.4a: Echosounder and RTK GPS Set-up

3.4b: Entrance Berm at Lake Cathie (15/08/2012)

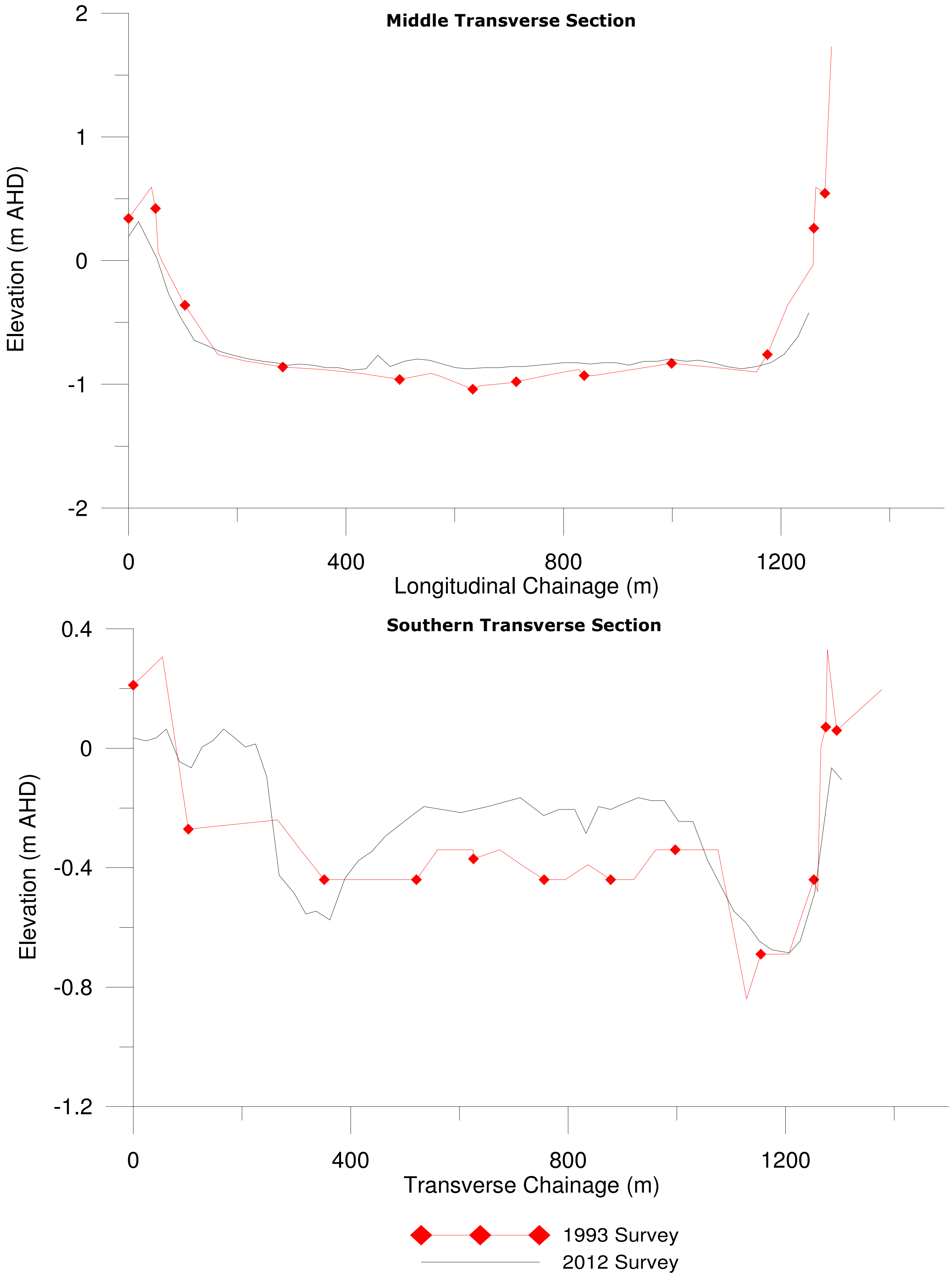
Boat Setup and Lake Cathie Entrance Berm



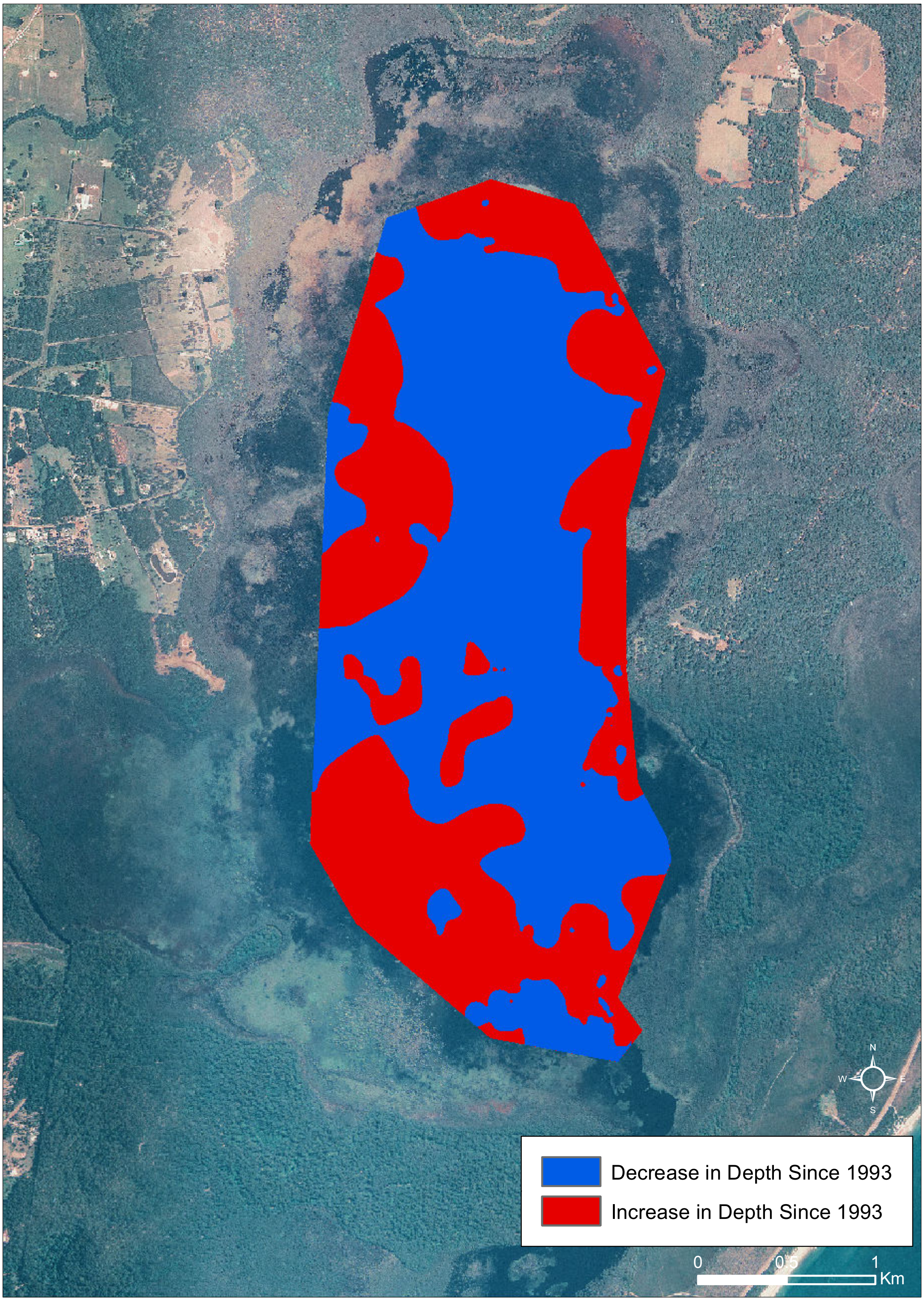
Indicative Location of Survey Comparison Sections



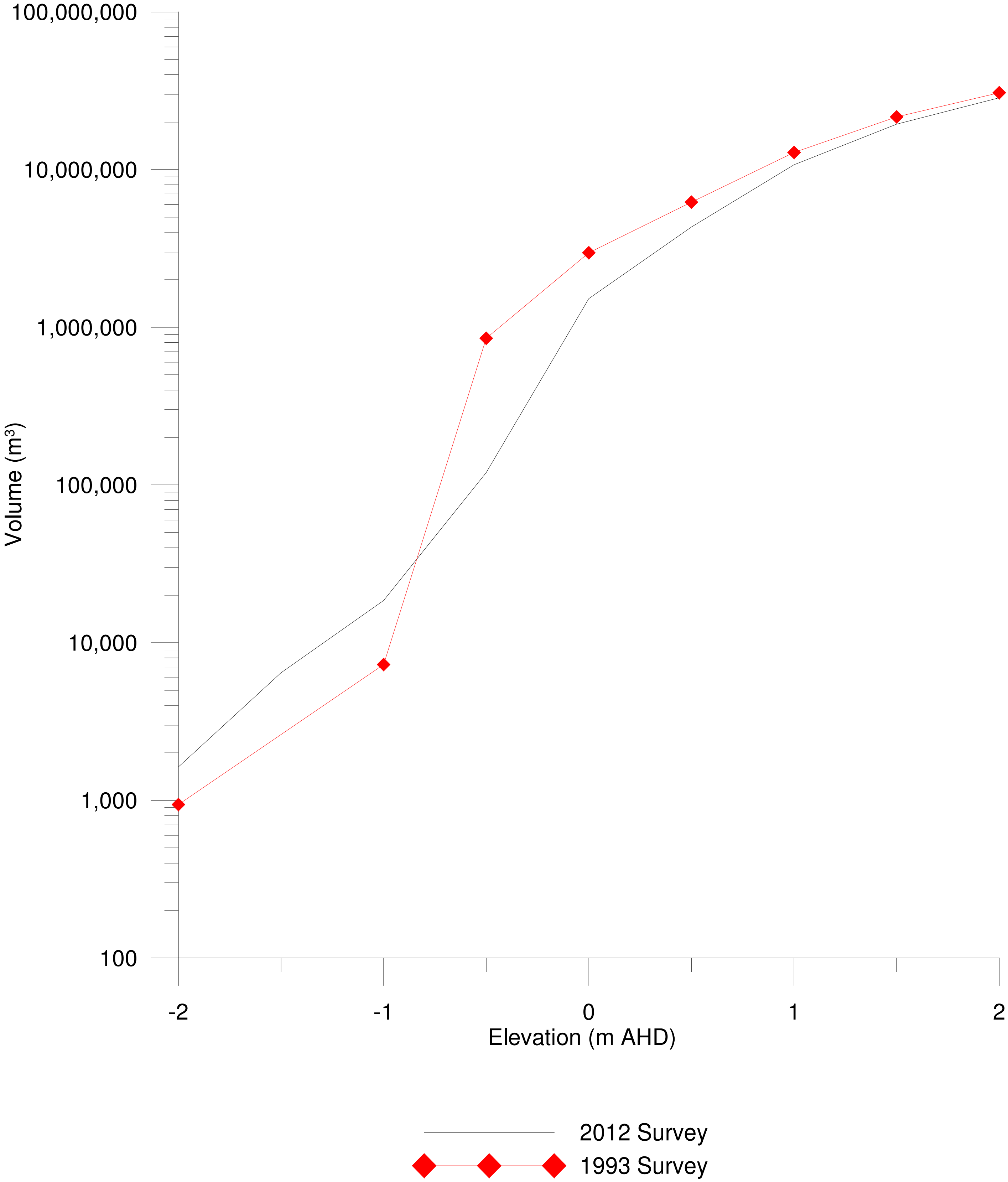
Lake Innes Cross-Section Comparison: 1993 vs 2012 Survey



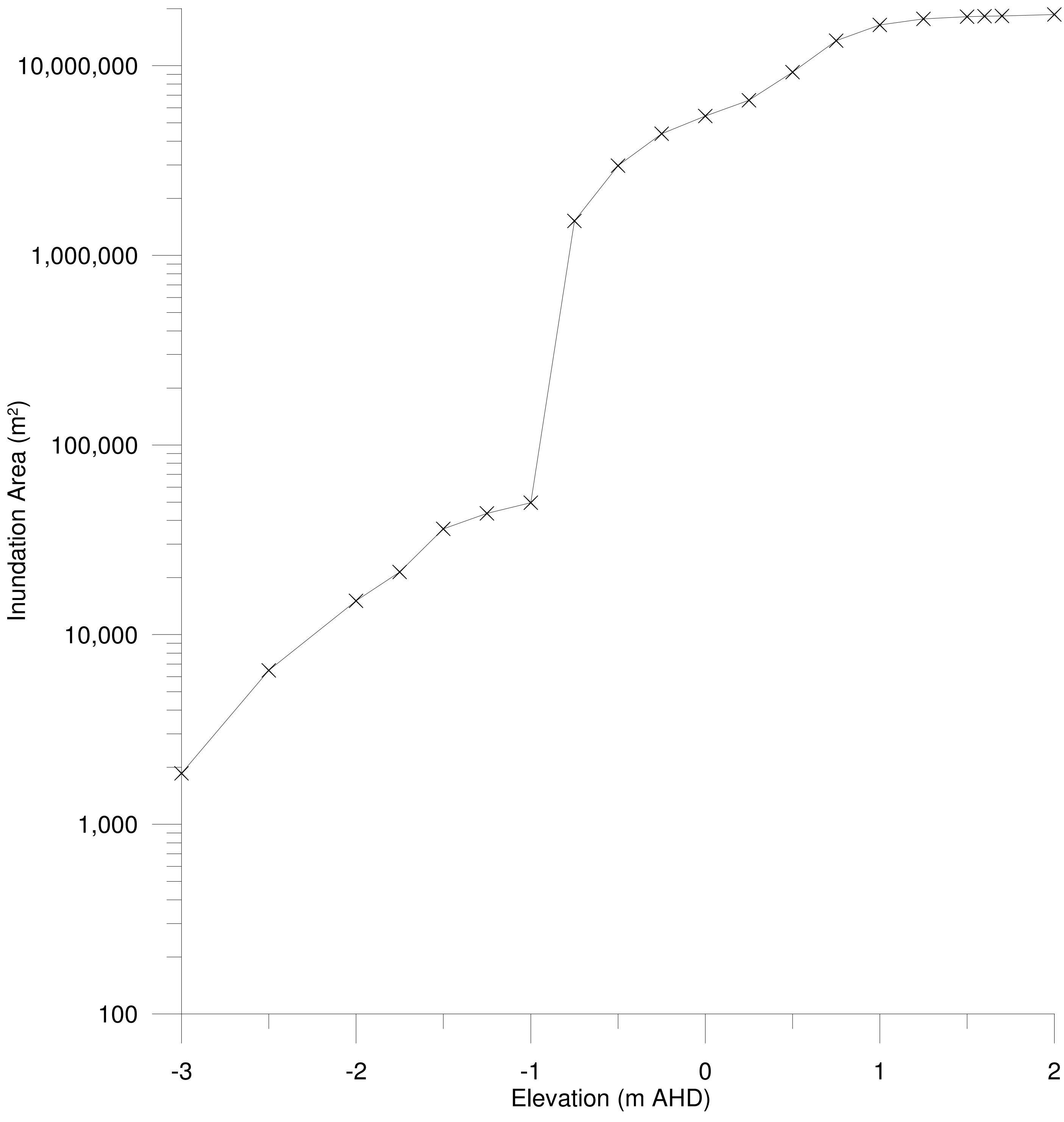
Lake Innes Cross-Section Comparison: 1993 vs 2012 Survey



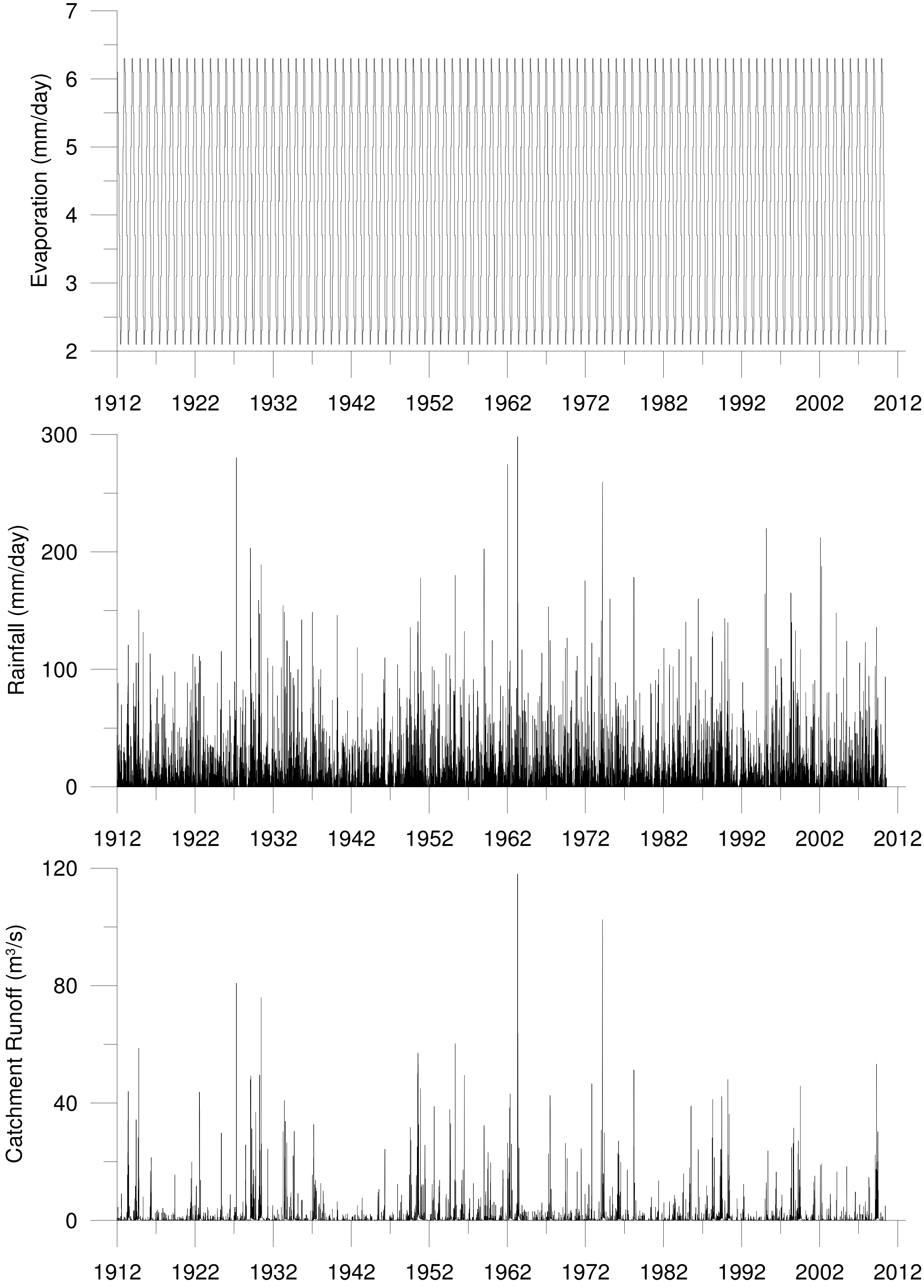
1993 and 2012 Interpolated Survey Comparison



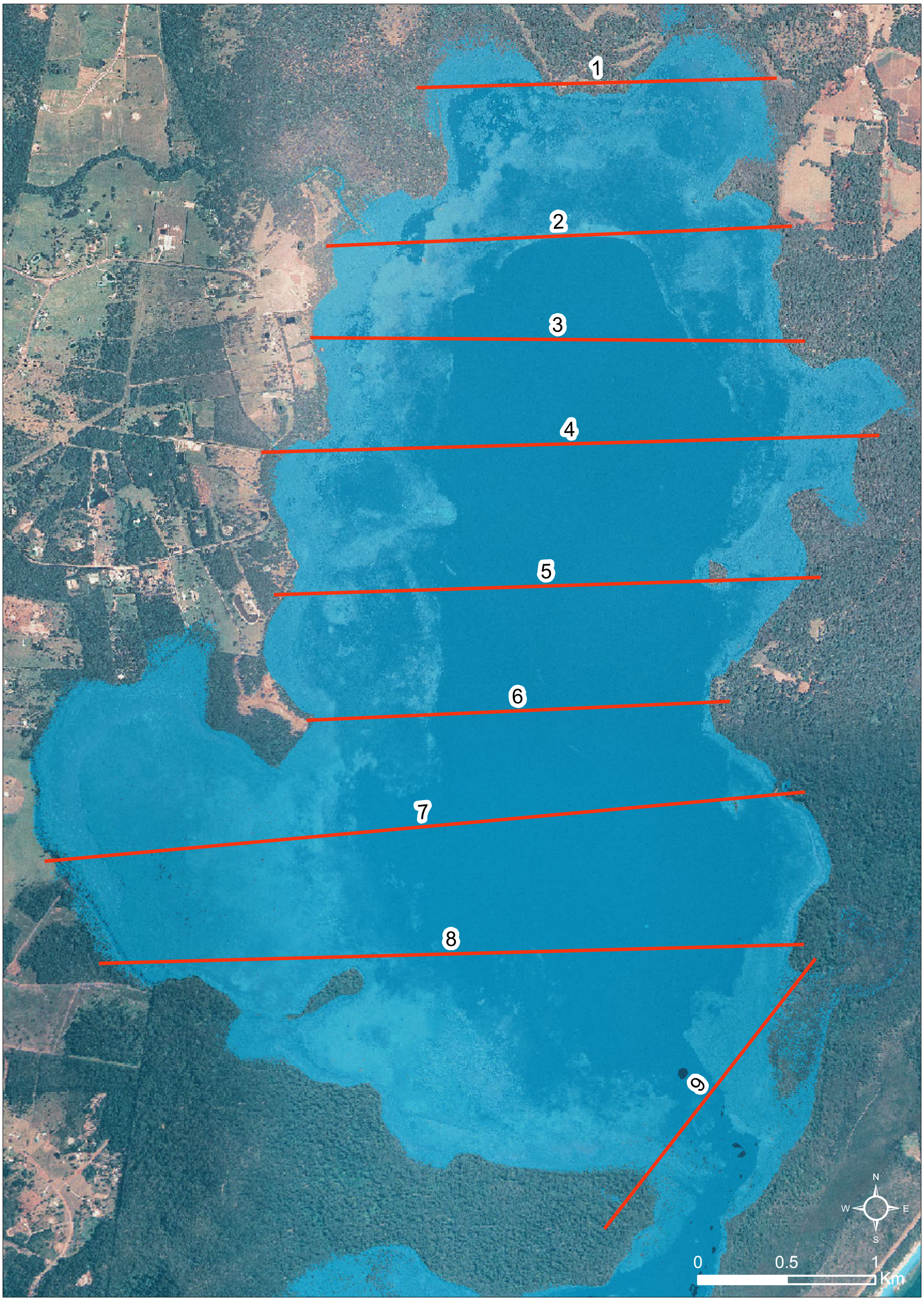
Lake Innes Survey Stage-Volume Comparison



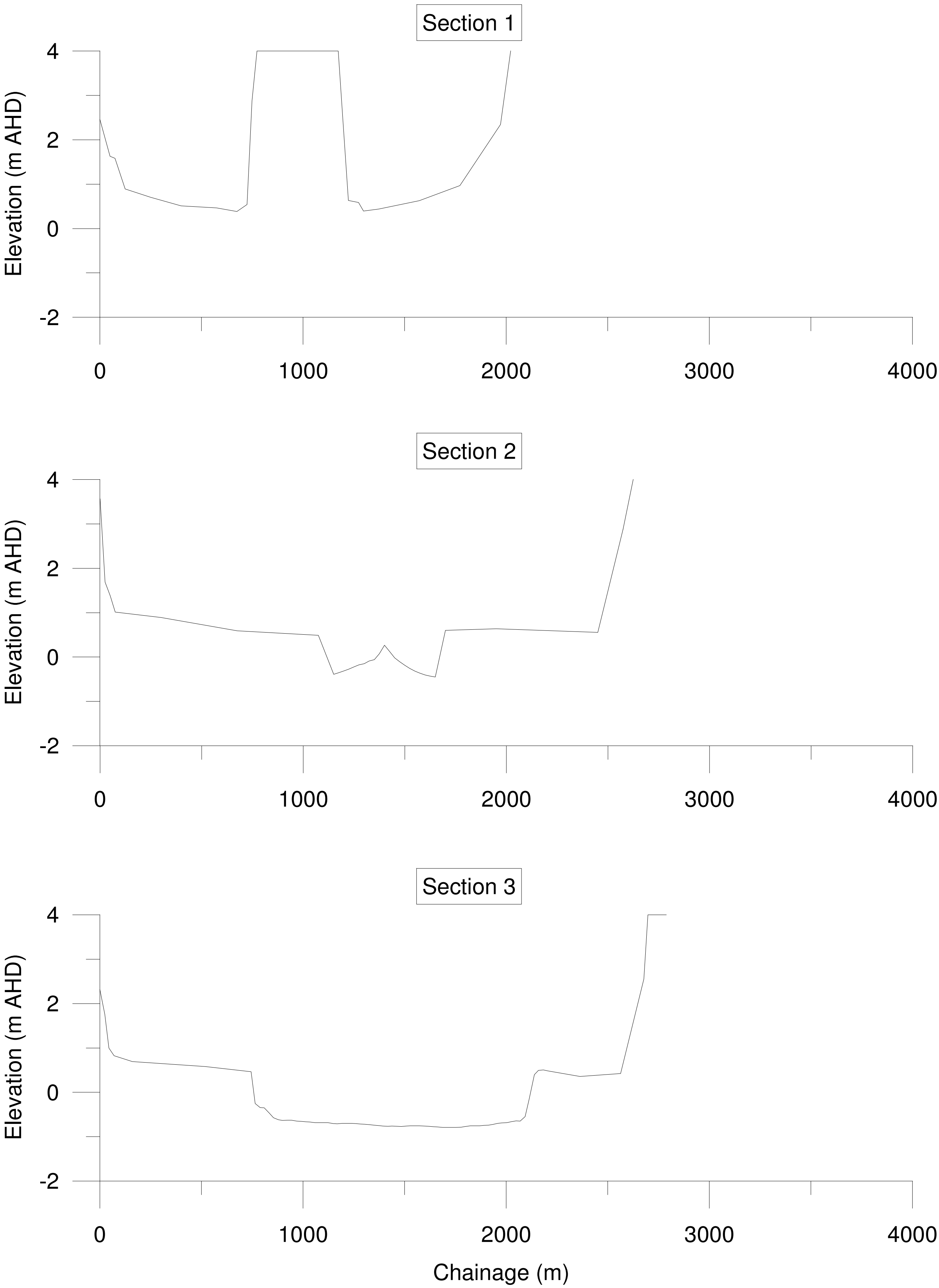
Lake Innes Survey Stage-Area Relationship



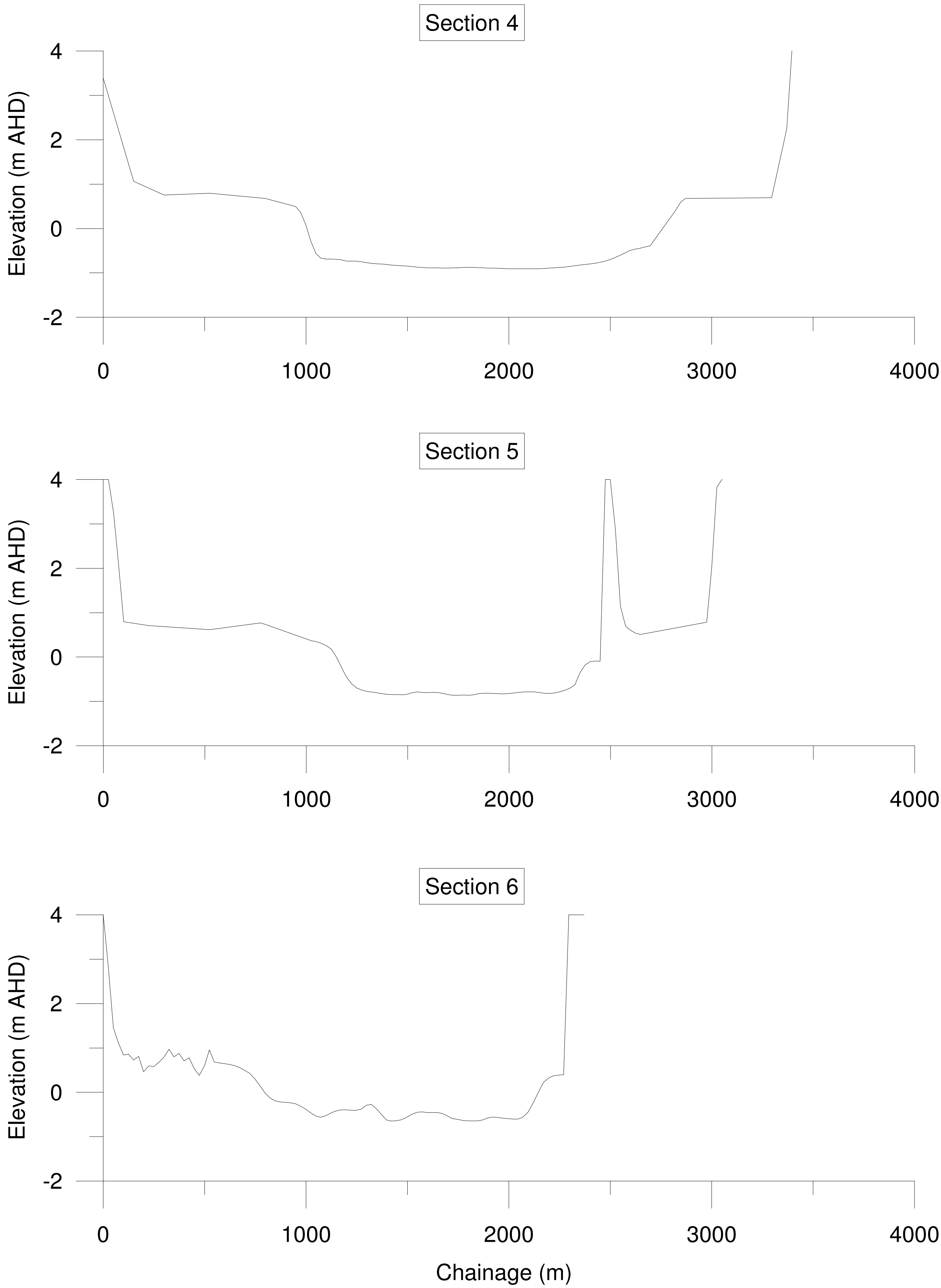
Rainfall, Evaporation and Catchment Runoff Timeseries: 1912 - 2010



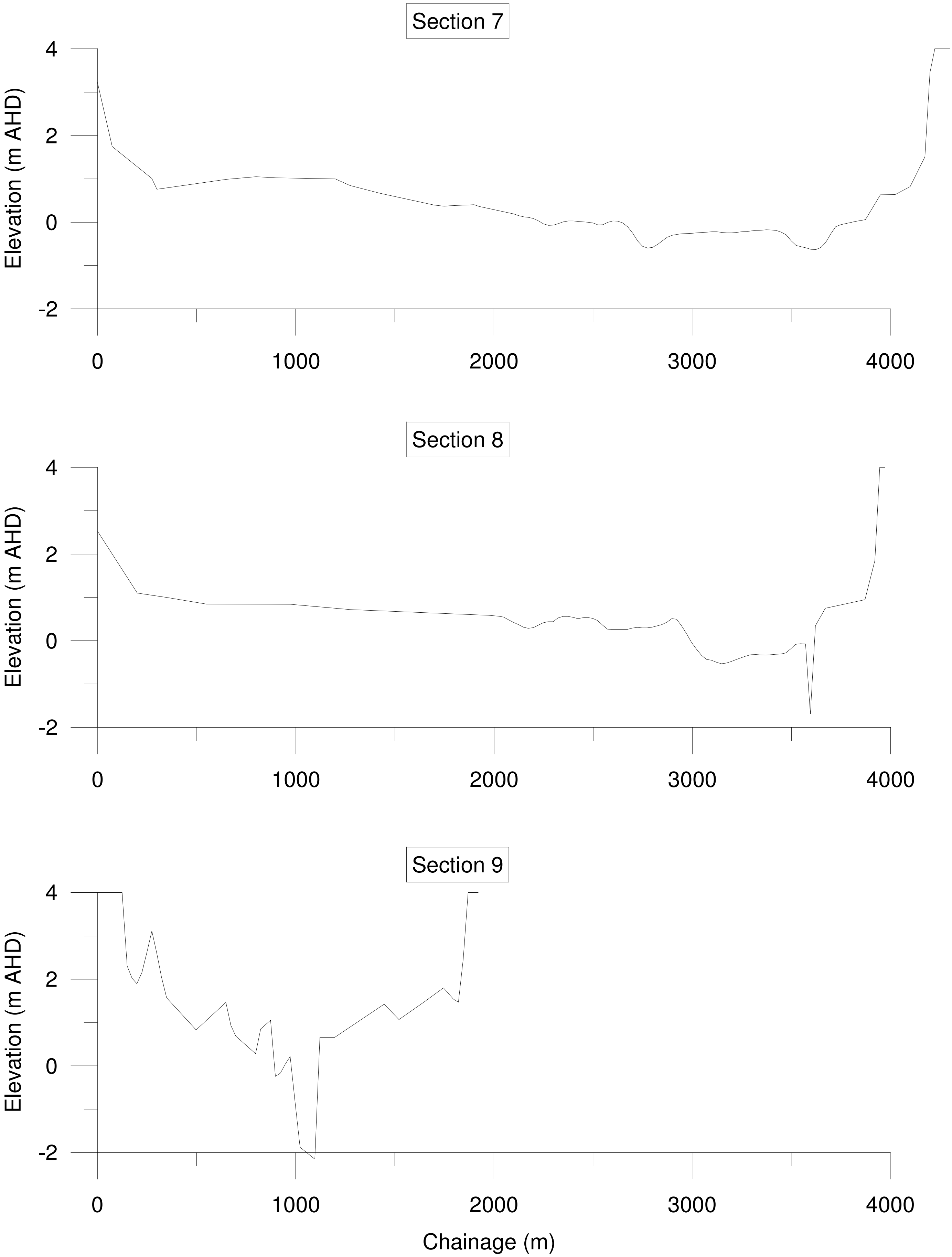
MIKE 1D Cross-Section Locations and Lake Extent at +1.6 m AHD



Lake Innes Model Cross-Sections



Lake Innes Model Cross-Sections



Lake Innes Model Cross-Sections

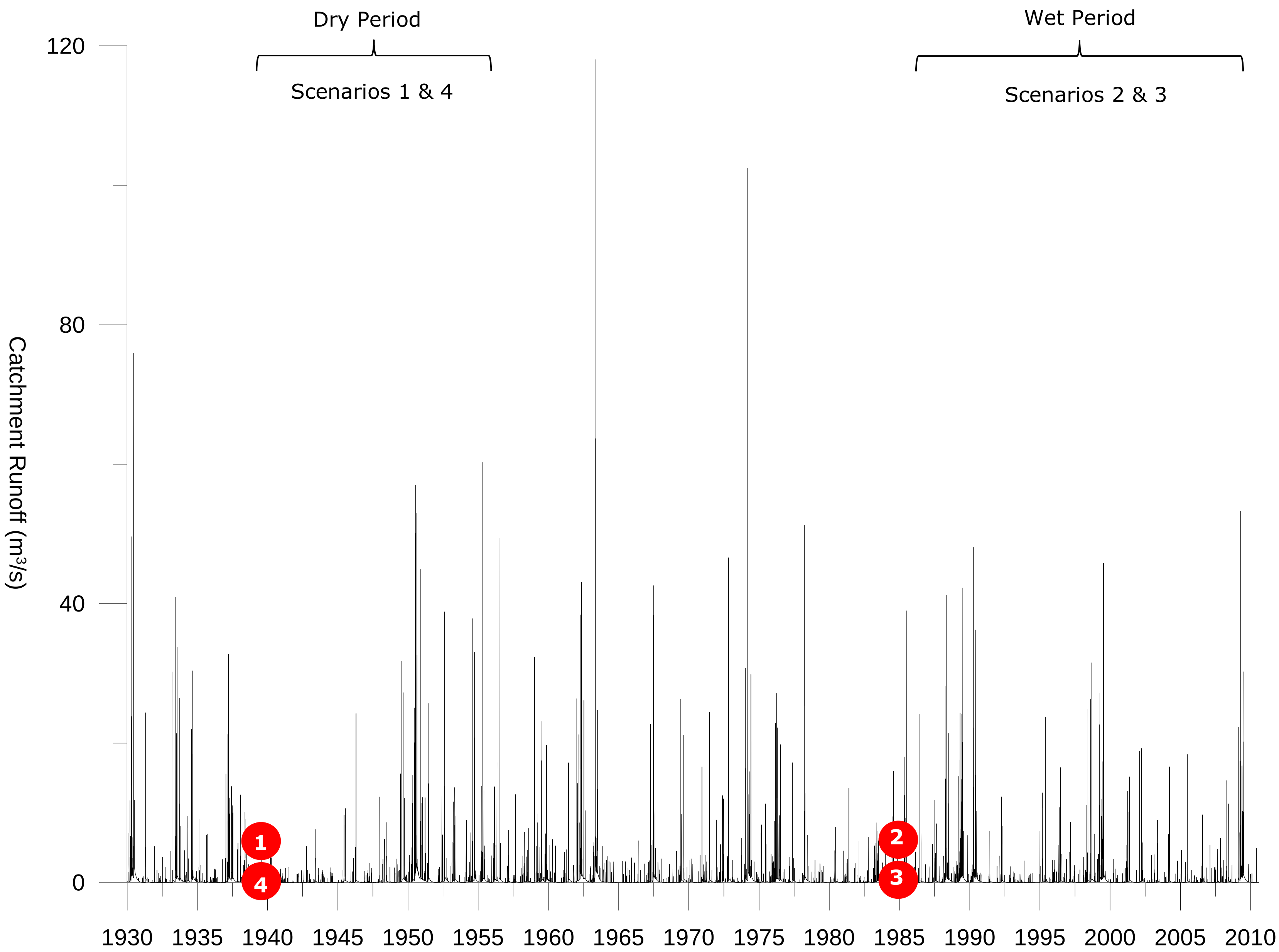
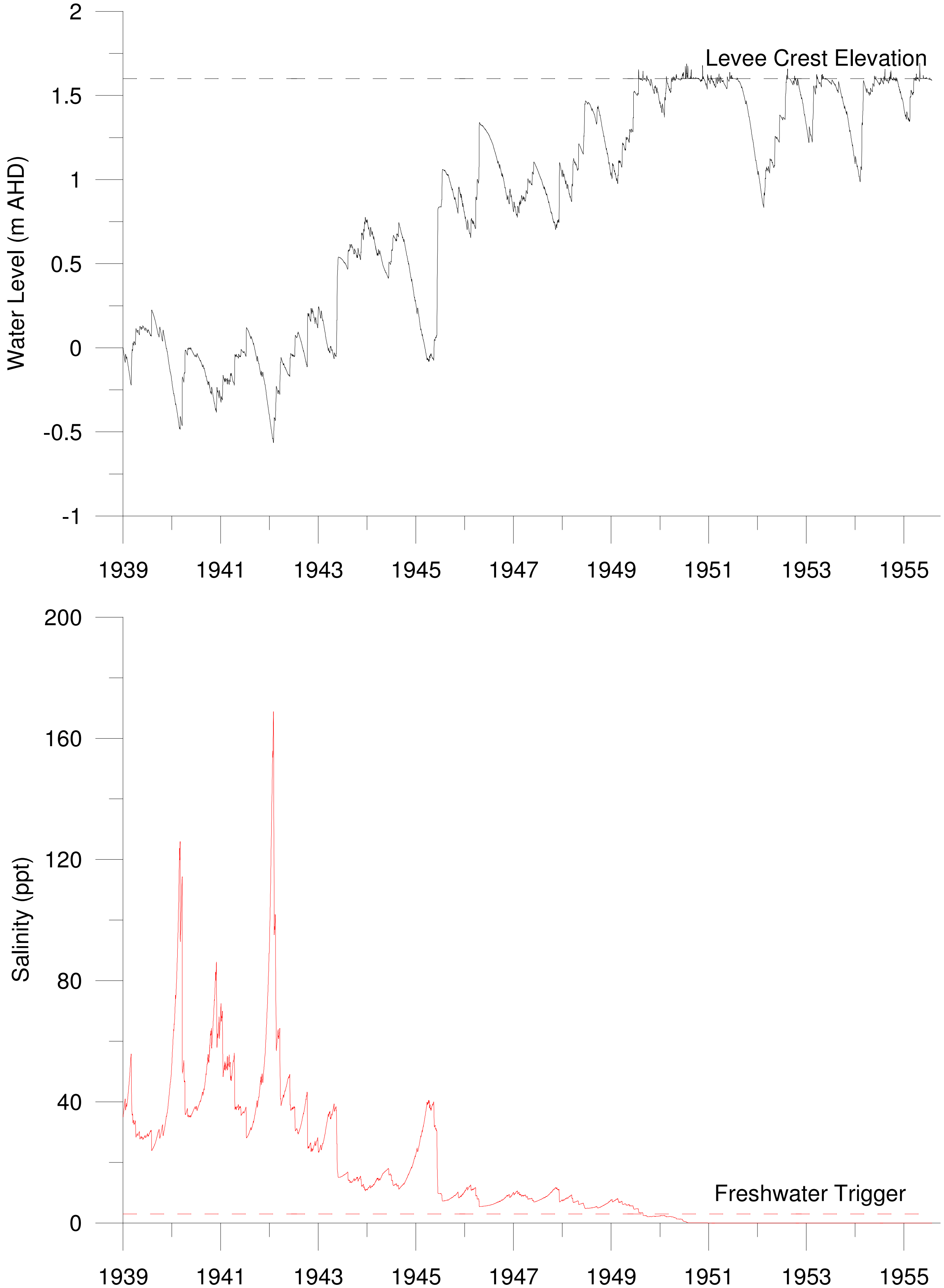
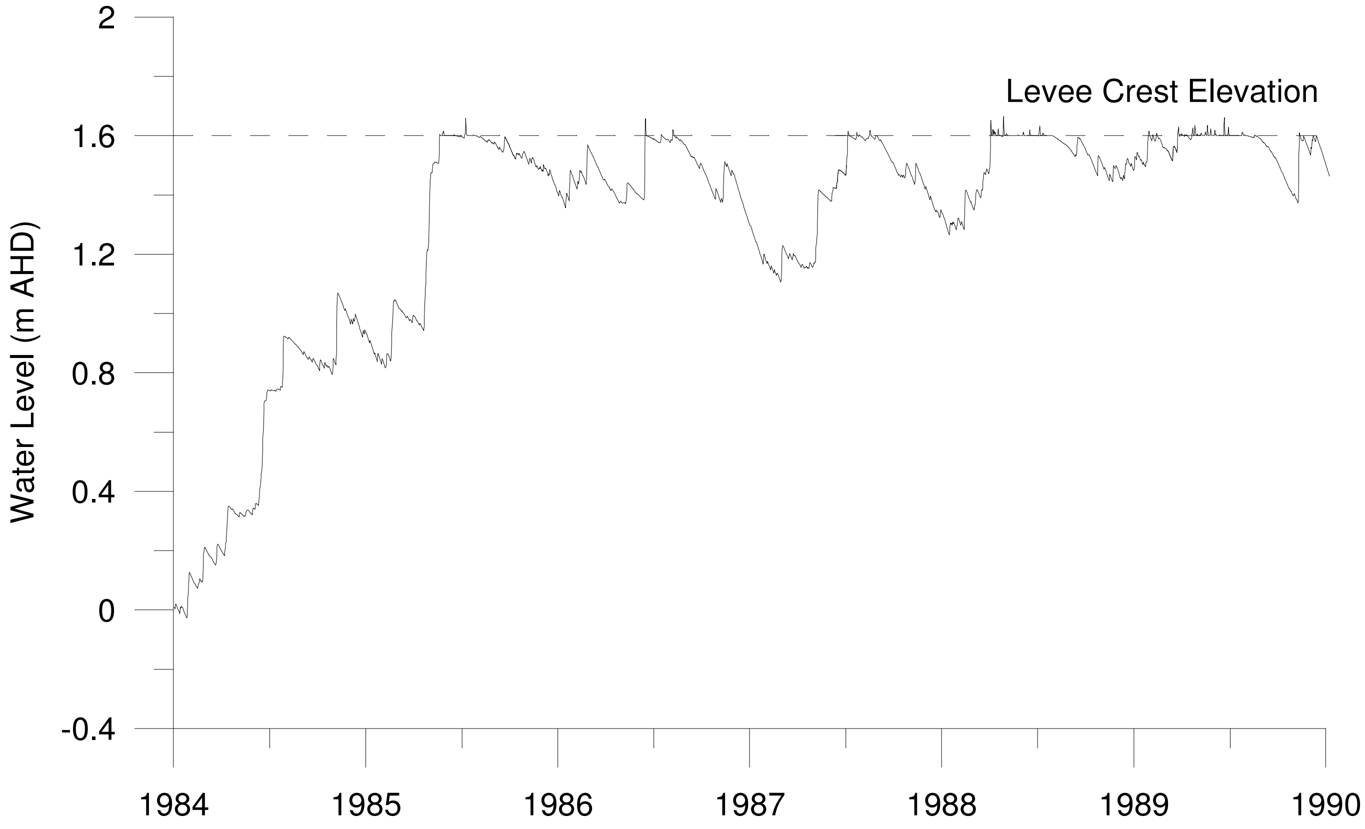
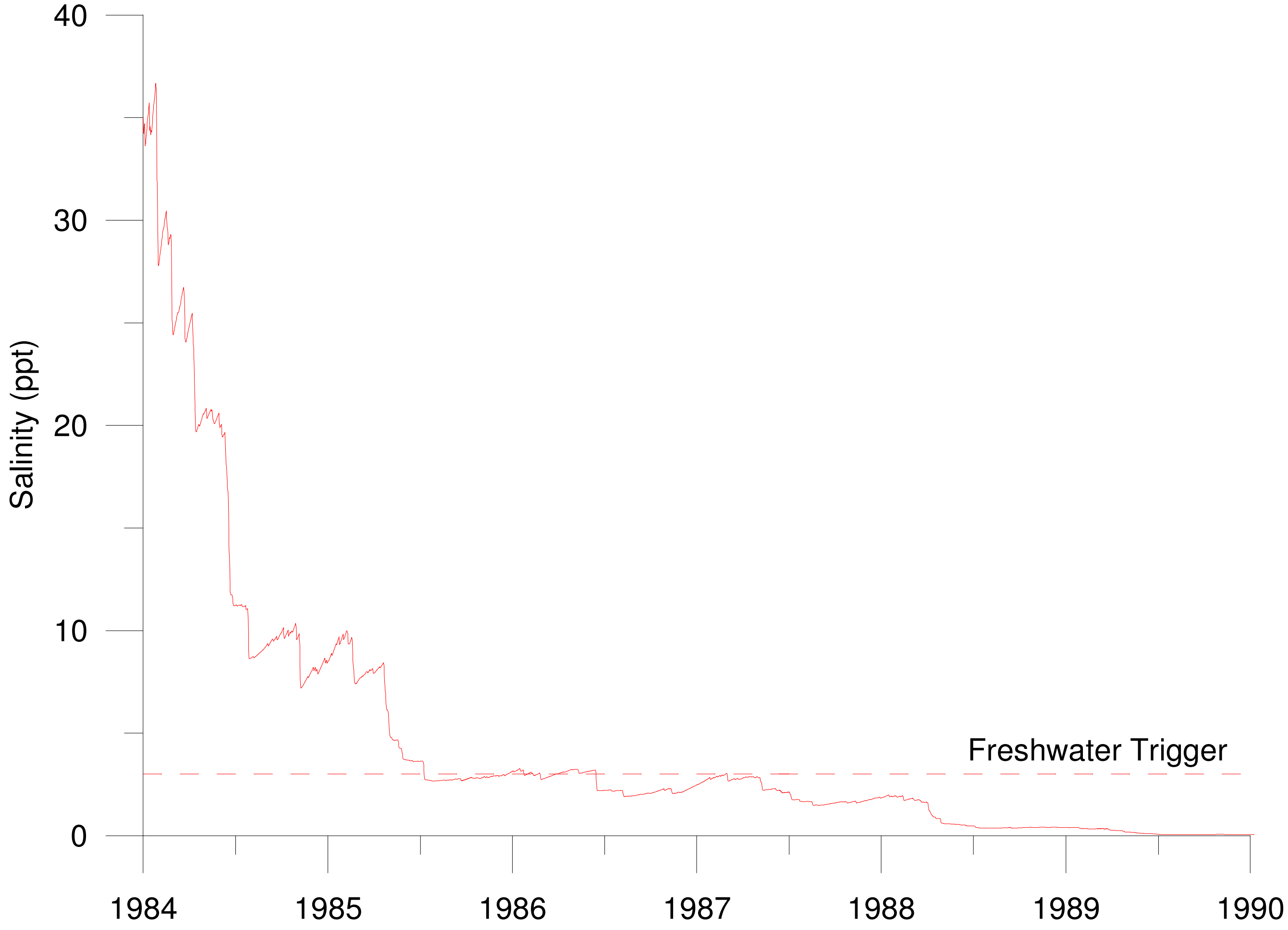


Figure 5.1 **Catchment Runoff and Scenario Start Dates**

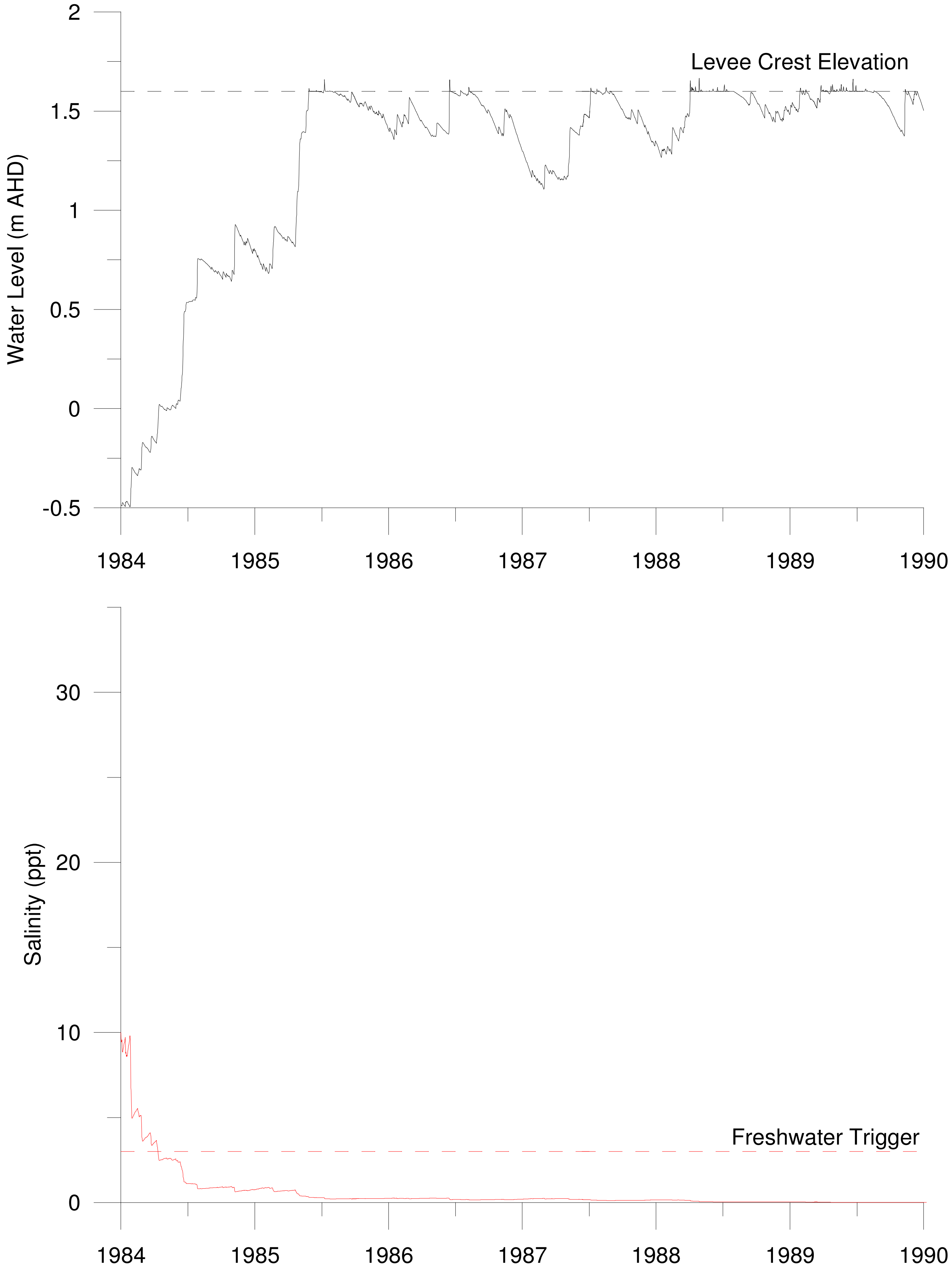


Scenario 1: Dry Period

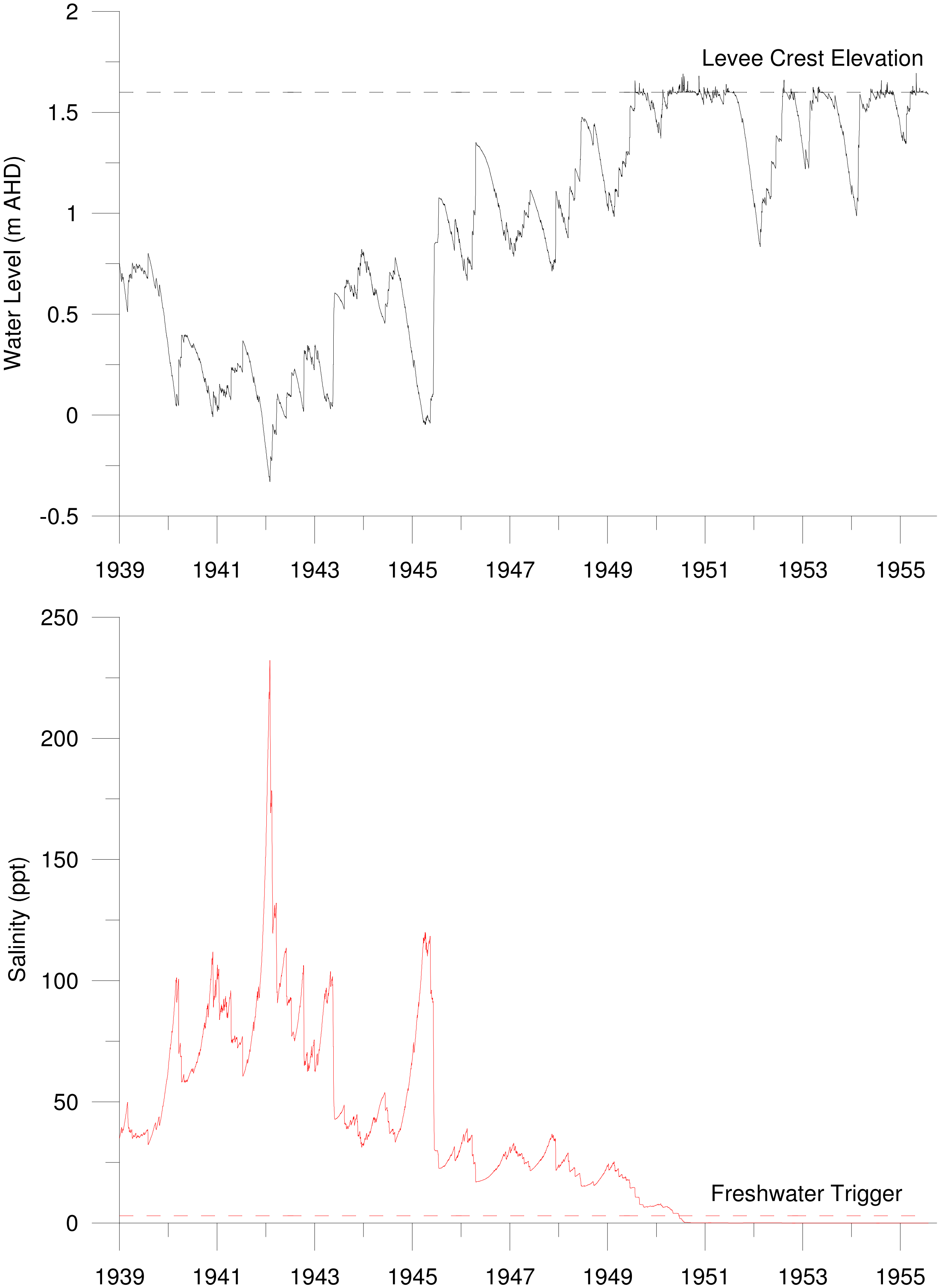




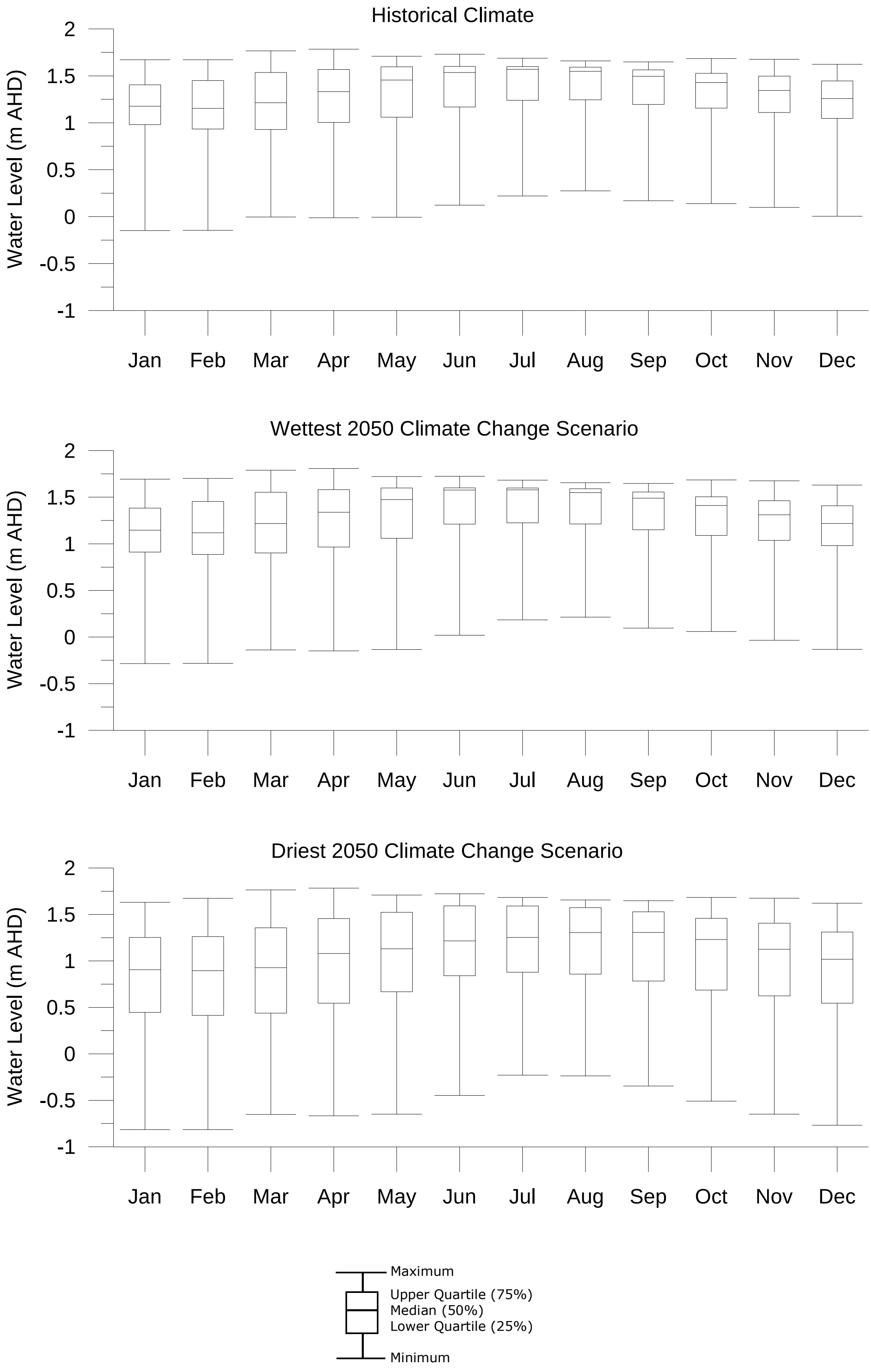
Scenario 2: Wet Period



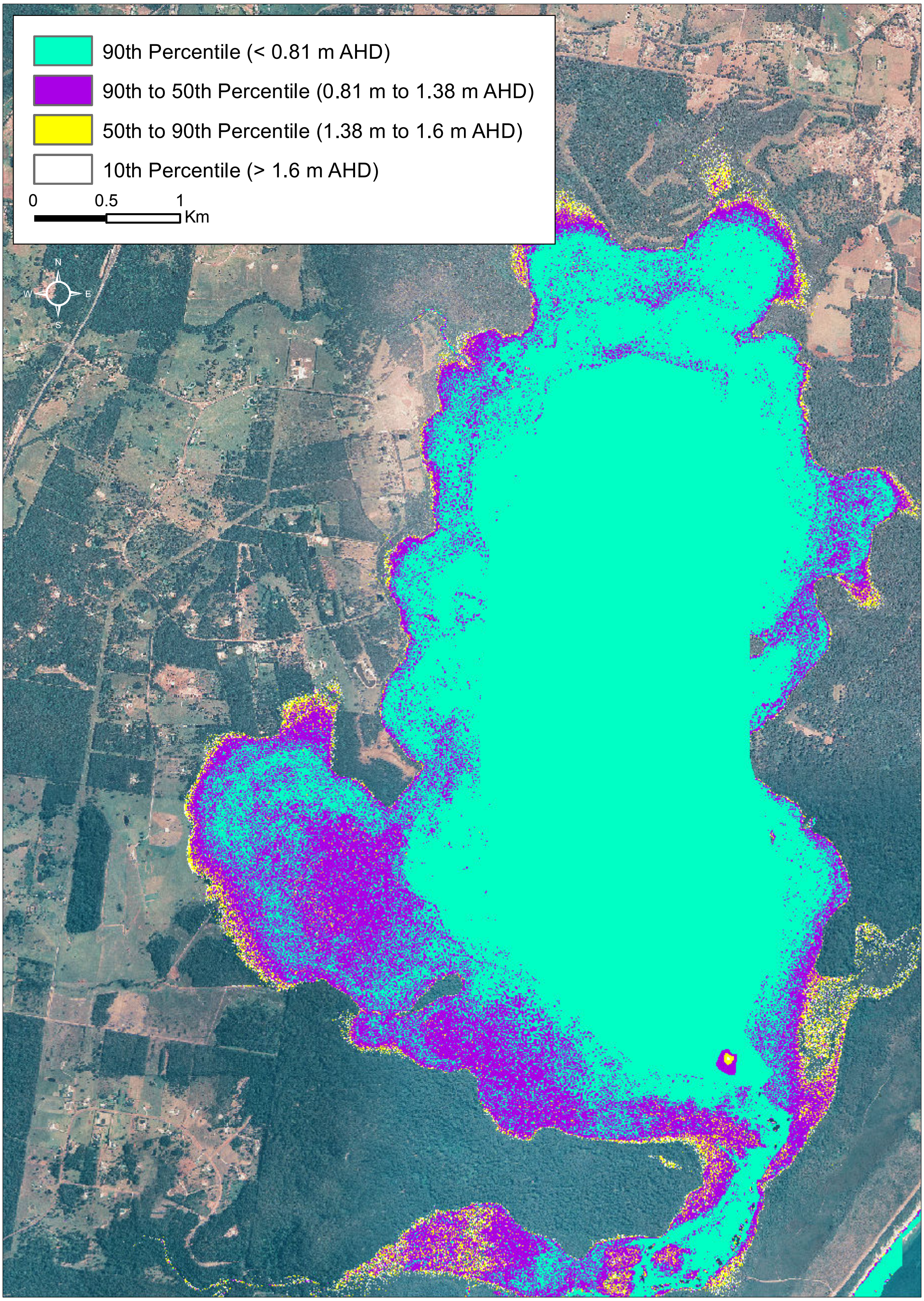
Scenario 3: Fast Saline Transition



Scenario 4: Slow Saline Transition



Long-Term Water Level Statistics



Lake Innes 99 Year Water Level Percentile Exceedence Contours

Location of Levee Assessed and Alternative Levee Location