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Waterhole refuge mapping and persistence analysis in the Lower Balonne and Barwon–Darling rivers

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Glossary

Term	Definition
Baseline	Baseline hydrological model that represents 114 years of historic inflows (1895-2009) under 2009 conditions of development (i.e. before the Basin Plan)
BOM	Bureau of Meteorology
cm	Centimetre
CTF	Cease to flow
DEM	Digital Elevation Model
DNRM	Queensland Department of Natural Resources and Mines
DO	Dissolved oxygen
DPI Water	New South Wales Department of Primary Industries Water
DSITI	Queensland Department of Science, Information Technology and Innovation
EC	Electrical conductivity
ESLT	Environmentally Sustainable Levels of Take
EWR	Environmental Water Requirements
GIS	Geographic Information Systems
GISP	Greenland Icesheet Precipitation
GL	Gigalitre
GS	Gauging Station
IAEA	International Atomic and Energy Agency
MDB	Murray–Darling Basin (referred to as northern Basin)
MDBA	Murray–Darling Basin Authority
ML	Megalitre
NS	Northern Standard hydrological model that represents 114 years of historic inflows (1895-2009) under a fully implemented Basin Plan
RMSE	Root Mean Square Error
SDL	Sustainable Diversion Limit

Term	Definition
SLAP	Standard Light Antarctic Precipitation
TDS	Total Dissolved Solids
ToC	Threshold of Concern
UEA	Umbrella environmental asset
UQ	University of Queensland
USGS	United States Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
WOD	Without development

Executive Summary

Australia's dryland rivers exist in an environment which is characterised by long periods without significant inflows of water. During these dry periods, rivers dry into a series of waterholes which are an important resource for agriculture, town water supplies, industry and other human consumptive uses. They also serve an important ecological function by providing refuge habitat for aquatic organisms. It is for these reasons that waterholes have been identified as important environmental habitats in the northern Murray–Darling Basin (northern Basin).

The length of time that waterholes are able to hold water without inflows (the persistence time) is an important determinant of how well they serve their functions as drought refuges for aquatic organisms. To maintain populations of aquatic organisms, a network of persistent waterholes is required to last through extended dry periods.

The spatial distribution of persistent waterholes is also important in their functioning as drought refuges. The refuge waterholes need to be numerous enough and distributed such that when they are connected during flow, the biota within the waterholes are able to move throughout the system and recolonise other parts of the river.

Water resource development has altered many dryland river systems by changing the frequency and magnitude of flow events, thus impacting how often waterholes are re-filled. Changed hydrology may also threaten waterhole persistence by altering the frequency with which sediment is flushed through the system, potentially reducing the volume of water they hold.

To inform the management of river systems in a way consistent with a healthy working Basin sought under the Basin Plan, there is a need to understand how long waterholes can persist and how the spatial distribution of persistent waterholes changes as a drought progresses. The waterholes project was commissioned by the Murray–Darling Basin Authority to improve understanding of the location and persistence of waterholes in the Lower Balonne and Barwon–Darling regions of the northern Basin as part of the Northern Basin review. The project was undertaken by scientists in the Department of Science, Information Technology and Innovation (Queensland) and the Department of Primary Industries, Water (NSW). This research project provides best available knowledge on waterholes and their persistence.

Key objectives

This project addressed knowledge gaps about the location and persistence of waterholes in the Lower Balonne and the Barwon–Darling, with detailed field work and modelling done for a subset of over thirty waterholes along the Culgoa, Narran and Barwon–Darling rivers. The research questions addressed were:

- Where are persistent and refuge waterholes across the Lower Balonne and Barwon–Darling regions?
- How long do waterholes persist in this region?
- Does groundwater impact the persistence time of waterholes?
- Does sedimentation affect waterhole persistence?

- Can the persistence time of waterholes across the northern Basin be predicted using a generic model?
- Do hydrological modelling scenarios show an impact from water resources development and a benefit from the recovery of environmental water to the persistence of waterholes (modelling period between 1895–2009 for a range of different management conditions, including without development, 2009 pre-Basin Plan baseline conditions of development, and hypothetical recovery scenarios)?

To answer these questions a combination of techniques were used: these include remote sensing to detect water during actual periods of no flow between 1988–2015, and mapping the shape and depth of waterholes and measuring water loss to develop a model to predict persistence. Field work was also undertaken to answer the questions about groundwater interactions and sedimentation processes.

Key Findings: Barwon–Darling

Key findings from this project for the Barwon–Darling were:

1. Waterholes in the Barwon–Darling persist under water resource development because the river is generally deep (measured to be up to 8 metres) and no flow spells are short, due to flows from several major tributaries and changed hydrology resulting from weirs. Therefore, there was no need to assess the impact of hypothetical water recovery scenarios for waterhole persistence in the Barwon–Darling.
2. Groundwater interaction is unlikely to affect waterhole persistence in the Barwon–Darling.

Key Findings: Lower Balonne

Key findings from this project for the Lower Balonne were:

1. **Distribution** – remote sensing analysis found that the Lower Balonne has about ten waterholes that retain water for one year or longer without flow (Figure 1). These waterholes are located in the mid to lower reaches of the Narran River, and the mid reach of the Culgoa River. Only half of these refugial waterholes remained wetted across the entire time-series between 1988–2015, with all of these being on the Narran River (Figure 2).

   There are also waterholes that persisted across the time-series but did not experience periods of no flow longer than a year. These waterholes are directly below Beardmore Dam, and at the lower end of the Culgoa River.

   The identification of persistent waterholes across the focus regions is important for water management, as these waterholes are likely to provide the only habitat for populations of aquatic biota during future dry periods.

2. **Persistence modelling** – the waterholes in the Culgoa and Narran river valleys were generally less than 3 metres deep and had average modelled persistence time of 377 and 355 days respectively (that is, about a year). After a year, only some waterholes remain to provide drought refuges. On the Culgoa River, the maximum modelled persistence time was 587 days (1.6 years). On the Narran River, the maximum modelled persistence time was 637 days (1.75 years).

3. **Depth-Persistence relationship** – depth is a very good predictor of persistence in the study region (with natural and weir pool waterholes having similar water-loss characteristics). In the Culgoa, Narran and Moonie river valleys (Moonie waterholes investigated as part of a previous project), the persistence of a waterhole can be predicted using a single depth measurement with the following formula:

   $$\text{Persistence (days)} = \text{Depth (metres)} \times 168.91$$

   The formula indicates that for every one metre of depth, the waterhole lasts roughly 170 days. This formula can be applied to other waterholes in the region once their depth is known.

4. **Groundwater** – groundwater contribution to waterholes along the Narran and Culgoa rivers is minor.

5. **Sedimentation** – analysis of sediment data and core samples is expected to be completed by mid 2016. Results will be released in a supplementary report. The probing results are available and provided in Appendix A of this report. These results give an indication of the depth of soft sediment in the waterholes, ranging from 13 to 49 centimetres average accumulation. When available, the additional results and analyses will provide information on how waterholes are scoured, and if the persistence of waterholes is at risk from filling with sediment over time.

6. **Assessment of hypothetical water recovery scenarios**

   a. Persistence thresholds at the individual modelled waterhole and reach scales were used to assess whether water resource development poses a risk to waterholes in the Lower Balonne acting as refugia. The hydrology modelling has shown that waterholes are under more stress more often under water resource development (as represented by the baseline conditions scenario) as compared to the without development scenario. An important persistence threshold of 550 days was simultaneously breached more often across the reaches of the Culgoa and Narran rivers. This threshold represents the system at a critical stage with only 10% of modelled waterholes retaining water and none being deeper than half a metre. Importantly, water resource development also resulted in system failures for parts of the Narran River (periods of no flow exceeding 720 days) on two separate occasions that did not occur under without development scenario.

   a. While there is no evidence that complete region wide loss of waterholes is likely to occur in the Lower Balonne under the baseline conditions, the results show water resource development poses a significant risk to the function of waterhole as refugia in the region. The ecological consequence of the risks could include reduced population viability or loss of local populations of biota that rely on the network of connected waterholes (such as fish and turtle species). Ecological recovery, following a prolonged drought that exceeds the refuge persistence times, would depend on repopulation from other parts of the Basin.

Recommendations

These findings give a sufficient understanding of the system to make the following recommendations:

- Identified waterholes that provide important refuge most of the time and those that never dried up, should be maintained to ensure the viability of populations of organisms that rely on aquatic habitat.
- To have a high likelihood of sustaining waterholes across the Lower Balonne region, flows should occur every one and half years (550 days). This threshold represents the system at a critical stage with only 10% of modelled waterholes retaining water and none being deeper than half a metre. Spells without flow longer than this would be of major concern for the sustainability of waterhole function.
- Flow indicator gauges should be specified separately on the Culgoa and Narran rivers to represent the different flows and waterhole characteristics along the two rivers. Brenda, or the downstream Weilmoringle, gauge is considered an appropriate gauge to investigate flows needed to sustain waterholes located in the Culgoa River valley. An additional gauge on the Narran River should be used to investigate flows needed to sustain the identified refugial waterholes in that river valley. Downstream gauges are generally preferred for this purpose as waterholes further upstream will have been filled if flow is registered at a downstream gauge.
- Identify and model different flow management options that can protect specific events during drought that will ensure waterholes do not dry up during these times.

Further work is recommended to improve the physical and ecological understanding of waterholes as drought refuges. Three key areas of further research include:

- Collect additional data on waterhole depths at cease to flow to give a better understanding of waterhole persistence throughout the region.
- Review the impact of sedimentation on waterholes after the supplementary report is available.
- Investigate the depths at which habitat and water quality decline in persistent waterholes across the Lower Balonne.
- Investigate how the spatial distribution of waterholes across the Lower Balonne maintains populations of aquatic organisms, which could be informed by the movement behaviour of important species of biota.

Similar work could also be conducted in other areas of the northern Basin where there are temporary rivers that contain waterholes at risk from water resource development.

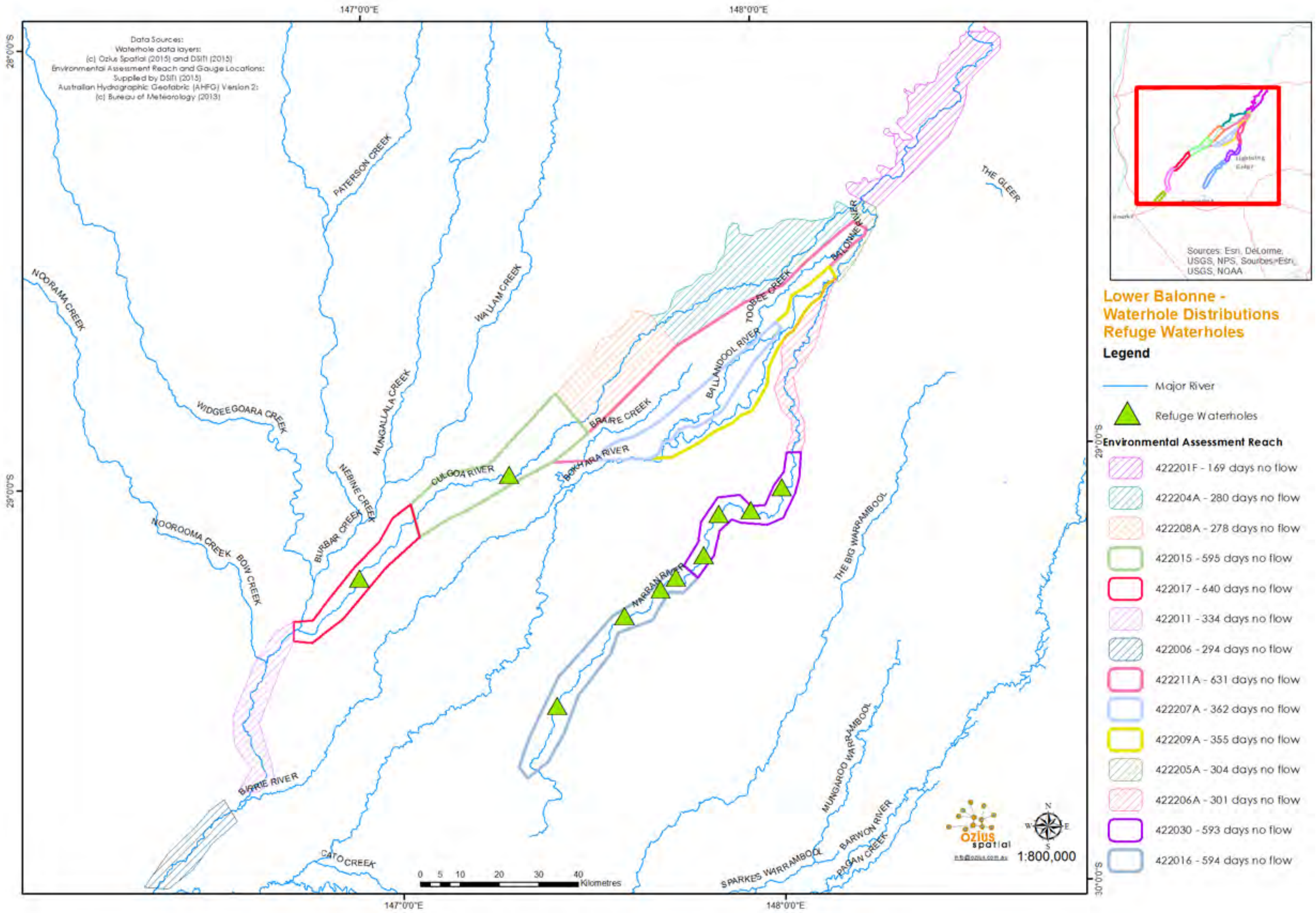

Figure 1 – Locations of refuge waterholes (i.e. those that retained water after 350 days without flow) across the Lower Balonne. The longest no flow period captured by Landsat for each gauge is indicated in the legend. Hatched areas had a maximum no flow period less than 350 days.

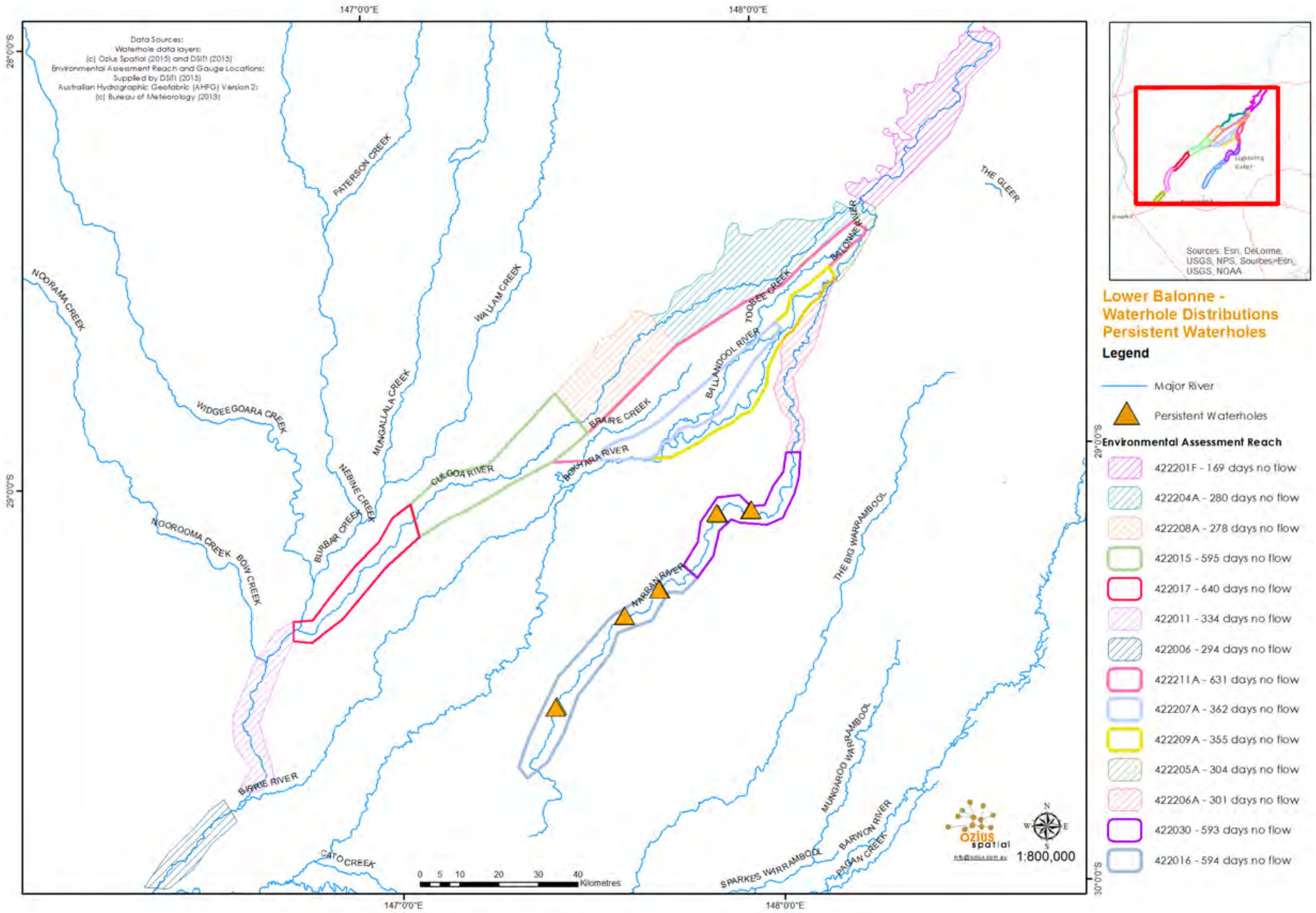

Figure 2 - Location of waterholes that retained water during all dry periods longer than 350 days from 1988 to 2015 in the Lower Balonne. The longest no flow period captured by Landsat for each gauge is indicated in the legend. Hatched areas had a maximum no flow period less than 350 days.

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1.1 Background

The *Water Act 2007* introduced key reforms in the Murray–Darling Basin (the Basin), including the establishment of the Murray–Darling Basin Authority (MDBA) to manage this vital resource in an integrated and sustainable way (Sheldon et al. 2014). Under the Act, the MDBA were required to prepare a strategic plan for water resource management and, developed the Murray–Darling Basin Plan (Basin Plan) (Commonwealth of Australia 2012).

An important aspect of the Basin Plan is the introduction of new limits on the amount of water that could be taken for consumptive uses to ensure there is a healthy and working basin including the river and groundwater systems across all catchments. The long term average sustainable diversion limits (SDLs) were determined based on an assessment of the environmentally sustainable levels of take (ESLT) for each catchment (MDBA 2011a). A shared reduction target was also set for each zone within the Basin Plan, which includes the southern Basin and northern Basin zones (Figure 1.1).

Refugial waterholes were identified as an important environmental asset for the Lower Balonne ‘umbrella environmental asset’ (UEA); however specific information about their location and how long they could persist during no flow spells in this catchment was very limited (DERM 2011). The watering requirements of refugial waterholes were not explicitly accounted for in the environmental water requirements (EWRs) developed for Barwon–Darling and Narran Lakes UEAs, even though they were identified as potentially important components of the ecosystem in these areas (Sheldon et al. 2014).

The Northern Basin Review was established to undertake research and investigations in the northern Basin by 2015. For the Northern Basin Review, northern Basin is broadly described as the Darling River and its tributaries upstream of Menindee Lakes (Figure 1.1). The aim of the Northern Basin Review is to address knowledge gaps through research projects, hydrologic modelling of water recovery scenarios and social and economic assessments (Sheldon et al. 2014). To address the knowledge gaps regarding refugial waterholes in the northern Basin the MBDA engaged Queensland’s Department of Natural Resources and Mines (DNRM) and Department of Science, Information Technology and Innovation (DSITI) to develop and undertake the research project presented here, with assistance from the New South Wales (NSW) Department of Primary Industries (DPI) Water.

Figure 1.1 Northern Basin zone (Source: MDBA 2015)

1.2 Waterholes as refugia in temporary rivers

1.2.1 The role of waterholes as refugia in temporary rivers of the northern Basin

The northern Basin is characterised by ephemeral riverine ecosystems (i.e. temporary rivers), that dry up into a series of waterholes during times of drought (DERM 2010). These waterholes are an important resource for agriculture, town water supplies, industry and other human consumptive uses. They also serve an important ecological function by providing refugial habitat to aquatic populations during prolonged periods without surface flow (DERM 2011).

Waterholes provide critical refuges for the biota of temporary rivers, enabling resistance and resilience of aquatic populations by providing habitat to ‘ride out’ no flow spells (Humphries & Baldwin 2003; Magoulick & Kobza 2003; Davis et al. 2002) and allowing dispersal during subsequent flow events (DERM 2010; Balcombe et al. 2007; Puckridge et al.1998). The species composition of aquatic biota utilising refuges varies within a waterhole over time and spatially between waterholes throughout a region (Marshall et al. 2006; McGregor et al. 2006; Arthington et al. 2005). As a result, a mosaic of waterholes through space and time is needed to maintain viable populations of all dependent aquatic species (Sheldon et al. 2010).

There are three major attributes of waterholes which contribute to their ability to provide refuge for biota. The first attribute is their persistence, the length of time a waterhole can retain water during no flow spells. The second attribute is their refuge quality which includes aspects such as water quality, habitat availability and the quality and quantity of available food resources. In general, longer dry spells produce harsher refuge conditions, including reduction of dissolved oxygen and changes in water temperature, food and habitat availability (Beesley & Prince 2010; Bond et al. 2008; Bouvy et al. 2003; Lake 2003; Magoulick & Kobza 2003; Seehausen & Bouton 1997). The final attribute is connectivity between waterholes, which enables movement of biota, recolonisation and gene flow (Puckridge et al. 1998, Humphries et al. 1999, Thoms and Sheldon 2000, Davis et al. 2002, Balcombe et al. 2007).

Although viable populations of freshwater biota in temporary rivers depend upon networks of waterhole refuges, each displaying all three attributes; the fundamental need of aquatic biota is the persistence of wetted habitat during a prolonged no flow spell. The persistence time of waterhole refuges (i.e. the length of time they contain water in the absence of flow) is vitally important as it defines the maximum survival time for any obligate aquatic biota that reside in them (Balcombe et al. 2007). To understand the function of waterholes as refuges, DERM (2010) focussed on determining the persistence of waterholes.

1.2.2 Factors influencing waterhole persistence

DERM (2010) developed a conceptual model to identify the important processes determining the persistence time of a waterhole once flow has ceased (Figure 1.2). This was a simplified model that identified three main factors and associated parameters: the amount of time between flow events which is dictated by the flow regime; local sources of water loss or gain such as rainfall and evaporation and how much water a waterhole can hold based on its size, shape and depth. By quantifying these attributes and associated parameters, waterhole persistence can be calculated.

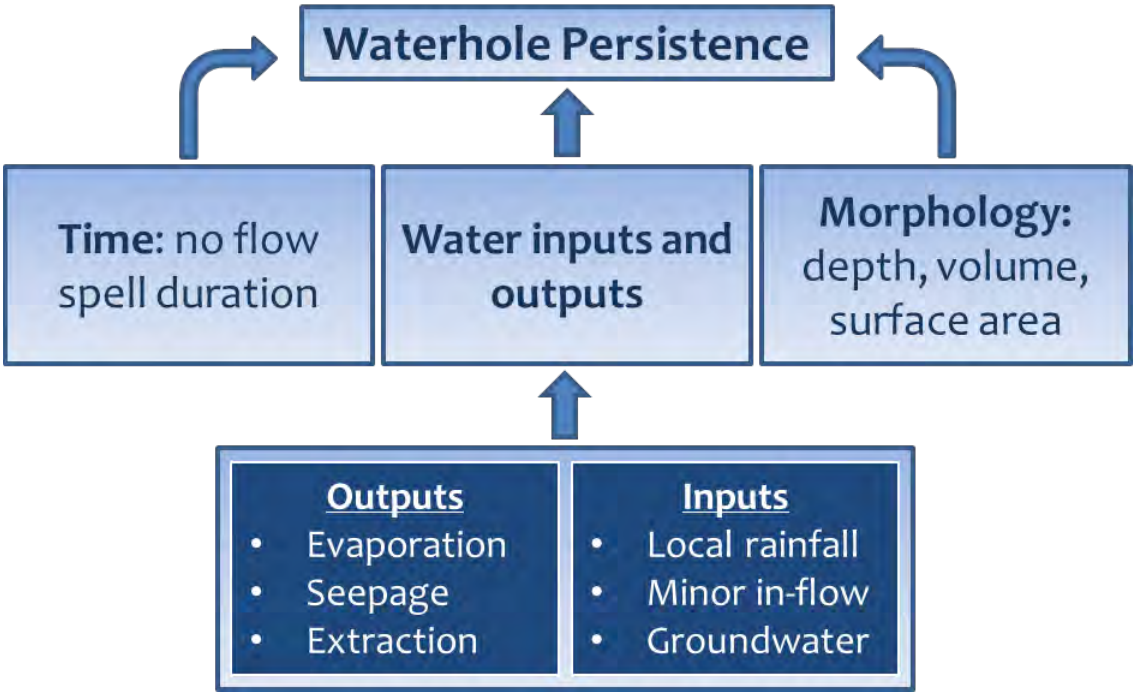

Figure 1.2 Conceptual diagram of waterhole persistence

1.2.3 Key threats to waterholes in the northern Basin

Water resource development across the Basin, including extensive modification of the natural flow regime, has resulted in major declines in the health of water-dependent ecosystems (MDFRC 2011).

A number of key threats and issues relating to water-dependant ecosystems in the northern Basin have been identified (NSW DPI 2012):

- over-commitment of water to upstream irrigation, or to irrigation generally
- impact of feral pest fish on in-channel ecosystems
- water quality problems such as increased incidence of blue green algal blooms, salinity, nutrients and agricultural chemicals
- adverse effects of changes in the river and floodplain system on Aboriginal people and their cultural or spiritual values, including their use of the river and wetlands, and the reduction in traditional foods
- the need to maintain employment, social and/or economic benefits of irrigation
- loss of habitat and/or limited opportunities for fish to move during low or no flow spells through instream structures such as weirs and culverts, and pumping.

Water resource development in the northern Basin specifically threatens waterholes by:

- reducing waterhole persistence through pumping during no flow periods
- increasing the duration of no flow spells by extraction during low flows
- modifying connectivity between waterholes during flow events.

There are additional pressures that threaten the persistence of waterholes through changes to physical shape, size and location (Larned et al. 2010; Davies et al. 2009; Choy et al. 2002;

Puckridge et al. 1998), one of which is sediment infilling, which has been identified as a key driver of change in waterhole morphology (Hooke 2007).

1.3 Environmentally Sustainable Levels of Take in the northern Basin

1.3.1 Environmental watering requirements for waterholes in the Lower Balonne floodplain

The MDBA determined environmental watering requirements (EWRs) for 11 sites in the northern Basin within areas that are considered to be ‘umbrella environmental assets’ (UEAs). These EWRs informed the environmentally sustainable levels of take (ESLTs) for each catchment. The rationale behind using UEAs is underpinned by the assumption that the provision of an adequate flow regime at a set of representative sites would provide the EWRs of the broader suite of key environmental assets and key ecosystem functions (MDBA 2011a). As such, the hydrological modelling of flow requirements was specified at a fixed gauge for a set of flow indicators that collectively represent a flow regime that supports the achievement of site-specific ecological targets at the UEA. Magnitude (discharge or volume based), duration, timing and frequency of particular flows were used to describe the site-specific flow indicators. EWRs were determined for each environmental asset based on background ecological information of flow requirements needed to maintain the asset, and hydrological analysis of modelled flow data at relevant flow gauges.

The Lower Balonne Floodplain was identified as a UEA (Lower Balonne UEA), defined as the floodplain system, including the channels, waterholes and floodplains of the Balonne (downstream of St George), Culgoa, Birrie, Bokhara and Narran rivers, extending from St George in Queensland to the confluence with the Barwon River in New South Wales (Figure 1.3). Within this area, in-channel waterholes and billabongs were identified as important components of the ecosystem because they provide vital habitat and act as refugia during drought. A flow indicator of 1,200ML/day for seven days at Brenda gauging station on the Culgoa River, with a maximum interval of between 22 and 28 months (1.8 to 2.3 years) was developed to represent the watering requirements of waterholes (MDBA 2012). The magnitude and duration attributes were determined by hydrological analyses that calculated the size of in-channel events that could pass through the lower Balonne to the Barwon, therefore, refilling all waterholes in the reach. The return interval reflects estimated waterhole persistence time, determined by applying a depth-persistence time relationship developed for the nearby Moonie River (DERM 2010), to an estimate of the waterhole depths of a known number of waterholes from previous studies in the Lower Balonne (Woods et al. 2012).

Existing ecological information was applied in a similar way to quantify watering requirements for other ecosystem components, such as floodplain vegetation, in the Lower Balonne and Barwon–Darling UEAs. No specific watering requirement was developed for waterhole refugia in the Barwon–Darling.

Figure 1.3 Lower Balonne Floodplain in the northern Basin (Source: MDBA 2015)

1.3.2 Knowledge gaps

The MDBA acknowledged that there was a higher degree of uncertainty for EWRs determined for UEAs in northern Basin due to a lack of information on flow-ecology relationships, compared to UEAs in the southern Basin. Concerns were also raised about the assumptions that site-specific flow indicators could adequately represent the watering requirements of environmental assets, such as refugial waterholes, at the scale of UEAs or the catchment more broadly (Reid-Piko et al. 2010). The crucial knowledge gaps, and information required to understand the suitability of the current EWRs in maintaining refugial waterholes in the northern Basin, are outlined in Table 1.1.

Table 1.1 Crucial knowledge gaps relating to refugial waterholes in the northern Basin.

Threat	Effect on asset	Knowledge gap	Information required
Increase in no flow spell occurrence and duration	Spells may exceed waterhole persistence time, causing local extinction of aquatic biota	Waterhole persistence times in target river valleys	Distribution of refugial waterholes across the northern Basin
			Relationship between spell length and amount of waterhole habitat at the reach scale
			Water loss rate
			Waterhole shape and size
			Connection to groundwater
			Depth/Persistence relationship
Change in the provision of sediment scouring flow events	Sediment accumulation in waterholes, leading to reduced volume and persistence	Sediment status of waterholes	Amount of soft sediment in waterholes
			Historical rate of sediment accumulation
		Effect of flows on sediment dynamics	Identification of flow events or other conditions that lead to sediment infilling
			Identification and quantification of scouring capacity of flows

1.4 Project purpose

This project addresses crucial knowledge gaps (Table 1.1) required to understand if the current EWRs set at the Lower Balonne Floodplain are suitable for maintenance of refugial waterholes, and determines if additional flow indicators are needed. Waterholes in the Barwon–Darling upstream of Menindee Lakes were also investigated, to understand whether particular flow requirements should be specified for this part of the northern Basin.

This broad project is composed of several underlying projects. These underlying projects were developed in response to addressing crucial knowledge gaps, answered as a series of key questions:

1. What is the spatial distribution of waterholes in the Lower Balonne and Barwon–Darling?
2. What are the characteristics of waterhole habitat availability in the Lower Balonne and Barwon–Darling at reach scales?
3. What is the persistence time of waterholes in the Lower Balonne and Barwon–Darling?
4. Does groundwater influence the persistence time of waterholes in the Lower Balonne and Barwon–Darling?
5. Does sedimentation affect waterhole persistence in the Lower Balonne and Barwon–Darling?
6. Can the persistence time of waterholes across the northern Basin be predicted using a generic model?
7. Do hydrological modelling scenarios show an impact from water resources development and a benefit from the recovery of environmental water to the persistence of waterholes (modelling period between 1895–2009 for a range of different management conditions, including without development, 2009 pre-Basin Plan baseline conditions of development, and hypothetical recovery scenarios)?

These questions are summarised below with reference to the relevant chapter in which detailed analysis is presented.

1.4.1 What is the spatial distribution of waterholes in the Lower Balonne and Barwon–Darling?

Water resource development can alter the length of no flow spells and consequently the spatial and temporal distribution of refuge waterholes (DSITIA 2014a). Identifying where refuge waterholes are, and understanding how habitat availability is threatened by changes in waterhole distribution, is important to environmental assessment, particularly when evaluating different management scenarios.

There are logistical issues with identifying all waterbodies in space and time, but remote sensing has been successfully used to identify surface water on images using a Landsat-based Water Index developed by Danaher & Collett (2006). DSITIA (2014a) applied remote sensing and hydrological information to identify refugial waterholes in the Flinders and Gilbert catchments in northern Queensland. To obtain relevant hydrological information, the in-channel river system was divided into environmental assessment reaches within which relationships can confidently be drawn between gauged flow data and the hydrological conditions experienced by refugial waterholes. Associated gauges were then used to identify no flow spells across the Landsat time-series (1988–2013).

While there is some information on the location of refugial waterholes at catchment scales in the northern Basin (Silcock 2010; Webb 2009), there is no information on how comprehensive this mapping is (Sheldon et al. 2014). To address this knowledge gap, the same method used by DSITIA (2014a) was used to identify known and additional waterholes in the Lower Balonne and Barwon–Darling, including both natural and weir pools (Chapter 2). Four spatial ‘waterhole’ mapping layers were developed based on the no flow spell hydrology of the region:

1. ‘Maximum waterhole extent’ layer (after 30 days of no flow).

2. ‘Maximum time-series extent’ layer (less than 350 days of no flow, persistent throughout time-series).
3. ‘Refuge waterhole extent’ layer (after 350 days of no flow, not persistent throughout time-series).
4. ‘Persistent waterhole extent’ layer (after 350 days of no flow, persistent throughout time-series).

Surface water was identified for each layer over the Landsat era (1988–2015). The key aim of this mapping exercise was to identify potential refugial waterholes and which of these waterholes persisted throughout this time-series.

1.4.2 What are the temporal patterns of waterhole habitat availability in the Lower Balonne and Barwon–Darling at reach scales?

Individual waterholes will retain water for varying durations after the cessation of flow and as no flow spells increase in duration, fewer waterholes remain across the system. Typically, when water levels are low the range of threats to obligate biota increase, including extreme water temperature fluctuations, low dissolved oxygen levels, concentration of toxicants, increased predation, food source limitation and increased disease transmission (Waltham et al. 2013). Although waterholes that persist during maximum no flow spell durations may be considered persistent refuges for obligate biota, it is unknown at what point along the drying continuum the degradation of quality and loss of available habitat results in the waterhole failing to function as a refuge. Persistence characteristics of a waterhole can be threatened by water resource management; to understand these threats it is important to characterise the range of persistence characteristics experienced under natural no flow conditions. The persistence characteristics of refuge waterholes can be established by considering the distribution of no flow spells over a range of prevailing climatic conditions under modelled natural conditions. This distribution of no flow spells under natural flow conditions can be used to set Thresholds of Concern (ToC) which in turn can be used to assess the risk of specific water management on waterhole persistence.

The concept of a ToC has been used by the Queensland Government to assess the risk of water management on environmental assets (i.e. refugial waterholes) as they represent failure points, and can be used to determine minimum requirements from a flow regime (DSITIA 2014a; DERM 2011). To determine a ToC for refugial waterholes based on persistence characteristics, DSITIA (2014a) investigated the frequency of waterhole habitat loss during different no flow spells. DSITIA (2014a) analysed Landsat images for each environmental assessment reach to describe loss of waterhole habitat for no flow spells of increasing duration.

The persistence characteristics of waterholes in the Lower Balonne and Barwon–Darling were investigated by looking at the relationship between no flow spell duration identified for each assessment reach and available waterhole habitat (Chapter 2). The aim of this investigation was to determine if water habitat characteristics for each reach could be utilised to establish an ecological threshold, thus assisting in the determination of the minimum persistence thresholds for waterholes across the Lower Balonne and Barwon–Darling.

1.4.3 What is the persistence time of waterholes in the Lower Balonne and Barwon–Darling?

The persistence time of a waterhole determines how long it provides wetted habitat during a no flow spell (as outlined in Section 1.2.1). Understanding and predicting persistence (maximum duration of no flow spell over which they can maintain water) is a critical step in providing the knowledge needed to best manage this vital habitat.

DERM (2010) developed a statistical model to predict individual waterhole persistence using key parameters which could be easily measured, or estimated. The model was tested by collecting depth loss measurements and morphological characteristics from 15 waterhole sites in the Moonie River. Waterhole models were successfully calibrated for all sites, meaning that measured and predicted waterhole depth closely matched, giving an insight into the hydrological function of these waterholes and the ability to predict their persistence over long time periods. The estimated minimum persistence times for these modelled waterholes, in the absence of water gains, were between 350–820 days. DERM (2010) also identified maximum depth of a waterhole as the best predictor of its persistence and modelled persistence times were used to develop a simple predictive relationship between depth and persistence time. However, there was no understanding of whether or not this relationship was transferable to other rivers in the northern Basin.

Although flow requirements have been recommended for refuge waterholes in the Lower Balonne to target persistence, little was known about their persistence time. There was also a lack of information regarding the permanence of refugial waterholes in the Barwon–Darling (Sheldon et al. 2014). To address this knowledge gap, the persistence times of waterholes in the Lower Balonne and Barwon–Darling were investigated based on the statistical ‘waterhole persistence’ model developed for the Moonie River (DERM 2010) (Chapter 3). Water depth loss was measured and morphology was mapped at a set of representative waterholes (natural and weir pools) across three river valleys (Culgoa, Narran and the Barwon–Darling rivers).

Key factors (as outlined in Section 1.2.2) were considered in water loss model calibration by using data from stream gauging stations associated with the appropriate environmental assessment reaches. Additional investigations into groundwater contribution to the waterhole (gains or seepage loss) (Chapter 4) were conducted to determine if any modifications are needed for this empirical model. Calibrated models for representative waterholes were then used to predict persistence time (days) from maximum depth to empty, thus providing information needed to understand the persistence of waterholes in the region.

1.4.4 Does groundwater impact the persistence time of waterholes in the Lower Balonne and Barwon–Darling?

DERM (2010) used radon (^{222}Rn) concentrations to investigate the connectivity of groundwater to waterholes in the Moonie River when testing the waterhole persistence model, as it was expected that groundwater-connected waterholes may be more persistent. Radon is found in waters in contact with subsurface sediments and has a short half-life, so dissipates quickly when exposed to atmospheric gas exchange (Cook et al. 2003); therefore it is a good indicator of recent local influx of groundwater to surface waters (Burnett et al. 2010). One waterhole had high radon levels compared to the rest of the waterholes, yet its water loss rate was markedly higher than that at other sites. This suggested that for the Moonie system, some waterholes may actually lose water, especially when local groundwater levels are low. This highlights the need to identify, and account for, groundwater interactions when modelling waterhole persistence, as it is a potential driver of waterhole water loss rates.

To assist in the interpretation of measured water loss rates and model calibration examined in Chapter 3, groundwater-surface water interactions were investigated in each of the three river valleys (Chapter 4). Sampling locations across the three river valleys were determined by interpolating conductivity readings recorded during bathymetric mapping of each representative waterhole (Chapter 3). Replicate water samples were collected at each site and analysed for radon concentration. Analysis of conductivity, temperature, ions and stable isotopes were used, along with the radon concentrations from both the waterholes and proximal groundwater sources (where available), as lines of evidence to indicate groundwater interaction.

This investigation was designed to improve the understanding of groundwater interactions within waterholes across the Lower Balonne and Barwon–Darling.

1.4.5 Does sedimentation affect waterhole persistence in the Lower Balonne and Barwon–Darling?

Changes in waterhole morphology can threaten the persistence time of a waterhole. Sediment infilling has been identified as a key driver of change in waterhole morphology (Hooke 2007). The effect of sedimentation on waterhole morphology, and therefore persistence time, was investigated in the Moonie by collecting and ageing sediment cores to estimate the age of deposited layers and establish sedimentation rates (DERM 2010). Results suggested that most sediment in the cores had been deposited after European settlement and that a majority of the sediment was most likely deposited in the last 50 years. An assessment of the morphological characteristics of waterhole refugia in the Moonie River indicated that reduced waterhole depth, due to sedimentation, posed a greater risk to waterhole persistence than current water resource management (DERM 2010).

In the Lower Balonne floodplain, the main river channels are naturally unstable, meaning that small changes in flow can result in changes in channel morphology (Smith et al. 2006). Also, management infrastructure in the upper Condamine–Balonne catchment has increased sediment movement to the Lower Balonne floodplain (Cullen et al. 2003). To determine if sedimentation is impacting waterhole persistence in the Lower Balonne and Barwon–Darling, the sediment status of representative waterholes was investigated, with the aim to build a better conceptual understanding of sediment dynamics in waterholes across the northern Basin. Sediment status was investigated using probing and coring techniques (Appendix A). Probing was conducted at the same representative waterholes investigated in Chapter 3, to gain important information on the accumulation of soft sediment across the study region. Sediment cores were also collected at a select number of sites across the three river valleys. These cores will be analysed to estimate the age of deposited layers, based on sedimentation rates established using OSL dating. Results will also be compared with previous studies to develop a more comprehensive understanding of flow-sediment relationships for each river valley and presented in an additional supplementary report.

When finalised, this research project will improve our understanding of sedimentation processes in the Lower Balonne and Barwon–Darling and determine if sedimentation is a threat to the refuge function of waterholes investigated.

1.4.6 Can the persistence time of waterholes across the northern Basin be predicted using a generic model?

DERM (2010) analysed depth-persistence relationships for multiple river valleys to determine if depth was the best predictor of persistence time of a waterhole. Results were presumed not to be transferable across different catchments in Queensland, due to difference in water loss characteristics. However, this study assumed that catchments within the northern Basin would have similar water loss characteristics and that the depth-persistence relationship had the potential to be applied broadly in the region.

In order to develop a predictive model that could be applied across several river valleys, the depth-persistence relationship across the Lower Balonne was compared to what was found in the Moonie (Chapter 5).

1.4.7 Do hydrological modelling scenarios show an impact from water resources development and a benefit from the recovery of environmental water to the persistence of waterholes (modelling period between 1895–2009 for a range of different management conditions, including without development, 2009 pre-Basin Plan baseline conditions of development, and hypothetical recovery scenarios)?

Hypothetical water recovery scenarios for the northern Basin were evaluated by modelling the risk they posed to waterhole persistence in the northern Basin, relative to the risk from the 'without development' and Baseline scenarios (Chapter 6). A key aspect of this risk assessment was the establishment of a ToC for individual modelled waterholes and three stress levels of ToC for waterholes at a reach scale. All levels of ToC were based on the knowledge gained from persistence times of modelled waterholes in the northern Basin (Chapters 3), while the ToC for individual modelled waterholes was based on their modelled persistence time to 0.5 metres, assuming that they would not provide refugia past this threshold (DSITIA 2014a). This approach was based on the method used by DERM (2011).

To assess the potential risk to refugial waterholes, a matrix of failures against the ToCs were developed for modelled waterholes considered to be persistent, i.e. their persistence threshold was known (Chapter 3). This identified if the persistence of these waterholes was impacted by water resource development, relative to without development. To assess the potential risk to a range of waterholes across the northern Basin, a matrix of failures against ToCs was developed which showed when each environmental assessment reach was stressed over the flow simulation period, meaning that the relevant stress level of ToC was exceeded. This identified the extent of simultaneous risks to waterholes through space and time, and reaches where increasing stress thresholds had an impact on waterhole persistence. Periods of simultaneous risks to waterholes were further investigated to examine the effect of different flow management options.

This assessment of water management scenarios against ToCs at different scales will provide additional information needed to determine the water management needed to maintain the persistence of waterholes in the northern Basin. A synthesis of these findings was also used to determine if additional flow indicator sites are required to reassess ESLTs in the Lower Balonne floodplain.

2 Using remote sensing to identify refuge waterholes and characterise waterhole persistence

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This chapter addresses the following knowledge gaps:

- *What is the spatial distribution of waterholes in the Lower Balonne and Barwon–Darling?*
- *What are the temporal patterns of waterhole habitat availability in the Lower Balonne and Barwon–Darling at reach scales?*

2.1 Introduction

Water resource development can alter the length of no flow spells and consequently the spatial and temporal distribution of refuge waterholes (DSITIA 2014a). Identifying where these waterholes are, and understanding how changes in distribution can threaten habitat availability, is important when evaluating the environmental consequences of altering the length of no flow spells under different management scenarios. As obligate biota utilising refuges can vary within a waterhole over time, and spatially between waterholes throughout a region, both the availability of habitat and distribution are important for their role as refugia (DERM 2011).

There are few sources of information about the location of waterholes across the northern Murray–Darling Basin (northern Basin) (Silcock 2010; Webb 2009). The Murray–Darling Basin Authority (MDBA) used the locations of 22 'substantial' waterholes (Webb 2009) to inform the spatial extent of watering required to maintain waterholes within the Lower Balonne 'umbrella environmental asset' (UEA). However, the mapping was undertaken during a single dry period and it is unclear how representative the results are of habitat availability over time and following different antecedent conditions.

A review of the flow indicators set for northern Basin identified the spatial and temporal distribution of the in-channel permanent waterhole refugia in the Lower Balonne as a knowledge gap (Sheldon et al. 2014). A risk assessment of MDBA flow scenarios also found insufficient information on the characteristics of waterhole habitat availability in the northern Basin (DERM 2011). Improved knowledge of the amount and spatial distribution of refuge habitat in the region is required to better inform assessments of flow management options.

A combination of remote sensing analysis and hydrological information has recently been successfully used by DSITIA (2014a) to identify the distribution of waterholes in the Flinders and Gilbert catchments in northern Queensland. DSITIA (2014a) utilised the time-series of Landsat imagery to derive instream water classifications observed under specific flow conditions based on the Landsat-based Water Index developed by Danaher & Collett (2006). This study also investigated the persistence characteristics of waterholes (i.e. water habitat availability) by quantifying the surface area of wet pixels present in Landsat images representing a range of preceding no flow spell durations.

Based on the methods used by DSITIA (2014a), this chapter addresses the following key knowledge gaps:

1. What is the spatial distribution of waterholes in the Lower Balonne and Barwon–Darling?
2. What are the temporal patterns of waterhole habitat availability in the Lower Balonne and Barwon–Darling at reach scales?

A key outcome of this chapter was to identify the distribution of waterholes across the Lower Balonne and Barwon–Darling and gain an understanding of the persistence characteristics of waterholes at a river reach scale. This chapter also investigates how the refugial waterholes identified in the single survey by Webb (2009) were classified by the approach to mapping waterholes used for this project.

2.2 Methods

2.2.1 Distribution

Waterholes across the Lower Balonne floodplain and Barwon–Darling were identified by time-series remote sensing analysis of Landsat imagery for the years 1988–2015. The assessment included waterhole features within river channels that are maintained primarily by in-channel flows and retain water during dry spells. Floodplain features, relicts no longer connected to the active channel, and off-stream storages were excluded. Surface water on the Landsat images was identified using a modification of the Landsat-based Water Index thresholds for water classification (Danaher & Collett 2006). The identification process was undertaken in stages as described below.

2.2.1.1 Defining environmental assessment reaches

To account for the hydrological complexity of the region and the assessment of multiple river valleys with variable flow regimes, segments of the river channels across the Lower Balonne and Barwon–Darling were divided into environmental assessment reaches (Figure 2.1 & Figure 2.2). The environmental assessment reaches defined homogeneous regions of the floodplain and river in-channels where relationships can confidently be drawn between gauged flow data and the hydrological or hydraulic conditions experienced by waterholes (DSITIA 2014a). For the Barwon–Darling, some assessment reaches were defined by gauges where no flow data was available. The hydrology of areas outside the environmental assessment reaches cannot be represented by flows at the gauging stations and they were therefore excluded from the assessment.

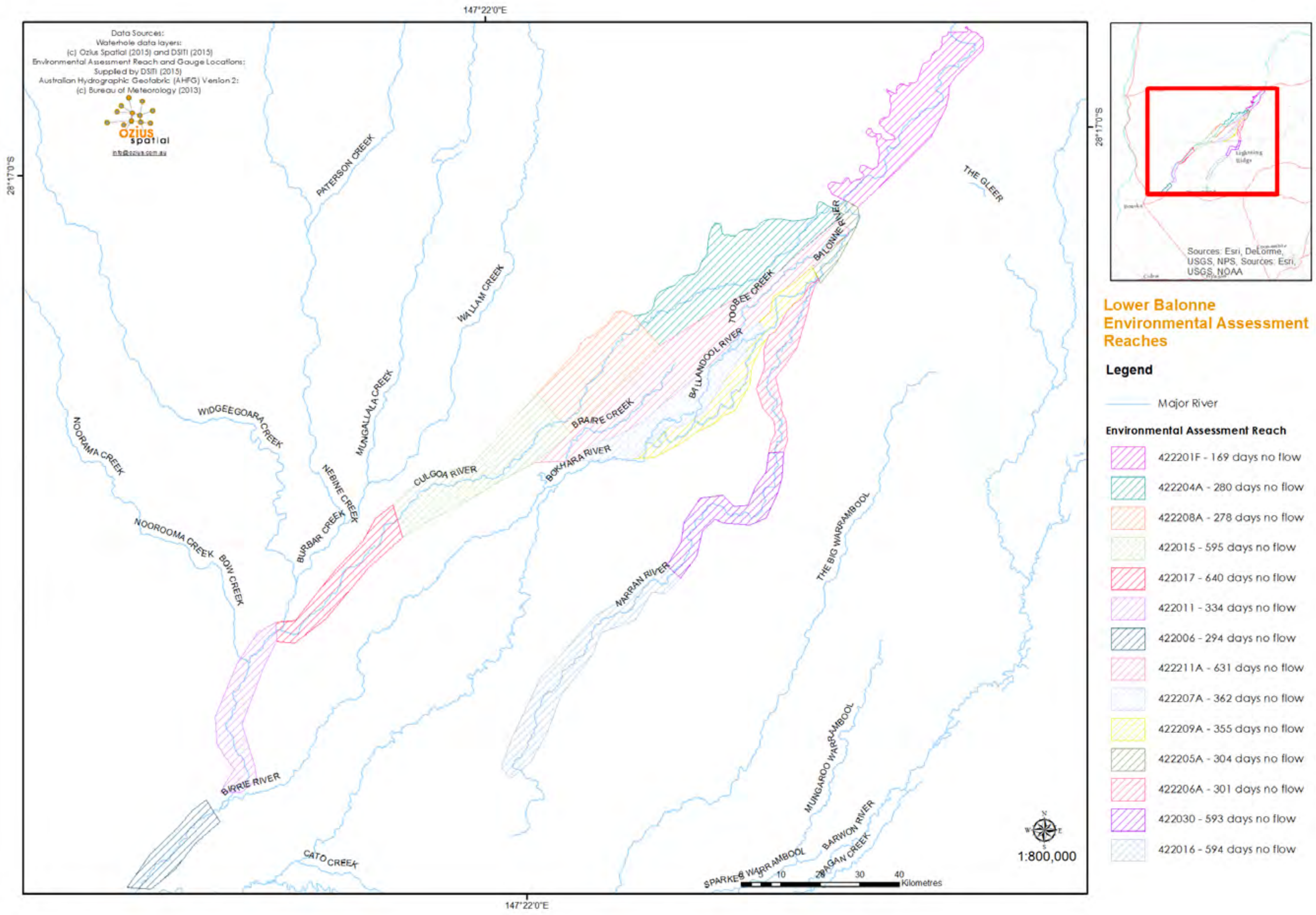

Figure 2.1 Environmental assessment reaches in the Lower Balonne and associated flow gauges (Reaches are labelled in ascending order).

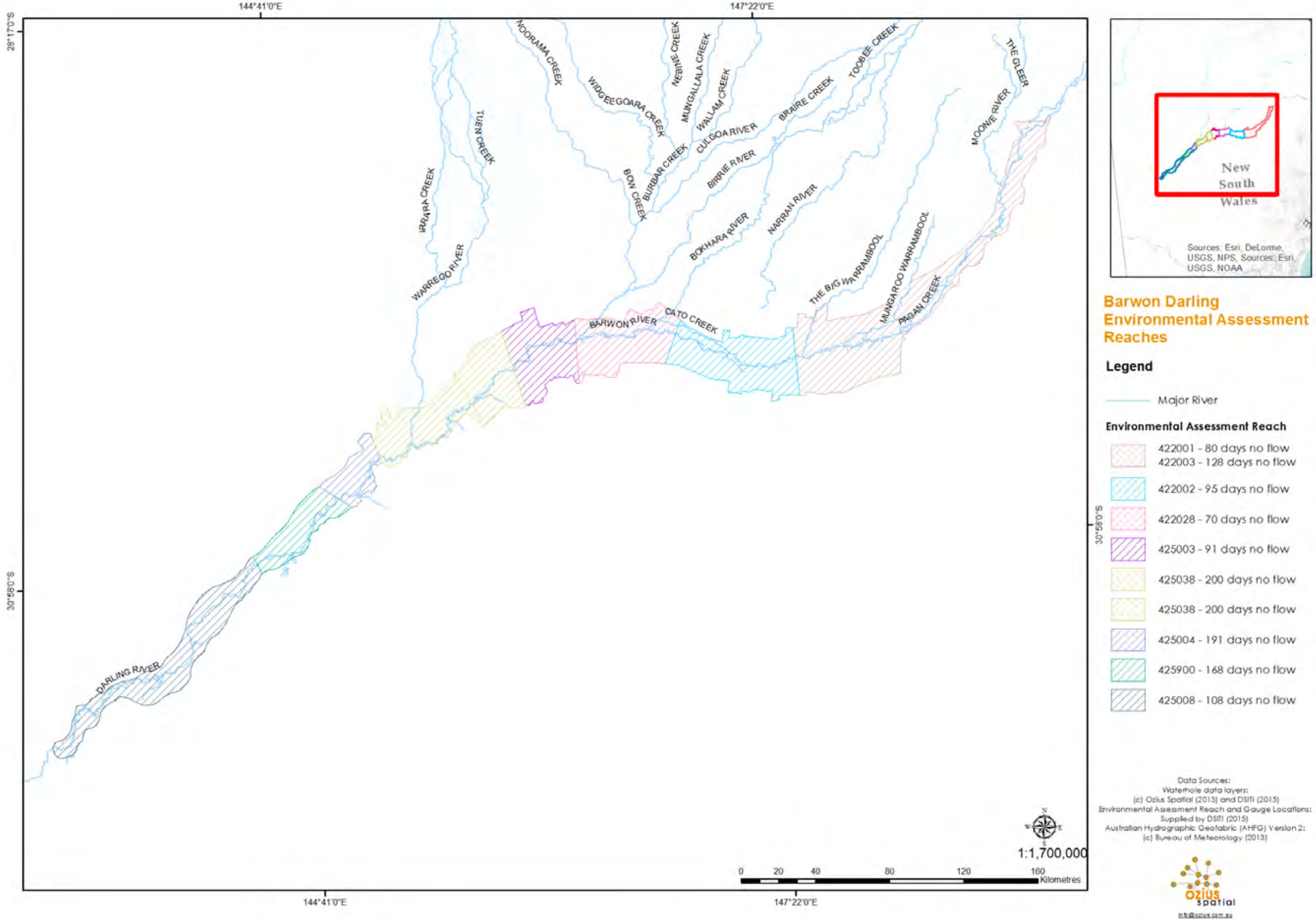

Figure 2.2 Environmental assessment reaches in the Barwon–Darling and associated flow gauges (Reaches are labelled in ascending order).

2.2.1.2 Collating hydrological information

Gauging stations linked to environmental assessment reaches were analysed over the Landsat era to ensure that flow data was available for the duration of the Landsat series. No flow spells were identified from the gauge data for each assessment reach. By examining individual assessment reaches separately, the hydrological variability across, and within, river valleys is accounted for. A total of 25 gauges were used to identify the frequency and duration of no flow spells (no flow defined as a flow of <2 ML/day, Chapter 3) across the Landsat time-series.

2.2.1.3 Landsat scene selection

No flow spells were identified for each assessment reach and those >30 days long were cross-referenced with available Landsat time-series to obtain a sample of Landsat images representing different no flow durations. Landsat images were selected for each environmental assessment reach independently to ensure the complete representative range of gauge-specific hydrological flow conditions were sampled by accounting for ‘overlap’ with other reaches. By selecting all no flow spells > 30 days, a range of antecedent conditions was captured and importantly, the longest no flow spell within the available Landsat time-series (1988–2015) was sampled.

To reduce the likelihood of cloud shadow falling on a water body leading to potential misclassification of extent, Landsat images with >2% cloud cover present were removed from the sample population. A total of eight Landsat scene footprints were required to cover the project area. A total of 242 Landsat images were analysed as no flow samples across the Lower Balonne and Barwon–Darling river valleys (Table 2.1).

Table 2.1 Overview of Landsat scenes and number of images analysed across the Lower Balonne and Barwon–Darling.

Landsat scenes	Number of images analysed
p092r079	31
p092r080	35
p092r081	24
p093r080	40
p093r081	42
p094r081	8
p094r082	30
p095r082	32
Total path rows 8	Total Scenes 242

As each Landsat scene covered a number of environmental assessment reaches and their associated gauge, Landsat scene dates were reviewed to ensure that images covered relevant gauges within the Landsat scene. For each Landsat image, a water classification was undertaken to identify the available water habitat (wet pixel area) along the river system within each assessment reach.

2.2.1.4 Modification of the Water Index

Landsat images were pre-processed using standard techniques to produce geometrically and radiometrically corrected images (de Vries et al. 2007). The Landsat-based Water Index (Danaher & Collett 2006) was applied and each Landsat scene was classified into binary water/non-water pixels. The default water index threshold was originally optimised for large, open waterbodies such as oceans and lakes. This default water mask was evaluated for its sensitivity in detecting waterholes in the northern basin by comparing the water extent it produced with the extent of in-stream riverine water bodies within the Landsat image. This default water mask was found to significantly underestimate the presence of water in rivers in the region. Subsequently the default threshold was modified in order to optimise surface water extent identification in inland rivers, including water under sparse vegetation, water across a range of water quality conditions and in small, narrow river reaches, to ensure instream waterholes were identified.

Environmental assessment reaches were clipped to the drainage line system to exclude water features on the floodplain using the Australian Hydrographic Geofabric Version 2 (Geofabric) (BOM 2010). To account for spatial scale alignments, a 200 metre buffer was applied to major drainage lines and a 100 metre buffer applied to minor drainage lines.

Water pixels within the river channels and connected drainage lines were identified and counted for each scene date relevant to each environmental assessment reach and connected drainage lines. A landuse mask was applied using the Queensland Land use mapping from 2006 (DSITIA 2014b) and NSW land use mapping (ACLUMP 2009) to remove water storages, and irrigation channels within the buffered drainage lines from the classification.

2.2.1.5 Defining waterhole location and extent

The images for each no flow spell were ‘stacked’ into a data-cube to create a time-series of water in the river channels. Within the data-cube, wet pixels were cumulatively counted. Each count of wet pixels represented the extent of a waterhole present under the respective flow conditions across the time-series; a single wet pixel represents an area of 30 metres x 30 metres that contains a dominant signal of water based on the modified Water Index.

Four spatial ‘waterhole extent’ layers were developed:

1. **‘Maximum waterhole extent’ layer (after 30 days of no flow):** wet pixels present after 30 days of no flow and at least 4 connected pixels in area (3600 m^2). Represents the distribution and size of waterholes early in a dry spell.

2. **‘Maximum time-series extent’ layer (less than 350 days of no flow, persistent throughout time-series):** wet pixels persisting in images under all no flow spell conditions analysed within environmental assessment reaches that experienced no greater than 350 days of no flow across the time-series.

3. **‘Refuge waterhole extent’ layer (after 350 days of no flow, not persistent throughout time-series):** wet pixels persisting at least 350 days of no flow within the maximum waterhole extent (i.e. can be fewer than four connected pixels). These waterholes may not persist during the longest spells but are present in the majority of years and are likely to provide important habitat. A persistence threshold of 350 days was selected as the majority

of gauging sites in the Lower Balonne had a maximum no flow spell of approximately 350 days or less under pre-development modelled hydrological conditions for 114 years.

4. **'Persistent waterhole extent' layer (after 350 days of no flow, persistent throughout time-series):** wet pixels persisting in images under all no flow spell conditions analysed and greater than 350 days. For the purpose of this assessment, waterholes are only considered 'persistent' throughout the time-series and not permanent as this study was limited to the no flow conditions experienced over the past 27 years.

Waterhole extent layers were ground-truthed by comparing them with bathymetric Digital Elevation Models (DEMs) developed for representative waterhole sites (Chapter 3). Bathymetric DEMs provided a visualisation of waterhole depths at cease to flow and were compared with wet pixels observed in the Landsat water classification at around 30 days of no flow. Deeper sections of the DEMs correlated with wet pixels representing water over 350 days of no flow to validate the waterhole extent mapping.

2.2.2 Reach-scale waterhole habitat persistence

To determine the persistence characteristics of waterhole habitat at a reach scale, spatial analyses were undertaken to examine the rate of loss of waterhole area at all environmental assessment reaches (described in Section 2.2.1 above). Landsat images were analysed to determine the amount of waterhole habitat remaining (i.e. the total number of wet pixels within the maximum waterhole extent for each assessment reach) after no flow spells of increasing duration across the time-series.

Images relating to spell lengths ranging from 30 days to the maximum captured spell were arranged into a data-cube for analysis, and the total surface area of wet pixels (i.e. waterhole habitat) per no flow spell duration was generated.

To visualise the relationship between no flow spell length and waterhole habitat availability, the sum of wet pixels (within the 'maximum waterhole extent', as described in Section 2.2.1 above) was plotted against spell duration for each environmental assessment reach. Analysis approaches, including linear regression and quantile regression, were then undertaken in order to derive a relationship to help estimate what spell length might equate to zero waterhole habitat remaining in each reach. This spell length would inform critical risk thresholds that could be applied at each reach to protect waterhole habitats.

2.3 Results

2.3.1 No flow hydrology

Over the Landsat era, no flows spells in the Barwon–Darling are considerably shorter compared to the Lower Balonne, with the longest period of no flow in reaches located in the main river channel not exceeding 321 days as recorded on the Darling River at Wilcannia (gauge 425008) (Table 2.2). No flow spells in the Lower Balonne ranged from 292 to 682 days, with prolonged periods of no flow recorded in the lower reaches of the Narran and mid reaches of the Culgoa river valleys.

For the reaches assessed in the Culgoa and Narran river valleys, Landsat images were available across the longest no flow spell (Table 2.2) giving confidence in the water extent mapped in this region. Also, the majority of reaches assessed in the Barwon–Darling had Landsat images available across the longest no flow spells. Suitable images were not available for end of no flow spells at gauge 425008 and 425003.

Table 2.2 No flow spell summary statistics for the Landsat era (1988–2015) and Landsat images sampled by main environmental assessment reach.

Environmental Assessment Reach	Number of gauged no flow spells (1988– 2015)	Average gauged no flow spell duration (days)(1988– 2015)	Longest gauged no flow spell (days) (1988– 2015)	Longest Landsat sampled spell (days)
Downstream of Beardmore Dam				
Balonne River at St George (422201F)	29	76	218	169 (77.5%)
Balonne-minor River at Hastings (422205A)	43	142	342	304 (88.9%)
Culgoa River valley				
Culgoa River at Whyenbah (422204A)	31	122	292	280 (95.9%)
Culgoa River at Woolerbilla (422208A)	14	143	325	278 (85.5%)
Culgoa River at Brenda (422015)	29	171	600	595 (99.2%)
Culgoa River at Weilmoringle (422017)	30	184	611	640 (95.5%)
Culgoa River at U/S Collerina (Mundiwa) (422011)	25	119	358	334 (93.3%)
Culgoa River at D/S Collerina (Kenebree) (422006)	35	117	316	294 (93.0%)
Narran River valley				
Narran River at Dirranbandi-Hebel Rd (422206A)	40	104	362	301 (83.0%)
Narran River at New Angledool (422030)	16	178	677	593 (87.6%)
Narran River at Wilby Wilby (Belvedere) (422016)	28	208	682	594 (87.1%)
Bokhara River valley				

Environmental Assessment Reach	Number of gauged no flow spells (1988– 2015)	Average gauged no flow spell duration (days)(1988– 2015)	Longest gauged no flow spell (days) (1988– 2015)	Longest Landsat sampled spell (days)
Bokhara River at Hebel (422209A)	40	127	358	355 (99.2%)
Ballandool River at Hebel-Bollon Rd (422207A)	32	131	605	362 (59.8%)
Briarie Creek at Woolerbilla-Hebel Road (422211A)	32	145	672	631 (93.9%)
Barwon–Darling River valley				
Darling River at Wilcannia Main C (425008)	17	52	321	108 (33.6%)
Darling River at Tilpa (425900)	2	179	182	168 (92.3%)
Darling River at Louth (425004)	21	39	225	191 (84.9%)
Darling River at Myandetta (425038)	6	57	239	206 (86.2%)
Darling River at Bourke Town (425003)	5	59	198	91 (46%)
Barwon River at Beemery (422028)	4	56	95	70 (73.7%)
Barwon River at Brewarrina (422002)	1	113	113	95 (84.1%)
Barwon River at Collarenebri (422003)	6	80	161	128 (79.5%)

2.3.2 Waterhole extent

Waterholes were identified in all assessment reaches across the Lower Balonne and Barwon–Darling (Appendix B – Waterhole Maps). The surface area of 'maximum extent' waterholes (four or more connected wetted pixels after 30 days of no flow) varied within and between river valleys with the largest extent of waterhole area identified in the Barwon–Darling (Table 2.3). Although the main channels of Barwon–Darling did not experience no flow spells longer than 350 days, 'maximum time-series extent' waterholes (pixels that were wet throughout all dry spells in the time-series) were present in all reaches with the exception of the reach associated with gauge 425900 (Table 2.3). A large proportion of the waterhole habitat area was retained throughout the no flow spells in the Barwon–Darling with 'maximum time-series extent' between 62 and 511 hectares.

The assessment reaches in the Lower Balonne had a waterhole area of 'maximum extent' between 16 to 221 hectares (Table 2.3). Seven reaches had no flow periods that did not exceed 350 days, such as the upper reaches of the Narran, and the upper and lower reaches of the Culgoa. 'Maximum time-series extent' waterholes were only present in three of these reaches with two reaches downstream of Beardmore Dam (Figure 2.3). The largest area of 'maximum time-series extent' waterholes, at 43 hectares after 218 days of no flow, was mapped immediately downstream of Beardmore Dam, in the assessment reach associated with St George gauge (422201F). For the remaining four reaches that did not have 'maximum time-series extent' waterholes, these reaches had experienced no flow spells that caused waterholes to dry up completely (Table 2.2). These reaches also had a minimal area of wetted habitat at the start of the dry spell, between 16.5 to 85.4 hectares.

'Refuge waterhole extent' (wet pixels present after 350 days of no flow, but not persistent throughout time-series) was mapped in four assessment reaches in the Lower Balonne where no flow spells exceeded 350 days. Refuge waterhole extent was zero in the Bokhara River valley. Only 37 hectares of wetted surface area was available after spells longer than 350 days across all four reaches and the largest area was mapped in the lower reaches of the Narran (Table 2.3). Of the 37 hectares of wetted surface area mapped across the Lower Balonne, ten refugial waterholes were identified and eight of these waterholes were within the mid to lower reaches of the Narran River valley (Figure 2.3).

Of the ten refugial waterholes identified in the Lower Balonne, only five persisted throughout the time-series (Figure 2.4). These persistent waterholes were located throughout the mid to lower reaches of the Narran River valley, and in total less than four hectares of wetted habitat was available (Table 2.3).

Table 2.3 Surface area of 'maximum waterhole extent' (after 30 days of no flow), 'time-series maximum extent' (less than 350 days of no flow, persistent throughout time-series), 'refuge waterhole extent' (after 350 days of no flow, not persistent throughout time-series) and 'persistent waterhole' (after 350 days of no flow, persistent throughout time-series) extents identified in each environmental assessment reach.

Environmental Assessment Reach	Maximum Waterhole Area (ha)	Time-series Maximum Waterhole Area (ha)	Refuge Waterhole Area (ha)	Persistent Refuge Waterhole Area (ha)
Downstream of Beardmore Dam				
Balonne River at St George (422201F)	221.6	43	-	-
Balonne-minor River at Hastings (422205A)	106.9	18.2	-	-
Culgoa River valley				
Culgoa River at Whyenbah (422204A)	31.3	0	-	-
Culgoa River at Woolerbilla (422208A)	16.5	0	-	-
Culgoa River at Brenda (422015)	160	-	3.7	0
Culgoa River at Weilmoringle (422017)	102.4	-	0.18	0
Culgoa River at U/S Collerina (Mundiwa) (422011)	57.3	1.2	-	-
Culgoa River at D/S Collerina (Kenebree) (422006)	85.4	0	-	-
Narran River valley				
Narran River at Dirranbandi-Hebel Rd (422206A)	37.6	0	-	-
Narran River at New Angledool (422030)	203.8	-	3.8	0.4
Narran River at Wilby Wilby (Belvedere) (422016)	307	-	29.5	3.3
Bokhara River valley				
Bokhara River at Hebel (422209A)	112.5	-	0	-
Ballandool River at Hebel-Bollon Rd (422207A)	62.1	-	0	-

Environmental Assessment Reach	Maximum Waterhole Area (ha)	Time-series Maximum Waterhole Area (ha)	Refuge Waterhole Area (ha)	Persistent Refuge Waterhole Area (ha)
Biarie Creek at Woolerbilla-Hebel Road (422211A)	40.8	-	0	-
Barwon–Darling River valley				
Darling River at Wilcannia Main C (425008)	589.3	318.6	-	-
arling River at Tilpa (425900)	382.3	0	-	-
Darling River at Louth (425004)	284.1	46.3	-	-
Darling River at Myandetta (425038)	1067.0	511.2	-	-
Darling River at Bourke Town (425003)	295.7	226.8	-	-
Barwon River at Beemery (422028)	140.0	81.6	-	-
Barwon River at Brewarrina (422002)	355.6	355.6	-	-
Barwon River at Collarenebri (422003)	283.6	168.4	-	-

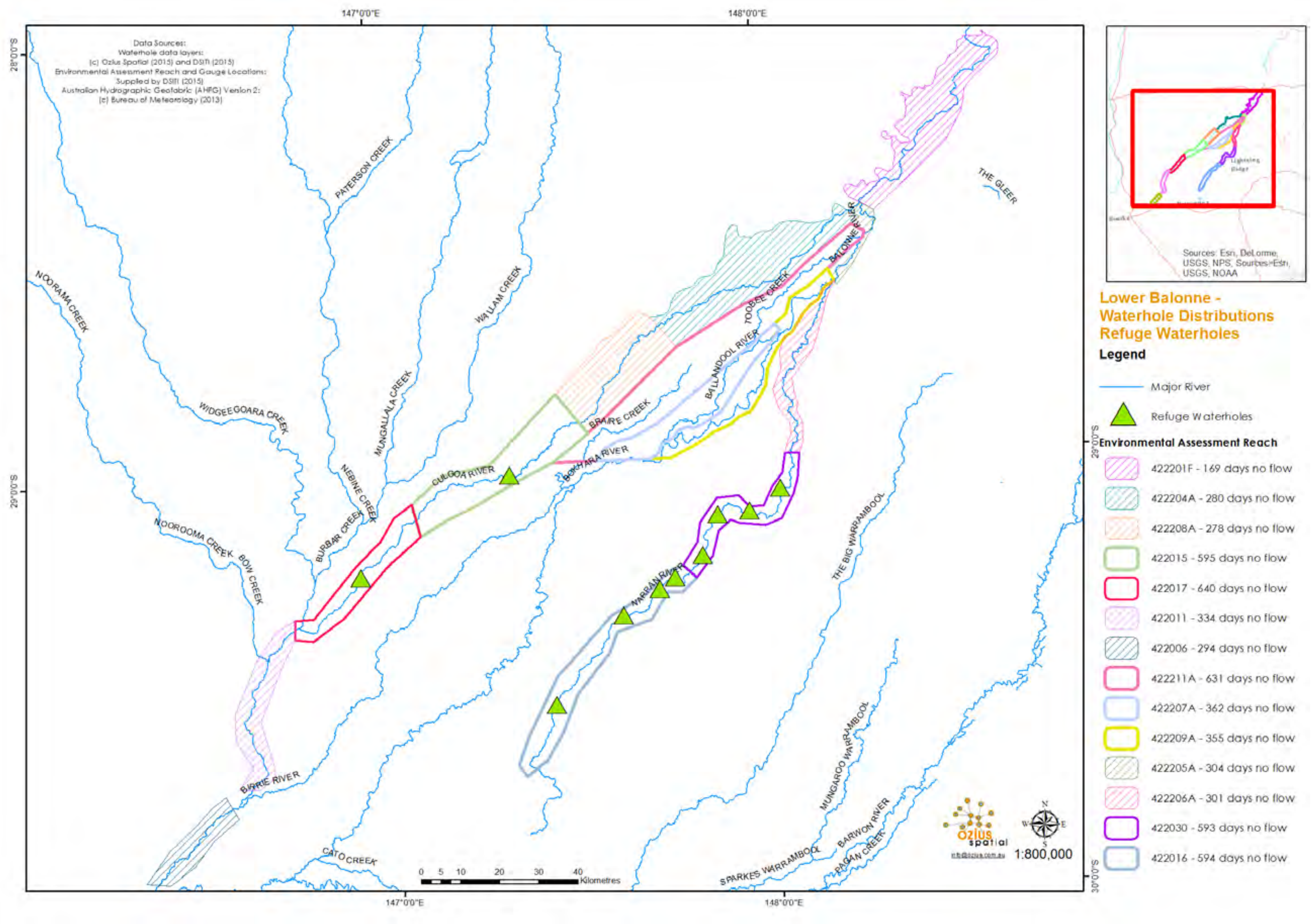

Figure 2.3 Location of refuge waterholes (i.e. those that retained water after 350 days without flow) across the Lower Balonne. Hatched environmental assessment reaches had less than 350 days of no flow

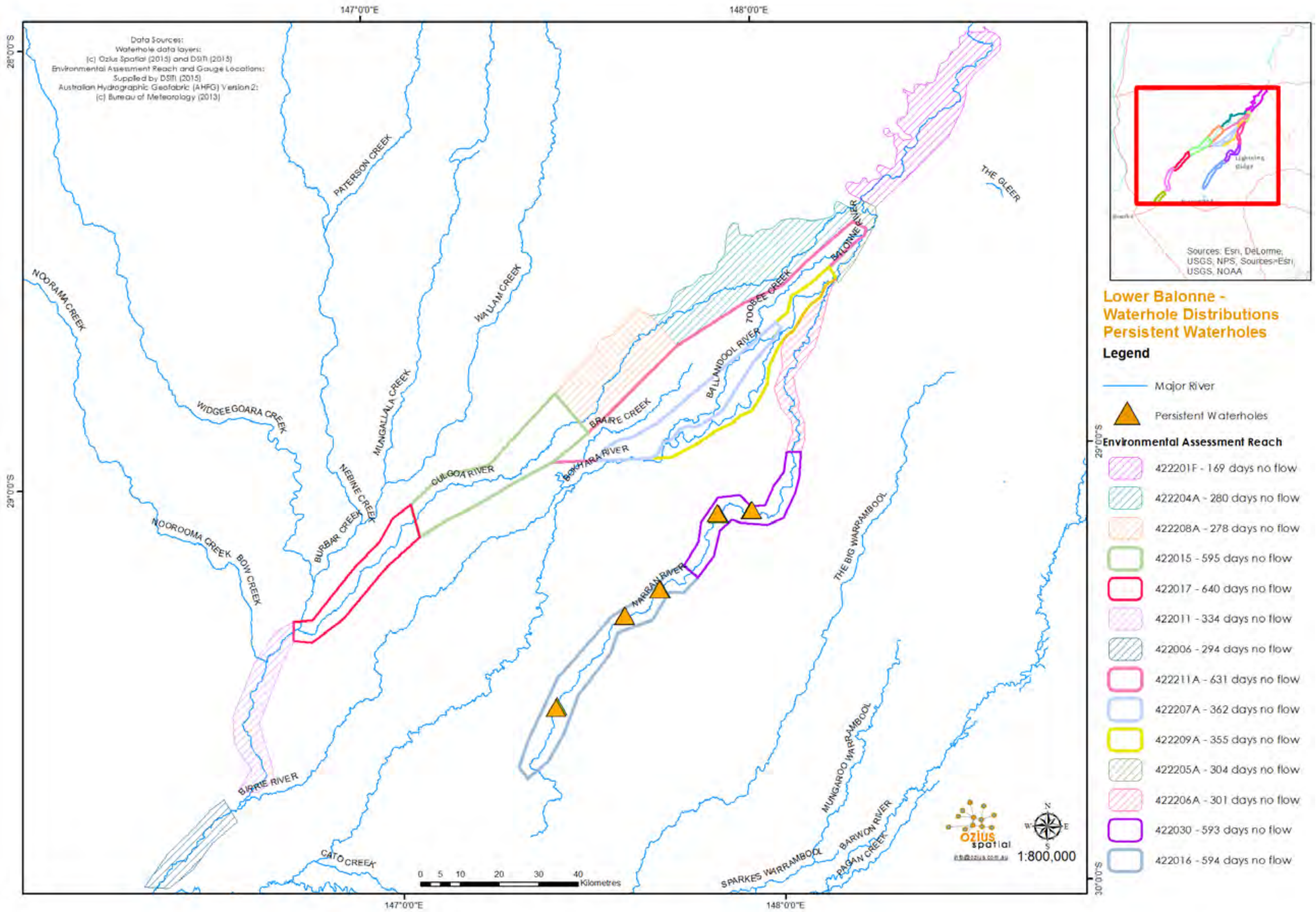

Figure 2.4 Location of persistent waterholes (i.e. those that retained water after 350 days without flow and throughout the time-series) across the Lower Balonne. Hatched environmental assessment reaches had less than 350 days of no flow

2.3.3 Reach-scale waterhole habitat persistence

Remote sensing analysis identified waterhole areas, defined as the surface area of wet pixels present in Landsat image, in the assessment reach for each no flow spell (exceeding 30 days of no flow) across the time-series. This means that the waterhole area identified for each no flow spell was based on availability of wetted habitat across the entire assessment reach, and this area could either represent an individual waterhole or a series of waterholes. Analysis showed that in all assessment reaches, waterholes retained a small amount of wetted habitat during the longest gauged no flow spells within the Landsat time-series and that waterholes had larger wetted habitats at the start of the no flow spell (after 30 days no flow) (Table 2.4).

Table 2.4 Summary of time-series waterhole persistence for each environmental assessment reach (at longest Landsat sampled no flow spell).

Environmental Assessment Reach	Longest Landsat sampled no flow spell (days)	Wetted habitat (hectares)
Culgoa River valley		
Culgoa River at Whyenbah (422204A)	280	98
Culgoa River at Woolerbilla (422208A)	278	18
Culgoa River at Brenda (422015)	595	154
Culgoa River at Weilmoringle (422017)	604	191
Culgoa River at U/S Collerina (Mundiwa) (422011)	334	92
Culgoa River at D/S Collerina (Kenebree) (422006)	294	7
Narran River valley		
Narran River at Dirranbandi-Hebel Rd (422206A)	301	141
Narran River at New Angledool (422030)	593	181
Narran River at Wilby Wilby (Belvedere) (422016)	418	121

The spell length that equates to zero wetted habitat was estimated by extrapolating the relationship between wetted habitat and spell length. The projected maximum persistence time was longer than the longest measured spell. This may be appropriate if a robust statistical relationship could be developed between the spell length and wetted habitat data. However the data, particularly for shorter spells, were scattered with different spells of similar lengths producing a broad estimate of habitat size (Figure 2.5). Further data analysis and investigation of the factors leading to variation in the relationship between spell length and wetted habitat availability is required. It is not currently possible to determine risk thresholds based on the reach scale habitat availability data.

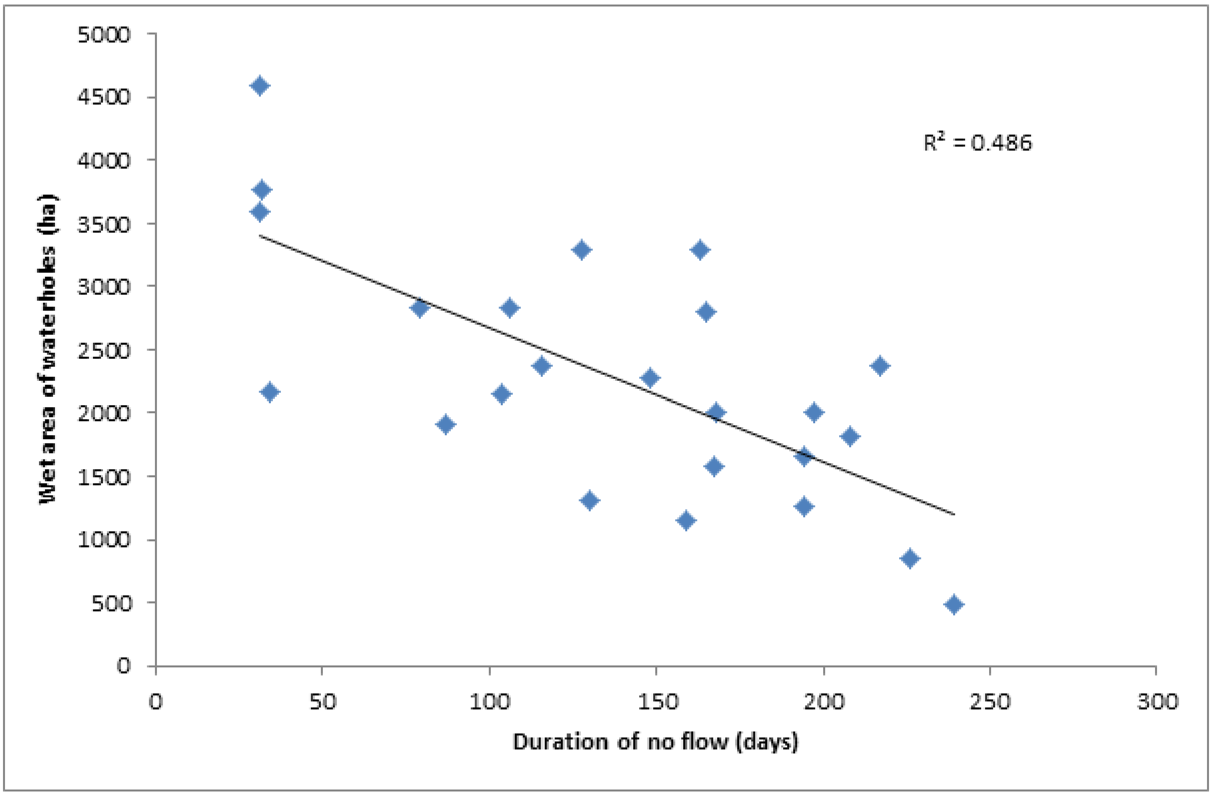

Figure 2.5 Relationship between waterhole area and duration of no flow days for the Narran River at Wilby Wilby (Belvedere) environmental assessment reach (associated with gauge 422016), after standardisation by duration and amount of wet area

2.4 Discussion

2.4.1 Distribution

The remote sensing approach applied here successfully identified four spatial layers of waterhole extents relative to each environmental assessment reach across the Lower Balonne and Barwon–Darling regions. The key spatial layer, refugial waterhole extent, was defined as wetted habitat present after 350 days of gauged no flow but not persistent throughout the time-series. Based on this, there are not many (ten) refugial waterholes in the Lower Balonne and most (eight) were confined to the mid to lower reaches of the Narran River. Although refugial waterholes may not persist during the longest spells, they are present in the majority of years with no flow and are likely to provide important habitat. However, this important habitat was restricted to 37 hectares, and only five of the ten refugial waterholes persisted throughout the time-series with a combined wetted area reduced to 3.7 hectares. Refugial waterholes were also restricted in the Culgoa River valley to <4 hectares at the Brenda and Weilmoringle gauges, and this habitat did not persist throughout the time-series. This observation corresponds with the longest predicted persistence time for a modelled waterhole in the Culgoa, which does not exceed >550 days of no flow (Chapter 3).

It is important to note that seven reaches in the Lower Balonne, and all of the reaches in the Barwon–Darling, did not experience spells without flow >350 days during the Landsat era. In these reaches, maximum time-series waterhole extents were identified, defined as wetted habitat present throughout time-series. Large areas of maximum time-series waterholes were identified in all but one reach in the Barwon–Darling indicating that a substantial area of wetted habitat is available during the generally short no flow spells. In the Lower Balonne, however, maximum time-series waterholes were mainly confined to the reaches immediately downstream of Beardmore Dam. The identification of both persistent and maximum time-series waterholes across the Lower Balonne is important for water management, as these waterholes are likely to provide the only habitat for populations of obligate biota during prolonged no flow spells and should be maintained.

2.4.2 Comparison with previous study

Persistent waterholes identified in this study were compared with the ‘substantial’ waterholes in the study from Webb (2009). All four substantial waterholes identified in the Narran River by Webb in 2007 were also identified using the remote sensing approach. Yet in the Culgoa, only two of three substantial waterholes identified by Webb (2009) were identified by remote sensing and were defined as refugial rather than persistent. Webb (2009) did note that waterholes identified in November 2007 were after a period of low to no flow across the Lower Balonne region therefore antecedent conditions prior to Webb’s study may have contributed to the differences observed.

The locations of the substantial waterholes were examined during longer no flow events captured by the satellite imagery, such as those in experienced in 2003, and either did not contain water or contained only small areas of wet pixels (i.e. less than four connected wetted pixels). This study has comprehensively assessed waterhole distribution over multiple no flow and antecedent conditions in each river valley, including the driest period since 1988.

2.4.3 Assumptions/recommendations for future studies

This remote sensing approach relies on the gauges assigned to each environmental assessment reach for flow statistics and interpretation. An assumption made in this approach is that the gauge associated with each assessment reach can broadly define the areas represented. It is also assumed that these gauges capture the beginning and end of long no flow spells across the reach. It is possible that gauges may not capture the beginning and end of long no flow spells, i.e. due to weirs, and this can affect the identification of the maximum extent for each spatial layer. To account for these assumptions, assessment reaches were identified using expert opinion. This approach was also reliant on a broad drainage layer to assist in defining the in-channel areas across the river valleys. This layer did not capture all in-channel areas and had to be reviewed to ensure that no significant areas of waterhole extent were omitted.

The analysis of wetted habitat availability generally showed a negative relationship between the persistence of waterhole areas within a reach and increasing no-flow spell duration, however not all observations closely fit the relationship. This analysis was reliant on the availability of the Landsat data set in the northern Basin region, and the number of longer no flow spell lengths was dependent on the associated gauge of the assessment reach. As some reaches had variable persistence over the no flow series, this implied that other factors (such as local rainfall, seasonality) may be influencing the persistence of wetted habitat within for each environmental reach. This can be investigated further when more historical data is available.

Key considerations for future studies include:

- Ground-truthing of refugial and persistent waterholes during no flow spells exceeding 350 days, or using relationships referred to in other components of this project (Chapter 6).

- Review of the spatial alignment of the drainage layer to capture the entire drainage line to ensure it is suitable for basin-wide spatial analysis.
- Review or inclusion of additional environmental assessment reaches, and associated gauges, to assist with spatial statistics and interpretation of surface water within the river valley.

Given that the remote sensing approach utilises historical data, it will become increasingly effective over time to analyse future no flow spells.

3 Modelling waterhole persistence in the Lower Balonne and Barwon–Darling rivers

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This chapter addresses the following knowledge gap:

- *What is the persistence time of waterholes in the Lower Balonne and Barwon–Darling?*

3.1 Introduction

The length of time that a waterhole contains water (i.e. its persistence time) is the period which it sustains obligate aquatic biota (Balcombe et al. 2007) and remains viable as a reservoir of water for human use. An understanding of the persistence time of waterholes is fundamental to effective management of water in an area dominated by temporary rivers such as the northern Basin (DERM 2010).

During dry periods when rivers stop flowing, shallow sections dry up and create a series of disconnected waterholes. This is when the persistence time becomes important. The persistence time of a waterhole is determined by the amount of water present when the waterhole is full and the rate at which water is lost:

Persistence time = Water (volume)/Change Rate (Gains - Losses/Time)

The persistence time is dependent on the losses and gains experienced during the period. If water gain (from sources such as flow, rain or groundwater influx) is greater than loss (to evaporation, seepage or extraction) the waterhole will fill, extending the persistence time. If the physical parameters of a waterhole are known along with the background loss rate, a model can be developed to predict persistence time under a variety of scenarios.

The benefits of a model to predict the persistence time of waterholes are plentiful. Water managers can manipulate losses and gains to compare a range of scenarios and determine optimal water management regimes. Also the minimum persistence time of waterholes can be determined, that is, the shortest length of time a waterhole will retain water in the complete absence of gains, representing the conditions during an extreme dry spell. The ability to identify waterholes that have the capacity to persist longest can assist managers to ensure that adequate conditions are maintained to provide biota with suitable refuge during drought (Rayner et al. 2009; Carini et al. 2006).

To develop a waterhole persistence model, several parameters are required:

- Measurement of the shape and volume of the waterhole to determine capacity.
- Water depth measurements during an extended drying period to determine loss rate.
- Rainfall and flow data so that gains can be accounted for and the background loss rate determined.
- Data on the interactions with groundwater and any pumping of water may also provide insight if those interactions are important at the site.

This chapter describes the development of 30 waterhole persistence models for the northern Basin, specifically within the Culgoa, Narran and Barwon–Darling river valleys.

Models were then used to determine the minimum persistence times for these sites. The calibrated models are a valuable tool for water management, providing a means of evaluating and comparing flow scenarios quickly. The waterhole persistence modelling approach is based on that of Lobegeiger et al. 2013.

3.2 Methods

3.2.1 Site selection

Three river valleys in the northern Basin were chosen by the MDBA to represent waterhole persistence in the region, for the purpose of the Northern Basin Review: the Culgoa, the Narran and the Barwon–Darling. These river valleys were divided into assessment areas, based on environmental assessment reaches (Chapter 2).

3.2.1.1 Narran and Culgoa river valleys

Within each of the Narran and Culgoa rivers, 15 waterholes of a range of sizes were selected both with and without weirs (Figure 3.1). The site selection strategy used was designed to achieve a balanced spatial design including waterholes representative of those in the respective river valleys.

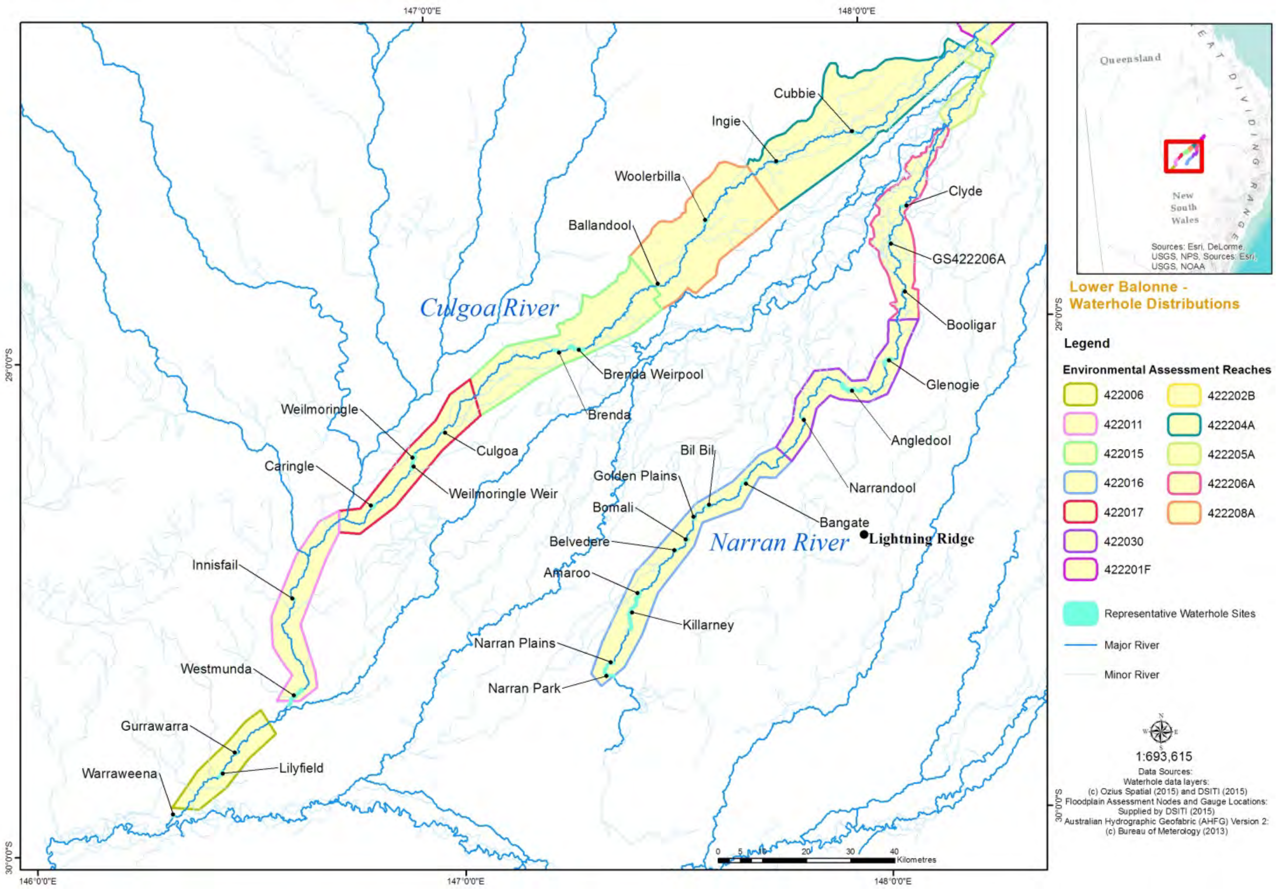

Figure 3.1 Narran and Culgoa River waterhole study sites

Within the environmental assessment reaches, sites were selected based on four criteria:

- Spatial distribution – Ensuring coverage of the length of the river valley and the location of at least one waterhole per environmental assessment reach.
- Access – Depth loggers needed to be downloaded every two months so sites had to be readily accessible.
- Natural vs Weir – A mixture of weir affected and natural sites were targeted.
- Previous studies – Information on some sites was available from previous studies (e.g. Thoms et al. 2004). Where possible, these sites were included in the study design so that valuable additional information could be incorporated.

Many waterholes in the region have been made artificially deeper with the installation of weirs and rock walls at the downstream end; in some instances these walls may be as high as two metres. In some reaches, these waterholes provide a significant proportion of the waterhole habitat during dry spells, therefore it was important to include both weir pools and natural waterholes to ensure representation of waterhole types (Table 3.1).

Table 3.1 Culgoa and Narran River valley sites. A total of 30 sites, 9 of which had been augmented with weirs were selected across the two valleys.

Site Name	Latitude	Longitude	Natural vs Weir Pool
Culgoa River valley			
Cubbie	-28.61049	147.97784	Natural
Ingie	-28.6683	147.80261	Natural
Woolerbilla GS	-28.78385	147.63031	Natural
Ballandool	-28.90783	147.51321	Natural
Brenda	-29.02882	147.26564	Natural
Brenda Weir pool	-29.02796	147.31221	Weir pool
Culgoa NP (NSW)	-29.18325	147.00017	Natural
Weilmoringle Weir	-29.25396	146.92188	Weir pool
Weilmoringle GS	-29.24327	146.92389	Natural*
Caringle	-29.33033	146.82761	Natural
Innisfail	-29.50803	146.63242	Natural
Westmunda (Grogan's Hole)	-29.70533	146.62436	Natural
Gurrawarra	-29.81595	146.47699	Natural
Lilyfield	-29.85022	146.44121	Natural
Warraweena	-29.93411	146.3232	Natural
Narran River valley			
Clyde	-28.76764	148.08948	Natural
GS422206A	-28.84097	148.05302	Natural
Booligar	-28.93873	148.08159	Natural
Glenogie	-29.07827	148.03789	Natural*
Angledool	-29.13709	147.94771	Natural*
Narrandool	-29.19076	147.83507	Natural
Bangate (Sorrento Hole)	-29.31740	147.68872	Natural
Bil Bil	-29.36072	147.60225	Weir pool
Golden Plains	-29.38503	147.57106	Natural
Bomali	-29.4291	147.55040	Natural
Belvedere	-29.44701	147.52798	Natural
Amaroo	-29.53071	147.43658	Natural*
Killarney	-29.58680	147.41068	Weir pool
Narran Plains	-29.67077	147.36882	Natural
Narran Park	-29.69681	147.36775	Natural*

*Study site is part of impounded area when waterhole is full, but disconnects from the weir pool into a separate waterhole as it dries.

3.2.1.2 Barwon–Darling River valley

Using the hierarchical classification scheme of Thoms et al. (2004) five functional process zones or river zones were identified along the Barwon–Darling River between Goondiwindi and Wentworth, all nested within a valley zone characterised by highly variable styles of river channel anabranching. Functional process zones are sections of river characterised by relatively uniform discharge and sediment regimes and similar channel morphology. The use of functional process zones ensures that waterholes from all types of zone are represented and a representative selection of variations in river channel and waterhole morphology are included. Waterhole sites were selected covering each of the zones.

Waterholes were selected based primarily on spatial distribution and access, using information from the community and landholders (Figure 3. 2). Several waterholes had been previously identified from aerial surveys conducted during a dry period in 2009. Twelve sites were selected from the study area (Table 3.2) consisting primarily of pools associated with weirs, as few natural waterholes occur in the region and could be accessed. These weir-affected pools represent waterholes that are part of the impounded area when full but disconnect from the weir pool when drying. One natural waterhole (Ellendale) was included.

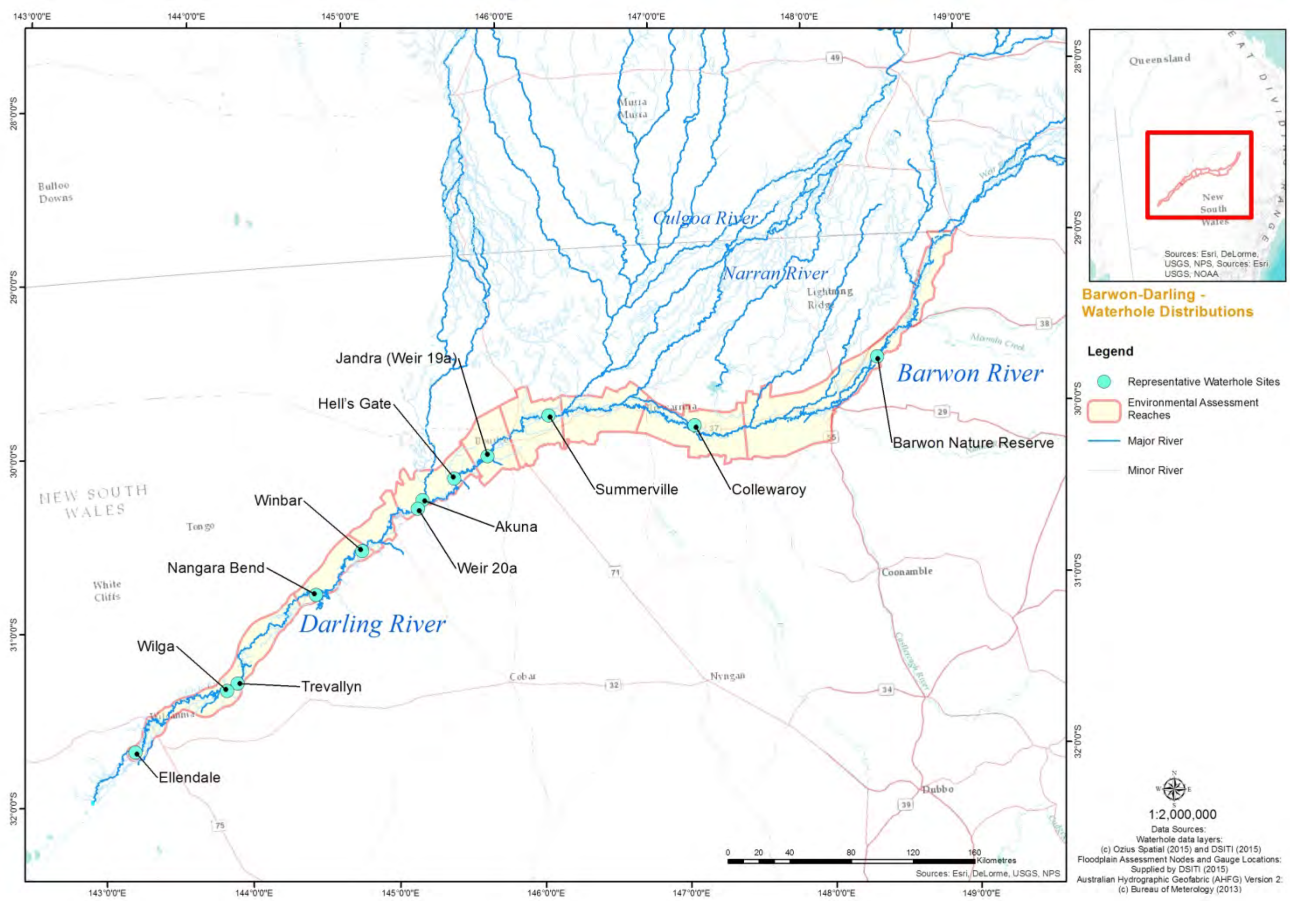

Figure 3.2 Barwon–Darling River valley waterhole study sites

Table 3.2 Barwon–Darling River valley sites. A total of 12 sites, 11 of which were associated with weirs, were selected across the river valley.

Site Name	Latitude	Longitude	Natural vs Weir Pool
Barwon–Darling River valley			
Barwon Nature Reserve	-29.71471	148.42895	Weir pool*
Collewaroy	-30.06863	147.18816	Weir pool*
Summerville	-29.96333	146.21500	Weir pool*
Jandra (Weir 19a)	-30.17973	145.78933	Weir pool*
Hell's Gate	-30.29673	145.55716	Weir pool*
Akuna	-30.40981	145.33416	Weir pool*
Weir 20a	-30.45681	145.30083	Weir pool*
Winbar	-30.67888	144.90566	Weir pool*
Nangara Bend	-30.91258	144.57516	Weir pool*
Trevallyn	-31.38991	144.00055	Weir pool*
Wilga	-31.42735	143.92533	Weir pool*
Ellendale	-31.73641	143.27033	Natural

*Study site is part of impounded area when waterhole is full, but disconnects from the weir pool into a separate waterhole as it dries

3.2.2 Water loss measurements

3.2.2.1 Narran and Culgoa river valleys

Depth loggers (Schlumberger Mini Diver), recording water depth at 30 minute intervals, were installed to measure the rate at which water was lost from each waterhole (Figure 3.3) (after DNRM 2013a). Loggers were installed in May 2014 in an effort to capture the end of the 2014 drying season (April–September), the 2014/15 wet season (October–March) and the complete 2015 drying season, ideally capturing several months of continuous drying.

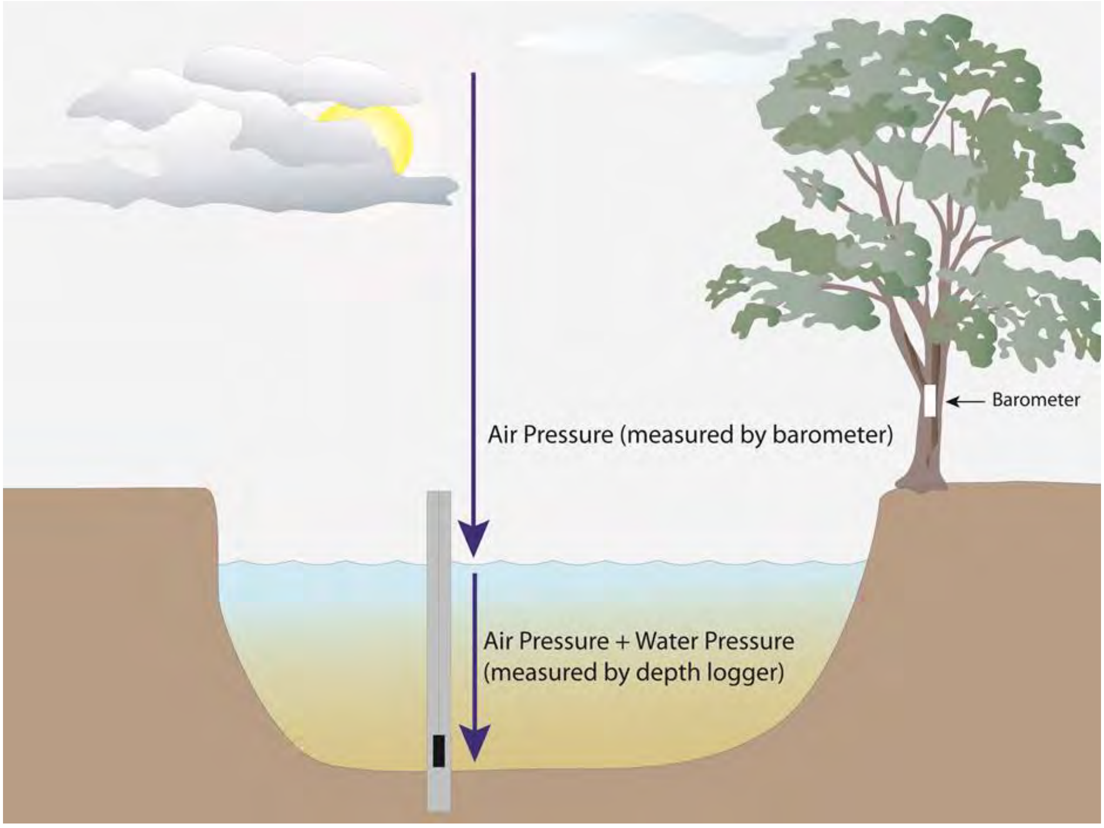

Figure 3.3 Diagram of depth logger and barometer installation

The barometric pressure at each waterhole was also measured every 30 minutes with a separate logger (Schlumberger Baro–Diver) in order to permit compensation of depth records for local atmospheric pressure (Figure 3.3). The use of a site specific barometer improves the accuracy of depth measurements over using weather data as it accounts for local variability in pressure. Once compensated for atmospheric pressure, the water pressure can be converted to depth, which can then be examined over time to establish a rate of water loss.

To ensure continuity of data, loggers were downloaded every two months to confirm they were functioning correctly and for data backup in case loggers were lost in flooding. Upon each download, the data were examined in the field for any variations outside expectation and manual depth measurements were taken at the logger site to enable corrections to be made for instrument measurement drift.

Once a full data set was accumulated, the depth data were converted to a daily average to remove diurnal fluctuations and, if required, linear corrections were applied based on manual site measurements to correct instrument drift errors. Then the longest continuous period of drying was identified for use in the model calibration, ensuring the most accurate representation of the system possible.

3.2.2.2 Barwon–Darling River valley

Depth loggers were installed utilising the same procedure as in the Narran and Culgoa rivers (DNRM 2013a), with some minor modifications. Due to the large depth and surface dimensions of the study sites in the Barwon–Darling the installation was fixed to the bank (Figure 3.4). Rather than installing loggers on a post within the river channel, this installation enables greater protection from possible high flows during the sampling period, ease of access to download logger and minimises potential issues as a navigation hazard for recreational watercraft users.

Figure 3.4 Logger installation at Trevallyn (Photo: Neal Foster).

The installation comprised of a number of sections of PVC pipe (total length dependent on waterhole depth) configured as an outer sheath, fixed with steel posts driven into the bank. The data logger was attached to a smaller diameter PVC conduit which was slid inside the outer sheath as far down into the water column as possible. Once installed, the opening of the outer pipe was sealed and locked to minimise tampering.

3.2.3 Bathymetric survey of waterholes and DEM development

3.2.3.1 Narran and Culgoa river valleys

Bathymetric surveys of each site were conducted in February and March 2015 following a flow event so that the waterhole was as close to cease to flow (CTF) as possible without actually disconnecting from the river. This was to ensure that the entire area and perimeter of the waterhole at its CTF extent could be accessed and mapped. Surveys were undertaken following a Queensland Government standard method (DNRM 2014). A depth-sounder (Tritech PA200) paired with a GPS (Garmin GPS 60) was used to record depth-location data along a longitudinal profile of the waterhole following the thalweg until the water became too shallow to cross (approximately 20 centimetres) or an impasse was encountered. Then the cross sectional profile of the waterhole was mapped by crossing the waterhole in a zigzag pattern for its entire length.

3.2.3.2 Barwon–Darling River valley

Bathymetric surveys of ten sites were conducted using a modified version of the method used in the Narran and Culgoa rivers (DNRM 2014). Nangara Bend could not be surveyed for logistical reasons.

In the Barwon–Darling, the impact of water impoundment was such that mapping the vast extent of waterholes at CTF was impractical. The mapping technique was modified to target sections of the impounded area that disconnect into separate waterholes during drying. This ‘sub-waterhole’ extent was identified with a reconnaissance run and once approximate physical dimensions of the ‘sub-waterhole’ areas were established, a more intensive survey was conducted.

The surveys were conducted in May 2015 using the CEE Hydrosystems Ceeducer Pro. Data post-processing was performed using the HYPAC hydrographic software package.

3.2.3.3 Developing DEMs

Once collected, the bathymetry data was interpolated to generate Digital Elevation Models (DEMs) in ESRI ArcMap v10.x; depth profiles of the waterholes (DNRM 2013b). This method was updated by using a semi-automated toolkit (Bathymetry Toolkit v.20) designed to transform the field-collected bathymetry data into a derived relative bathymetric DEM. The toolkit was also used to perform volumetric analysis of the bathymetric DEMs to derive water volume and surface area of a waterhole at different stages of a drying cycle.

A bathymetric DEM surface was created by inputting field-collected depth-location data to create a point cloud that was then interpolated to produce a raster DEM. Bathymetry was recorded on a 0.4 metre pixel (x,y) grid with a 0.01 metre height sensitivity (z), depending on field sampling distance and field capture techniques.

Where necessary, adjustments were made to the DEMs to slice off surveyed areas above the CTF level, either based on field measurements or by examining the depth profile of shallower sections at the ends of surveyed waterholes or between connected waterholes.

Once the DEMs were finalised, surface area and volume were calculated at one centimetre intervals to determine the wetted extent of the waterholes at different height stages, representing the change in habitat availability as waterholes dry.

3.2.4 Developing waterhole models

3.2.4.1 Aligning depth loss data and bathymetry data

As depth loggers were unlikely to be positioned exactly in the deepest point of the waterhole, adjustments needed to be made to the depth logger data to relate it to bathymetry data in order to develop models for each waterhole. Firstly, the installation method means that the depth logger is suspended some distance above the bottom of the waterhole. The depth of water below the logger needs to be calculated so that the measurements can be corrected to the total water depth at that location. Secondly, the DEM is built relative to CTF (Section 2.3.2.3), so the depth logger data must also be adjusted to CTF. Lastly, the depth logger depth at CTF is adjusted to match the maximum depth recorded in the DEM.

There are five key steps to adjust the depth logger data to relate to the DEM:

1. Determine maximum depth of the waterhole at CTF (maximum waterhole depth recorded during bathymetry minus how much the DEM was adjusted to CTF)
   i.e. 1.9 metres minus 0.6 metres = 1.3 metres
2. Relate this adjustment to a DEM datum (100 metres was used as a default datum in the absence of actual elevation data)
   i.e. 100 metres plus 0.6 metres = 100.6 metres
3. Determine how much to adjust the logger depths to a DEM datum based on depth recorded at the logger during bathymetry (1.6 metres)
   i.e. 100.6 metres minus 1.6 metres = 99.0 metres

4. Adjust all corrected daily depths (installation difference of 0.1 metre) by 99.0 metres to find CTF at the logger
   i.e. 1.5 metres plus 99.0 metres = 100.5 metres
5. Adjust corrected depths of logger back to the maximum depth in the DEM by subtracting CTF depth of the waterhole in a DEM datum
   i.e. 100 metres minus 98.7 metres = 1.3 metres

Figure 3.5 provides a conceptual diagram of this process.

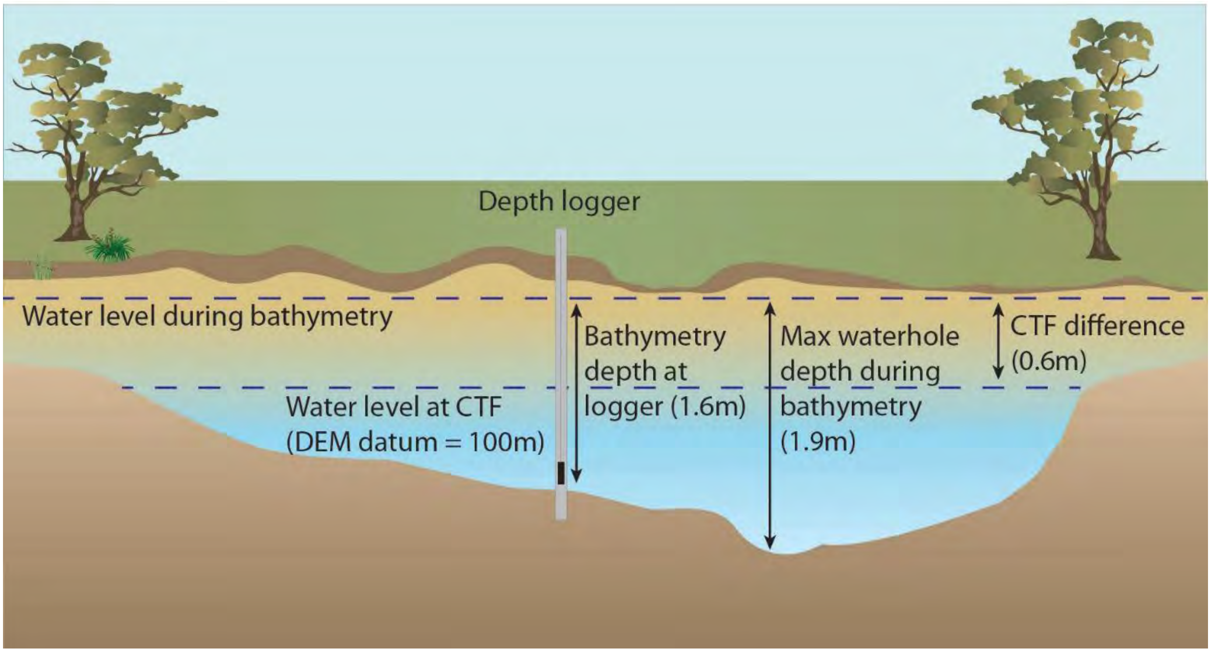

Figure 3.5 Conceptual diagram of adjusting the depth logger data to relate to the DEM

3.2.4.2 Waterhole persistence model

Models for each waterhole were developed using the Waterholes plugin within the Eco Modeller package (eWater 2012), which is a waterhole water balance model that operates during no flow periods in an input flow time-series. The volume of water within the waterhole is determined at a daily time-step and is the combination of:

- Gains: rainfall directly on the water surface, runoff from the near channel area, infiltration from local alluvial aquifers (where local alluvial aquifers can be affected by local rainfall).
- Losses: evaporation, loss to local aquifers, loss to deep drainage (regional groundwater). If data on daily pumping rates are available, this can also be incorporated. For this study such data were unavailable.

The Waterholes plugin has a collection of parameters to define the rates of losses and gains and how they interact. The Waterholes plugin has an optimisation function (genetic algorithm) where the user can select which parameters to include in the optimisation. The optimisation process is based on minimising the Root Mean Squared Error (RMSE) by comparing the predicted and measured depth.

3.2.4.3 Building and calibrating models

The Waterholes plugin tracks the volume and depth of water in the waterhole subject to a range of influences including: river flow, evaporation, seepage and rainfall (both on the surface and surrounding runoff) (Section 3.2.4.2, above). The climate data (evaporation and rainfall) for each site was interpolated Bureau of Meteorology (BOM) data collated from SILO Data Drill. Flow information was sourced from gauging stations associated with each environmental assessment reach (Table 2.2 in Chapter 2). The lag time for the flow to reach the site due to distance of the gauge to the site may be accounted for in the model.

The volume and surface area at one centimetre intervals for the depth of the waterhole were used to create a bathymetry table representing the relationship between depth, surface area and volume of a waterhole (Figure 3.6). This information forms the basis of the model by outlining the physical parameters of the waterhole.

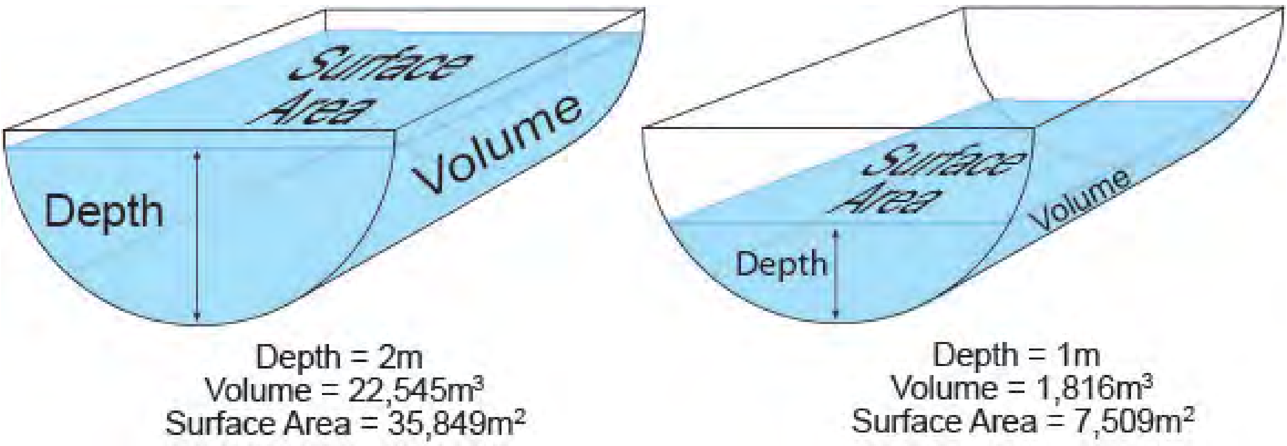

Figure 3.6 Conceptual model of a waterhole at 2 metre and 1 metre depths.

Using the surface area information the amount of water loss due to evaporation was calculated for a given depth on a daily basis. The model then applied that water loss to calculate the depth and volume values for the following day, and so on until the waterhole dries.

The gains from rainfall were calculated in a similar way. Each day, the volume of rain was applied across the surface area of the waterhole to calculate the direct gain from rain falling into the waterhole. The model adds the additional volume of water to the total and the depth and surface area are recalculated for the next day.

The end result of these calculations was a basic waterhole water balance model. Cumulative losses and gains can be weighed to calculate a daily loss/gain which is then applied to the waterhole volume to calculate values for the following day.

Though this model took into account the major water losses and gains, there were other potentially important factors, for example, groundwater losses or gains. The model is only as representative of a system as the input parameters it considers, so rain or evaporation information that has been averaged over a large distance may not accurately reflect local conditions (and therefore impacts) at the waterhole. In order to more accurately reflect the dynamic system it represents, the model was calibrated against real data.

Once the theoretical model was developed, calibration was used to examine how the model performed against what was observed at the site for a given period. Using the drying data from the depth logger (Section 3.2.2, above) the longest, ideally continuous, period of drying was used for calibration because it provides the best opportunity to understand loss and gain rates over time and at a range of waterhole depths, to enable a robust calibration. Once this period was identified and calibration parameters entered and saved, the model was run for the same period using the climate data and plotted alongside the field-measured data for comparison. Then, the RMSE was used to summarise the overall fit of the model to the observed water loss data. Using the observed data as a reference point, the model parameters were adjusted so that the best possible fit was obtained. For a detailed description of these calibration parameters see Appendix C – Calibration Parameters.

This adjustment first involved reducing the calibration parameters to only three basic parameters (evaporation scaling, seepage rate and local catchment area), and all at low values i.e. evaporation scaling was one, as there was little usable data. Next, these parameters were manually adjusted and optimised using the optimise function (Section 3.2.4.2, above). Depending on how low or high these values were for these basic parameters after optimisation, additional parameters were also incorporated by manually adjusting at low values and then optimised with calibrations aimed to minimise the RMSE as much as possible. The parameters and values used to calibrate the models across each river valley are summarised in Table 3.3. A good calibration across a relatively long stable period establishes the rates of the various influences on the waterhole depth and makes the model more robust and reflective of the environment in which the waterhole exists.

Table 3.3 Summary of parameters, and value range, used to calibrate waterhole models in the Culgoa and Narran river valleys

Calibration Parameters	Culgoa River valley	Narran River valley
Evaporation Scaling	0.68 - 1	0.5 - 1
Seepage Rate (mm/d)	0 -2.29	0 - 4.3
Local Catchment Area (m^2)	0 - 80000	0 - 149747.9
Max daily inflow (mm/d)	0 - 10	0 - 6.9
Local GW catchment area (m^2)	0 - 10000	0
Inflow to Waterhole (%)	0 - 4.5	0 - 2.06
Lost to deep drainage (%)	0 - 5.5	0

3.2.5 Uncalibrated models

Suitable periods of depth loss were not captured at the three study sites with DEMs (Akuna, Weir 20A and Ellendale), meaning there was no prolonged period of draw down. For these sites, model calibration was not possible, so models were built and run without calibration. In this instance, the model parameters were estimated based on site and system knowledge and the model was run in an uncalibrated state. The physical parameters of the waterhole were based on the DEM data which remain accurate, but the actual influences of losses and gains could only be estimated.

Uncalibrated models provide some insight into the persistence times of waterholes if the environmental condition data is reflective of the impacts at the site, but a calibrated model allows for confirmation of the accuracy of the model, at least throughout the calibration period.

3.2.6 Calculating minimum persistence time

Once the waterhole models were built (and calibrated where possible), the input and loss parameters are able to be manipulated to reflect various scenarios. The simplest, but perhaps the most useful, of these scenarios is calculation of the minimum persistence time; the shortest time in which the waterhole can dry from completely full at cease to flow. This was done quite simply by reducing all gains to the model waterhole to zero.

The manipulated model used the calibrated parameter inputs with an average evaporation rate over the extent of the input data set to generate the daily depth until the waterhole was dry. Once calculated, the minimum persistence times for each waterhole were coupled with the maximum depth of the waterhole (extracted from the DEM, Section 3.2.3.3) to examine the relationship between depth and persistence time.

3.3 Results

3.3.1 Water loss measurements

Depth loggers were successfully downloaded several times throughout their approximately 14 months of deployment. Across the waterholes the most consistent period of drying was the three months of September to November 2014. During this time the river valleys experienced low rainfall (Figure 3.7) which was approximately 50 millimetres less than the long term average for the region and temperatures approximately 2°C hotter than the long term average.

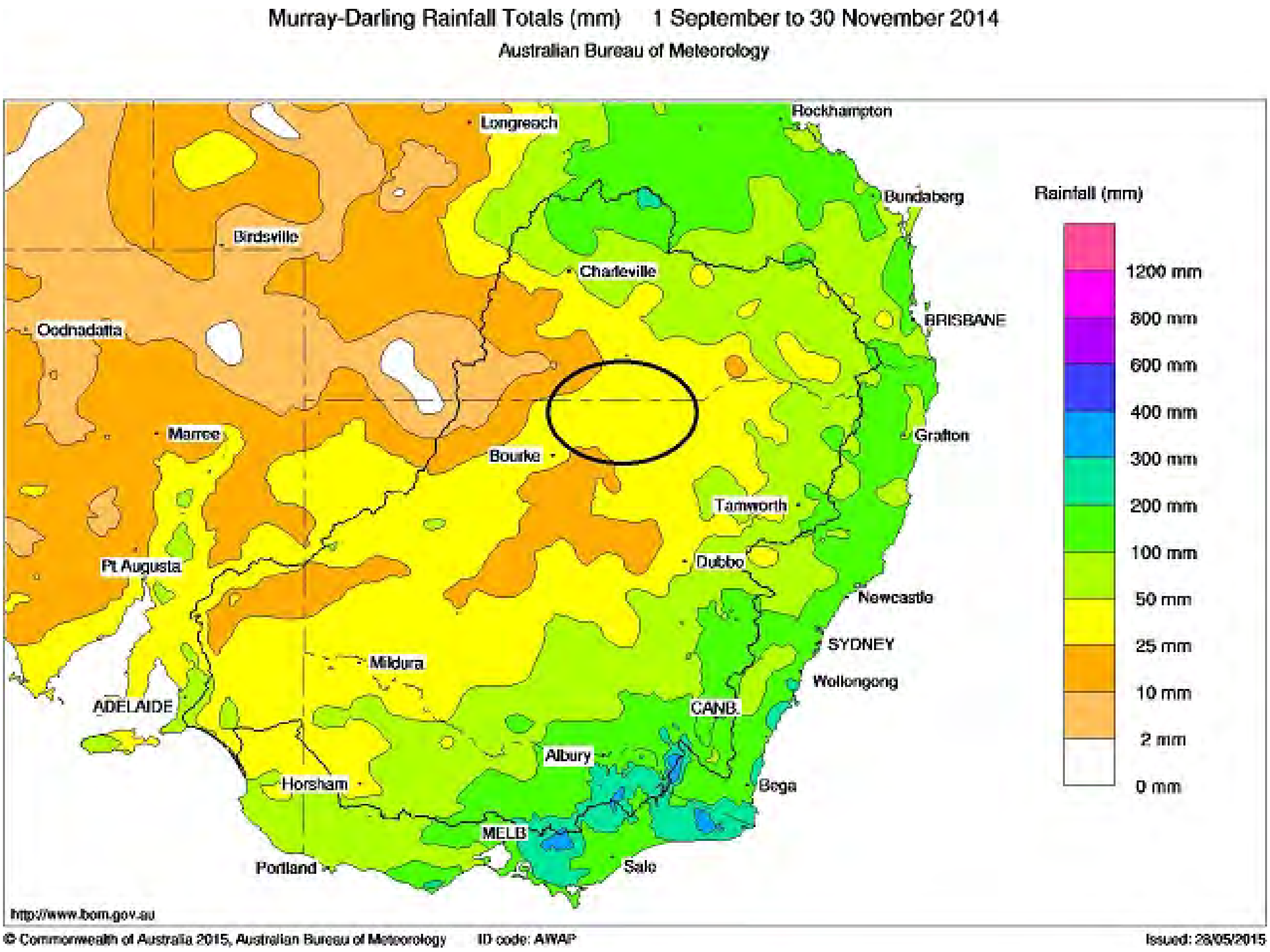

Figure 3.7 Rainfall map for the study area (circled) during the peak drying period. Rainfall for this time of year was slightly below the long term average.

The period of September to November 2014 was identified as an ideal period of drying for the vast majority of sites because of below average rainfall. Despite this, localised rainfall meant that some sites experienced significant input during this period so the period of calibration had to be adjusted accordingly. Ideal drying conditions were identified by using the CTF depth calculated during the DEM building phase by looking for the longest period of drying with little to no input. The CTF depth was used as a starting point for selecting the drying period because any water loss data above the cease to flow depth would represent flow reduction rather than drying, and not be included in the model. Lastly, some sites had suitable calibration periods that continued into January 2015 which captured the waterholes at their lowest points in the drying cycle for that year, so these waterholes were able to be calibrated for a majority of the depth range (Figure 3.8).

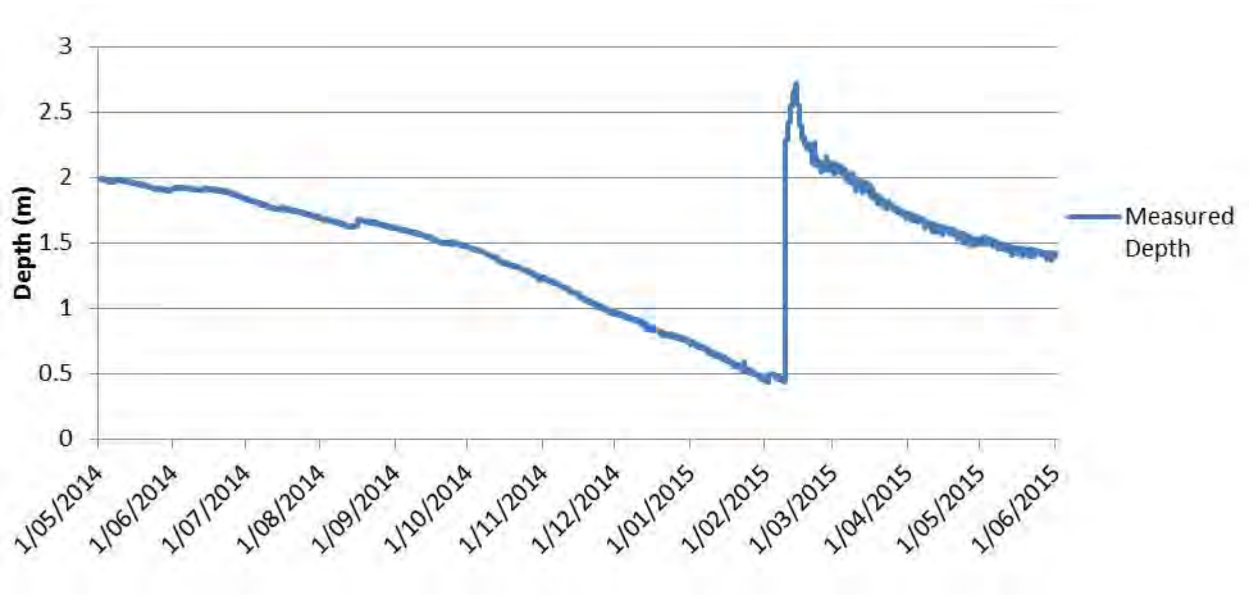

Figure 3.8 Raw depth logger data for Bomali waterhole from 01/05/14 to 01/06/15 showing two drying periods. The first period during late 2014 and early 2015 was used in calibration for the models.

The draw down period and amount (depth change) used in calibration of models in the Narran and Culgoa river valleys was varied (Table 3.4). The least amount of draw down captured was observed for the larger waterholes across the Culgoa and Narran river valleys, such as Killarney and Ballandool. However, average draw down across the river valleys was over 30 per cent of the maximum depth at CTF and considered suitable for calibration.

Three sites in the Culgoa River valley were not able to be calibrated (Warraweena, Weilmoringle Weir and Brenda Weir pool) because drying data below CTF was not sufficient for calibration. Throughout the period of logger deployment these sites remained relatively deep, such that the logger could not be retrieved in the 2015 season because the logger pole was completely submerged.

Table 3.4 Date ranges used in the calibration of models for each site and the amount of draw down captured (depth change and % of full depth) for the Culgoa and Narran River valleys. Note none of the depth loggers in the Barwon–Darling had drying periods suitable for calibration.

Site Name	Calibration Start Date	Calibration End Date	Depth Change (m)	% of Full Depth
Culgoa River valley				
Cubbie	29/05/2014	29/12/2014	1.25–2.44	47.5
Ingie	15/06/2014	01/12/2014	1.29–2.19	41.1
Woolerbilla GS	27/09/2014	01/01/2015	1.85–2.58	28.3
Ballandool	18/09/2014	01/11/2014	2.37–2.7	12.2
Brenda	24/10/2014	10/01/2015	2.19–2.82	22.3
Brenda Weirpool	N/A*	N/A*	N/A*	N/A*
Culgoa NP (NSW)	03/09/2014	12/01/2015	0.93–1.91	51.3
Weilmoringle Weir	N/A*	N/A*	N/A*	N/A*
Weilmoringle GS	04/11/2014	20/12/2014	2.51–2.97	15.5
Caringle	24/05/2014	24/12/2014	0.37–1.59	76.7
Innisfail	18/09/2014	10/01/2015	0.4–1.29	69.0
Westmunda (Grogan's Hole)	27/07/2014	01/12/2014	1.77–2.37	25.3
Gurrawarra	16/10/2014	19/01/2015	0.8–1.68	52.4
Lilyfield	23/08/2014	24/11/2014	1.47–2.08	29.3
Warraweena	N/A*	N/A*	N/A*	N/A*
Narran River valley				
Clyde	03/09/2014	31/10/2014	1.45–1.87	22.5
GS422206A	07/05/2014	01/01/2015	0.18–1.82	90.1
Booligar	07/05/2014	08/01/2015	0.97–2.57	62.3
Glenogie	10/05/2014	01/12/2014	2.13–2.90	26.6
Angledool	11/12/2014	15/01/2015	2.85–3.06	14.6
Narrandool	22/08/2014	20/12/2014	0.55–1.29	57.4
Bangate (Sorrento Hole)	08/11/2014	04/02/2015	2.47–3.00	17.7
Bil Bil	07/11/2014	01/01/2015	1.27–1.68	24.4
Golden Plains	22/10/2014	08/01/2015	0.44–1.31	66.4
Bomali	11/10/2014	01/02/2015	1.11–2.06	46.1
Belvedere	09/11/2014	09/02/2015	0.60–1.32	54.5
Amaroo	10/11/2014	09/02/2015	0.83–1.30	36.2
Killarney	06/01/2015	10/02/2015	2.20–2.43	9.5
Narran Plains	04/05/2015	03/12/2015	1.45–2.56	43.4
Narran Park	06/07/2015	12/02/2015	1.11–2.41	53.9

*Insufficient data

None of the depth loggers in the Barwon–Darling had drying periods suitable for calibration. Due to the depth of the channels, a number of sites did not reach CTF or did not have sufficient drying to calibrate (Figure 3.9). The models are able to be run without calibration, but due to the limitations of the input data, the accuracy of the outputs cannot be assured.

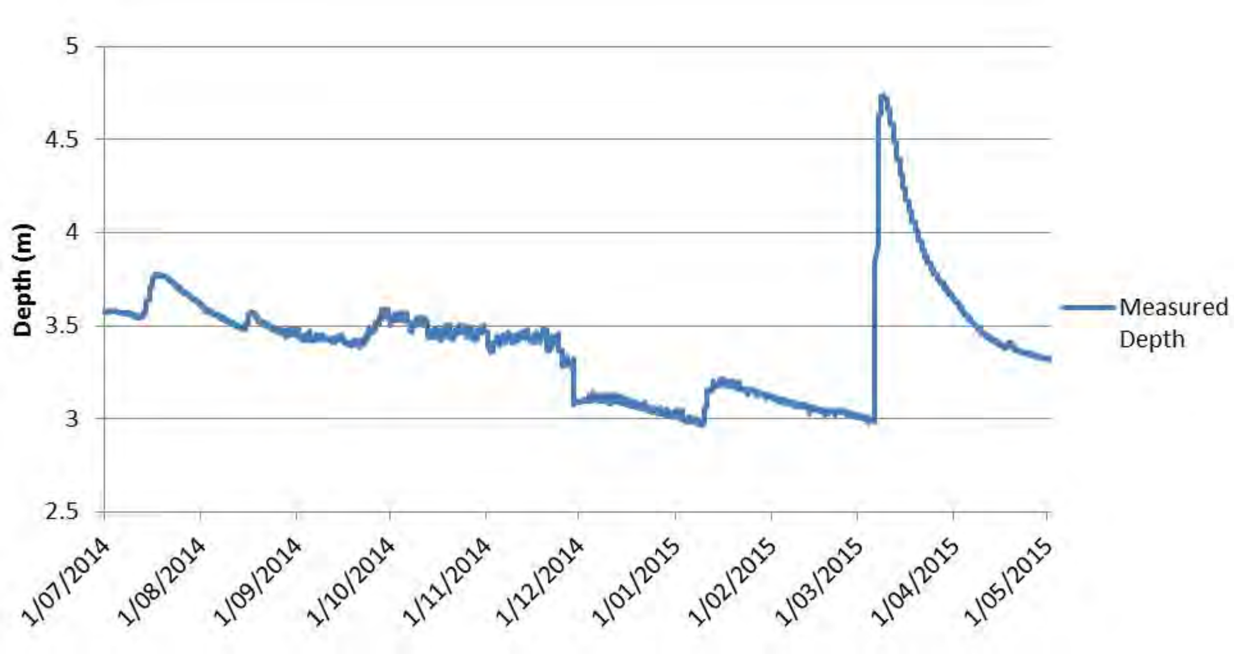

Figure 3.9 The Ellendale depth logger did not have sufficient dry down to calibrate. The drop in depth at the start of December may be from extraction. The drying period in early December only covers approximately 20 centimetres.

3.3.2 Bathymetric survey of waterholes

Bathymetric surveys were conducted at all sites in the Narran and Culgoa river valleys and nine sites in the Barwon–Darling River valley (Figure 3.10). The bathymetric profiles for all sites in the Narran and Culgoa were successfully interpolated to generate DEMs which represent the depth of the waterholes (Figure 3.11). Final DEMs for each site are available in Appendix C – Digital Elevation Models.

Figure 3.10 Google Earth™ image of Bomali Waterhole and the bathymetry track.

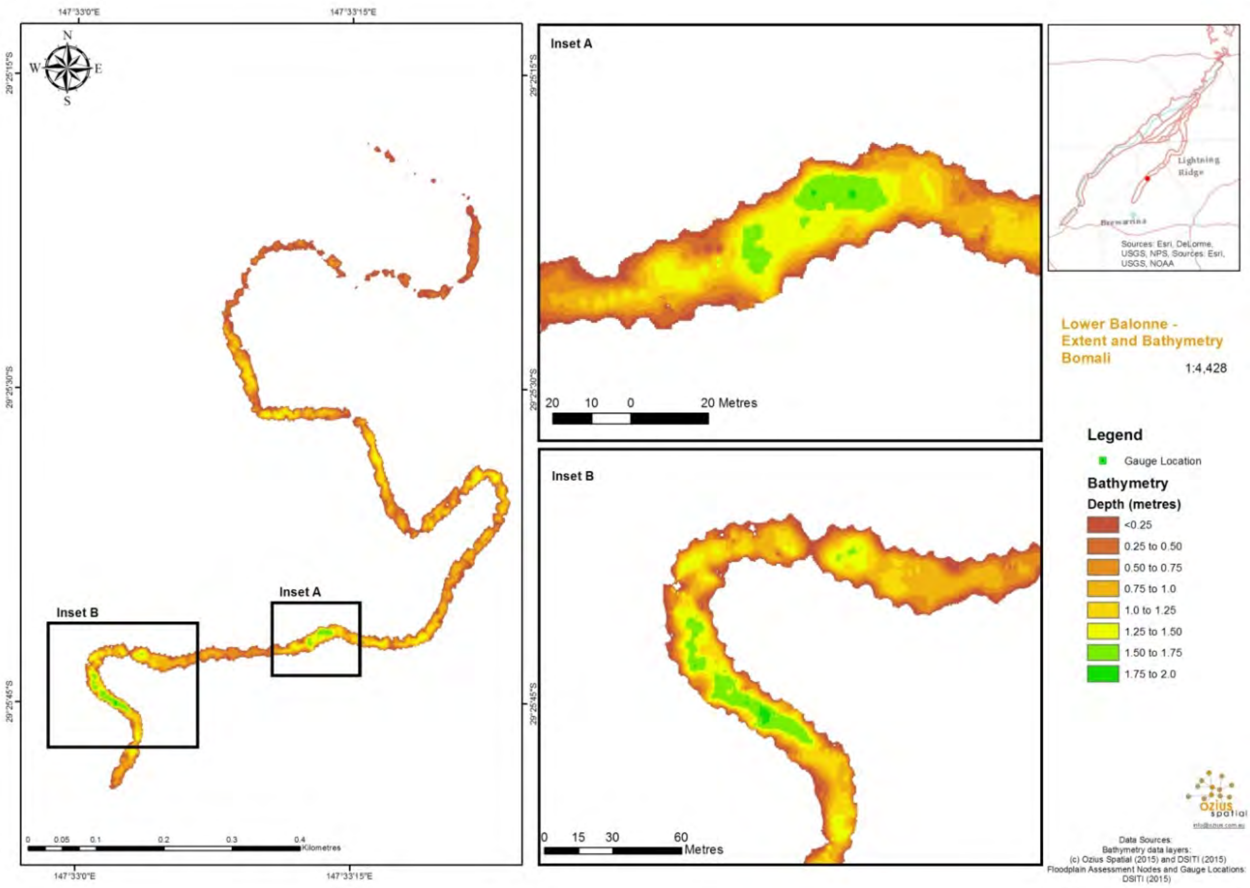

Figure 3.11 Digital Elevation Model (DEM) of Bomali Waterhole; deeper areas are green. The deeper pool within inset B contains the depth logger, though inset A also contains a relatively deep area that will split from the main waterhole prior to it completely drying.

In the Barwon–Darling, only four bathymetric profiles could be successfully interpolated to generate DEMs (Hell's Gate, Akuna, Weir 20A and Ellendale). Due to the proximity of Akuna and Weir 20A, their profile was not separated.

3.3.3 Calibrating the Waterhole Models

The models calibrated well to the observed drying periods (Table 3.5). The Root Mean Squared Error (RMSE) was used to assess the calibration performance of the model. The RMSE is the square root of the mean of the square of all error. The errors in the predicted daily water depth (predicted observed) are squared, and summed, divided by the number of observations and then the square root is taken. The RMSE has the same units as the input variable, in this case water depth. Hence a RMSE value of 0.05 implies that the average error in depth prediction from the model is 0.05 metres (5 centimetres). Only one site had a RMSE above 0.05 (Caringle, RMSE = 0.0541) due in part to an inflow event in the middle of the calibration period. Results indicate that the calibrated water loss models accurately represent loss from these representative waterholes.

Table 3.5 Root Mean Square Error (RMSE) of the difference between the observed water depth and predicted water depth (m) for the calibration period, lower is better

Site Name	Root Mean Square Error (RMSE)	Site Name	Root Mean Square Error (RMSE)
Culgoa River Valley		**Narran River Valley**	
Cubbie	0.0421	Clyde	0.0079
Ingie	0.0407	GS422206A	0.0353
Woolerbilla GS	0.0193	Booligar	0.0164
Ballandool	0.0138	Glenogie	0.0356
Brenda	0.0098	Angledool	0.0071
Brenda Weirpool	N/A	Narrandool	0.0170
Culgoa NP (NSW)	0.0329	Bangate (Sorrento Hole)	0.0147
Weilmoringle Weir	N/A	Bil Bil	0.0084
Weilmoringle GS	0.0434	Golden Plains	0.0360
Caringle	0.0541	Bomali	0.0122
Innisfail	0.0185	Belvedere	0.0154
Westmunda (Grogan's Hole)	0.0235	Amaroo	0.0126
Gurrawarra	0.0378	Killarney	0.0068
Lilyfield	0.0080	Narran Plains	0.0407
Warraweena	N/A	Narran Park	0.0311

3.3.4 Physical characteristics determining persistence time of waterholes

Using the calibrated models, the minimum persistence time of the waterholes was calculated (Table 3.6). The persistence time is the time it takes for a waterhole to completely dry. In order to determine the persistence time, the Waterholes plugin produces a 'run to empty' depth time-series. The run to empty time-series sets the waterhole depth to the maximum modelled depth, and then applies a constant daily evaporation (the mean of the entire evaporation series) with no inputs (rainfall or flow). Hence the run to empty represents a long dry period with no significant rainfall or flow. The assumption of applying a constant evaporation rather than a temporally varying evaporation essentially represents an average drying result as opposed to a worst case where summer evaporation is applied when the water surface loss is a maximum.

Given that the evaporation rates through the region are similar (Section 3.2.4.3, above), key differences between sites in the run to empty case is a reflection of the waterhole bathymetry. By comparing the persistence times of the waterholes and their respective depths, the relationship between depth and persistence time was determined.

Table 3.6 Depth and calculated persistence time for each waterhole.

Site Name	Maximum Depth (m)	Persistence Time (days)
Culgoa River valley		
Cubbie	2.66	405
Ingie	2.19	301
Woolerbilla GS	2.58	437
Ballandool	2.70	384
Brenda	2.82	514
Culgoa NP (NSW)	1.91	295
Weilmoringle GS	2.97	587
Caringle	1.68	247
Innisfail	1.45	236
Westmunda (Grogan's Hole)	2.37	486
Gurrawarra	1.68	236
Lilyfield	2.08	396
Narran River valley		
Clyde	1.87	253
GS422206A	2.04	261
Booligar	2.57	342
Glenogie	2.9	478
Angledool	3.05	637
Narrandool	1.29	202
Bangate (Sorrento Hole)	3.00	563
Bil Bil	1.68	263
Golden Plains	1.31	165
Bomali	2.06	347
Belvedere	1.32	214
Amaroo	1.30	327
Killarney	2.43	448
Narran Plains	2.74	419
Narran Park	2.41	388
Barwon–Darling River valley		
Hell's Gate	4.36	1083
Akuna/20A	8.57	1956
Ellendale	5.84	1414

3.3.4.1 Run to empty

Overall, persistence time is well estimated by the water depth (Section 3.3.4, above). The general rate of decline of water level (slope in Figure 3.12) for the run to empty analysis is governed by the waterhole bathymetry (assuming a similar evaporation rate across sites).

In the Culgoa River valley, the minimum persistence time for waterholes ranged from 236 days (Gurrawarra) to 587 days (Weilmoringle GS). Generally the rates of water loss from the waterholes were similar (Figure 3.12). The average persistence time for the Culgoa River valley was 377 days.

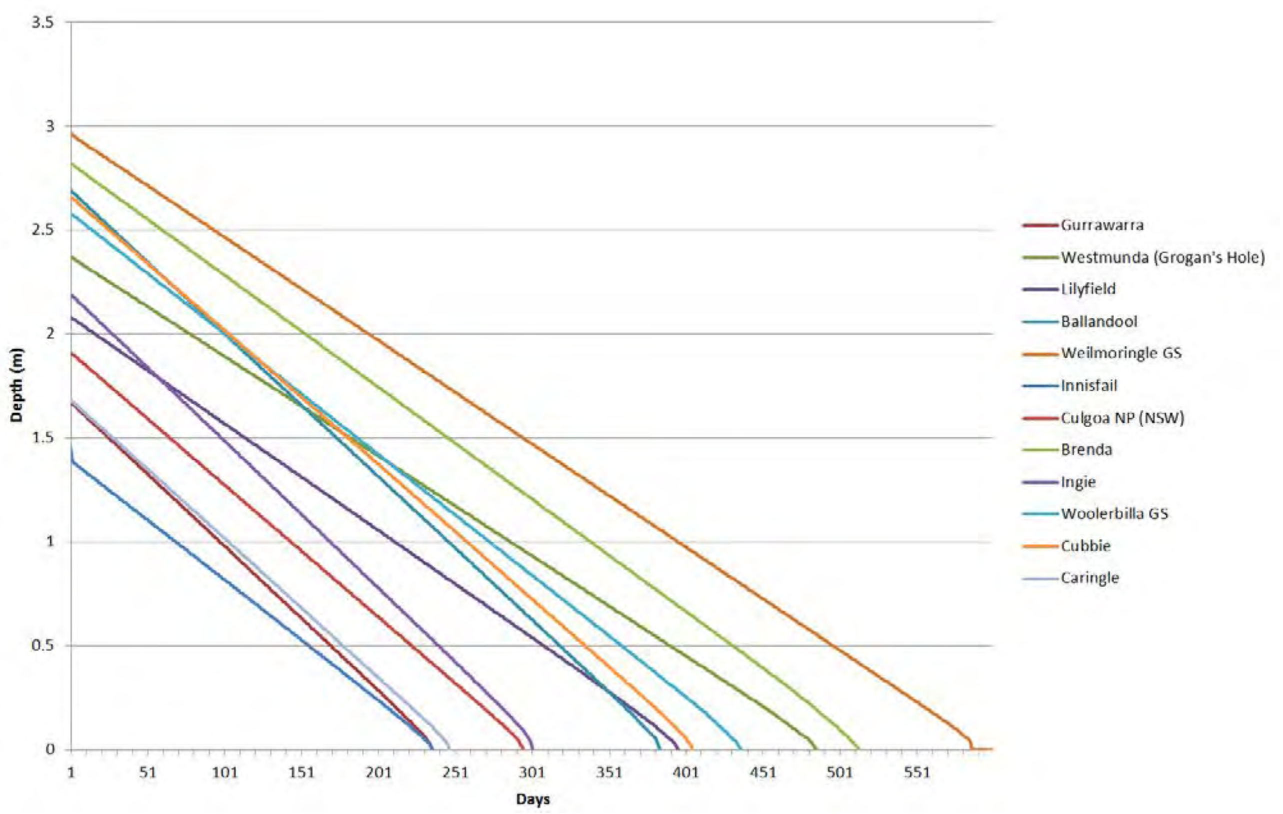

Figure 3.12 Daily depth results of the run to empty scenario for all modelled sites in the Culgoa River valley. The gradient of the lines shows the loss rate of water from the modelled waterholes which are relatively consistent across the sites.

In the Narran River valley, the minimum persistence time for the waterholes ranged from 165 days (Golden Plains) to 637 days (Angledool). Similar to the Culgoa, the rates of water loss from the waterholes were generally similar (Figure 3.13), though Amaroo displays a markedly slower loss rate than the other sites. Killarney and Bomali also have somewhat slower rates of loss. Slightly increased stable isotope data and higher EC-values were observed at Amaroo, Killarney and Narran Park (Chapter 4). However, low radon concentrations were observed at these sites, suggesting the salinity increase is not caused by groundwater discharge to the river but is best explained by evaporation. Overall, groundwater contributions appear to be very small in the Lower Balonne and the average persistence time for the Narran River valley was 355 days.

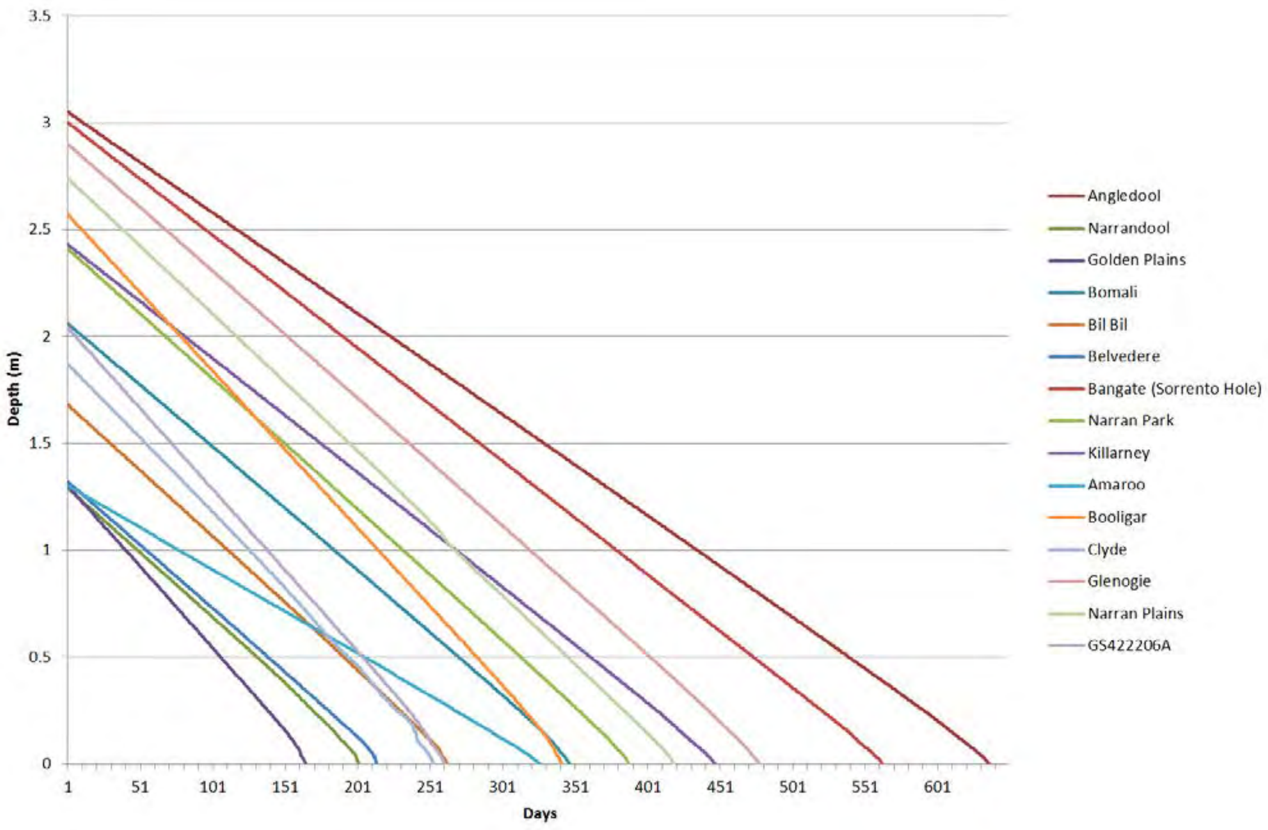

Figure 3.13 Daily depth results of the run to empty scenario for all sites in the Narran River valley. The gradient of the lines shows the loss rate of water from the modelled waterholes which are relatively consistent across the sites, except Amaroo which loses water more slowly.

In the Barwon–Darling, the minimum persistence time for waterholes ranged from 1083 days (Hell's Gate) to 1953 days (Akuna/Weir 20A). These models were uncalibrated, so not supported by water loss results, thus there is low confidence with these results.

3.4 Discussion

3.4.1 Understanding waterholes in the northern Basin

The modelling of the representative waterholes has greatly increased the understanding of what waterholes look like, how deep they are and how long they persist within the Narran, Culgoa and Barwon–Darling River valleys.

3.4.1.1 Depths of waterholes

The DEM, adjusted to the cease to flow level of the waterhole extent, revealed that waterholes in the Culgoa and Narran rivers were shallow (1.29–3.05 metres), and waterholes in the Barwon–Darling were deep (4.36–8.57 metres). Previously studied waterholes in the nearby Moonie River tended to range in size somewhere between the Culgoa/Narran and the Barwon–Darling waterholes (DERM 2010). In the Moonie catchment, the depth of the modelled waterholes was found to be an excellent predictor of persistence (explored for these regions in Chapter 6), so this broadly suggests that modelled waterholes in the Culgoa and Narran River valleys persist for less time compared to the Moonie or the Barwon–Darling.

The understanding of the depths, and depth profiles, of modelled waterholes gained from this study can inform future studies in refugia habitat quality by informing the targeting of sites most likely to be refugial. It also allows the monitoring of parameters that affect depth or channel location, such as sedimentation and scouring, by providing a high-resolution understanding of the current situation.

3.4.1.2 Persistence of waterholes

In the Culgoa and Narran rivers, approximately half the modelled waterholes would go dry after one year without input. After two years without input none modelled waterholes would still contain water (Figure 3.12 & Figure 3.13). This means that in order to retain a proportion of the waterholes permanently, there needs to at least be refilling events at least approximately every 18 months.

If the waterholes are to act as refuges, then input events must be at a frequency that tops up the waterholes before they become dry. In order to retain 50 centimetres of water depth the maximum duration with no inputs is approximately 550 days, which leaves only one of the modelled waterholes in the Narran River (Angledool), and none in the Culgoa River. This water depth is a conservative estimated minimum depth to reduce the probability of stochastic failure of refuge function as a result of water quality and biological factors (DERM 2010). To retain half of the modelled waterholes across both the Culgoa and Narran Rivers, a maximum no flow period of approximately 300 days required.

Waterhole habitat quality should also be a consideration. While the time it takes for waterholes to dry completely has been modelled here, it is likely that conditions in waterholes would rapidly decline at low water levels (DERM 2010). This means that waterholes may no longer act as refuges even before they dry, meaning a precautionary approach should be used when setting spell duration targets relative to calculated persistence times. An assumption has been made that a waterhole may lose its ability to be a refuge once the depth is less than 50 centimetres, however this has not been tested (e.g. how water quality changes through the drying cycle).

3.4.2 Assumptions of the models

There are several assumptions made in the models which must be considered when interpreting their results:

- Assumption 1 – Water loss measured during the draw down period is representative of water loss generally. To test for this assumption, models can be recalibrated with longer or multiple drying sequences to compare results and ascertain if the draw down period is representative.
- Assumption 2 – Modelled flow inputs from a single gauging station are representative of all associated waterholes within the assessment reach. To broadly account for this assumption, gauges associated with an assessment reach were determined using expert opinion.
- Assumption 3 – Predicting persistence in the ‘run to empty’ scenario is purely theoretical as the model uses an average evaporation rate from the complete data set. This can differ from the observed rate at the site for a variety of reasons, e.g. seasonality, thus predicted persistence times may vary accordingly.

The model platform is also being continually updated to include additional features and accommodate more detailed information to reduce the number of assumptions. Despite these assumptions, this modelling represents a significant improvement on understanding of waterhole persistence and provides a sound basis for defining waterhole persistence times.

4 Groundwater discharge to waterholes along the Lower Balonne and Barwon–Darling rivers system

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This chapter addresses the following knowledge gap:

- *Does groundwater impact the persistence time of waterholes in the Lower Balonne and Barwon–Darling?*

4.1 Introduction

Documenting groundwater/river interaction is critical to understanding hydrological processes, which in turn informs the protection and management of groundwater and surface water resources (Winter 2007; Brodie et al. 2007; Sophocleous 2002; Winter 1995). Underestimating the groundwater inflows to rivers may also result in water resources being doubly allocated (i.e., river water and groundwater allocations might partially represent the same water). While estimating the fluxes of groundwater to gaining rivers is commonly attempted, it is not always straightforward (Cartwright et al. 2014; Brodie et al. 2007; Sophocleous 2002).

An accurate understanding of groundwater contributions to the riverine water balance is especially necessary within dryland regions, where surface water resources may diminish during low flow to poorly connected (or disconnected) waterholes. These are essentially enlarged channel segments capable of holding larger volumes of water, however their persistence (and therefore vulnerability) during dry periods may vary greatly (Bunn et al. 2006). A critical question is therefore the degree to which groundwater interacts with these waterholes, and the mechanisms by which this occurs. Although previous work has not investigated this directly, the emerging knowledge of freshwater ‘lenses’ locally surrounding waterholes within otherwise saline regional groundwater (Cendon et al. 2010) suggests some interaction is physically plausible. However, the local or regional groundwater levels are not generally well enough known to determine the degree of interaction from actual gradients between the waterhole and groundwater, and alternative methods are generally needed. Recent work in dryland river systems in Australia has shown a wide variety of potential interactions with groundwater, from strongly losing to perched (Villeneuve et al. 2015), to losing but connected (Cendon et al. 2010), and even to gaining conditions (Meredith et al. 2015). Therefore, some degree of complexity in surface and groundwater interactions should also be expected when considering waterholes specifically.

Geochemical tracers may be used to determine baseflow in systems where there is a broad knowledge of groundwater chemistry.

The different geochemical tracers of groundwater/surface water interaction have potential advantages and disadvantages. Major ion concentrations and stable isotope ratios are relatively easy to measure and are often measured as part of general water quality studies (hence databases with time series measurements may already exist. In-river modification by evaporation, mineral precipitation, or biogeochemical processes may modify major ion chemistry.

Providing that groundwater and surface water have distinct geochemical concentrations, changes in concentration of that component in the river may be used to define the distribution of gaining and losing river reaches and to quantify groundwater inflows in gaining reaches (Cook 2012; Brodie et al. 2007).

Radon (^{222}Rn), which is part of the Uranium (^{238}U) to Lead (^{206}Pb) decay series, is commonly used for quantifying groundwater inflows to rivers. Radon has a half-life of 3.8 days and the activity in groundwater reaches secular equilibrium with its parent isotope radium (^{226}Ra) over a few weeks (Cecil & Green 2000). Because the concentration of radium in minerals is several orders of magnitude higher than dissolved radium concentrations in surface water, groundwater radon activities are commonly two or three orders of magnitude higher than those of surface water (Cook, 2012; Cecil & Green 2000; Hoehn et al. 1992; Ellins et al. 1990). This makes radon a potentially useful tracer in catchments where groundwater and surface water have similar major ion concentrations or stable isotope ratios. Radon activities in rivers decline downstream from regions of groundwater inflow due to radioactive decay and degassing to the atmosphere.

While radon is an important tracer that may indicate groundwater discharge to streams, radon concentrations alone are insufficient to indicate which groundwater reservoirs are discharging into the stream and which reservoirs contribute at what times. The distinction between groundwater from more regional aquifers versus return flow from bank storage or shorter-term localised perched aquifer systems around the stream is important to determine in terms of long-term flow sustainability. Radon concentrations measured in streams will not in isolation allow predictions on which of the above reservoirs contribute to the stream. The short half-life of radon (3.8 days) causes secular equilibrium in the groundwater reservoir after approximately 5 half-lives or 3 weeks. Hence, the radon concentrations in the reservoirs are only dependant on the amount of uranium/thorium containing minerals or radium and the emanation rate and not on the residence time of the water once secular equilibrium is reached. Therefore, radon concentrations in riverbanks, perched aquifer systems or regional groundwater will be indistinguishable if radium concentrations in the host material are also the same.

Combining radon, however, with other geochemical tracers such as major ions or stable isotopes, may allow the groundwater contributions from relatively short-term reservoirs (e.g. bank storage) and regional groundwater to be distinguished. Chloride concentrations for example often increase due to mixing with more evaporation enriched soil waters and significant increases can only be achieved over thousands of years. Hence, short or medium term reservoirs should only have small concentrations of chloride in the absence of mixing compared to some older, regional groundwater.

Here we investigate the potential interaction of waterholes with groundwater, in particular the potential role that groundwater discharge may play in waterhole persistence during low flow conditions within the Culgoa, the Narran and the Darling rivers. Outcomes from this investigation will assist in the interpretation of measured water loss rates and model calibration examined in Chapter 3 by sampling the same waterhole locations.

This investigation will improve our understanding of groundwater interactions within waterholes across the Lower Balonne and Barwon–Darling.

4.2 Site setting

4.2.1 Location

The Narran, the Culgoa and the Darling rivers are part of the greater Barwon–Darling River system, located in the central northern part of the MDBA in the border region between Queensland and NSW (Figure 1.1 in Chapter 1). The Narran and the Culgoa rivers have their headwaters in the Condamine-Balonne River Catchments and drain to the west. The Darling is a continuation of the Barwon River (after the Culgoa River confluence) and many tributaries in the eastern and northern part of the Barwon–Darling River and also drains the highly intermittent rivers to the west.

4.2.2 Geology and hydrogeology

The rivers in the area are incised in larger floodplains comprised of Tertiary and Quaternary riverbed sediments. These sediments are underlain by a variety of bedrock Palaeozoic and Mesozoic bedrock formations from the New England Orogen, the Lachlan Orogen and the Gunnedah Basin. The bedrock consists of consolidated, partly metamorphosed and fractured marine sand, silt and clay stones and volcanic and igneous intrusions.

The Tertiary and Quaternary sediments provide the main aquifer systems in contact with the river systems. The stratigraphy and extent of the aquifers is poorly understood. The aquifers in the western part of the study area along the Darling River comprise the Cubbaroo Formation (Miociene), the Gunnedah Formation (Pliocene) and the Narrabri Formation (Quaternary), which comprise the surficial geology in the area. All formations are terrestrial deposits of fluvio-lacustrine consisting of well sorted, quartzose and lithic sand and fine gravels, interbedded with predominantly yellow to brown clays (Meredith et al. 2009). These aquifers are part of an extensive, closed an internally draining groundwater basin. The deep aquifer is only found within a Paleozoic palaeochannel that formed adjacent to the modern Darling River, within the underlying Great Artesian Basin (d'Hautefeuille and Williams 2003, Meredith et al. 2015). The young alluvial aquifers have variable depth and the Palaeozoic basement crops out in some areas of the incised river channel. The Darling River receives high saline groundwater at low flow in some of these areas which is believed to come from the Tertiary and Quaternary aquifers. The conceptual idea of the aquifer/river interaction assumes a freshwater lens in the proximate river banks in the upper parts of the alluvial aquifer sequences. The river is losing at high flow, recharging the freshwater lens in the river banks. At receding flows water from the freshwater lens drains back into the river one river heights is below the bottom of the fresh water lens, saline groundwater from the lower alluvial aquifer units drains into to river (Meredith et al. 2009). A salt interception scheme was put in place on the upper Darling to reduce the impact of high salinity groundwater to the river system. The scheme comprises groundwater bores around the area of known saline groundwater discharge to the river, which pump groundwater to drop the water table below the river level during times of low river flow (MDBA 2011b).

4.2.3 Climate

A semi-arid climate dominates the three river catchments with long-term average annual rainfall of ~355mm/year at Bourke, 399 mm/year at Cobar and 305mm/year at Louth (BOM 2015). Long term average rainfall in Bourke indicates generally higher rainfall in the summer months from November to April, which is in line with the general wet season patterns in southeast Queensland and northern NSW. Temperatures are also highest during these month and average temperatures range from 18°C in July to 37°C in January. The mean annual potential evaporation of ~2,400 mm/year, determined at Cobar, exceeds rainfall for the area.

4.2.4 Hydrology

The area has a low topographic gradient (1/6,000m) and the rivers developed large meander bends with flood plains more than 12 kilometres wide. The rivers are incised in the flat landscape with approximate bank heights of 6–8 metres on the Narran and the Culgoa rivers and more than 10 metres in parts of the Darling River. The rivers are highly episodic with large flow increases during the main runoff events and ceased flow during dry seasons, especially in the Narran and the Culgoa, when waterholes develop. This results in a highly variable flow regime, with significant implications for the way surface and groundwater interacts, as well as the ecosystems dependant on these water resources.

4.3 Sampling and analytical techniques

This study estimates groundwater inflows to the parts of the Darling River, the Culgoa River and the Narran River between Dirranbandi and Lightning Ridge, in the North East to Tilpa, NSW, in the South West, a total length of >500 kilometres (Figure 1. in Chapter 1). For convenience, the study area is subdivided into upstream sites (the Culgoa River and the Narran River) and downstream sites (the Darling River) sites. Discharge data and semi-continuous electrical conductivity (EC) data in the river are available for a number of sites (Appendix D) (Data source: Queensland Department of Natural Resources and Mines (2015) and the NSW Department of Primary Industry (2015)).

The preliminary mapping of the electrical conductivity (EC) in all representative waterholes of the Narran and the Culgoa rivers (Chapter 3) was undertaken during the bathymetric survey in February/March 2015 and had the purpose of finding potential groundwater discharge regions along the waterholes. A HOBO EC logger (Onset Computer Corporation) was attached to the front of the bathymetry vessel and programmed to record EC-readings every 10 seconds. A handheld GPS unit recorded the location and the two datasets were matched by the common time stamp in R (R statistics). The resulting spatial EC-data was interpolated over the waterholes in GRASS GIS 2015 by using inversed distance squared weighing method.

One hundred surface water samples from 27 representative waterholes along the Narran and Culgoa Rivers and one groundwater sample from the Narran Park waterhole were taken in two sampling campaigns during February-March 2015 and May-June 2015 (Appendix D). Twelve surface water samples from 10 representative waterholes along the Darling River and 8 groundwater samples adjacent to these waterholes were taken on a single campaign in September 2015 (Appendix D). The location of these waterholes is listed in Table 3.1 in Chapter 3. Surface water samples were taken using a sampling pole from the riverbanks or from a boat on the river by submerging the pole gently under water and filling the sampling cup close to the riverbed. Groundwater samples were obtained from NSW DPI groundwater monitoring bores by using a SuperTwister groundwater pump after adequate purging of >5 bore volumes. The groundwater sample on the Narran River was taken from a bank in the waterhole by digging a hole of ~1m depth and purging it several times. All samples were prepared for major ion, stable isotope (δ^2H and δ^{18}O) and radon analysis.

Electrical Conductivity (EC), dissolved oxygen (DO), pH and temperature were measured in the field using a calibrated Thermo-Fisher AquaRead Meter and probes.

Major cation concentrations were analysed on samples that had been filtered through 0.45 µm cellulose nitrate filters and acidified to pH <2 using a PerkinElmer Optima 7300 DV inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Advanced Water Management Centre at the University of Queensland) equipped with WinLab32 for ICP software after digestion using a CEM Mars Xpress Microwave. 9.0ml of sample added to 1.0ml concentrated HNO_3. Samples were ramped for 10 minutes to 160° C then held for 10 minutes. Major anion concentrations were analysed using a Thermo-Fisher Dionex ICS2100 Ion Chromatography System at the Advanced Water Management Centre at the University of Queensland. Samples with salinities over 300mg/L total dissolved solids (TDS) were diluted prior to analysis. The precision of major ion concentrations based on replicate analyses is 2–5 per cent. Additional groundwater major ion geochemistry was taken from the NSW DPI Web database (2015).

Radon activities in groundwater and surface water were determined using a portable radon-in-air monitor (RAD-7, Durridge Co.) following methods described by Burnett and Dulaiova (2006) and are expressed in Bq/m^3 water. 0.5 L of sample was collected by bottom-filling a glass flask and radon was degassed for 5 minutes into a closed air loop of known volume. Counting times were 4 x 30 minutes for surface water and 4 x 15 minutes for groundwater. Typical relative precision is 3 per cent at 10,000 Bq/m^3 and ~10% at 100 Bq/m^3. Radon emanation rates were measured by sealing a known dry weight of sediment in airtight containers with water for more than five weeks by which time the rate of radon production and decay will have reached steady state. Subsequently, 40 ml of pore water was extracted and analysed for radon activities using the same method as above, but with counting times of 12 hours.

Oxygen and hydrogen isotope ratios were measured on samples that were filtered and kept in cool in sample containers without headspace. Samples were analysed using an Isoprime dual inlet isotope ratio mass spectrometer (DI-IRMS) coupled to a multiprep bench for online analysis at the Stable Isotope Geochemistry Laboratory at the University of Queensland. δ^2H values were analysed after online equilibration at 40° C with Hokko coils. δ^{18}O values were analysed as above, but after equilibration with carbon dioxide. δ^2H and δ^{18}O values (reported in per mil (‰)) were normalised to the standard mean ocean water (VSMOW-SLAP) scale, following a three point normalisation based on four replicate analyses of three laboratory standards per analytical cycle. All laboratory standards were calibrated against International Atomic and Energy Agency (IAEA) (Vienna Standard Mean Ocean Water (VSMOW), Standard Light Antarctic Precipitation (SLAP), Greenland Icesheet Precipitation (GISP)) and United States Geological Survey (USGS) (USGS45, USGS46) international water standards. Accuracy and precision were better than ± 2 ‰ for δ^2H and ± 0.1 ‰ for δ^{18}O at 1σ. Both compositions were measured as deviations relative to VSMOW.

4.4 Results and discussion

4.4.1 Culgoa and Narran rivers

Quantifying groundwater fluxes to rivers using geochemical tracers requires determination of groundwater composition of the tracers involved. Generally groundwater bores from the local aquifers, river banks and parafluvial zones are sampled to obtain the 'end member' concentration for the potential groundwater sources. Unfortunately, there are only few state monitoring groundwater bores in the Narran and Culgoa River Valleys and none in the proximity of the river (within ~2 km), meaning the groundwater concentrations for total dissolved solids (TDS; the electrical conductivity is used as a proxy for the total dissolved solids) and radon are not known. Groundwater in the major aquifers is expected to be saline in the region. Accessible groundwater bores in the Narran and Culgoa alluvial plains are scarce and we were not able to sample groundwater from the two catchments, however, one groundwater/parafluvial zone sample from a sand bank in the Narran Park waterhole was able to be taken with and EC of 2779 μS/cm and a radon concentration of 10,600 Bq/m^3. This sample is probably not representative of the regional groundwater but rather represents mixed water from parafluvial zones, the river bank and the regional groundwater.

Sampling locations for radon were based on the results from EC mapping. The ECs during the mapping exercise were spread over a large range from waterholes with very low EC-values of ~30 μS/cm at Brenda waterhole, to ~600 μS/cm at Cubbie waterhole (Appendix D). Some lower EC-values were recorded, however we consider it highly unlikely that true surface water values would be lower than ~30 μS/cm. These readings are likely to be the result of measurement errors related to the logger being in contact with the riverbed sediments, and were excluded from analysis.

Variability in waterhole EC-values may indicate potential groundwater discharges to the river. Higher EC-values may be due to fluxes of high saline groundwater into the waterhole, assuming no electrical conductivity change due to nutrients and surface runoff, and tributary contributions. The TDS in rivers is generally expected to increase downstream due to 'flushing' of solutes along the way and higher salinities are usually expected with increasing distance from the headwater catchment. The variability of the EC-values is highest in the Gurrawarra, Golden Plains and Narran Park waterholes and lowest in Caringle, Weilmoringle Weir and Angledool waterholes. This only takes into consideration the upper and the lower quartiles. While higher variability can potentially indicate that the waterholes may have groundwater contributions, robust trends within the waterholes were not observed, and the variability might instead be the result of separated pools or contributions from tributaries rather than groundwater contributions. Furthermore, the variability could not be reproduced by hand measurements at selected points in a later campaign in May/June 2015. The reason for the discrepancy is likely due to the different discharge conditions during the EC-mapping survey at high flow (~2,000ML/Day at Brenda) and the actual spot sampling campaign at much lower discharges (~100ML/Day at Brenda) (Figure 4.1). This reliance on the time period of sampling for the detection of groundwater inputs is very important, and this is discussed in further detail in subsequent sections.

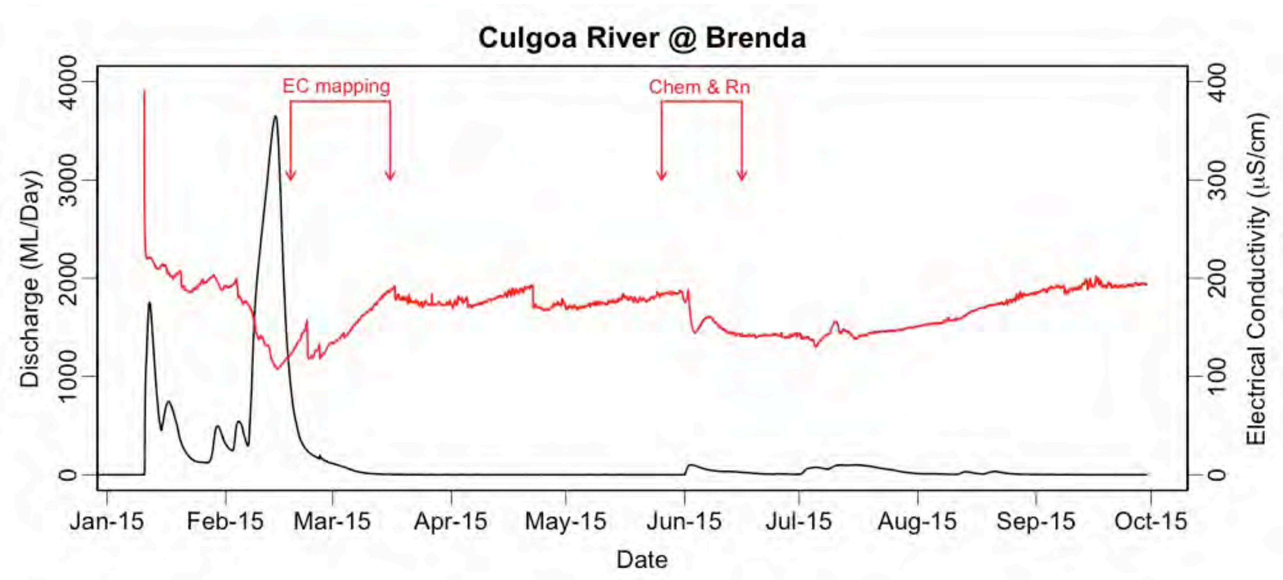

Figure 4.1 Discharge of the Culgoa River at Brenda.

ECs in the Culgoa and the Narran Rivers during the sampling campaign in May/June 2015 range from 77 to 292 µS/cm. The lower flow conditions of ~100ML/Day allow a better distinction between the waterholes with respect to their EC content. Generally EC-values are higher in the Narran than in the Culgoa with values ranging from 101 to 292 µS/cm (median = 194) in the Narran and 77 to 217 µS/cm (median = 124) in the Culgoa River, respectively. Radon concentrations in the rivers range from 40 to 269 Bq/m^3 (median =139). Both radon and EC concentrations are slightly higher in the Narran River than the Culgoa River, ranging from 40 to 269 Bq/m^3 and 40 to 234 Bq/m^3, respectively. The radon budget in waterholes is complicated by hyporheic exchange, which can probably be neglected due to low flow during sampling period, and diffusive fluxes from the riverbed sediments, which is probably a more significant contributor. The lowest radon values measured within an individual waterhole would be a reasonable approximation for the diffusive flux (~45 bq/m3).

On the Narran River EC-values in Amaroo, Killarney and Narrandool are highest. While this is potentially an indication of groundwater contributions to the waterholes, radon values for the same waterholes suggest that Narrandool, Narran Park, Bomali and some parts of Killarney may also have some groundwater contributions (indicated by higher radon concentrations combined with higher EC-values) but this is not true for Amaroo and the rest of Killarney (Figure 4.2A). Higher radon concentrations but low EC may be the result of water contribution from parafluvial zone or from bank return storage where salinities are low but radon can accumulate to secular equilibrium levels (Cartwright et al. 2014). However, these rivers have not developed large parafluvial zones so bank return flow would be the most likely source. While some samples from the Culgoa have slightly elevated radon concentrations in combination with low EC (e.g. Ballandool, Booligar, Westmunda), groundwater fluxes on the basis of the radon concentrations would only be small (Figure 4.2A), considering that diffusive fluxes from the riverbed are likely to be similar to the lowest values detected for each waterhole. Higher EC-values on the Culgoa River occur at Culgoa National Park and Weilmoringle Weir with slightly higher radon concentrations ranging from 128 to 200 and 119 to 182 Bq/m^3, respectively. There is the possibility of small groundwater inflow or bank return flow to these waterholes (Figure 4.2B).

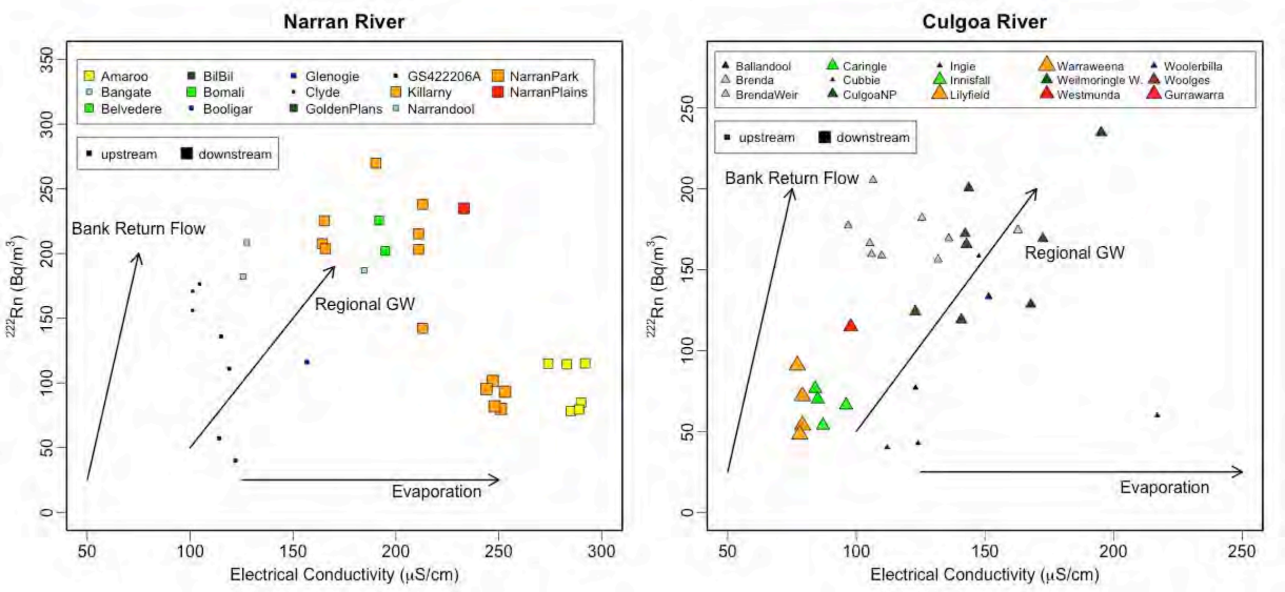

Figure 4.2 A) Radon concentrations and EC-values for water samples in the Narran River. B) Radon concentrations and EC-values for water samples in the Culgoa River. Increasing symbol size represents increasing distance within flow direction.

Groundwater is one potential cause of increasing salinities in rivers, and evaporation is another, especially when flow ceases. Stable isotopes $\delta^{18}O$ and $\delta^{2}H$ fractionate during evaporation and the residual water becomes enriched in both isotope pairs. The stable isotope ratios of the water samples from the waterholes follow an evaporation trend, which progresses towards more enriched values along the flow path of the Narran River (Figure 4.3). The most enriched values are found at Killarney, Amaroo and Narran Park with $\delta^{18}O$ of +5.14 ‰ and $\delta^{2}H$ of 19.32 ‰. These waterholes also have the highest EC-values and lowest radon, which in the case of Killarney and Amaroo suggests that the salinity increase is not caused by groundwater discharge to the river but is best explained by evaporation. The waterholes with possible groundwater contribution on the Culgoa River, Culgoa National Park and Weilmoringle Weir, also have high stable isotope ratios indicating significant evaporation and subsequent increases in salinity. Regional groundwater is believed to have much more depleted stable isotope values, which is inferred from values obtained in the Darling River groundwater bores and reported by Meredith et al. 2015 ($\delta^{18}O$ of ~-1.5 ‰ and $\delta^{2}H$ of ~-30 ‰, Meredith et al. 2015; $\delta^{8}O$ of -3.9 ‰ and $\delta^{2}H$ of -30.4 ‰, data obtained during this study in the bores on the Darling flood plains). Hence, groundwater discharge to the river would not only increase the EC and radon concentrations but would also mix the highly enriched stable isotope surface water values with more depleted groundwater isotope values. This should result in more depleted isotope values than reported for the waterholes in this study.

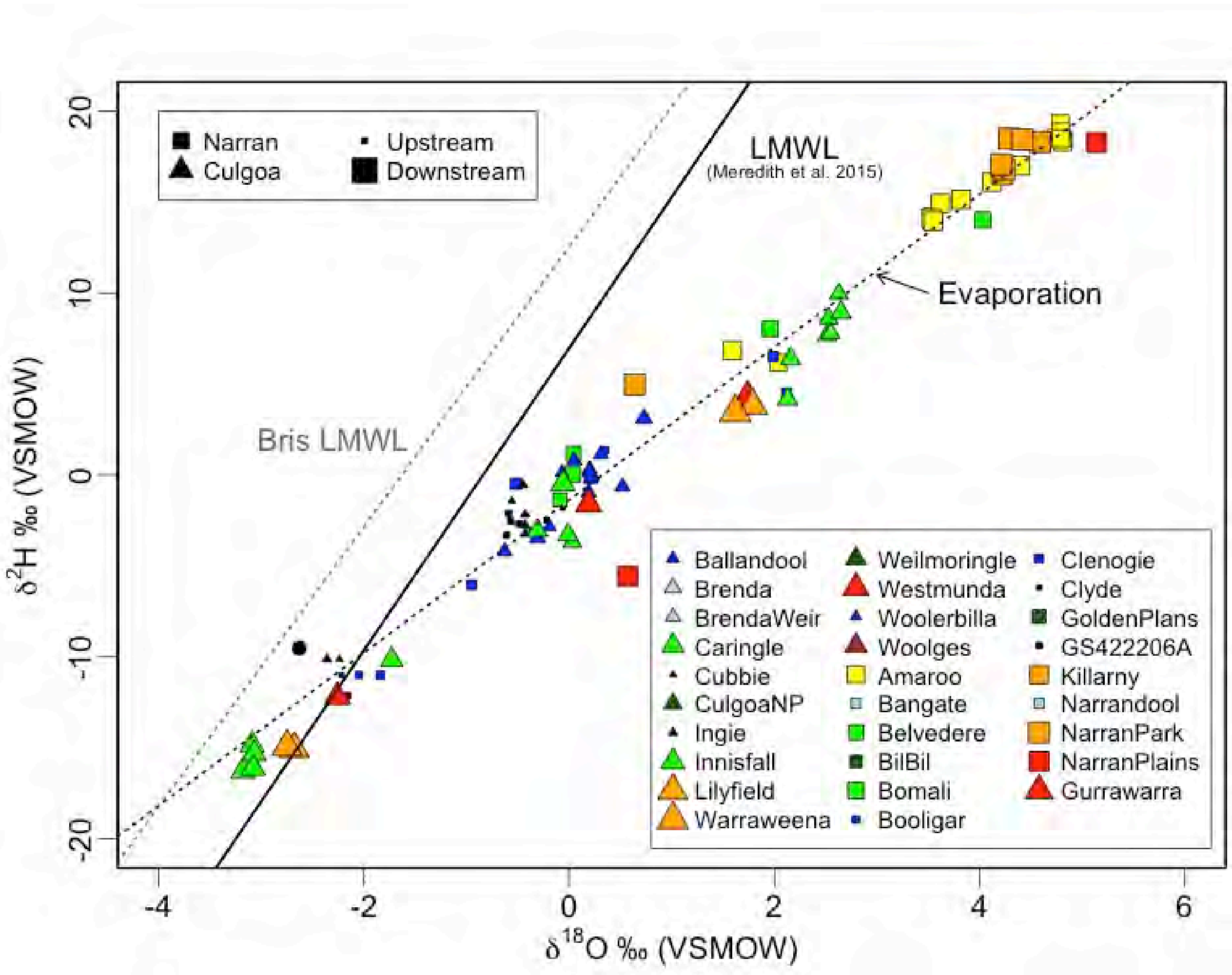

Figure 4.3 Stable isotopes δ18O and δ2H for the sampled waters on the Narran and Culgoa Rivers. All samples follow an evaporation trend (black dashed line). The Cobar local meteoric water line (black dashed line) by Meredith et al. 2015 and the Brisbane local meteoric water line (grey dashed line) are shown as references. Symbol size increases with distance from most upstream sites.

In summary, radon concentrations are generally very low. While some waterholes show evidence for possible (and minor groundwater contributions) due to slightly increased radon concentrations and higher EC-values compared to locations in the same vicinity, the maximum salinity increase is not large. Thus in combination with the stable isotope data and the low radon concentrations, the observed data is best explained by evaporation processes. Generally, groundwater contributions appear to be very small, especially during the sampling period of this study.

4.4.2 Darling River

Twelve surface water samples and eight groundwater samples were taken at the end of September 2015 (Figure 4.4). The sample locations were predetermined by previous work by the NSW DPI Water. The locations are summarised in Appendix D. Weir 19A was not part of the original sampling strategy but was included after reviewing a report on the salt interception scheme around Weir 19A (Glen Villa) (D'Hautefeuille & Williams 2003).

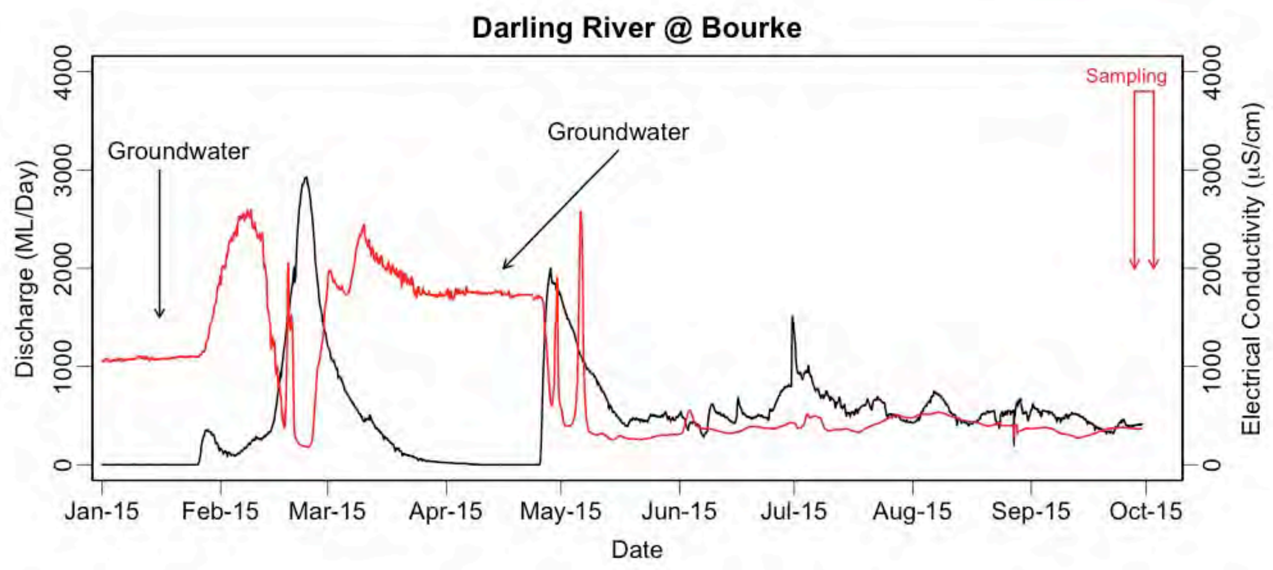

Figure 4.4 Discharge of the Darling River at Bourke. River water and groundwater samples were taken at the end of September 2015. The black line indicates river discharge and the red line indicates the electrical conductivity, which is used as a proxy for the total dissolved solids. The electrical conductivity is highest at low flow indicating significant 'groundwater' discharge to the river.

Two aquifers were also targeted for sampling: the shallow Narrabri Formation (10 to 25m depth) and the deeper Gunnedah Formation (30 to 50m depth) (Appendix D). The EC was variable in the Narrabri formation with fresh groundwater of 541vµS/cm in bores B36842-1 377vµS/cm in B36853-1 bore and brackish to saline water of 12700 µS/cm in B36937-1 and 34570 µS/cm in B56852-1. Variability was less in the bores in the Gunnedah formation with mostly saline groundwater in bores BB36852-2, B36937-2 and B36853-2 (EC= 35089 to 40370 µS/cm) with the exception of bore B36842-2, which had an EC of 1976 µS/cm. While these bores are far apart, B36842 is located close to Tilpa and B36937 is located close to Glen Villa, it indicates that there is a larger freshwater lens or multiple fresh water lenses in the proximity of the river, similar to that described for waterholes on Cooper Creek (Cendon et al. 2010) as well as the Murray River in Cartwright et al. (2011). The extent of these lenses is not clear but alluvial sediment heterogeneities and bedrock topography may be key factors influencing the geometry of lens or lenses. Bores B36937 and B36853 are within the vicinity of the Upper Darling salt interception scheme, which is indicated as an area of preferential groundwater discharge to the Darling River (D'Hautefeuille. & Williams 2003). Radon concentrations are, however, highest in the Narrabri Formation (range of 2905 to 13236 Bq/m^3) and lowest in the Gunnedah Formation (range of 74 to 4687 Bq/m^3) (Appendix D). The really low radon values of 74 and 178 Bq/m^3 in the groundwater are surprising and would need further investigation to identify the causes of the large discrepancies in radon concentration between the two geological formations. It also presents a considerable paradox when attempting to determine the groundwater contributions to the Darling River on the basis of surface water EC and radon values.

River water EC ranges from 309 to 504 µS/cm and radon concentration are very low, ranging from 22.09 to 102.19 Bq/m^3 at the time of sampling in September 2015 (Figure 4.5). Larger groundwater fluxes in the river occurred during very low flow conditions with EC-values exceeding 2,000 µS/cm and ~15,000 µS/cm in the area of Glen Villa, highlighting the reason why the salt interception scheme was set in place (Figure 4.5). D'Hautefeuille & Williams (2003) report that at higher flows

>4,500ML/Day the fresh water lens feeds back into the stream and it requires extended periods of low flow to deplete this freshwater lens to the extent that saline groundwater then reaches the river. During the sampling in September 2015 river flow was not at its minimum with flow still exceeding 400 ML/Day, but much lower than the 4,500ML/Day reported by D'Hautefeuille & Williams (2003). The river water during this period was still very fresh and the low radon concentrations indicate little groundwater inflow. Groundwater in the Gunnedah Formation is also not likely to feed the river as the salinity would increase drastically if this groundwater discharged to the river. Despite groundwater fluxes not being of great importance, the steep increase of EC and radon after Weir 19A towards Hell's Gate indicates small groundwater fluxes to the river at this location whereas all the locations further downstream appear to be losing or neutral (Figure 4.5).

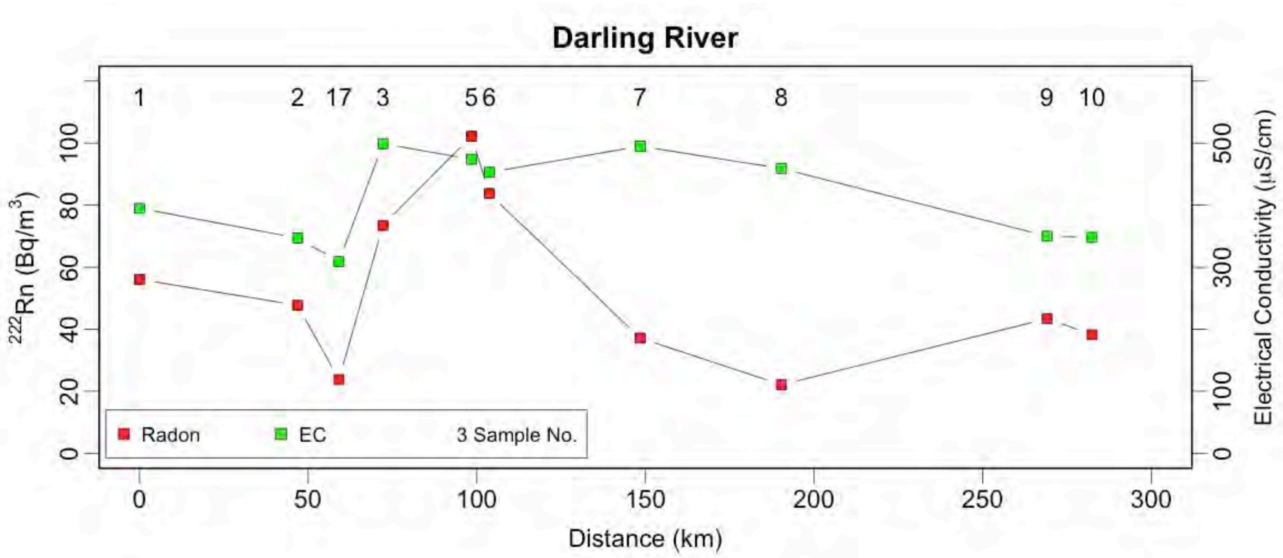

Figure 4.5 Radon and EC along the flow path on the Barwon and Darling rivers from Summerville to Wilga. Sample numbers indicate locations (Appendix D).

The source of this groundwater, however, is probably not from the extended fresh water lens or the saline groundwater but from a third source, as indicated by the stable isotopes. The stable isotopes of groundwater from both formations have average $\delta^{18}O$ and $\delta^{2}H$ of -3.93 ‰ and -30.39 ‰, respectively (Figure 4.6). The increase in $\delta^{18}O$ at point 17 however indicates that water with more enriched stable isotope ratios is discharged to the river. We would otherwise expect the δ18O ratios to drop towards more depleted values (Figure 4.7). Contributions from local bank return flow or small parafluvial zones, which would have similar stable isotope ratios as the river water could potentially be the source of this water.

In summary, no significant groundwater fluxes appear to occur along the Darling at the time of sampling. The changes in radon can probably be attributed to local bank return flow in direct proximity of the river flow rather than groundwater from the freshwater lens or the regional saline groundwater.

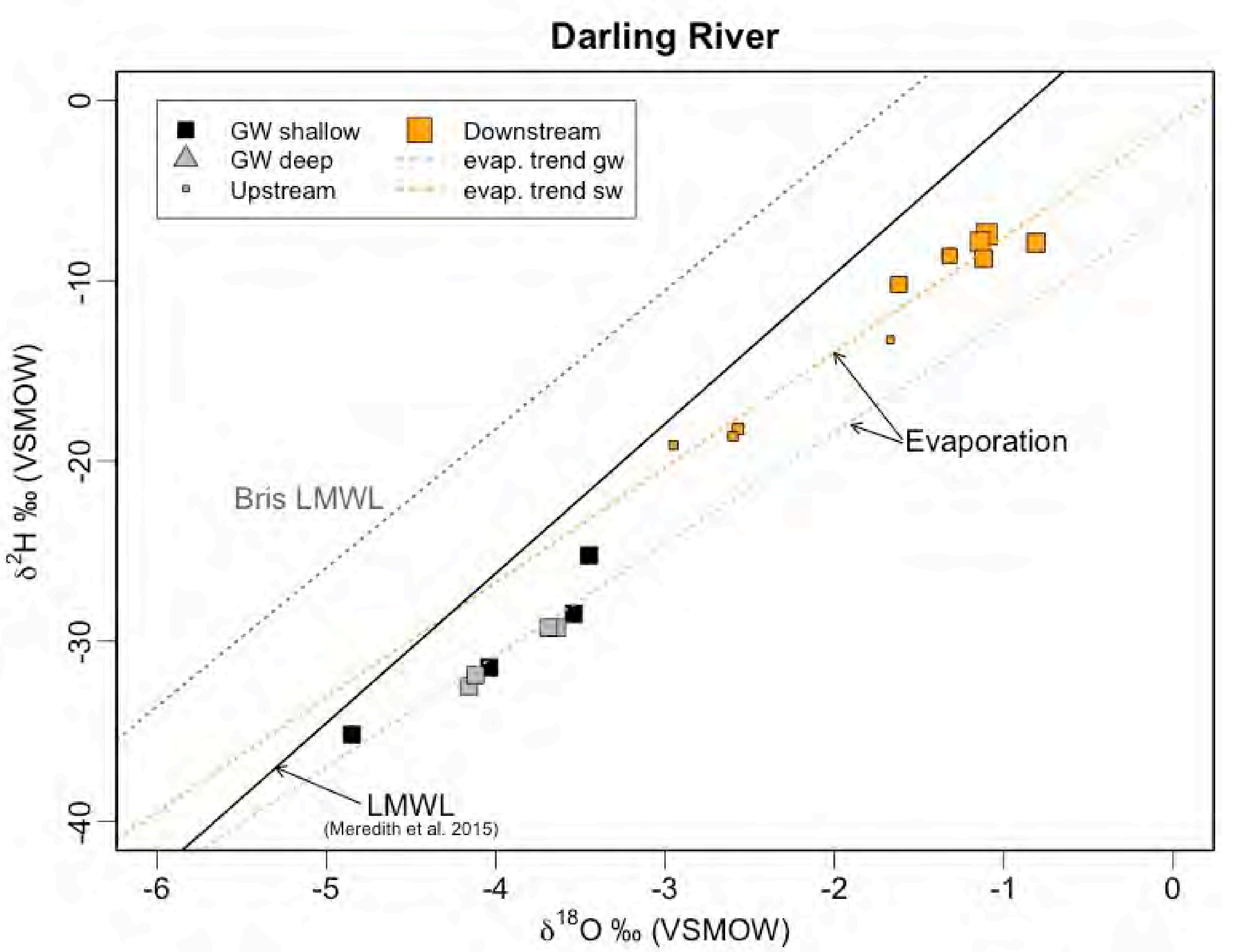

Figure 4.6 Stable isotope compositions for δ18O and δ2H for the Barwon and Darling rivers samples and the groundwater samples from the Gunnedah Formation (grey) as well as the Narrabri Formation (black). All samples show an evaporation trend (orange = surface water; grey = groundwater). The Cobar local meteoric water line (black dashed line) by Meredith et al. 2015 and the Brisbane local meteoric water line (grey dashed line) are shown as references. Symbol size for the surface water samples increases with distance from most upstream sites.

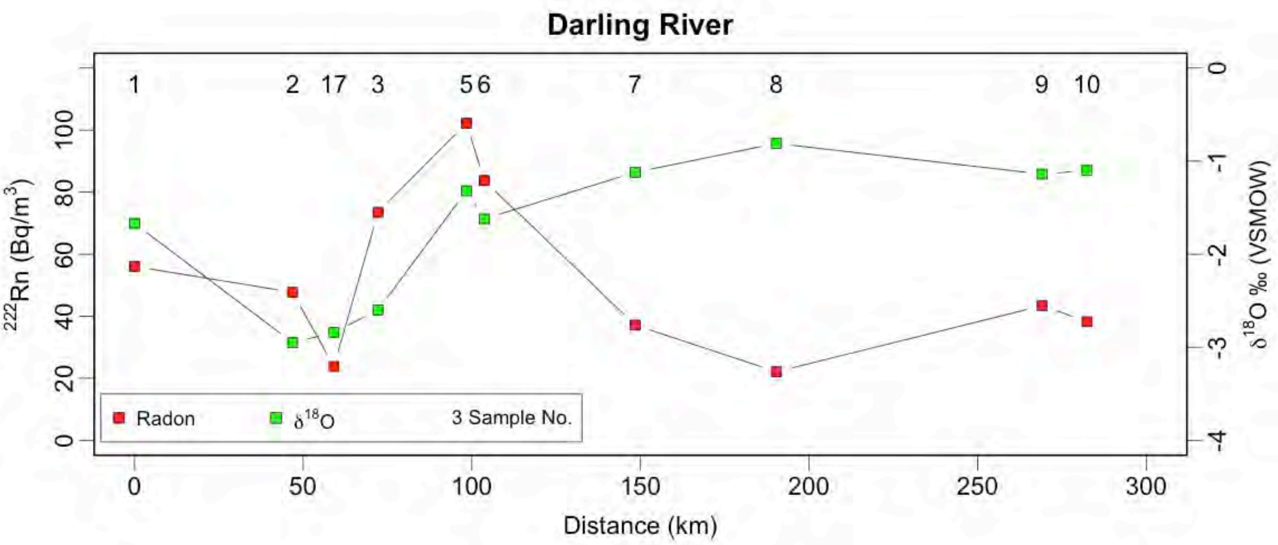

Figure 4.7 Radon and δ18O along the flow path on the Barwon and Darling rivers from Summerville to Wilga. Sample numbers indicate locations (Appendix D).

4.4.3 Summary of inferred processes

Groundwater fluxes to the waterholes are variable in space and especially in time. While we sampled during conditions that did not represent the lowest baseflow conditions, we can still identify potential groundwater interaction with the waterholes within three distinct hypotheses that can be tested using the geochemical indicators:

- Hypothesis 1 – Surface water geochemistry mainly evolves downstream due to evaporative and dissolution processes, then changes minimally within waterholes under low flow.
- Hypothesis 2 – Surface water geochemistry is homogeneous downstream, with the major evolution occurring under low flow within isolated waterholes due to evaporation.
- Hypothesis 3 – Groundwater discharge provides a major signal under low flow to waterholes in some areas.

In addition, some combination of all these options is also possible. These hypotheses can each be tested accordingly: If 1) then EC should increase in concentration downstream, δ^{18}O and δ^{2}H should become progressively enriched downstream, and radon should decline in concentration downstream; if 2) then same as 1) however, it should be difficult to detect downstream trends in these values; if 3) then EC and radon should increase in concentration relative to upstream or downstream locations with less or negligible groundwater contributions.

As already mentioned, in order to confidently suggest hypothesis 3, distinctions in the major ion and stable isotope signals between surface water and groundwater should also exist. On the basis of existing work in similar areas, it is reasonable to expect higher groundwater EC concentrations, but not necessarily distinct stable isotope values (Meredith et al. 2015).

Much of the stable isotope and major ion data suggests that some combination of hypothesis 2 and 3 dominate the surface water geochemistry in all rivers. Previous work also suggests that most waterholes display a dominant evaporation signature, which is mostly responsible for driving increases in EC and enrichment in δ^{18}O (Gibson et al. 2008). Some slight departures from this model are suggested by the radon data, where upstream locations for the Narran have increasing EC and radon together until Killarney. This may indicate some interaction with groundwater and / or bank storage further upstream. Otherwise we would expect radon concentrations similar to the lower diffusive fluxes or to decline downstream. For Killarney and Amaroo, radon declines and remains at low concentrations while EC continues to increase slightly. This suggests that evaporation continues, but that groundwater exchanges are negligible. These downstream locations on the Narran River coincide with the most persistent waterholes (in terms of predicted persistence times, Chapter 3). This may appear at first to be contradictory evidence; however, it is likely that instead of gaining groundwater fluxes, the dominant gradients would likely promote losing fluxes. The losing flux is also likely to vary considerably in space and time, and if the loss rate was low at these locations this would also result in more water remaining in the waterhole, but at the same evaporative rate as other locations. Sediment properties may also be responsible for the persistence with riverbed permeability being lower. This requires further investigation, but it may be possible that this causes the observed evolution in EC and δ^{18}O compared to other waterholes (same evaporation rate, but more volume exposed to this process over time given lower groundwater losses), which would also be consistent with the radon data.

4.4.4 Conclusions

The groundwater contribution to the waterholes along the Narran and Culgoa River are minor during the time of sampling, supported by generally low radon concentrations across the waterholes. Slightly higher salinities (to ~ 300μS/cm) are attributed to mostly evaporation as indicated by stable isotope enrichments. The small groundwater amount that are anticipated derive most likely from bank return flow and not from regional groundwater.

Groundwater contributions along the Darling River are similarly small at the time or sampling. As for the Narran and the Culgoa River, flow in the river was not at baseflow, where only small groundwater can be expected. The literature review and the analysis of discharge/electrical conductivity data, however, suggest that groundwater discharge to the river significantly increases at lowest flow conditions.

4.4.5 Limitations and further study

The lack of background groundwater information within the river reaches of interest naturally places a large constraint on the ability to interpret groundwater interaction processes within these rivers. Likewise, the lack of surface water quality or gauging data restricts the water balance calculations that can be undertaken to verify the geochemical tracer work. These important caveats need to be carefully considered in attempting to interpret both the inferred groundwater interaction processes presented here, as well as the confidence that can be placed in them.

5 Transferability – A model relating waterhole persistence to maximum depth

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This chapter addresses the following knowledge gap:

- *Can the persistence time of waterholes across the northern Basin be predicted using a generic model?*

5.1 Introduction

Waterhole persistence (i.e. the length of time it contains water in the absence of flow) is important in systems dominated by temporary rivers for a variety of reasons; fundamentally, persistent waterholes serve as a source of water and support a suite of important environmental functions during times of drought (Bunn et al. 2006). Temporary river systems that are heavily reliant on waterholes are widely distributed across Western Queensland (DERM 2010) and, more broadly, throughout Central Australia (Sheldon et al. 2010). Indeed, Australia is largely characterised by the temporary nature of its river systems, so waterhole persistence is an important issue nationwide (Thoms & Sheldon 2000).

Intrinsically linked to the spatial distribution of temporary rivers in Australia is the variety of different conditions present within each catchment. Each catchment brings its own set of environmental conditions, which establish different parameters for the flow regime, thereby changing the conditions under which waterholes are formed (Negus et al. 2015). However, natural conditions of water loss during drought are likely to vary considerably less than other factors as they are dominated by two main losses; evaporation and groundwater seepage (DERM 2010).

The loss to groundwater seepage is largely unknown, the emerging knowledge of freshwater ‘lenses’ locally surrounding waterholes within otherwise saline regional groundwater (Cendon et al. 2010) suggests some interaction is physically plausible. As a result most waterholes are thought to at least contribute to groundwater in a minor way (Chapter 4). Evaporation, on the other hand, is the primary natural contributor to water loss in the vast majority of waterholes, though there can be some variation in the loss rate at the site due to local conditions (climate, wind fetch, etcetera).

A strong relationship between depth and waterhole persistence has been established in the Moonie River by persistence modelling (DERM 2010) and this strong relationship was also observed in the Culgoa and Narran Rivers using the same model (Chapter 3). While these three rivers are located within different catchments, (Moonie and Condamine–Balonne) they are within the same climatic region and experience relatively similar climatic conditions. Given the similar strength of the depth-persistence time relationship in all three rivers and their spatial proximity, these rivers are ideal to examine the variability in the depth-persistence time relationship between catchments. Presumably this relationship is also true in the Barwon–Darling, but there is insufficient confidence in the uncalibrated models to include in this assessment.

Similarity in the depth-persistence time relationship across catchments would allow the creation and application of a model to predict persistence at a much larger scale than previously considered, which would have significant management implications. In this instance, the term ‘model’ refers to a mathematical equation that can estimate persistence based on site measurements of maximum waterhole depth. Ideally, a model to determine waterhole persistence would be:

- **Accurate** – First and foremost the model must be able to predict persistence with a reasonable level of confidence and be an accurate representation of the natural system.
- **Transferable** – The model should be transferable within the systems it is developed on, that is, it should maintain similar levels of accuracy across a variety of waterholes within, and between, systems.
- **Simple –** The model should be relatively easy to apply and not require complicated inputs or measurements, which can introduce error or require specific training.
- **Quick** – Ideally the model should be able to be applied ‘on the spot’ so an estimate of persistence can be produced in the field.
- **Cost-effective** – The model does not involve costly, either financially or time intensive measurements.

The management implications of this model are significant; the ability to predict persistence at previously un-visited sites allows for more informed land-use planning for landholders and better water management evaluation for water managers.

5.2 Methods

Data was collected at field sites across two separate projects; the Refugial Waterholes Project (DERM 2010) and as part of this study in the Lower Balonne (Chapter 3). For each site the maximum depth was measured and the minimum persistence time was predicted based on extensive modelling.

The data were collated into a single data set which consisted of four variables:

1. **River** – Categorical variable which indicates in which of the three rivers a site was located.
2. **Site** – The waterhole from which the measurements of maximum depth and persistence were recorded/modelled.
3. **Max Depth** – Maximum depth of the waterhole at cease to flow in meters.
4. **Persistence –** The minimum persistence time of the waterhole, calculated using a site specific model (Chapter 3) in days.

Numerical and graphical exploratory analyses of each key variable were undertaken to detect outliers and violation of homogeneity, to check the distribution of observations, and to quantify the strength of the (linear) relationship (via the Pearson correlation coefficient).

The data for each river were plotted separately to examine the nature of the relationship within river systems. A linear regression was added to visually represent the relationship and highlight any potential outliers. The gradients of these lines are the rate at which the waterholes in that system dry. Furthermore, all three river systems were plotted together with their individual regression lines and an overall regression to compare the data across the sites.

A series of regression models were proposed to link to different hypotheses about the nature of the depth-persistence relationship. The four models are described as follows:

Model 1 The drying rate and minimum possible persistence are specific to each river system. This is the most complex model to fit.

Model 2 The drying rate is dependent on river system but the minimum possible persistence time is zero for all rivers.

Model 3 The minimum possible persistence is dependent on river system but drying rate is common across all rivers.

Model 4 The drying rate is common across all rivers and the minimum possible persistence is zero for all rivers. This model only has one parameter to estimate (i.e. drying rate).

For a more comprehensive examination of the different models, see Appendix E.

Analysis of variance was used to statistically compare nested models to quantify the likelihood of the more sophisticated model, assuming 5% significance level. Model validation was employed to verify assumptions of normality, homogeneity, independence and a correct model specification. Typically this was through graphical inspection of the model residuals.

Finally leave-one-out-cross-validation was used to assess the predictive performance of the model based on the new information.

5.3 Results

Data for 41 waterholes have been analysed. Maximum depth ranged from 1.29 metres to 4.8 metres and persisted for between 165 and 826 days (Table 5.1). Of the 41 sites, there were 12 from the Culgoa River, 15 from the Narran River and 14 from the Moonie River.

Table 5.1 Summary statistics for maximum depth and persistence across the 41 waterholes in Culgoa, Narran and Moonie rivers.

	Max Depth (metres)	Persistence (days)
Minimum	1.290	165.0
1st Quartile	2.010	307.5
Median	2.575	421.5
Mean	2.577	435.3
Maximum	4.800	826.0

The Pearson correlation coefficient for depth and persistence time is 0.92, which indicates a strong linear relationship between the variables.

Plots of persistence time against depth revealed that the waterholes in the Moonie tended to be deeper and persisted for longer than those in the Culgoa or Narran rivers (Figure 5.1).

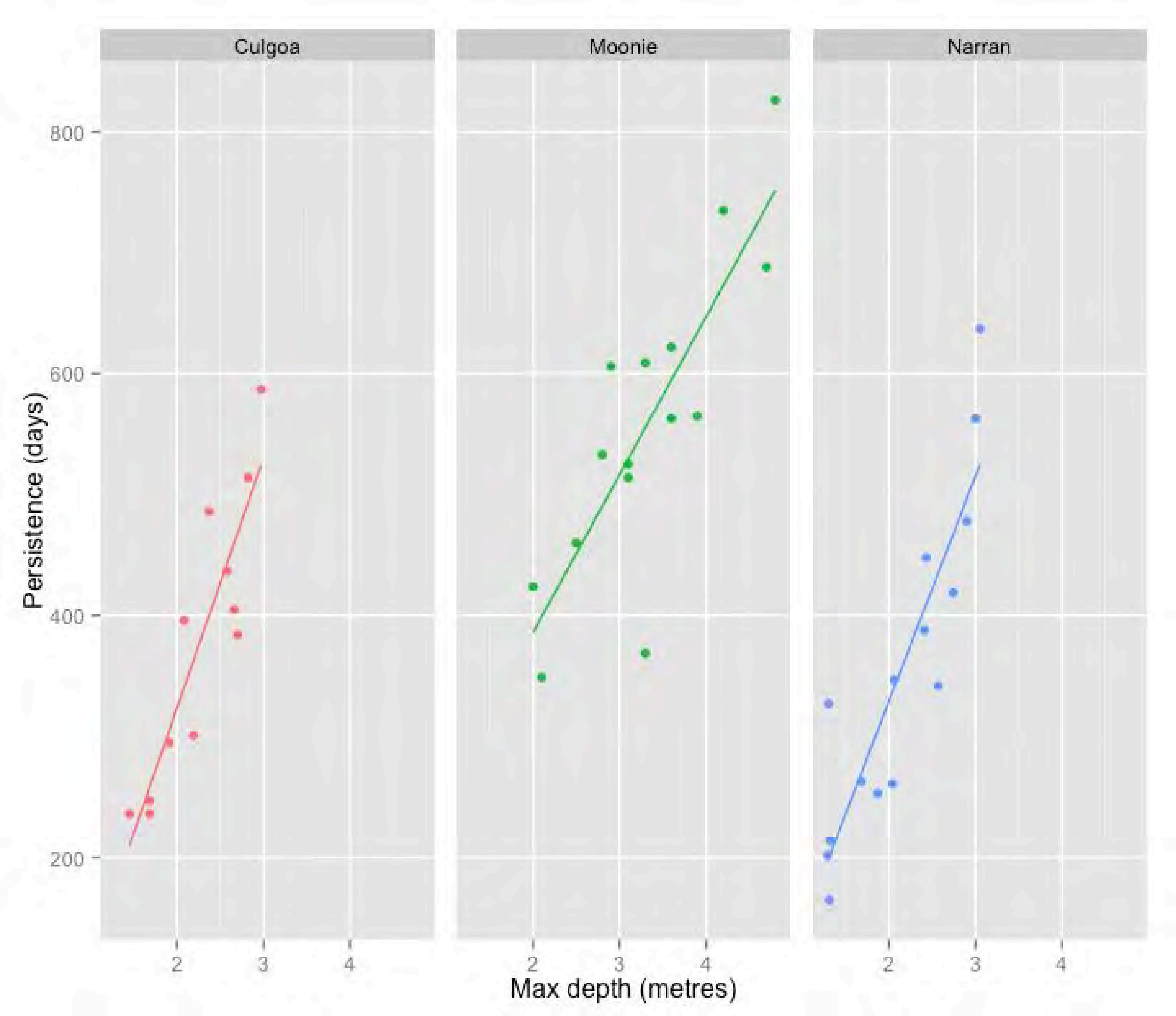

Figure 5.1 Waterhole persistence time and depth for three river valleys, with lines of best fit added to help with visual assessment. The relationship differs slightly for each of the three valleys; Culgoa (Persistence= 168.71 x Depth), Narran (Persistence= 167.60 x Depth), and Moonie (Persistence= 169.57 x Depth).

There appears to be slight variations in the drying rates between the catchments, with the gradients of the linear regressions for the Culgoa and Narran more similar than that of the Moonie (Figure 5.2). The minimum possible persistence times also vary, assuming the linear relationship holds.

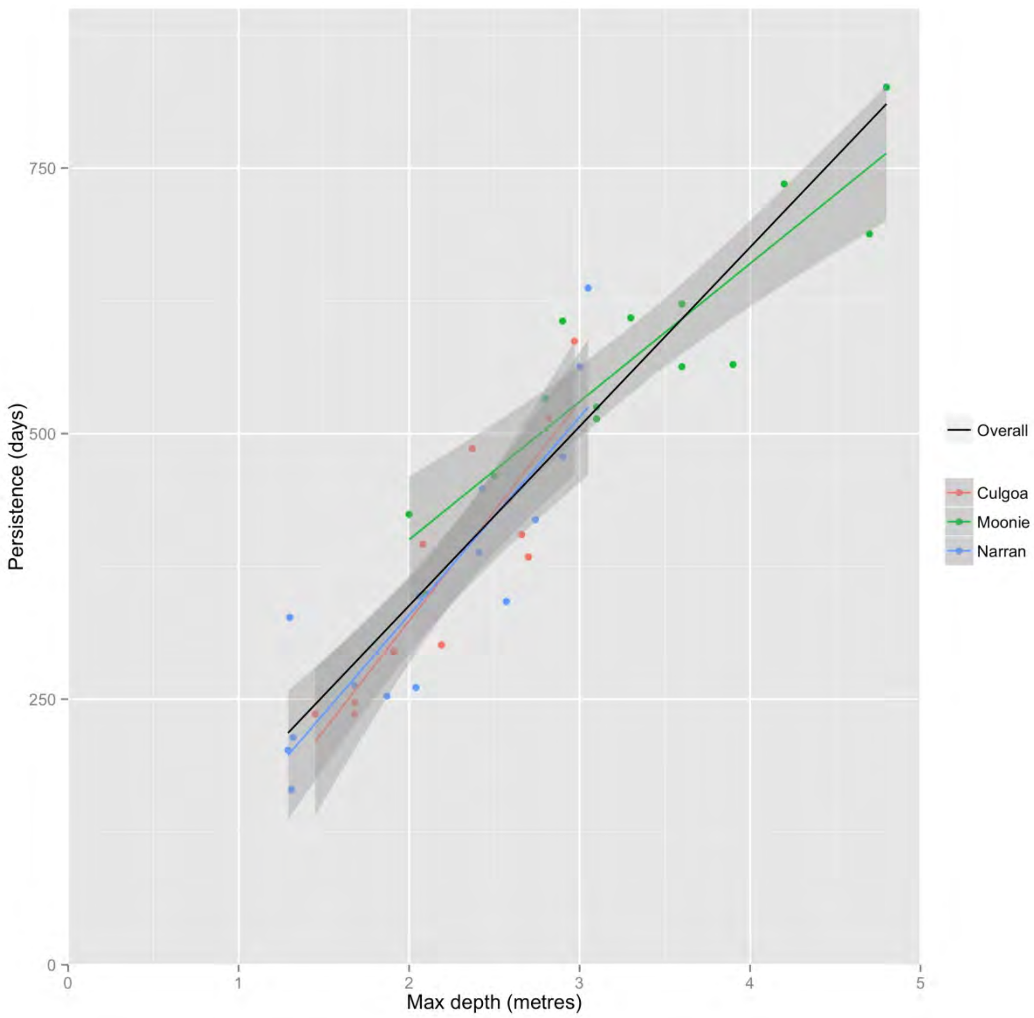

Figure 5.2 Waterhole persistence time (days) and maximum depth (metres) for three river systems, with individual lines of best fit (red, green, blue) and overall line of best fit (black). Shaded grey areas represent the 95% confidence interval for the individual lines of best fit.

We were able to formally test the degree of complexity required in the resulting model under the general premise of null hypothesis (H_0): simpler model v alternative hypothesis (H_1): more complicated model, using analysis of variance. The following models were compared and p-values noted:

- Model 3 vs Model 1 ($p = 0.077$)
- Model 2 vs Model 1 ($p = 0.104$)
- Model 4 vs Model 3 ($p = 0.783$)
- Model 4 vs Model 2 ($p = 0.973$)

None of the tests suggest that there is sufficient evidence to support the need for a more complicated model at a 5% significance level; the simplest model (Model 4) is the most parsimonious and statistically valid.

5.3.1 Model confidence and predictions

Persistence can be modelled across the three river valleys using model 4 with the following specification:

Persistence (days) = Depth (metres) x 168.91

The estimate of 168.91 is the drying rate (days/m), which has a standard error of 3.44 days/m. We are very confident that Model 4 is representative of the true persistence-depth relationship (Figure 5.3, dotted lines). There is, not surprisingly, less confidence in predicting persistence time for new maximum depth observations (Figure 5.3, dashed lines), where the standard error is 121 days.

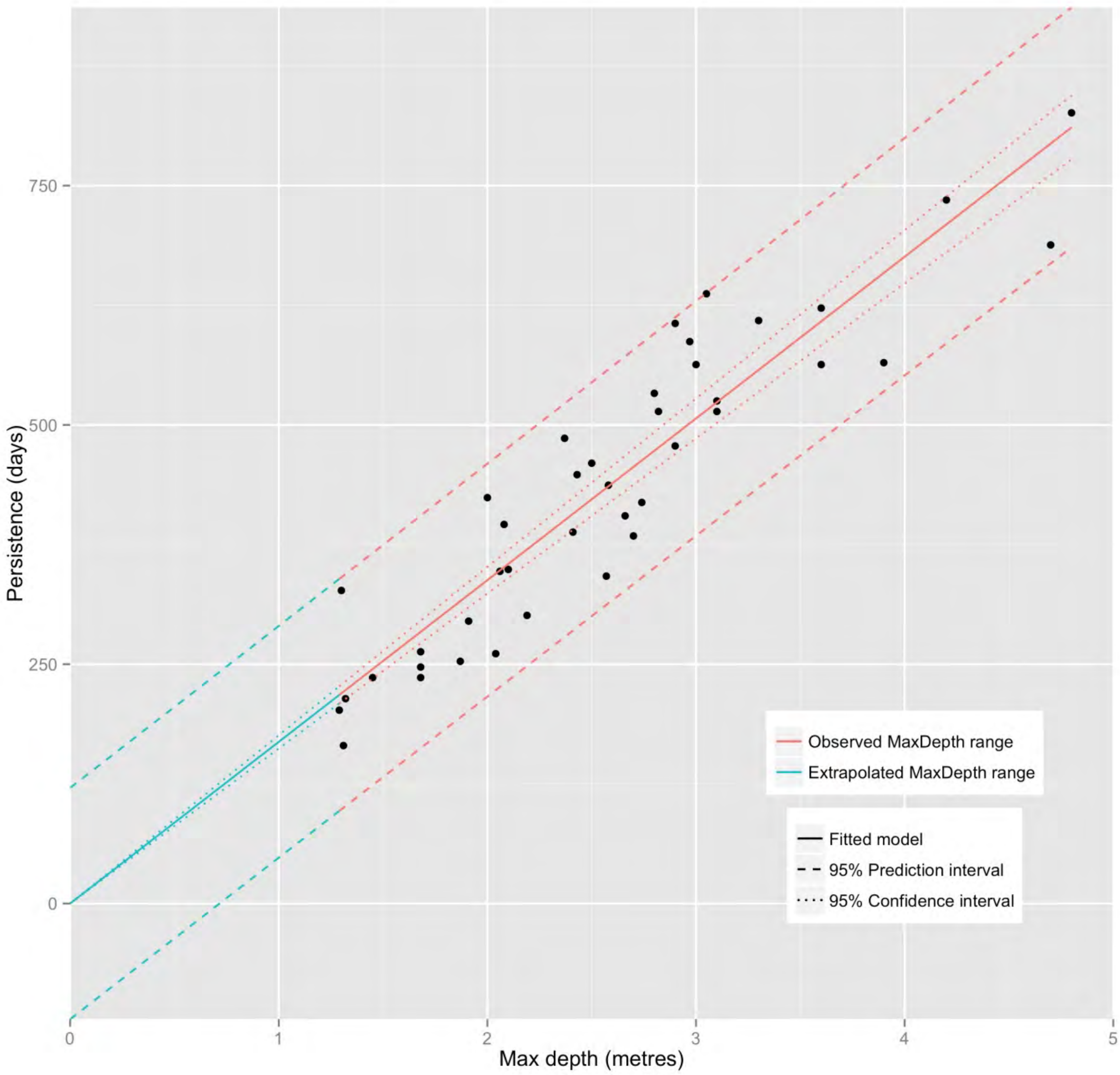

Figure 5.3 Scatterplot of the observations and the fitted linear model 4 (solid line). The 95% confidence interval (dotted lines) will contain the average persistence with probability of 0.95, whilst the 95% prediction interval (dashed lines) is the range of persistence time for a given maximum depth reading with probability 0.95.

5.4 Results

5.4.1 Management implications

The final model achieves all of the goals for a successful prediction model:

- **Accuracy** – The strong relationship between depth and persistence in waterholes means that the use of depth is able to produce an accurate estimate of persistence.
- **Transferability** – The model is able to be used across the three river valleys with no modifications for location.
- **Simplicity** – The model is very simple to use and the input data are simple to acquire.
- **Speed of Calculation** – The model requires only one measurement and a simple calculation and therefore can be deployed at the site.
- **Cost-Effectiveness** – Only one measurement and one calculation is required, so the model is a comparatively cheap way to estimate persistence.

This model allows water managers to estimate waterhole persistence 'at site' using only a single depth measurement with a reasonable level of confidence. The ability to predict persistence without taking extensive measurements over a length of time enables a quick and cost effective way of evaluating the longevity of sites. By using a single measurement of depth at the deepest point of the waterhole, sources of water can be evaluated for their suitability for an array of land uses.

Importantly, the depth of a waterhole can be used to evaluate the potential for the site to act as a refuge for biota which is crucial when selecting locations for conservation and ongoing monitoring.

5.4.2 Limitations

There are limitations within the model that must be understood to understand the scope in which the model may be used. Primarily, this model examines the background water loss rate; any non-natural extractions should be considered when estimating waterhole persistence.

5.4.2.1 Prediction confidence

Firstly, there are no observed data for the depth range 0 – 1.3 m, which is a relatively large range of data (compared to the data set as a whole). Given the lack of data for shallower waterholes, there is no way of confirming whether the relationship between depth and persistence stays linear through this range (Hocking 1996). The assumption that the model makes is that the relationship is linear across the possible range of maximum depth values observed and assumed, but in fact it is likely not; as the depth decreases so too does the volume and likely the temperature which in turn may increase the evaporation rate. Therefore, the model must be used with caution when predicting persistence in shallower waterholes until more data can clarify this relationship.

Secondly, the number of observations per river system was limited. A larger sample size of representative waterholes would give a better understanding of the distribution of depths and persistence times within each river valley and increased confidence in the final results. This may have an impact on the testing of which model best describes the relationship between depth and persistence.

Thirdly, there is an underlying assumption that the data are normally distributed, which is an assumption used in calculating the confidence and prediction intervals. There were no indications in the model validation that this is not the case, but greater sample sizes would yield greater confidence in this assumption.

Lastly, the 95% prediction interval appears to be quite large (±121 days), but if the data are normally distributed, the predictions will be on average much closer to the centre of that range (i.e what the model predicts). A 95% confidence interval provides the range in which 95% of values are expected to fall, that is, throughout that range the model should only be wrong in 5% of predictions.

5.4.2.2 Climatic component

The driver for natural water loss in waterholes is a combination of evaporation and groundwater. Discerning which of the two loss factors are most important across the river valleys requires further investigation. Presumably there is some correlation with climate, which is a driver for evaporation, but further investigation is required. Other factors such as wind fetch from river orientation may play a large role as well.

Also, the Moonie samples were taken in 2009, while the Culgoa and Narran river systems were sampled in 2015. The model could be impacted because of this difference; it may be different because of different conditions during sampling. It is feasible that the relationship may be stronger had the samples been collected in the same time period.

5.4.3 Taking the model further

Given the success with which this model can predict persistence across three river valleys, the ease of its use and the broad management implications, it would be worth investigating how this model might apply in a wider range of catchments within the Basin. As more catchments are incorporated into the model, the predictions become more robust and the management implications become exponentially greater as more regions can potentially benefit from the model.

In order to investigate the effect of climate, the next catchment to be surveyed would ideally have a similar river system in a climatically different location. It may be that by incorporating an element of climate into the model, its accuracy can be increased as will its area of application, though the corresponding increases in complexity may be prohibitive.

6 Evaluation of hypothetical MDBA water recovery scenarios on waterhole persistence

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This chapter addresses the following knowledge gap:

- *Do hypothetical hydrological modelling scenarios show a benefit to the persistence of waterholes in the Lower Balonne and Barwon Darling (based on modelling 114 years of natural inflows (1895-2009) under a range of different management conditions?*

6.1 Introduction

6.1.1 Background

Environmental water requirements (EWRs) for the Lower Balonne ‘umbrella environmental asset’ (UEA) (Chapter 1) are aimed at maintaining the ecological values and associated site-specific ecological targets for the UEA (MDBA 2011a). The EWRs specified for the UEA are intended to represent the broader environmental flow needs of river valleys or reaches and thus the needs of a broader suite of key environmental assets and functions (MDBA 2011a). The Lower Balonne river system and its floodplain was identified as an important component of the ecosystem, including in-channel waterholes and billabongs that act as refugia during drought. Due to the variability of flows in the Lower Balonne floodplain, this system experiences long periods without flow during which time waterholes act as vital refugia for obligate aquatic species.

EWRs have previously been determined for refugial waterholes based on limited knowledge of their depth and location in the catchment, flow requirements from previous studies in nearby catchments, and analysis of modelled and actual flow data at relevant gauges (Sheldon et al. 2014). Based on this information, a flow indicator of 1,200 ML/day for 7 days at Brenda gauge should occur at a maximum interval of 22 to 28 months (1.8 to 2.3 years) was proposed to ensure that an unspecified number of deeper waterholes will be maintained as drought refuges by specifying a flow that would pass through the Culgoa River before the waterholes become dry (Sheldon et al. 2014).

To assess options for achieving Basin-wide environmental outcomes, the MDBA modelled different water recovery scenarios over the range of climatic conditions experienced from 1895 to 2009 (MDBA 2012). In the Condamine-Balonne region, five recovery scenarios were modelled to inform the Basin Plan (203, 60, 100, 130 and 150 GL/y recovery options). Depending on the scenario, a combination of random and targeted buyback approaches were used that predominantly spatially targeted the Lower Balonne region (downstream of Beardmore Dam) (MDBA 2012). More information on the hydrology modelling used to inform the Basin Plan is outlined in MDBA’s

“Hydrologic modelling to inform the proposed Basin Plan: Methods and results report” (MDBA 2012).

6.1.2 Water recovery scenarios

Five hydrological modelling scenarios, including three alternative water recovery scenarios developed to help inform the Northern Basin Review, were provided by the MDBA. These scenarios were used to model the persistence of the Lower Balonne Floodplain waterholes under a range of plausible flow scenarios (each using the same 114 years of historic inflows with a different level of water development). These include models for without development, current diversion limits (set at 2009 conditions of development) and three hypothetical water recovery scenarios that incorporate additional information from the Northern Basin Review (Table 6.1). It should be noted that these five scenarios are different to the recovery scenarios used to inform the Basin Plan.

Table 6.1 Water recovery scenarios for the northern Basin

Scenario	Description
Without Development (WOD)	The WOD scenario represents no infrastructure or consumptive users such as irrigation, town water supply and industrial water, and all rules governing flows have been removed (MDBA 2012). This scenario is the best available approximation of the natural conditions in the Basin.
Baseline	The Baseline scenario is the best available estimate of current water use of the Basin as at June 2009 (MDBA 2012). It represents water sharing arrangements and levels of development and infrastructure of the Basin including entitlements, water allocation policies, water sharing rules, operating rules and infrastructure (dams, locks and weirs). This is the standard to assess the Basin Plan. The level of development follows the Murray–Darling Basin Cap for all States, unless the state’s water usage level is lower than the Cap level (MDBA 2012).
Northern Standard (NS)	The NS scenario represents the river system in the northern Basin under a fully implemented Basin Plan with its current 2012 settings. This scenario represents SDLs in the Basin Plan, where 390GL/y of water has been recovered from the Northern Basin for the environment. This includes a shared reduction of 143GL/y within the Northern Basin zone to achieve outcomes in the Barwon–Darling River. Water recovery in the Condamine Balonne in this scenario is 140 GL/y. The NS forms the starting point for comparison with alternative Basin Plan settings as part of the Northern Basin Review i.e. it acts as a benchmark scenario where changes to SDL settings and water recovery strategies can be compared and measured (MDBA 2014). The NS was developed in conjunction with the Northern Basin Intergovernmental Working Group and involved collaboration between MDBA and the Basin States.
100 GL recovery from the Condamine-Balonne (NS100)	This scenario is similar to NS except with a lower target reduction water recovery of 100GL/y in the Lower Balonne. Bifurcation 1 (B1) is where the Balonne River splits into the Culgoa River and Balonne Minor River. Upstream of B1 has the same recovery of 10GL but downstream of B1 the recovery volume has been reduced.

Scenario	Description
20 GL recovery from upstream of Beardmore Dam (Beardmore)	This is another targeted reduction scenario transferring a volume of 20GL (of the total 140GL) from Lower Balonne to the Upper and Mid-Condamine regions (13GL in the Mid-Condamine and 7GL in the Upper Condamine).

6.1.3 Assessment of water recovery scenarios

The MDBA acknowledged that there was less ecological data to determine EWRs in the northern Basin, including in the Lower Balonne and Barwon–Darling regions, compared to the southern Basin (Chapter 1). Examination of the EWRs for refugial waterholes in the northern Basin revealed key knowledge gaps relating to the lack of information regarding flow requirements which maintain waterhole persistence as well as key information on the waterhole habitat requirements of dependent environmental assets and ecosystem functions (DNRM 2011). Additionally, the flow information used to develop refugial waterhole EWRs in the Lower Balonne UEA were based on the Culgoa river valley and did not encompasses the Narran, Bokhara and Birrie rivers (Figure 1.3 in Chapter 1).

In the absence of refugial waterhole EWRs based on locally relevant ecological and hydrological information, a risk-based approach was used to evaluate alternate water recovery scenarios in the northern Basin. The approach is consistent with previous water management scenario evaluations undertaken in the northern Basin (DERM 2011) where waterhole persistence times are used as an assessment endpoint. This also allows the incorporation of new information gained on persistence times from the Lower Balonne and Barwon–Darling river valleys (Chapter 3).

The key outcome of this assessment is to identify when refugial waterholes in the northern Basin are unlikely to persist at both the reach and individual waterhole scales. Outcomes will also inform recommendations on the need for additional flow indicators sites to represent the needs of refugial waterholes.

6.2 Methods

The risk-based approach uses waterhole failure thresholds (termed Thresholds of Concern, ToC) to represent critical loss of refuge function. The frequency at which these thresholds were breached was compared between the scenarios at the individual waterhole and reach scale.

6.2.1 Waterhole persistence and permanence

Individual waterhole persistence varies according to depth and rate of water loss, which includes evaporation, seepage and consumptive water use. Water loss models were developed for representative waterholes (including natural waterholes and weir pools) in the Lower Balonne and Barwon–Darling River valleys (Chapter 3). These models can be used to predict persistence time in relation to the frequency and duration of no flow spells under alternate water management arrangements.

Some waterholes that this project investigated (Akuna, Weir 20A and Ellendale, all located in the Barwon–Darling) persist longer than the longest spells without flow under any of the scenarios provided by MDBA. Such waterholes are permanent over the 114 year simulation period and are, therefore, not vulnerable to the water resource development scenarios. Other waterholes had their persistence characteristics altered under some scenarios reflecting a threat to their function as a refuge. Hence, these waterholes were the focus of further assessment outlined here.

6.2.2 Risk assessment framework

Risk to refugial waterholes was assessed at two spatial scales to reflect the ways waterholes support aquatic biota.

(i) *Individual waterhole scale*: A ToC was established representing the depth at which an individual waterhole has a high probability of losing its function as a refuge due to stochastic water quality and biological factors which intensify as waterholes become shallow (DERM 2010). This was based on a waterhole model run to 0.5 metres above empty (Table 6.2). At this depth there is a high risk of the waterhole being unable to support ecological values and ecosystem functions due to factors such as biological crowding, food availability and water quality.

(ii) *Reach scale*: Waterholes represent a mosaic of habitat within river systems which change over time. Biota utilising this habitat survive through dry spells, then move and recolonise after flow events to maintain their distribution. This means that not all waterholes need to persist during all dry spells for populations to survive in a reach; however, fewer waterholes increase the chance that other threats (e.g. local water quality impacts) reduce the viability of populations (Figure 6.1). ToCs representing three levels of reach scale waterhole habitat availability were developed based on the without development hydrology of the rivers and regional waterhole persistence characteristics (Table 6.3).

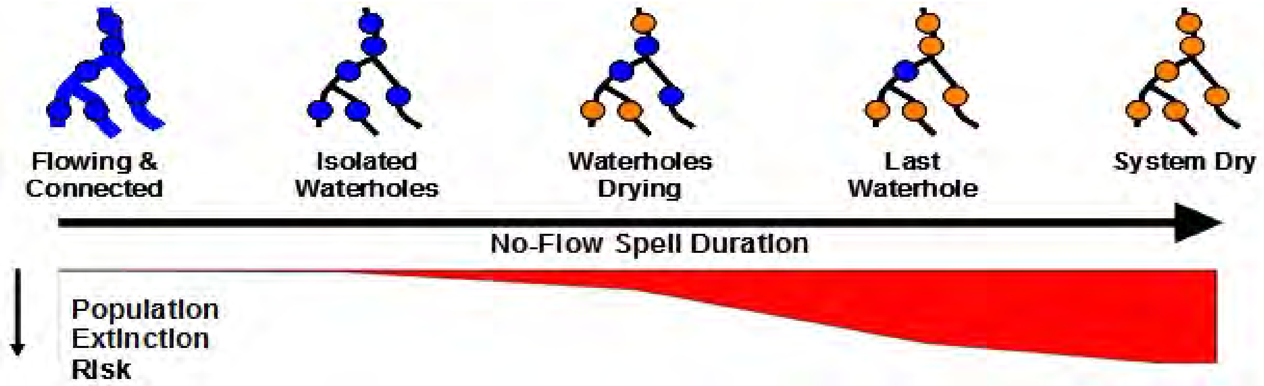

Figure 6.1 Waterhole distribution and population extinction risk with increasing no flow spell duration

The probability of a flow scenario achieving ecosystem outcomes for the maintenance of waterholes acting as refugia during spells without flow is directly related to the risk profiles it generates using these ToCs (Tables 6.2 & Table 6.3).

Table 6.2 Individual waterhole Thresholds of Concern (ToC).

Waterhole	Waterhole ToC (no. of days after cease to flow)
Culgoa River valley	
Woolerbilla GS	358
Brenda	430
Weilmoringle GS	495
Westmunda	389
Narran River valley	
Glenogie	402
Angledool	538
Bangate	473
Killarney	360

Table 6.3 Thresholds of Concern (ToC) levels

Level of ToC	Duration of no flow spell	Reason
Individual waterhole failure	variable	Based on the persistence times of modelled waterholes at 0.5 m, representing a point where there is a high risk of stochastic failure of individual waterholes (DERM 2010). These times were longer than 350 days of no flow (see below).
Reach scale waterhole stress #1	350 days	Based on the 80th percentile of no flow spell duration observed under WOD for gauges in the Lower Balonne (Appendix F). Longer spells represent extreme dry times under WOD and thus would be expected to naturally stress the system. This ToC represent waterholes under stress at an environmental assessment reach scale.
Reach scale waterhole stress #2	548 days	Based on the maximum persistence times of modelled waterholes in the Culgoa and Narran river valley i.e. under this spell duration 10% of the modelled waterholes retained water in the Lower Balonne (one waterhole in the Culgoa and two waterholes in the Narran). This ToC represents waterholes under critical stress at an environmental assessment reach scale.
Reach scale waterhole stress #3	720 days	Exceeds maximum persistence time of all modelled waterholes. This ToC represents complete loss of all persistent waterholes at an environmental assessment reach scale.

6.2.3 Scenario evaluation

6.2.3.1 Modelled daily flow time-series

Modelled daily flow time-series (ML/day) under each flow scenario (described in Table 6.1) was derived using the eWater Source model (eWater 2012). The eWater Source model is a hydrological system simulation model that operates on a daily time step. A daily flow time-series was derived for gauges representing the relevant environmental assessment reaches across the Lower Balonne floodplain (see Chapter 2). Additional environmental assessment reaches across the Bokhara and Birrie have been included in this assessment to assess all key river valleys within the Lower Balonne. As the eWater Source model has limitations in simulating low flows, for the purposes of this assessment no flow periods were defined as those < 2 ML/day (Craig Johansen, pers comm).

6.2.3.2 Assessing the risk to persistent waterholes

Risk was expressed as the frequency of ToC exceedance at the environmental assessment reaches.

As a general rule, the risk to biota reliant on refugial waterholes increases with more simultaneous waterhole failures, as greater areas of entire river valleys are simultaneously dry, meaning recolonisation must occur from further away and may be less likely if connectivity is restricted (DERM 2010). Therefore, to assess the risk the scenarios pose to reliant biota, we identified occurrences of simultaneous ToC failure across all environmental assessment reaches in the study region and over the simulation period. These risk profiles were compared across scenarios.

For the individual modelled waterholes with ToCs, water recovery scenarios were evaluated by counting the number of exceedances over the simulation period, and results were compared with the WOD and baseline scenarios. For these waterholes, risk to individual waterhole refuge function was considered to be high when there were no failures under WOD (i.e. they were permanent under WOD over the simulation period), but some number of failures occurred under water resource development scenarios. This represented loss of permanence over this period.

6.3 Results

6.3.1 Waterhole persistence and permanence

Persistence times were derived for all calibrated waterhole models by removing all water inputs and running the models to empty (see Chapter 3). In the Culgoa River valley, the minimum persistence time for waterholes ranged from 236 days (Gurrawarra) to 587 days (Weilmoringle Gauging Station (GS). Whereas in the Narran River valley, the minimum persistence time for waterholes ranged from 165 days (Golden Plains) to 637 days (Angledool). Although the most persistent waterhole was in the Narran River valley, most waterholes in the Culgoa River valley were modelled to persist longer than those in the Narran. Given that maximum no flow spells recorded at gauging stations in the Culgoa and Narran exceed these persistence times (Chapter 2) these waterholes are not permanent and are potentially at risk from water resource development. For the Barwon–Darling River valley, only one uncalibrated model, which did not incorporate water loss characteristics, was developed.

Analysis showed that waterhole depth was a robust predictor of modelled persistence time in the Lower Balonne (Chapter 5). This depth-persistence relationship is similar to that observed in the Moonie River valley and was considered to be representative of the northern Basin (DERM 2010). Using this information, a global model was developed where the minimum persistence times of waterholes can be predicted if maximum depth is known. Therefore, based on this depth-persistence relationship it is assumed that waterholes/weir pools in the Barwon–Darling, with an average depth of 5–8 m, can persist for over 1,400 days of no flow. However, this estimate is based on Barwon–Darling waterhole/weir pool depths beyond the range of the observations used to generate the predictive relationship. Despite this, only one environmental assessment reach in the Barwon–Darling (gauge 422028 - Beemery) had a recorded maximum no flow spell of 90 days. This suggests that these waterholes/weir pools are permanent in the Barwon–Darling, therefore they are not threatened by water resource development and were not considered further in this risk assessment.

6.3.2 Scenario evaluation

6.3.2.1 Modelled daily flow time-series

Daily flow time-series were modelled for gauges associated with 17 environmental assessment reaches across the Lower Balonne, covering the Culgoa, Narran, Bokhara and Birrie river valleys (Table 6.4). Cumulative frequency plots of all gauges under each flow scenario are provided in Appendix F. The WOD scenario had the shortest duration of maximum no flow spells across all reaches in the Culgoa and Narran River valleys, compared to the development scenarios. Under the WOD scenario, the maximum duration of a no flow spell over the simulation period was shortest in the Culgoa River valley (215 and 397 days). Longer no flow spells for the WOD scenario were modelled in the Narran River Valley (602 and 628 days) but the longest maximum no flow spells were recorded in mid to lower reaches of the Bokhara and Birrie river valleys, exceeding 1,000 days.

The maximum duration of no flow spells under the Baseline scenario, in comparison to WOD, had extended to over 600 days in the upper to mid reaches of the Culgoa (Table 6.4). The longest no flow spell over the simulation period in the Culgoa was recorded at Weilmoringle Weir (712 days). Further, no flow spells modelled for the mid to lower reaches of the Narran River valley exceeded 726 days under the Baseline scenario. In contrast to the Culgoa and Narran River valleys, the longest maximum no flow spells modelled under the Baseline scenarios, in comparison to WOD, have nearly halved for reaches located in the lower reaches of the Bokhara and Birrie River valleys (<728 days). While, the maximum duration of no flow spells modelled for reaches located the upper reaches of the Bokhara River valley were similar across all development and the WOD scenarios (617 to 650 days).

The longest duration of the no flow spells remained largely unchanged between the three water recovery scenarios and the Baseline scenario across all reaches (Table 6.4). There was a slight reduction in the length of maximum no flow spells modelled for the mid reaches of the Culgoa under the Northern Standard (NS) scenario when compared to the Baseline scenario.

Table 6.4 Frequency and duration of no flow spells (<2ML/day) (number, maximum is in light blue and hashtag and total is in darker blue and asterisk) over the simulation period (1895–2009) for the environmental assessment reaches under each hydrological modelling scenario – Without development (WOD), Baseline, Northern Standard (NS), NS100 and Beardmore. Percentage change from the Baseline scenario shown in brackets.

Environmental assessment reach	Number, maximum duration and total duration of no flow spells (<2ML/day)**				
	WOD	Baseline	NS	NS100	Beardmore
Downstream of Beardmore Dam					
Balonne River at St George (422201F)	-	276	280 (1.4%)	280 (1.4%)	285 (3.3%)
	-	298 days#	299 days# (0.3%)	299 days# (0.3%)	296 days# (-0.7%)
	-	10211 days*	10162 days* (−0.5%)	10162 days* (−0.5%)	9964 days* (−2.4%)
Balonne-minor River at Hastings (422205A)	363	344	338 (-1.7%)	338 (-1.7%)	344
	373 days#	604 days#	604 days#	604 days#	603 days# (−0.2%)
	17697 days*	29344 days*	29446 days* (0.3%)	29446 days* (0.3%)	29294 days* (−0.2%)
Culgoa River valley					
Culgoa River at Whyenbah (422204A)	255	311	308 (−1.0%)	308 (−1.0%)	308 (−1.0%)
	317 days#	601 days#	601 days#	601 days#	601 days#
	14242 days*	28508 days*	28608 days* (0.4%)	28608 days* (0.4%)	28608 days* (0.4%)
Culgoa River at Woolerbilla (422208A)	287	287	286 (−0.3%)	286 (−0.3%)	286 (−0.3%)
	375 days#	613 days#	613 days#	613 days#	613 days#
	16121 days*	28602 days*	28586 days* (−0.1%)	28599 days* (−<0.1%)	28599 days* (−<0.1%)

Environmental assessment reach	Number, maximum duration and total duration of no flow spells (<2ML/day)**				
	WOD	Baseline	NS	NS100	Beardmore
Culgoa River at Brenda (422015)	252	250	286 (14.4%)	249 (−0.4%)	249 (−0.4%)
	397 days#	673 days#	613 days# (-8.9%)	673 days#	673 days#
	16654 days*	28914 days*	28586 days* (−1.1%)	28928 days* (<0.1%)	28928 days* (<0.1%)
Culgoa River at Weilmoringle (422017)	245	227	228 (0.4%)	229 (0.9%)	229 (0.9%)
	397 days#	712 days#	685 days# (−3.8%)	685 days# (−3.8%)	685 days# (−3.8%)
	17114 days*	29437 days*	29369 days* (−0.2%)	29394 days* (−0.1%)	29394 days* (−0.1%)
Culgoa River at U/S collerina (Mundiwa) (422011)	272	348	348	348	348
	215 days#	346 days#	346 days#	347 days# (0.3%)	347 days# (0.3%)
	11693 days*	18351 days*	18283 days* (-0.4%)	18350 days* (−<0.1%)	18350 days* (−<0.1%)
Culgoa River at D/S Collerina (Kenebree) (422006)	278	352	350 (−0.6%)	351 (−0.3%)	351 (−0.3%)
	215 days#	348 days#	347 days# (−0.3%)	348 days#	348 days#
	11851 days*	18483 days*	18421 days* (−0.3%)	18478 days* (−<0.1%)	18478 days* (−<0.1%)
Narran River valley					
Narran River at Dirranbandi-Hebel Rd (422206A)	321	316	312 (−1.3%)	312 (−1.3%)	312 (−1.3%)
	618 days#	621 days#	622 days# (0.2%)	622 days# (0.2%)	622 days# (0.2%)

Environmental assessment reach	WOD	Baseline	NS	NS100	Beardmore
	29403 days*	30045 days*	30160 days* (0.4%)	30166 days* (0.4%)	30166 days* (0.4%)
Environmental assessment reach	Number, maximum duration and total duration of no flow spells (<2ML/day)**				
	WOD	Baseline	NS	NS100	Beardmore
Narran River at New Angledool (422012)	337	296	292 (−1.4%)	293 (−1.0%)	293 (−1.0%)
	602 days#	726 days#	726 days#	726 days#	726 days#
	26698 days*	31344 days*	31311 days* (−0.1%)	31355 days* (<0.1%)	31355 days* (<0.1%)
Narran River at Wilby Wilby (Belvedere) (422016)	289	246	242 (−1.6%)	245 (−0.4%)	245 (−0.4%)
	628 days#	739 days#	738 days# (−0.1%)	738 days# (−0.1%)	738 days# (−0.1%)
	27960 days*	32474 days*	32144 days* (−1.0%)	32301 days* (−0.5%)	32301 days* (−0.5%)
Bokhara River valley					
Bokhara River at Hebel (422209A)	298	273	270 (−1.1%)	270 (−1.1%)	275 (0.7%)
	629 days#	617 days#	617 days#	617 days#	617 days#
	30715 days*	28975 days*	28926 days* (−0.2%)	28930 days* (−0.2%)	28772 days* (−0.7%)
Ballandool River at Hebel-Bollon Rd (422207A)	302	278	278	278	274 (-1.4%)
	631 days#	650 days#	651 days# (−0.2%)	651 days# (−0.2%)	644 days# (−0.9%)
	31551 days*	29903 days*	30017 days* (−0.4%)	30019 days* (−0.4%)	29856 days* (−0.2%)
Bokhara River at Goodooga (422014)	223	268	266 (−0.7%)	266 (−0.7%)	268
	1119 days#	719 days#	719 days#	719 days#	677 days# (-5.8%)

	35420 days*	30851 days*	30847 days* (−<0.1%)	30856 days* (<0.1%)	30711 days* (−0.5%)
Environmental assessment reach	**Number, maximum duration and total duration of no flow spells (<2ML/day)****				
	WOD	Baseline	NS	NS100	Beardmore
Bokhara River at Bokhara (422005)	168	229	218 (-4.8%)	219 (-4.4%)	221 (-3.5%)
	1101 days#	718 days#	718 days	718 days#	717 days# (−0.1%)
	29810 days*	30323 days*	29977 days* (−1.1%)	30033 days* (−1.0%)	29831 days* (−1.6%)
Birrie River valley					
Birrie River at near Goodooga (422013)	227	267	264 (−1.1%)	264 (−1.1%)	265 (−0.7%)
	1105 days#	719 days#	719 days#	719 days#	677 days# (−5.8%)
	33591 days*	30794 days*	30768 days* (−0.1%)	30775 days* (−0.1%)	30625 days* (−0.5%)
Birrie River at Talawanta (422010)	194	249	243 (−2.4%)	243 (−2.4%)	242 (−2.8%)
	1114 days#	728 days#	727 days# (-0.1%)	727 days# (−0.1%)	724 days# (−0.5%)
	32492 days*	31283 days*	31120 days* (−0.5%)	31154 days* (−0.4%)	31007 days* (−0.9%)

** No flow periods as those below a threshold of 2 ML/day

6.3.2.2 *Risk to waterholes (individual waterhole scale)*

Eight of the modelled waterholes were considered to be refugial, as their predicted depth after 350 days of no flow exceeded 0.5 m (Chapter 3).

Risk results for the waterhole ToC indicated that four modelled waterholes provided refuge across the simulation period under WOD scenario, three of which were permanent refugial waterholes located in the Culgoa River valley (Table 6.5). However, under Baseline and water recovery scenarios, three of these waterholes are no longer permanent. Further, there are no permanent refugial waterholes in the Narran under water resource development with the ToC for Angledool exceeded on one occasion. Westmunda waterhole, located in the lower reaches of the Culgoa

River, is the only modelled waterhole to remain permanent under both the Baseline and water recovery scenarios.

Risk profiles also indicated that there was no benefit from any of the hypothetical water recovery scenarios for refugial waterholes located in the Lower Balonne, compared to the Baseline scenario. There were minor differences between these scenarios, such as an increase in exceeding the ToC under the Baseline scenario for the majority of refugial waterholes located in the Narran. However, the hypothetical water recovery scenarios still fail to mitigate the risk to these refugial waterholes. This is illustrated for refugial waterholes located in the upper and lower reaches of the Narran River valley, Glenogie and Killarney waterholes respectively, where they have failed to provide refuge at least 18 times over the simulation period.

Similar to the Narran, there were only minor differences in risk profiles between Baseline and the hypothetical water recovery scenarios for refugial waterholes in the Culgoa River valley. There were a mixture of slight increases and reductions in the number of periods that ToCs were exceeded for some waterholes under water recovery scenarios, in comparison to Baseline scenario, but overall little change between these scenarios. These reductions were relatively similar across all water recovery options. Overall, the hypothetical water recovery scenarios did not mitigate the risk from water resource development to refugial waterholes located in the Lower Balonne.

Table 6.5 Risk to individual refugial waterholes in the Lower Balonne, expressed as the number of times that their ToC was exceeded over the time-series for each scenario (loss of permanence under WOD is highlighted in red, and with an asterisk). Permanent is defined as retaining refuge throughout the simulation period.

Waterholes	WOD	Baseline	NS	NS100	Beardmore
Culgoa River valley					
Woolerbilla GS	1	11	12	12	12
Brenda	0	6*	3*	6*	6*
Weilmoringle GS	0	6*	6*	6*	6*
Westmunda	0	0	0	0	0
Narran River valley					
Glenogie	3	18	17	17	17
Angledool	0	1*	1*	1*	1*
Bangate	2	10	9	9	9
Killarney	7	22	20	20	20

6.3.2.3 Risk to waterholes (reach scale)

Stress Level 1

The percentage of reaches where no flow spell durations exceeded the stress Level 1 ToC of 350 days is summarised for each hydrological scenario, according to each water year, across the simulation period (Appendix F). In comparison to the WOD scenario there were more years under

Baseline and water recovery scenarios, where a greater percentage of reaches across the Lower Balonne simultaneously exceeded this ToC stress level. Under the WOD scenario the highest number of simultaneous reaches to exceed this ToC was seven of the 17 reaches; this occurred twice over the simulation period. Simultaneous exceedances were increased considerably by water resource development, with eight occasions where 14 of the 17 reaches simultaneously exceeded this ToC, placing broad landscape-scale stress on the function of waterhole refugia and the biota that utilise them. This was not alleviated by any of the water recovery simulations.

The Culgoa and Narran River valleys, which make up most assessment reaches across the Lower Balonne, experienced an increase in the number of periods where this stress level was exceeded under the water recovery scenarios, in comparison to WOD (Table 6.6). Also, risk profiles for reaches under the water recovery scenarios were not dissimilar to the Baseline scenario, indicating no benefit at a reach scale. The results further showed that the upper reaches of the Culgoa River valley were never stressed under WOD but are stressed multiple times under both water recovery and Baseline scenarios (Table 6.6). All reaches in the Narran River valley were under stress more often under both water recovery and Baseline scenarios compared to WOD. Unlike the Culgoa and Narran, exceedances of this stress level in the Bokhara and Birrie river valley did not markedly differ between all five scenarios.

Stress Level 2

The annual percentage of reaches where spell durations exceeded the stress Level 2 ToC of 548 days is shown in Appendix F. As was the case with Level 1 stress in comparison there were more years under Baseline and water recovery scenarios where a greater percentage of reaches across the Lower Balonne simultaneously exceeded this ToC level, compared to the WOD scenario. Under the WOD scenario the highest number of reaches simultaneously exceeding this ToC was seven of the 17 reaches; this occurred once over the simulation period. Simultaneous exceedances were considerably increased by water resource development, on five occasions seven of the 17 reaches simultaneously exceeded this ToC, while there were three occasions where nine reaches exceeded and one time when 11 reaches exceeded. This increase in simultaneous exceedances against this ToC would place broad landscape-scale critical stress on the function of waterhole refugia, with many to most long-term persistent waterholes drying threating the biota that utilise them. This was generally not alleviated by any of the water recovery simulations evaluated. There was one year (2005 see Appendix F) where a number of simultaneous exceedances of reaches occurred under WOD but not under any water resource development scenarios. This reflects the changed hydrology of the Birrie and Bokhara river valleys with a reduction in no flow spells under the influence of water resource development (Table 6.4), rather than alleviation of stress to waterholes in the Narran and Culgoa River valleys, and is not a consequence of the buy-back scenarios evaluated.

Table 6.6 The number of times that the Thresholds of Concern (ToC) levels (reach scale) were exceeded over the time-series for each scenario. Scenarios are WD = Without Development. Bl = Baseline, NS = Northern Standard, NS 100 = Northern Standard 100, Bd = Beardmore. Stress Level 1 is white, Stress Level 2 is orange and with a hashtag, Stress Level 3 is red and with an asterisk.

Environmental Assessment Reach	ToC														
	WD			Bl			NS			NS 100			Bd		
Downstream of Beardmore Dam															
Balonne River at St George (422201F)	0	0#	0*	0	0#	0*	0	0#	0*	0	0#	0*	0	0#	0*
Balonne-minor River at Hastings (422205A)	0	0#	0*	0	1#	0*	0	1#	0*	0	1#	0*	0	1#	0*
Culgoa River valley															
Culgoa River at Whyenbah (422204A)	0	0#	0*	10	1#	0*	11	1#	0*	11	1#	0*	11	1#	0*
Culgoa River at Woolerbilla (422208A)	1	0#	0*	10	1#	0*	11	1#	0*	11	1#	0*	11	1#	0*
Culgoa River at Brenda (422015)	2	0#	0*	10	5#	0*	11	1#	0*	10	5#	0*	10	5#	0*
Culgoa River at Weilmoringle (422017)	2	0#	0*	11	6#	0*	11	6#	0*	11	6#	0*	11	6#	0*
Culgoa River at U/S Collerina (Mundiwa) (422011)	0	0#	0*	0	0#	0*	0	0#	0*	0	0#	0*	0	0#	0*
Culgoa River at D/S Collerina (Kenebree) (422006)	0	0#	0*	0	0#	0*	0	0#	0*	0	0#	0*	0	0#	0*
Narran River valley															
Narran River at Dirranbandi-Hebel Rd (422206A)	9	1#	0*	12	1#	0*	12	1#	0*	12	1#	0*	12	1#	0*

Narran River at New Angledool (422012)	2	1#	0*	11	4#	1*	12	4#	1*	12	4#	1*	12	4#	1*
Narran River at Wilby Wilby (Belvedere) (422016)	6	2#	0*	16	4#	2*	15	4#	2*	15	4#	2*	15	4#	2*
Bokhara River valley															
Bokhara River at Hebel (422209A)	9	3#	0*	12	1#	0*	12	1#	0*	12	1#	0*	11	1#	0*
Ballandool River at Hebel-Bollon Rd (422207A)	9	3#	0*	11	3#	0*	12	3#	0*	12	3#	0*	11	3#	0*
Bokhara River at Goodooga (422014)	14	5#	5*	12	5#	0*	11	5#	0*	11	5#	0*	12	4#	0*
Bokhara River at Bokhara (422005)	8	5#	5*	12	6#	0*	14	5#	0*	14	5#	0*	13	5#	0*
Birrie River valley															
Birrie River at near Goodooga (422013)	12	5#	4*	12	5#	0*	11	5#	0*	11	5#	0*	12	4#	0*
Birrie River at Talawanta (422010)	10	5#	5*	12	5#	1*	13	5#	1*	13	5#	1*	12	5#	1*

Risk profiles of the second stress level ToC for most individual assessment reaches under water recovery scenarios also indicated an increase in the number of periods they were under critical stress, in comparison to WOD (Table 6.6). Critical stress represents 50 per cent of the modelled persistent waterholes lost at an environmental assessment reach scale (Table 6.3). Once more, the upper and mid reaches of the Culgoa River valley are under critical stress more often due to water resource development, on some occasions multiple times, when they were never stressed at this level under WOD. Due to the short duration of no flow spells in the lower reaches of the Culgoa River valley, these reaches were not critically stressed under all five scenarios (Table 6.6). Similarly, there was an increase in the number of periods the mid to lower reaches of the Narran River valley were critically stressed under water resource development. Unlike the Culgoa, the Narran River valley naturally (i.e. under the WOD scenario) experiences critical stress at some stage as this valley typically has prolonged no flow spells. Overall, the hypothetical water recovery scenarios still provide no benefit at the reach scale compared to Baseline scenario when the system is under critical stress.

Stress Level 3

The annual percentage of reaches where spell durations exceeded the stress Level 3 ToC of 720 days is shown in Appendix F. Importantly, under all five scenarios, there were no instances of dry spells resulting in simultaneous system failure in the Balonne and Culgoa river valley reaches against this ToC. In contrast to the assessment results for stress Level 1 and 2 ToCs, a comparison of the WOD scenario with the Baseline and water recovery scenarios indicated fewer years where reaches across the Lower Balonne simultaneously failed against this ToC level. Under WOD there were 6 occasions where simultaneous reach failures occurred, and only four of the 17 reaches failed. Whereas there were only two such occasions under all water resource development scenarios. As with stress Level 2 ToC, this result reflects the changed hydrology of the Birrie and Bokhara river valleys with fewer long no flow periods under the influence of water resource development (Table 6.4) rather than alleviation of stress to waterholes in the Narran and Culgoa valleys, and is not a consequence of the water recovery scenarios evaluated. Thus under the WOD scenario, failures against Level 3 ToC only occurred in the Bokhara and Birrie river valleys, and not in the other valleys (Table 6.6). However, under water resource development scenarios, the Bokhara and Birrie river valleys are no longer at the risk of system failure (Table 6.6). In contrast, under water resource development scenarios, the mid to lower reaches of the Narran now experience system failure. Although these failures have only occurred twice over the simulation period (in 1914 and 1917), exceeding this ToC level at a reach scale represents a loss of all refugial waterholes across most of the Narran River valley.

6.4 Discussion

6.4.1 Thresholds for risk to waterholes of MDBA

This project has identified risks to the persistence of refugial waterholes in the Lower Balonne at two spatial scales. As flow requirements of different waterholes have been shown to vary within and between river valleys within the Lower Balonne (Chapters 2 and 3), a range of risk thresholds at the reach scale were applied to evaluate risks from water resource development to waterholes that potentially act as refugia. Based on the average duration of no flow spells during WOD, and the period where 50 per cent of the modelled waterholes retained water (Chapter 3), the minimum risk threshold for refugial waterholes across all reaches was defined as one year without flow. This threshold represents the Lower Balonne under stress and does not represent system failure and loss of all refugial waterholes across the system. A threshold representing system failure, when all known waterholes in the region would be dry, was determined by using the minimum persistence times of modelled waterholes. This maximum risk threshold at a reach scale was defined as two years. Once this threshold is reached the results of this study suggest waterhole values have been lost. A moderate risk threshold of one and half years was also determined, representing the system at a critical stage with only 10% of modelled waterholes retaining water and none being deeper than half a metre. This is a threshold at which the system is approaching complete failure with increasing risk of failure occurring as time passes without flow. Spells without flow longer than this would be of major concern for the sustainability of waterhole function.

As waterholes may fail to provide suitable habitat at shallow depths, and persistence times vary, there was a need to determine a risk threshold for individual waterholes. By using the predicted persistence times, and assuming that at least half a metre is required to provide refuge, eight waterholes across the Narran and Culgoa rivers were identified as refugial. Although half of these refugial waterholes are part of a natural impoundment or weir pool, their water-loss characteristics were similar to all natural waterholes modelled (Chapter 3), and are therefore representative of waterholes across the Lower Balonne. Persistence time to the half metre depth level of these waterholes ranged from one to one and a half years, and no waterholes provided suitable habitat after one and a half years, either because they had dried completely, or were too shallow.

The selection of half a metre water depth to represent loss of refuge function of waterholes is based on understanding that the probability of water quality and biological effects rendering them unsuitable as refuge habitat increases as depth becomes shallow. Many of these factors are stochastic in space and time so actual failure cannot be predicted. Half a metre is a conservative level representing this phenomenon, and is anecdotally verified by field observations of biota in drying waterholes, but it should be noted that such stochastic failures can occur at both shallower and deeper depths.

The MDBA may be able to consider defining valley specific minimum and maximum risk thresholds for each river valley based on the range of persistence times identified for the modelled waterholes. For the Culgoa, these would range from 358 to 495 days, whereas the risk thresholds for the Narran would range from 360 to 538 days. No flow spells shorter than the smaller number would ensure maintenance of all modelled waterholes studied in each valley, while spells within this range would ensure at least one modelled waterhole is maintained. Further field evaluations could allow prediction of persistence times of additional waterholes identified by remote sensing (Chapter 2) using the depth persistence relationship established by the project (Chapter 5).

In conclusion, the minimum risk threshold determined at both the reach and individual waterhole scale in this project does not exceed one and half years of no flow. This shows that the existing EWR used by the MDBA (22 months) was an overestimate and was inadequate for the maintenance of refugial waterholes across the Lower Balonne.

6.4.2 Evaluation of water recovery scenarios

While there is no evidence that complete region wide loss of waterholes is likely to occur, the results of the evaluation show water resource development poses a significant risk to the function of waterhole as refugia in the region and generally this risk is not mitigated by the hypothetical water recovery scenarios evaluated.

The effect of water resource development has been to increase risk of valley scale loss of waterhole function in the Narran and Culgoa river valleys, while at the same time reducing this risk in the Birrie and Bokhara river valleys. The ecological consequence of the risks identified here could include loss of viability of biota that rely on functioning networks of connected waterholes to sustain their populations in this region. Examples include many of the region's fish and turtle species. Such losses could occur at reach to valley scales based on the results of our risk assessment. Recovery would depend on capacity of these species to repopulate from other locations, requiring specifict flow conditions at the necessary times, and capacity to surmount the many artificial barriers to longitudinal movements represented by the many weirs and road crossings in the region.

While it may be that loss of waterhole refugia at key times from the Narran and Culgoa River valleys is compensated for by increased availability in the Birrie and Bokhara, as it currently stands nothing is known of the quality of habitat in these latter valleys or pathways and frequency of movement opportunities from them to the remainder of the region for repopulation of lost habitat patches. The fact remains that the landscape template under which local populations evolved was one of no refugia during extended dry times in the Birrie and Bokhara, and permanent refugial waterholes perennially available in the Narran and Culgoa. How the dispersal traits, and behavioural responses of the various species that rely on refugial waterholes, respond to the reversal of the habitat template over population time-scales remains unknown. Yet these responses will determine the outcomes of the water resource development induced changes to provision of refugia.

It should also be noted that this risk assessment has partitioned hydrological threats from a number of other threats to waterhole function and populations of biota that rely upon it. Firstly, there is the additional threat from possible impacts of movement barriers, discussed above. Secondly, there is pumping from waterholes during no flow periods which would accelerate water loss and reduce persistence time. Thirdly, sedimentation which may reduce waterhole depth and further reduce persistence time. Lastly, there are various threats to the biota themselves, such as competition with exotic carp, which may reduce the fitness of native individuals to both survive in refugia and repopulate from them when flows return.

Failure to mitigate the risks to waterhole persistence under the various hypothetical water recovery scenarios evaluated reflects a lack of targeting the flows that break long no flow spells. The water entitlements recovered in these water recovery scenarios where focused on water harvesting and overland flow licences (Adam Sluggett, pers comm). The nature of these licence types (i.e. the rules around pumping thresholds) has focused water recovery impacts on higher flows (i.e. in-channel freshes and overbank flows), with little to no change to low flows (Adam Sluggett, pers comm). Our results also highlight that they have little or no impact on restoring the durations of long spells without flow (Figure 6.2). Therefore, it is recommended that alternate recovery scenarios (including the potential to explore management actions) should be considered to mitigate risks to the refuge function of waterholes.

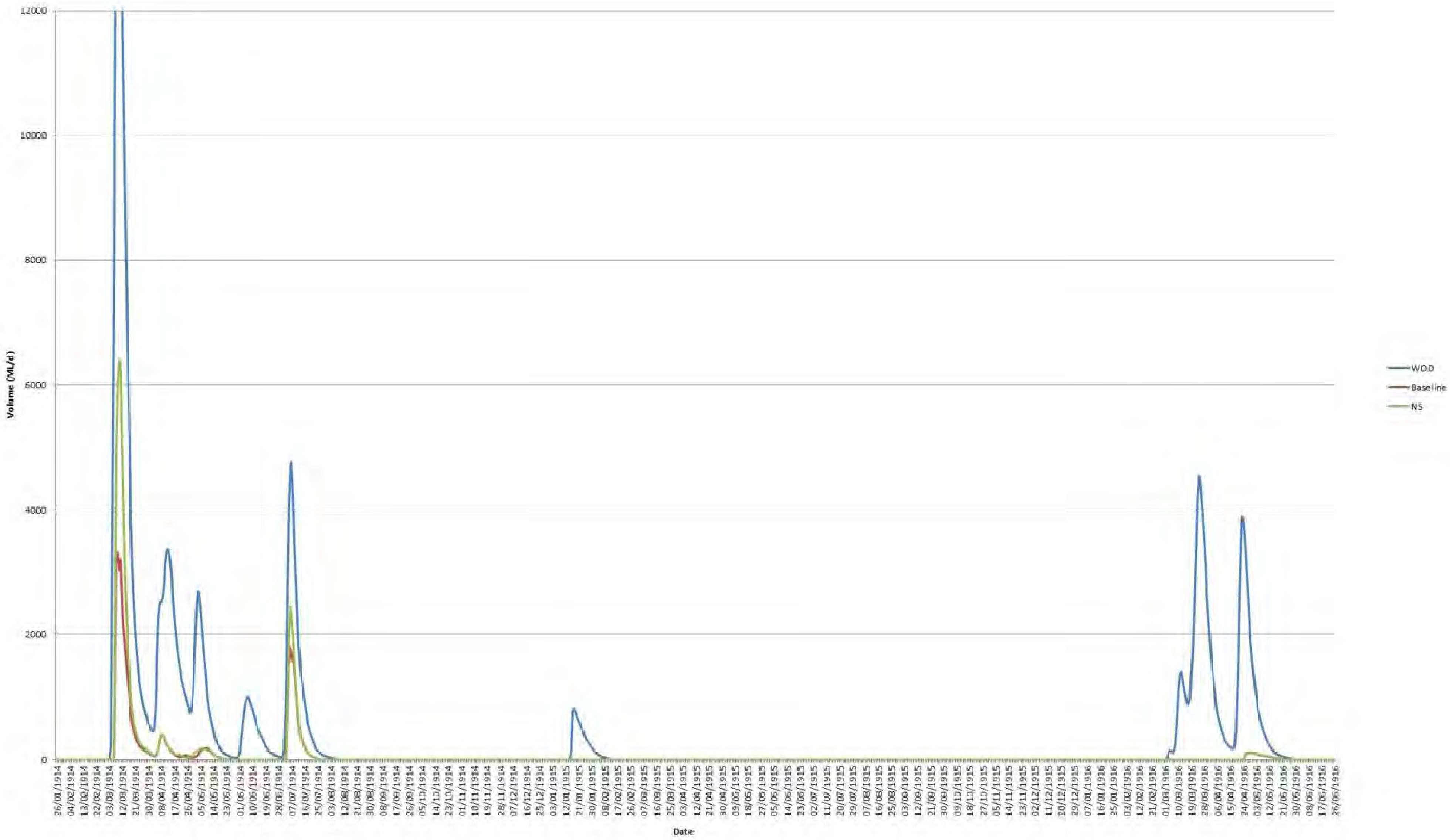

Figure 6.2 Modelled hydrology of three water management scenarios at gauge 422015 (Brenda), from 1914-1916. Scenarios include without development (WOD), Baseline and Northern Standard (NS).

Although sedimentation rates are not currently available, probing has indicated that soft sediments can move throughout the Lower Balonne system. This may threaten shallow waterholes and pose an additional threat to their persistence if scouring flows do not occur. Consequently, further scenario evaluation is warranted to quantify the risk. The data to enable this type of analysis is not yet available for inclusion in the report and will be provided in a supplementary report.

6.4.3 Flow indicator sites

The Lower Balonne floodplain is naturally characterised by flow variability (Sheldon et al. 2010), and modelled flow time-series data showed that flow variability, for the Culgoa and Narran River valleys, has increased under water resource development. Specifically, the maximum duration of no flow spells has increased for most reaches along these river valleys. This project has identified three refugial waterholes in the mid to upper reaches of the Culgoa (Woolerbilla GS, Brenda waterhole and Weilmoringle GS) and one of these waterholes (Brenda waterhole) is located downstream of the existing flow indicator site, Brenda gauge. As the upper reaches of the Culgoa are most at risk of water resource development, with modelled no flow spells exceeding one and half years, Brenda gauge is considered an appropriate flow indicator site to set the flow requirements for waterholes located in this river valley. Flows recorded at Brenda gauge are likely to have passed and filled waterholes in upstream locations.

This project has also identified that there are a number of refugial waterholes in the mid to lower reaches of the Narran River valley and that the lower reaches of the Narran have experienced system failure (720 days of no flow) under the water resource development scenarios. In light of this, it is recommended that an additional flow indicator site be located on the Narran River (potentially downstream of this reach to set the flow requirements for waterholes located in this river valley.

As the Bokhara and Birrie experienced system failure under WOD, it is unlikely that these river valleys supported refugial waterholes prior to water resource development. However, these river valleys were not included in the study area to model waterhole persistence. Therefore, more information is needed on waterholes in these valleys to be certain about their flow requirements, as risk assessment shows that their regional importance in providing refugia during dry times has been increased by water resource development.

6.4.4 Recommendations for future study

1. Review flow requirements needed to fill waterholes along the Culgoa and Narran river valleys. If required, update the 1,200 ML/day for seven days site-specific flow indicator.

2. Determine at what depths the probability becomes unacceptable of persistent waterholes failing to provide suitable habitat for key species across the Lower Balonne, to validate the half a metre assumption used here by undertaking assessment of water quality in relation to habitat value during low/no flow spells.

3. Investigate the persistence time of additional waterholes identified using remote sensing (Chapter 2) across the Lower Balonne, including the Birrie and Bokhara river valleys.

4. Determine the need for additional flow indicators sites to provide refugial waterhole functions in the Birrie and Bokhara river valleys would be required to set flow requirements for these valleys.

5. Incorporate knowledge of the movement behaviour of important species of biota with patterns in the spatial and temporal distributions of waterholes. This investigation should also look at the locations and effects of barriers to movement, in order to better understand risks to population viability of these species as a result of water resource development, and how water recovery may mitigate these risks.

7 Conclusions and Recommendations

7.1 Conclusions

This project addressed crucial knowledge gaps (Chapter 1) required to understand if the current EWRs set for the Lower Balonne Floodplain are suitable for maintaining refugial waterholes and whether specific flow requirements should be set for waterholes in the Barwon–Darling, upstream of Menindee Lakes. Knowledge gaps were filled by answering a series of key questions, the results of which are outlined below and summarised in Table 7.1.

Question 1. What is the spatial distribution of waterholes in the Lower Balonne and Barwon–Darling?

Findings:

- Ten refugial waterholes (≥350 days of no flow, not persistent throughout time-series), were identified in the Lower Balonne, eight of which are confined to the mid to lower reaches of the Narran River valley. These refugial waterholes had a combined water surface area of 38 hectares.
- Only five of these refugial waterholes persisted throughout the time-series at which point water availability was reduced to 3.7 hectares.
- In the Barwon–Darling and parts of the Lower Balonne (immediately downstream of Beardmore Dam), gauged no flow spells did not exceed 350 days. In these reaches, waterhole habitats present at the end of the longest recorded dry spell were identified.

What does this mean?

- No flow spells longer than 350 days pose a risk to waterholes in the Lower Balonne.
- The identification of waterholes that last through extended dry spells is important for water management, as maintenance of these key habitats will help ensure the viability of associated obligate aquatic biota.
- The remote sensing approach was successful and can be applied to other valleys in the northern Basin.

Question 2. What are the characteristics of waterhole habitat availability in the Lower Balonne and Barwon–Darling at reach scales?

Findings:

- No flow hydrology was variable within, and between, the river valleys; the longest no flow spells were identified in the mid Culgoa and the mid to lower reaches of the Narran.
- Habitat availability was variable across assessment reaches and although availability did decrease with increasing no flow spell duration, this relationship was not statistically significant.

What does this mean?

- Single gauging locations are unlikely to representative of water habitat availability at the river valley scale.
- Spell length is a driver of waterhole habitat loss.

Question 3. What is the persistence time of waterholes in the Lower Balonne and Barwon–Darling?

Findings:

- The average persistence time for modelled waterholes in the Culgoa River valley was 377 days (maximum 587 days at Weilmoringle GS).
- The average persistence time for modelled waterholes the Narran River valley was 355 days (maximum 637 days at Angledool).
- In the Barwon–Darling, the persistence time, based on uncalibrated models, ranged from 1083 days (Hell's Gate) to 1953 days (Akuna/Weir 20A).
- Modelled waterhole persistence times were validated by remote sensing analysis (Chapter 2).

What does this mean?

- Modelled waterholes in the Lower Balonne do not persist as long as previously thought; the majority of waterholes did not persist longer than one year and none persisted beyond two years.

Question 4. Does groundwater influence the persistence time of waterholes in the Lower Balonne and Barwon–Darling?

Findings:

- Groundwater contribution to waterholes along the Narran and Culgoa rivers is minor.
- Groundwater interaction maybe be greater in the Barwon–Darling, but does not contribute significantly to waterhole persistence.

What does this mean?

- Groundwater interactions did not need to be explicitly included in the calibration of persistence models for the Lower Balonne (Chapter 3).

Question 5. Does sedimentation affect waterhole persistence in the Lower Balonne and Barwon–Darling?

Findings:

- The average depth of accumulated soft sediment in the Lower Balonne was 25 centimetres (approximately 11 per cent of average maximum waterhole depth in the Narran and Culgoa Rivers).
- The average depth of accumulated soft sediment for the Barwon–Darling was 28 centimetres (approximately 4 per cent of average maximum waterhole depth in the Barwon–Darling).
- Waterholes in the Lower Balonne were shallower than the Barwon–Darling.

What does this mean?

- Additional findings from sedimentation rate analysis will be provided in a supplementary report.

Question 6. Can the persistence time of waterholes across the northern Basin be predicted using a generic model?

Findings:

- There is a strong depth/persistence time relationship within each river valley studied.
- Across the studied river valleys, and the additional Moonie River valley (DERM 2010), this relationship was transferable.
- Persistence time (Days) = Depth (m) × 168.91

What does this mean?

- The persistence time of waterholes can be estimated based on a single depth measurement.
- Factors that threaten the depth of a waterhole e.g. sedimentation and extraction, threaten their persistence time.

Question 7. Do hydrological modelling scenarios show a threat or benefit to the persistence of waterholes in the Lower Balonne (based on modelling 114 years (1895-2009) under a range of different management conditions)?

Findings:

- Eight modelled waterholes were deep enough to provide refuge after 350 days of no flow, four of which were modelled to persist for the simulation period under ‘without development’ scenario.
- Under all water resource development scenarios, only one waterhole (located on the Culgoa) is modelled to persist through the entire simulation period. The remaining seven waterholes failed more frequently and no modelled waterholes in the Narran River valley persist over the simulation period.
- At the broader reach scale, parts of the system experience critical stress under ‘without development’ scenario over the simulation period. However, under water resource development large areas of the system failed simultaneously and this is not mitigated by hypothetical water recovery scenarios.

What does this mean?

- When assessed against the persistence thresholds at the individual modelled waterhole and reach scale, water resource development poses a risk to waterholes acting as refugia and this risk needs to be addressed by alternative flow management options.
- As a large proportion of the refugial waterholes are located in the mid to lower reaches of the Narran River valley (Chapter 2), and the duration of no flow spells is increased in these reaches under water resource development, there is a need to have an additional flow indicator site within this river valley.

7.2 Recommendations

1. Review flow requirements needed to fill waterholes along the Culgoa and Narran river valleys. If required, update the 1,200 ML/day for seven days site-specific flow indicator.

2. Determine at what depths the probability becomes unacceptable of persistent waterholes failing to provide suitable habitat for key species across the Lower Balonne, to validate the half a

metre assumption used here by undertaking assessment of water quality in relation to habitat value during low/no flow spells.

3. Investigate the persistence time of additional waterholes identified using remote sensing (Chapter 2) across the Lower Balonne, including the Birrie and Bokhara river valleys.

4. Determine the need for additional flow indicator sites to provide refugial waterhole functions in the Birrie and Bokhara river valleys, would be required to set flow requirements for these valleys.

5. Incorporate knowledge of the movement behaviour of important species of biota with patterns in the spatial and temporal distributions of waterholes and the locations and effects of barriers to movement, in order to better understand risks to population viability of these species as a result of water resource development, and how water recovery may mitigate these risks.

Table 7.1 Knowledge gaps and their corresponding outputs.

Threat	Effect on asset	Knowledge gap	Information required	Information gathered	Output
Increase in no flow spell occurrence and duration	Spells may exceed waterhole persistence time, causing local extinction of aquatic biota	Waterhole persistence times in the target river valleys	Distribution of refuge waterholes across catchments	Remote sensed mapping of waterholes present in satellite images that captured no flow spells across the assessment reaches	Comprehensive map of refuge and persistent waterhole locations across the northern Basin
			Relationship between spell length and amount of waterhole habitat at the reach scale	Remote sensing analysis of amount of wetted habitat in waterholes following no flow spells of a range of durations	Relationship between spell length and available waterhole habitat was investigated
			Water loss rate	Depth change using data loggers Climate data	Calibrated waterhole persistence models for scenario assessment. Maximum persistence times for assessment of consequence and incorporation risk assessment. Simple generic persistence measures for rapid estimates.
			Waterhole shape and size	Bathymetric mapping to develop a digital elevation model	
			Connection to groundwater	^{222}Radon, conductivity and stable isotope sampling to detect groundwater inflow	
			Depth/Persistence relationship	Comparison of depth/persistence relationship between river valleys and catchments	Model to predict persistence using depth measurement

Threat	Effect on asset	Knowledge gap	Information required	Information gathered	Output
Change in the provision of sediment scouring flow events	Sediment accumulation in waterholes, leading to reduced volume and persistence	Sediment status of waterholes	Amount of soft sediment in waterholes	Sediment probing to establish depth profile of soft sediments	Sediment profiles of representative waterholes
			Historical rate of sediment accumulation	Aging of subsamples from sediment cores	Analysis is ongoing. To be provided in a supplementary report.
		Effect of flows on sediment dynamics	Identification of flow events or other conditions that lead to sediment infilling	Analysis of sediment core stratigraphy and links to historical flow/climate data	Analysis is ongoing. To be provided in a supplementary report.
			Identification and quantification of scouring capacity of flows	Not covered in this project	

References

Australian Collaborative Land Use Mapping Program (ACLUMP). 2009. Land Use: New South Wales http://www.agriculture.gov.au/abares/aclump/ Accessed November 2015.

Arthington, AH, Balcombe, SR, Wilson, GA, Thoms, MC & Marshall JC 2005, 'Spatial and temporal variation in fish-assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone floodplain river, Cooper Creek, Australia', *Marine and Freshwater Research*, vol. 56, pp. 25–35.

Balcombe, SR, Bunn, SE, Arthington AH, Fawcett, JH, McKenzie-Smith, F.J & Wright, A 2007, 'Fish larvae, growth and biomass relationships in an Australian arid zone river: links between floodplains and waterholes', *Freshwater Biology*, vol.52, pp. 2385–2398.

Beesley, LS & Prince, J 2010, 'Fish Community Structure in an Intermittent River: the Importance of Environmental Stability, Landscape factors and Within-Pool Habitat Descriptors', *Marine and Freshwater Research*, vol. 61, pp. 605–614.

Bond, NR, Lake, S & Arthington, AH 2008, 'The Impacts of Drought on Freshwater Ecosystems: an Australian Perspective', *Hydrobiologia*, vol. 600, pp. 3–16.

Bouvy, M, Nascimento, SM, Molica, RJR, Ferriera, A, Huszar, V & Azevedo, SMFO 2003, 'Limnological Features in Tapacura Reservoir (Northeast Brazil) During a Severe Drought', *Hydrobiologia*, vol. 493, pp. 115–130.

Brodie, R, Sundaram, B, Tottenham, R, Hostetle r, S & Ransley, T 2007, *An overview of tools for assessing groundwater-surface water connectivity*, Canberra: Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Canberra.

Bunn, S, Thoms, M, Hamilton, S & Capon S 2006, 'Flow variability in dryland rivers: Boom, bust and the bits in between', *River Research and Applications,* vol. 22, pp. 179–186.

Bureau of Meteorology (BOM) 2010, *Australian Hydrological Geospatial Fabric (Geofabric),* Commonwealth of Australia Bureau of Meteorology, http://www.bom.gov.au/water/geofabric/

Bureau of Meteorology (BOM) 2015, Commonwealth of Australia Bureau of Meteorology, http://www.bom.gov.au

Burnett, WC & Dulaiova, H 2006, 'Radon as a tracer of submarine groundwater discharge into a boat basin in Donnalucata, Sicily', *Continental Shelf Research,* vol. 26, pp. 862–873.

Burnett, WC, Peterson, RN, Santos, IR & Hicks, RW 2010, 'Use of automated radon measurements for rapid assessment of groundwater flow into Florida streams', *Journal of Hydrology*, vol. 380, no 3-4, pp. 298–304.

Carini, G, Hughes, JM & Bunn, SE 2006, 'The role of waterholes as 'refugia' in sustaining genetic diversity and variation of two freshwater species in dryland river systems Western Queensland, Australia)', *Freshwater* Biology, vol. 51, pp. 1434–1446.

Cartwright, I, Hofmann, H, Gilfedder, B & Smyth, B 2014, 'Understanding parafluvial exchange and degassing to better quantify groundwater inflows using ^{222}Rn: The King River, southeast Australia', *Chemical Geology,* vol. 380, pp. 48–60.

Cartwright, I, Hofmann, H, Sirianos, M.A, Weaver, TR & Simmons, CT 2011, 'Geochemical and ^{222}Rn constraints on baseflow to the Murray River, Australia, and timescales for the decay of low-salinity groundwater lenses', *Journal of Hydrology,* vol. 405, pp. 333–343.

Cecil, LD & Green, JR 2000, 'Radon-222', pp. 175–194. In Cook, PG, Herczeg, AL (eds), *Environmental Tracers in Subsurface Hydrology,* Kluwer, Boston.

Cendon, DI, Larsen, JR, Jones, BG, Nanson, GC, Rickleman, D, Hankin, SI, Pueyo, JJ & Maroulis, J 2010, 'Freshwater recharge into a shallow saline groundwater system, Cooper Creek floodplain, Queensland, Australia', *Journal of Hydrology*, vol. 392, pp. 150-163.

Choy, SC, Thomson, CB & Marshall, JC 2002, 'Ecological condition of central Australian arid-zone rivers', *Water Science and Technology*, vol. 45, pp. 225–232.

Commonwealth of Australia (2012), Basin Plan 2012, Prepared by the Murray–Darling Basin Authority for subparagraph 44(2)(c)(ii) of the *Water Act 2007* https://www.comlaw.gov.au/Details/F2012L02240

Cook, PG 2012, 'Estimating groundwater discharge to rivers from river chemistry surveys', *Hydrological Processes,* vol. 27, pp. 3694–3707.

Cook, PG, Favreau, G, Dighton, JC & Tickell, S 2003, 'Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers', *Journal of Hydrology*, vol. 277, pp. 74–88.

Cullen P, Marchant, R & Mein, R 2003, *Review of science underpinning the assessment of the ecological condition of the Lower Balonne system*, report to the Queensland Government Independent Scientific Review Panel, Brisbane.

Danaher, TJ & Collett, L 2006, 'Development, optimisation, and multi-temporal application of a simple Landsat based Water Index', *Proceedings of the 13th Australasian Remote Sensing and Photogrammetry Conference*, Canberra, Australia.

Davies, BR, Thoms, MC, Walker, KF, O'Keeffe, JH, & Gore, JA 2009, 'Dryland rivers: Their ecology, conservation and management', pp. 484-511. In Calow, P. and G. E. Petts (eds), *The Rivers Handbook – Volume Two*. Blackwell Science Ltd, Published online.

Davis, L, Thoms, MC, Fellows, C & Bunn, S 2002, 'Physical and ecological associations in dryland refugia: waterholes of the Cooper Creek, Australia', *Proceedings of an international symposium, Australia September 2002*, The Structure, Function and management Implications of Fluvial Sedimentary Systems, Alice Springs, Northern Territory, pp. 77–84.

Queensland Department of Environment and Resource Management (DERM) 2010, *Refugial Waterholes Project: Research Highlights*, Queensland Government, Brisbane.

Department of Environment and Resource Management (DERM) 2011, *Assessment of flow scenario implications for ecological assets of the upper Murray–Darling Basin*, Queensland Government, Brisbane.

Queensland Department of Natural Resources and Mines (DNRM) 2013a, *Operations Support method: Depth logger installation and post processing of data (AEMF013) version 4.0*, Queensland Government, Brisbane.

Queensland Department of Natural Resources and Mines (DNRM) 2013b, *Operations Support method: Post-processing of waterhole bathymetric survey data (AEML013) version 3.0*, Queensland Government, Brisbane.

Queensland Department of Natural Resources and Mines (DNRM) 2014, *Aquatic Ecosystems Field Method: Bathymetric surveys of waterholes (WMO015A) version 3.0*, Queensland Government, Brisbane.

Queensland Department of Natural Resources and Mines (DNRM) 2015. Water Monitoring Information Portal. https://water-monitoring.information.qld.gov.au/host.htm

Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) 2014a, *Targeted review of the Water Resource (Gulf) Plan 2007: Environmental assessment*, Queensland Government, Brisbane.

Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) 2014b, *Land use summary 1999–2012: Condamine NRM region*, Queensland Government, Brisbane.

de Vries, C, Danaher, T, Denham, R, Scarth, P & Phinn, S 2007, 'An operational radiometric calibration procedure for the Landsat sensors based on pseudo-invariant target sites' *Remote Sensing of Environment*, vol. 107, no 3, pp. 414–429.

D'Hautefeuille, F & Williams, R 2003, *Upper Darling Salt Interception Scheme – Preliminary investigation to May 2003*, Parramatta: Centre for Natural Resources New South Wales Department of Infrastructure, Planning and Natural Resources.

Ellins, KK, Roman-Mass, A & Lee, R 1990, 'Using ^{222}Rn to examine groundwater/surface discharge interaction in the Rio Grande de Manati, Puerto Rico', *Journal of Hydrology*, vol. 115, pp. 319–341.

eWater 2012, *Eco Modeller*, eWater Limited,

http://ewater.org.au/products/ewater-toolkit/eco-tools/eco-modeller/

Gibson, JJ, Sadek, MA, Stone, DJM, Hughes, CE, Hankin, S, Cendon, DI & Hollins, SE 2008, 'Evaporative isotope enrichment as a constraint on reach water balance along a dryland river', *Isotopes in Environmental and Health Studies*, vol. 44, no 1, pp. 83–98.

GRASS GIS 2015. Geographic Resources Analysis Support System. https://grass.osgeo.org/#.

Hocking, RR 1996, *Methods and Applications of Linear Models: Regression and Analysis of Variance.* John Wiley, New York.

Hoehn, E, Von Gunten, HR, Stauffer, F & Dracos, T 1992, 'Radon-222 as a groundwater tracer. A laboratory study', *Environmental Science Technology*, vol. 26, pp. 734–738.

Hooke, JM 2007, 'Monitoring morphological and vegetation changes and flow events in dryland river channels', *Environmental Monitoring and Assessment*, vol. 127, pp. 616–631.

Humphries, P, King, AJ, & Koehn, JD 1999, 'Fish, flows and flood plains: links between freshwater fishes and their environment in the Murray-Darling River system'. *Environmental Biology of Fishes* 56, 129−151

Humphries, P & Baldwin, DS 2003, 'Drought and aquatic ecosystems: an introduction', *Freshwater Biology*, vol. 48, pp. 1141–1146.

Knighton, AD & Nanson, GC 2000. Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. *Geomorphology*, 35, 101–117.

Lake, S 2003, 'Ecological Effects of Perturbation by Drought in Flowing Waters', *Freshwater Biology*, vol. 48, pp. 1161–1172.

Larned, ST, Datry, T, Arscott, DB & Tockner, K 2010, 'Emerging concepts in temporary-river ecology', *Freshwater Biology*, vol. 55, pp. 717–738.

Lobegeiger, J, Marshall, J, Holloway, D, McGregor, G & Marsh, N 2013, *Waterhole persistence model Eco Modeller plugin (version 1.0)*, [computer software and guide].

Magoulick, DD & Kobza, RM 2003, 'The role of refugia for fishes during drought: a review and synthesis', *Freshwater Biology*, vol. 48, pp. 1186–1198.

Marshall, JC, Sheldon, F, Thoms, M & Choy, S 2006, 'The macroinvertebrate fauna of an Australian dryland river: Spatial and temporal patterns and environmental relationships', *Marine and Freshwater Research*, vol. 57, pp. 61–74.

McGregor, GB, Marshall, JC & Thoms, MC 2006, 'Spatial and temporal variation in algal-assemblage structure in isolated dryland river waterholes, Cooper Creek and Warrego River, Australia', *Marine and Freshwater Research*, vol. 57, pp. 453-466.

Meredith, KT, Hollins, SE, Hughes, CE, Cendon, DI, Hankin, S & Stone DJM 2009, 'Temporal variation in stable isotopes (^{18}O and ^{2}H) and major ion concentrations within the Darling River between Bourke and Wilcannia due to variable flows, saline groundwater influx and evaporation', *Journal of Hydrology,* vol. 378, pp. 313–324.

Meredith, KT, Hollins, SE, Hughes, CE, Cendon, DI, Chisari, R, Griffiths, A & Crawford, J 2015, 'Evaporation and concentration gradients created by episodic river recharge in a semi-arid zone aquifer: Insights from Cl-, $\delta^{18}O$, $\delta^{2}H$, and ^{3}H', *Journal of Hydrology*, vol.529, pp. 1070–1078.

Murray Darling Basin Authority (MDBA) 2011a, *The proposed "environmentally sustainable level of take" for surface water of the Murray-Darling Basin: Methods and outcomes*, MDBA publication no: 226/11, Murray-Darling Basin Authority, Canberra.

Murray Darling Basin Authority (MDBA) 2011b. Upper Darling – salt interception scheme. Murray-Darling Basin Authority Publication. 4 p.

Murray Darling Basin Authority (MDBA) 2012, *Assessment of environmental water requirements for the proposed Basin Plan: Lower Balonne River Floodplain*, MDBA publication no: 24/12, Murray-Darling Basin Authority, Canberra.

Murray Darling Basin Authority (MDBA) 2014, *Northern Basin water recovery modelling*, Commonwealth of Australia,

http://www.mdba.gov.au/about-basin/northern-basin/northern-basin-work-program/NB-review/water-recovery-modelling

Murray Darling Basin Authority (MDBA) 2015, http://www.mdba.gov.au/about-basin/northern-basin Accessed October 2015.
Murray Darling Freshwater Research Centre (MDFRC) 2011, *A Review of River Ecosystem Condition in the Murray-Darling Basin, MDFRC Publication 01/2011*, Murray–Darling Freshwater Research Centre, Canberra.

Miall, AD 1985, ‘Architectural Elements and bounding Surfaces: A new method of facies analysis applied to fluvial deposits’, Earth-Science Reviews, vol. 22, pp. 261-308.

Nanson, GC, Tooth, S & Knighton, AD 2002. A global perspective on dryland rivers: perceptions, misconceptions and distinctions. In Bull, L. L. J., & Kirkby, M. J. (Eds.). *Dryland rivers: hydrology and geomorphology of semi-arid channels*. Wiley. com.

Negus, P, Blessing, J, Clifford, S & Steward, A 2015, *Riverine Assessment in the Warrego, Paroo, Bulloo and Nebine catchments. Q–catchments: Technical Report 2012*, Brisbane: Queensland Department of Science, Information Technology and Innovation.

NSW Department of Primary Industries (DPI) 2012, Water Sharing Plan for the Barwon–Darling Unregulated and Alluvial Water Sources, Background Document, Sydney

NSW Department of Primary Industries (DPI) 2015, http://realtimedata.water.nsw.gov.au/water.stm?ppbm=STATE_OVERVIEW&so&3&sobkm_url. Accessed October 2015.

Puckridge, JT, Sheldon, F, Walker, KF & Boulton, AJ 1998, ‘Flow variability and the ecology of arid zone rivers’, *Marine and Freshwater Research*, vol.49, pp. 55–72.

Rayner, TS, Jenkins, KM & Kingsford, RT 2009, ‘Small environmental flows, drought and the role of refugia for freshwater fish in the Macquarie Marshes, aria Australia’, *Ecohydrology,* vol. 2, pp. 440–453.

R core team, 2015 https://www.r-project.org/ Accessed October 2015

Reid-Piko, C, Crase, L, Horwitz, P & Butcher, R 2010, *Ecosystem Services and Productive Base for the Basin Plan*, Murray-Daring Freshwater Research Centre, Wodonga

Rogers, K & Biggs, H 1999, ‘Integrating indicators, endpoints and value systems in strategic management of the rivers of the Kruger National Park; *Freshwater Biology*, vol. 41, pp. 439–451.

San Juan, C & Kolm, KE 1996, ‘Conceptualization, characterization and numerical modeling of the Jackson Hole alluvial aquifer using ARC/INFO and MODFLOW’, *Engineering Geology*, vol. 42, pp. 119–137.

Seehausen, O & Bouton, N 1997, 'Microdistribution and fluctuations in niche overlap in a rocky shore cichlid community in Lake Victoria', *Ecology of Freshwater Fish*, vol. 6, no 3, pp. 161–173.

Sheldon, F, Thoms, MC, Berry, O, Puckridge, J 2000, 'Using disaster to prevent catastrophe: referencing the impacts of flow changes in large dryland rivers', *Regulated Rivers: Research & Management*, vol. 16, pp. 403–420.

Sheldon, F, Balcombe, S & Capon, S 2014, *Reviewing the scientific basis of environmental water requirements in the Condamine-Balonne and Barwon Darling: A synthesis,* Murray-Darling Basin Authority, Canberra.

Sheldon, F, Bunn, SE, Hughes, JM, Arthington, AH Balcombe SR & Fellows, CS 2010, 'Ecological roles and threats to aquatic refugia in arid landscapes: dryland river waterholes', *Marine and Freshwater Research*, vol. 61, pp. 885–895.

Shepherd, KA, Ellis, PA & Rivett, MO 2006, 'Integrated understanding of urbanland, groundwater, baseflow and surface-water quality – the City of Birmingham, UK', *Science of the Total Environment,* vol. 360, pp. 180–195.

Silcock, JL 2010, 'Experiencing Waterholes in an Arid Environment, with Particular Reference to the Lake Eyre Basin, Australia: a Review', *Geographical Research,* vol. 48, no 4, pp. 386–397.

Smith, VH, Joye, SB & Howarth, RW 2006, 'Eutrophication of freshwater and marine ecosystems', *Limnology and Oceanography,* vol. 51, pp. 351–355.

Sophocleous, M 2002, 'Interactions between groundwater and surface water: the state of the science', *Journal of Hydrogeol*ogy, vol. 10, pp. 52–67.

Stewardson, M & Marsh, N 2003, Using the River Analysis Package (RAP) for Environmental Flow Studies. The Institution of Engineers, Australia 28th International Hydrology and Water Resources Symposium

Thoms, MC 2003, 'Floodplain-river ecosystems: lateral connections and the implications of humaninterference.' *Geomorphology* vol. 56, pp. 335-349.

Thoms, MC, Quinn, G, Butcher, R, Phillips, B, Wilson, G, Brock, M & Gawne, B 2002, Scoping study forthe Narran Lakes and Lower Balonne floodplain management study (R2011), Cooperative ResearchCentre for Freshwater Ecology, Canberra.

Thoms, MC & Sheldon, F 2000, 'Lowland rivers: an Australian perspective', *Regulated Rivers Research and Management*, vol. 16, pp. 375–383.

Thoms, MC, Sheldon, F & Crabb, P 2004, 'A hydrological perspective on the Darling River', in Breckwold, Boden and Andrews (eds), The Darling, Murray–Darling Basin Commission, Canberra, pp. 332-347.

Venables, WN. & Ripley, BD, 2002, Modern Applied Statistics with S. Fourth Edition. Springer-Verlag, New York.

Villeneuve, S, Cook, PG, Shanafield, M, Wood, C, & White, N 2015, 'Groundwater recharge via infiltration through an ephemeral riverbed, central Australia', *Journal of Arid Environments*, vol. 117, pp. 47-58.

Waltham, N, Burrows, D, Butler, B, Wallace, J, Thomas, C, James, C, & Brodie, J 2013, *Waterhole ecology in the Flinders and Gilbert catchments*, CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia.

Webb, M 2009, 'Biocomplexity in Dryland River Systems the influence on flow regime on ecological character and foodweb structure', Masters Thesis, University of Canberra, Canberra.

Wickham, H 2013, http://ggplot2.org/ Accessed October 2015

Winter, TC 1995, Recent advances in understanding the interaction of groundwater and surface water', *Reviews of Geophysics,* vol. 33, pp. 985–994.

Winter, TC 2007, 'The role of ground water in generating streamflow in headwater areas and in maintaining base flow', *Journal of the American Water Resources Association,* vol. 43, pp. 15–25.

Woods, RJ, Lobegeiger, JS, Fawcett JH & Marshall JC (Ed) 2012, Riverine and floodplain ecosystem responses to flooding in the lower Balonne and Border Rivers – Final Report. Department of Environment and Resource Management, Queensland Government

Appendix A – Sedimentation

Probing – Sediment Profiles

A longitudinal profile of sediment distribution within each waterhole was developed by ‘probing’ the substrate along the thalweg (the deepest longitudinal line) of the waterhole. Using a series of marked poles from a boat, the water depth was measured, then the probes were pushed into the sediment as far as possible and a second reading was taken. The difference between the two measurements represents the depth of soft sediment at each point. The soft sediment is likely the most transient element of the sediment.

If the waterhole was less than two kilometres in length, the total length of the waterhole was estimated and this figure divided by 21 to determine the interval between individual probes. The resulting data set is 20 equally spaced points across the centre of the waterhole.

For waterholes greater than two kilometres long, 20 points were sampled in a two kilometre stretch around the depth logger (as per the method described above). Then, additional probes were positioned at intervals of 10 per cent of the total waterhole length throughout the remainder of the waterhole.

A modified method was used in the Barwon–Darling due to the size of the waterholes. A standard probing interval of 240 metres was used to ensure equal coverage at all sites (as none were less than two kilometres in length).

Probing revealed an average sediment depth of 27 centimetres in the Culgoa and 24 centimetres in the Narran River valleys with a maximum sediment depth across the two valleys of 1.5 metres at Angledool (Table A.1). In the Barwon–Darling, only seven sites could be probed due to flow conditions at time of sampling. The average sediment depth for these sites was 28 centimetres and a maximum of 1.2 metres of sediment at Akuna (Table A.2). Rocky or very hard substrate was more prevalent in the Barwon–Darling as shown by the common minimum sediment depth of zero (0).

Sediment depth profiles were also developed (Figure A1 – A37). For all sites, probe number 1 is taken from the upstream end of the waterhole, and the flag (where present) indicates the location of the depth logger in the waterhole. Profiles also show waterhole depth at time of sampling. These depths differ from Digital Elevation Models (DEMs) (Chapter 3, Appendix C) as they were not sampled at the same time and are not adjusted to a cease to flow level.

Table A.1 Sediment probing depths for the Culgoa and Narran River valleys. Depths are in metres.

Site Name	Minimum Sediment Depth (m)	Maximum Sediment Depth (m)	Average Sediment Depth (m)
Culgoa River valley			
Cubbie	0.06	0.89	0.27
Ingie	0.08	0.46	0.20
Woolerbilla GS	0.06	0.89	0.27
Ballandool	0.07	0.75	0.19
Brenda	0.07	0.56	0.26
Brenda Weir pool	0.07	0.65	0.21
Culgoa NP (NSW)	0.06	0.46	0.17
Weilmoringle Weir	0.07	0.69	0.23
Weilmoringle GS	0.06	0.64	0.21
Caringle	0.08	0.31	0.20
Innisfail	0.10	0.95	0.32
Westmunda (Grogan's Hole)	0.09	1.01	0.39
Gurrawarra	0.06	1.03	0.49
Lilyfield	0.15	0.09	0.41
Warraweena	0.05	0.98	0.20
Narran River valley			
Clyde	0.06	0.58	0.16
GS422206A	0.08	0.48	0.21
Booligar	0.05	0.56	0.19
Glenogie	0.06	1.02	0.34
Angledool	0.07	1.5	0.59
Narrandool	0.06	0.55	0.17
Bangate (Sorrento Hole)	0.05	0.87	0.29
Bil Bil	0.07	0.49	0.21
Golden Plains	0.05	0.40	0.15
Bomali	0.07	0.31	0.19
Belvedere	0.13	0.42	0.22
Amaroo	0.07	0.67	0.17
Killarney	0.11	0.79	0.32
Narran Plains	0.11	0.34	0.20
Narran Park	0.07	0.46	0.20

Table A.2 Sediment probing results for the Barwon–Darling River valley.

Site Name	Minimum Sediment Depth (m)	Maximum Sediment Depth (m)	Average Sediment Depth (m)
Collewaroy	0.06	0.8	0.27
Summerville	0	0.65	0.23
Jandra	0	1	0.36
Hell's Gate	0	0.75	0.22
Akuna	0	1.2	0.37
20A	0	0.95	0.36
Ellendale	0	0.8	0.13

Depth profiles - Culgoa River

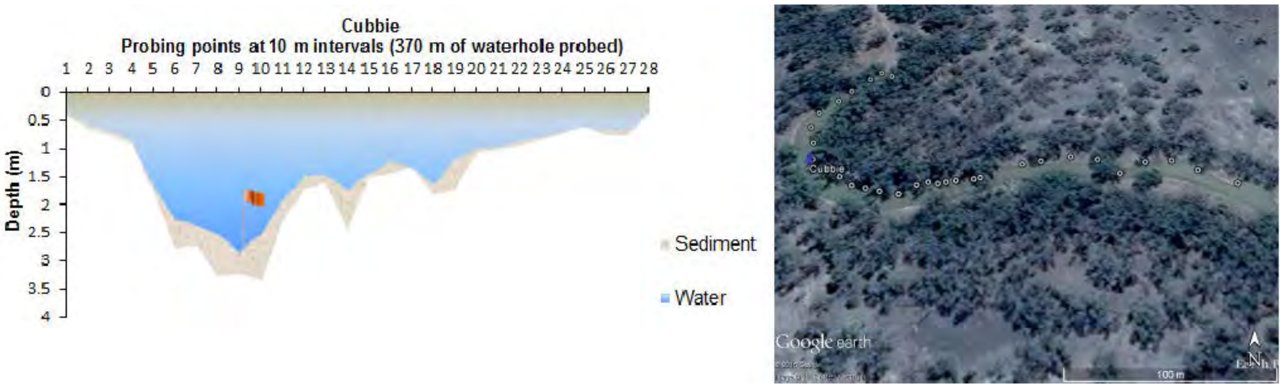

Figure A.1. Sediment depth profile along Cubbie Waterhole. Google Image © 2015 CNES/Astrium.

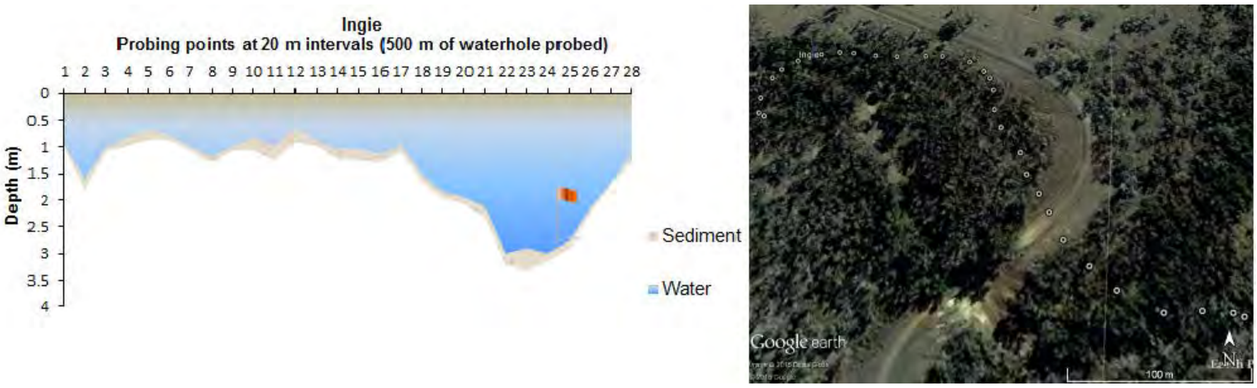

Figure A.2. Sediment depth profile along Ingie Waterhole. Google Image © 2015 DigitalGlobe.

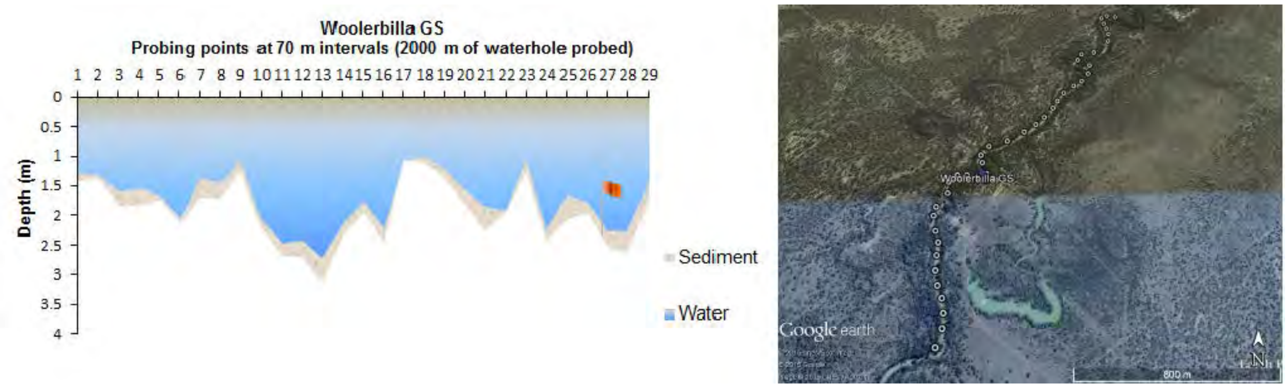

Figure A.3. Sediment depth profile along Woolerbilla Waterhole. Google Image © 2015 CNES/Spot Image.

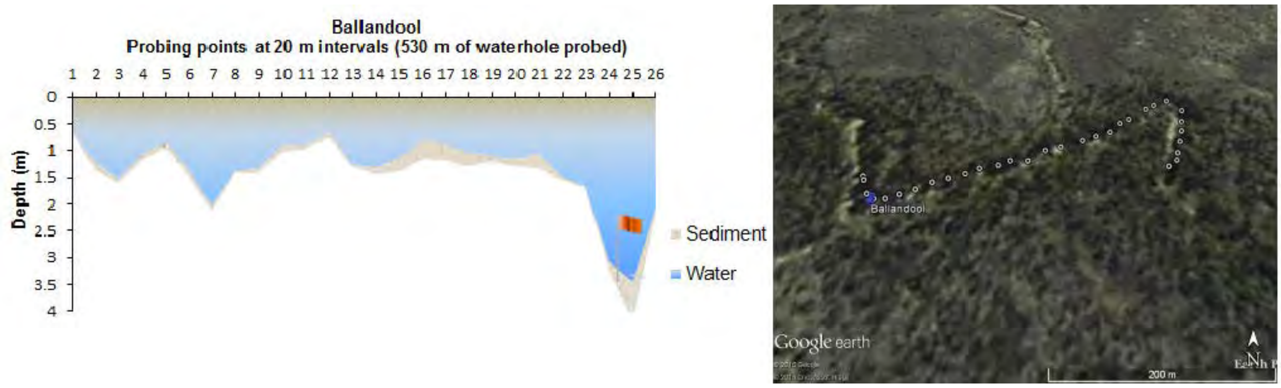

Figure A.4. Sediment depth profile along Ballandool Waterhole. Google Image © 2015 CNES/Spot Image.

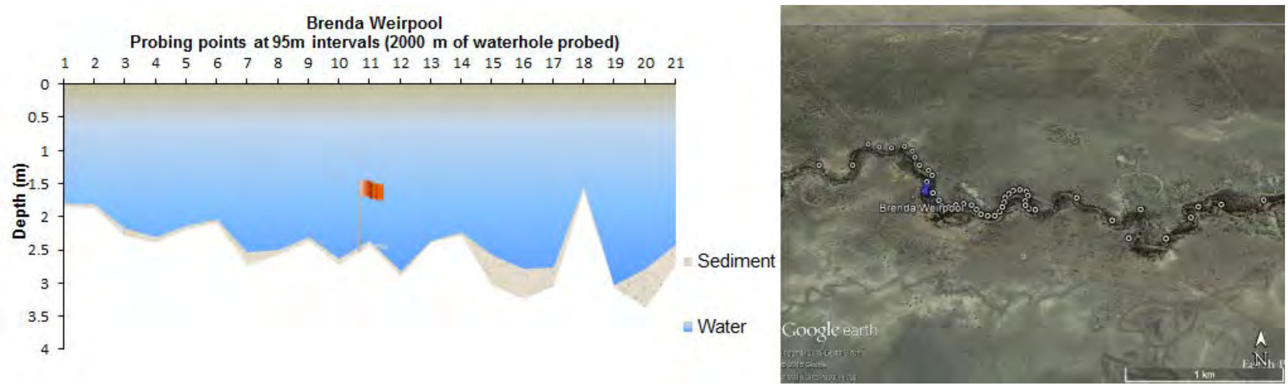

Figure A.5. Sediment depth profile along Brenda Weir Waterhole. Google Image © 2015 DigitalGlobe/CNES/Spot Image.

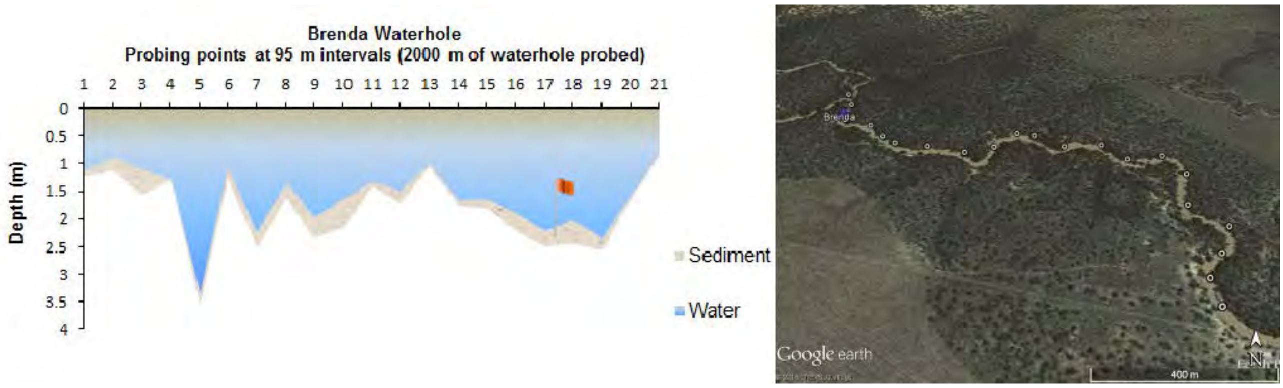

Figure A.6. Sediment depth profile along Brenda Waterhole. Google Image © 2015 CNES/Spot image.

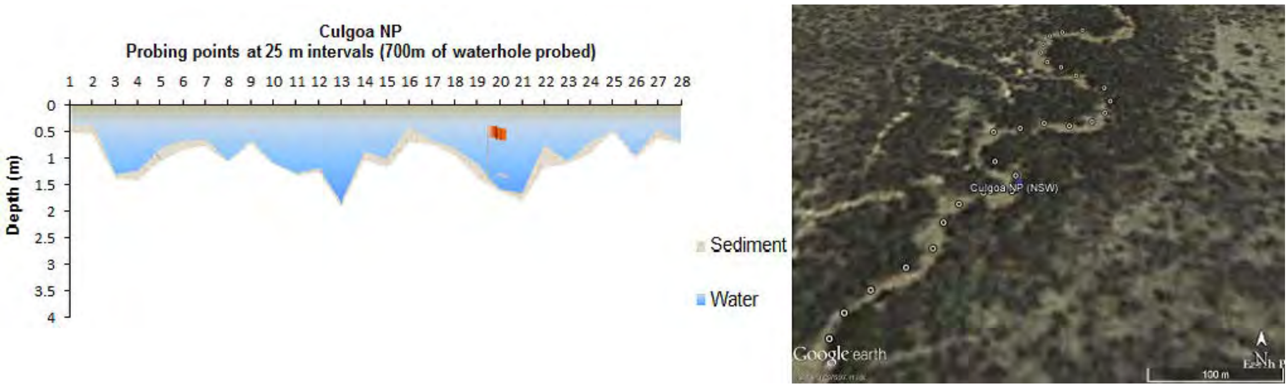

Figure A.7. Sediment depth profile along Culgoa National Park Waterhole. Google Image © 2015 CNES/Spot Image.

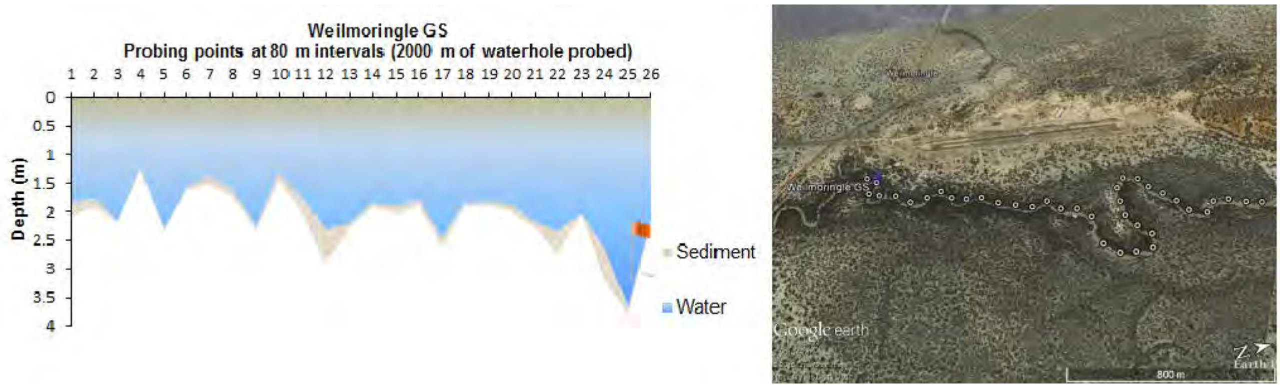

Figure A.8. Sediment depth profile along Weilmoringle GS Waterhole. Google Image © 2015 DigitalGlobe/CNES/Spot Image.

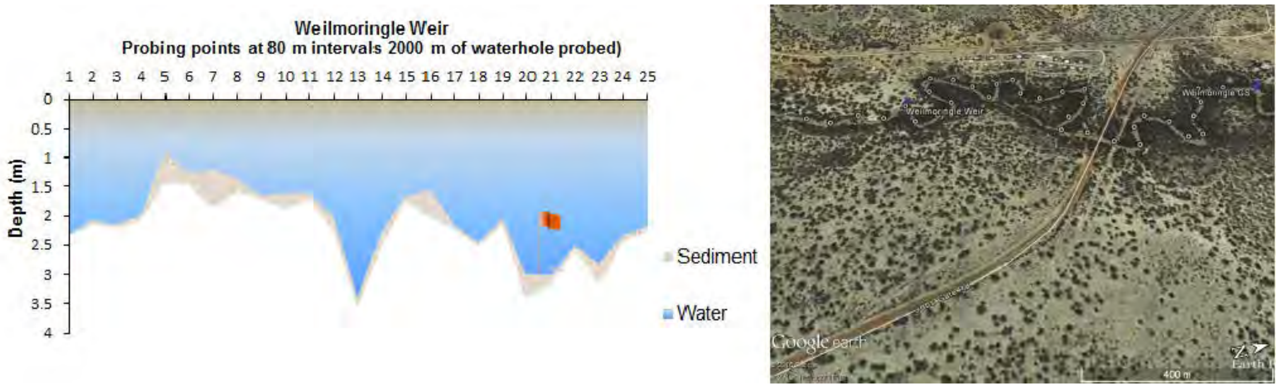

Figure A.9. Sediment depth profile along Weilmoringle Weir Waterhole. Google Image © 2015 CNES/Spot Image.

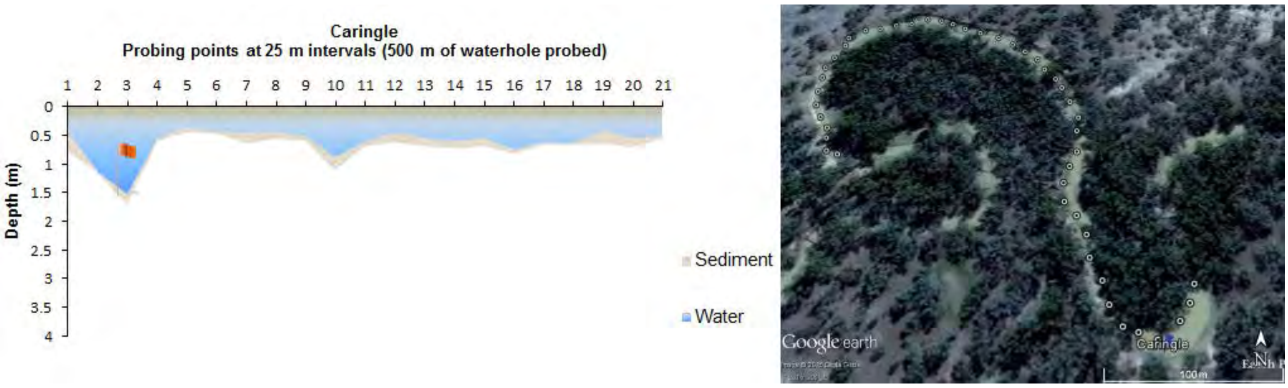

Figure A.10. Sediment depth profile along Caringle Waterhole. Google Image © 2015 DigitalGlobe.

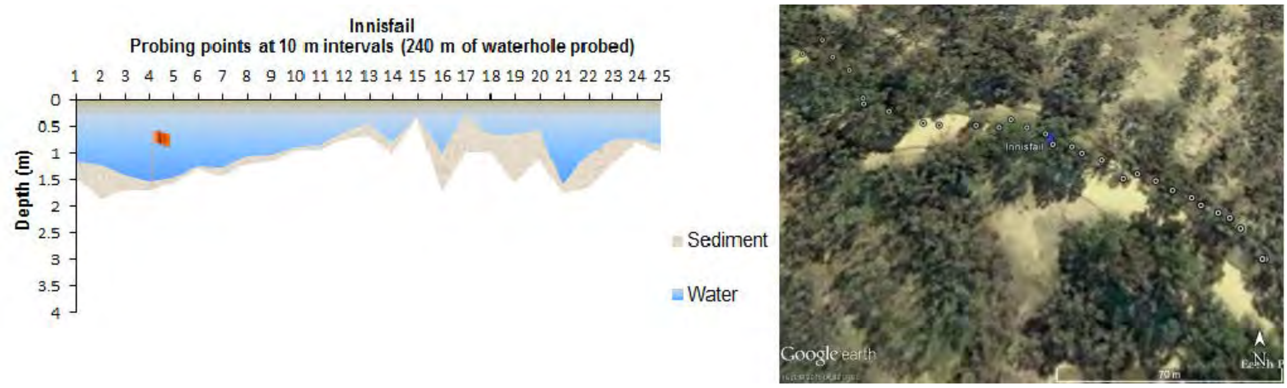

Figure A.11. Sediment depth profile along Innisfail Waterhole. Google Image © 2015 DigitalGlobe.

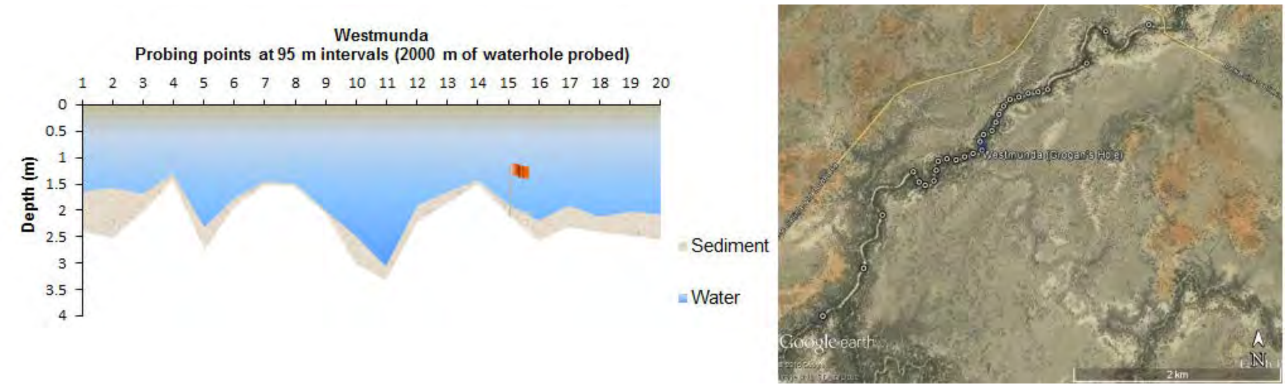

Figure A.12. Sediment depth profile along Westmunda (Grogan's Hole) Waterhole. Google Image © 2015 DigitalGlobe.

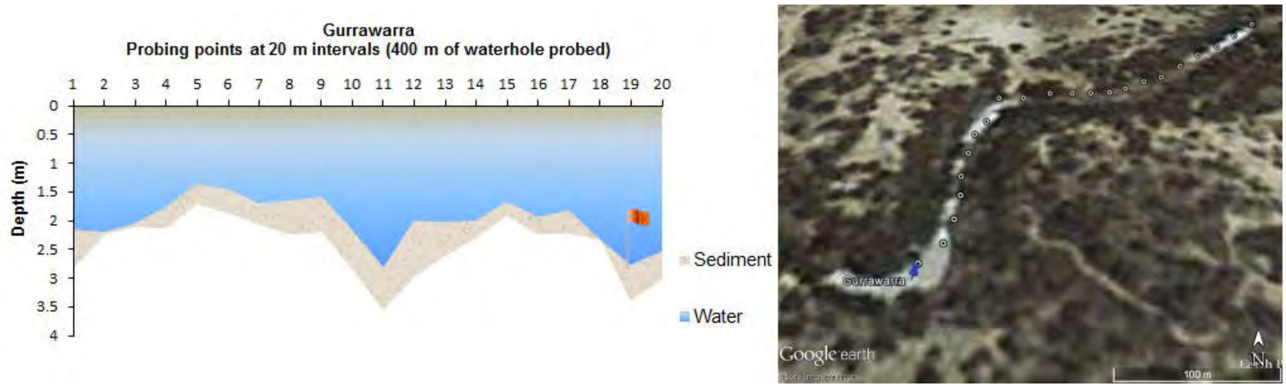

Figure A.13. Sediment depth profile along Gurrawarra Waterhole. Google Image © 2015 CNES/Spot Image.

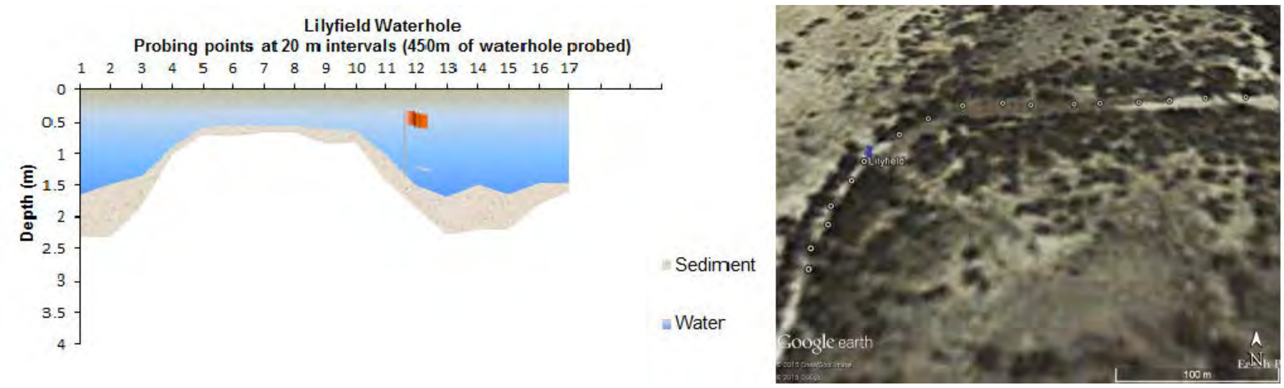

Figure A.14. Sediment depth profile along Lilyfield Waterhole. Google Image © 2015 CNES/Spot Image.

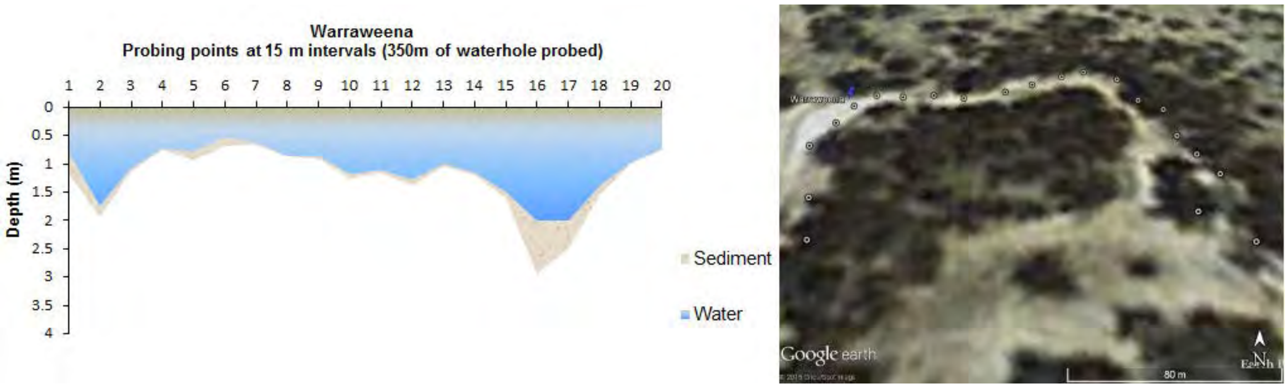

Figure A.15. Sediment depth profile along Warraweena Waterhole. Google Image © 2015 CNES/Spot Image.

Depth profiles - Narran River

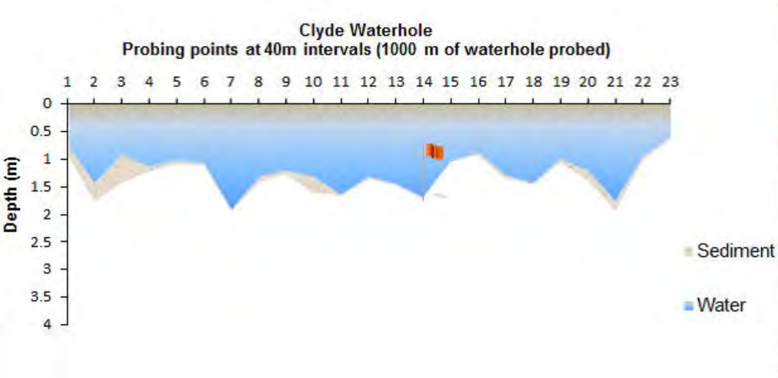

Figure A.16. Sediment depth profile along Clyde Waterhole. Google Image © 2015 DigitalGlobe.

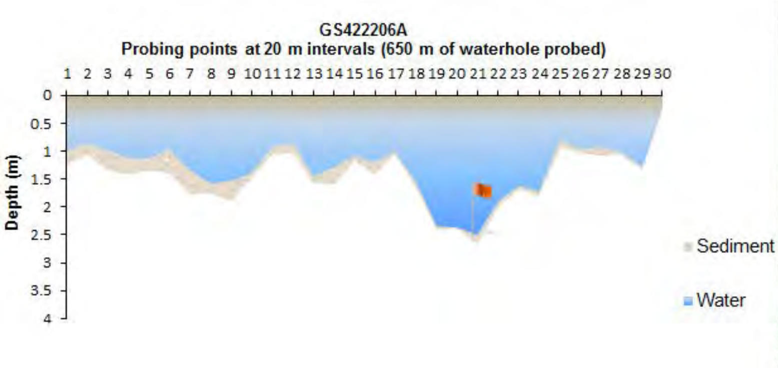

Figure A.17. Sediment depth profile along GS422206A Waterhole. Google Image © 2015 DigitalGlobe.

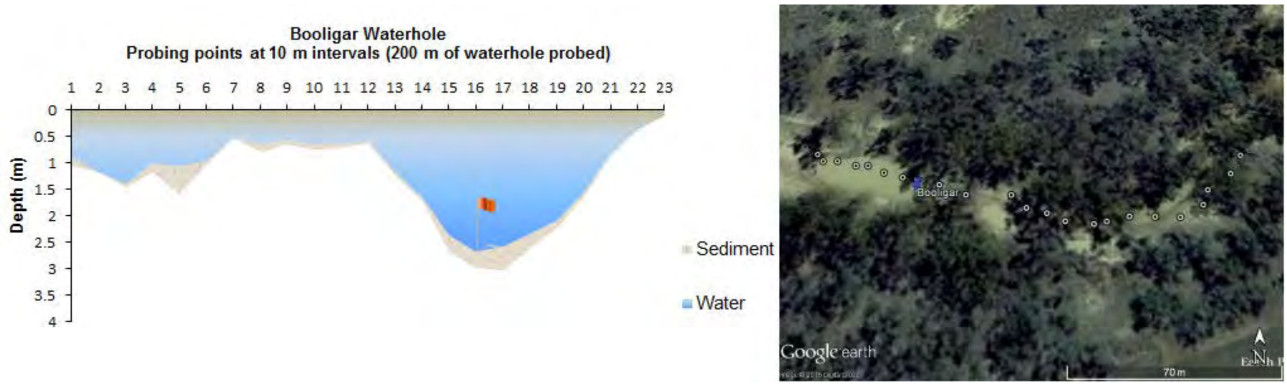

Figure A.18. Sediment depth profile along Booligar Waterhole. Google Image © 2015 DigitalGlobe.

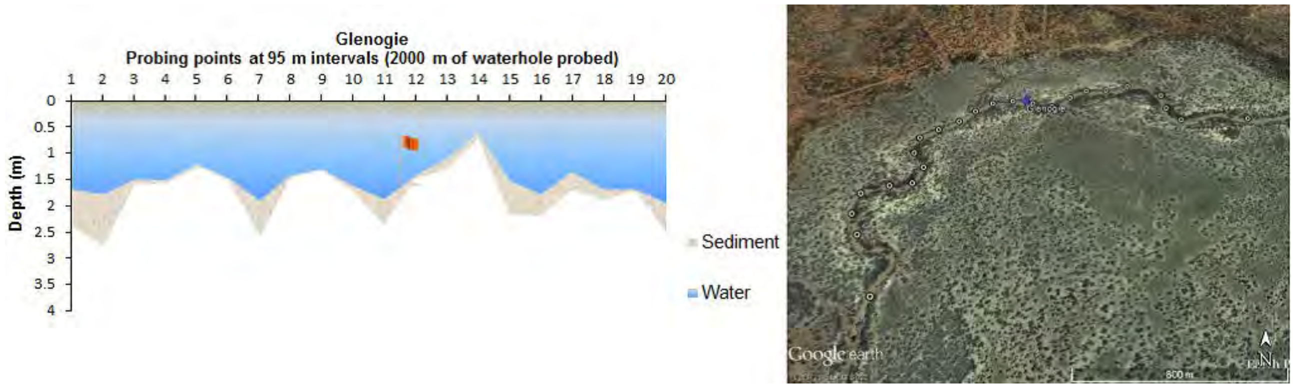

Figure A.19. Sediment depth profile along Glenogie Waterhole. Google Image © 2015 DigitalGlobe.

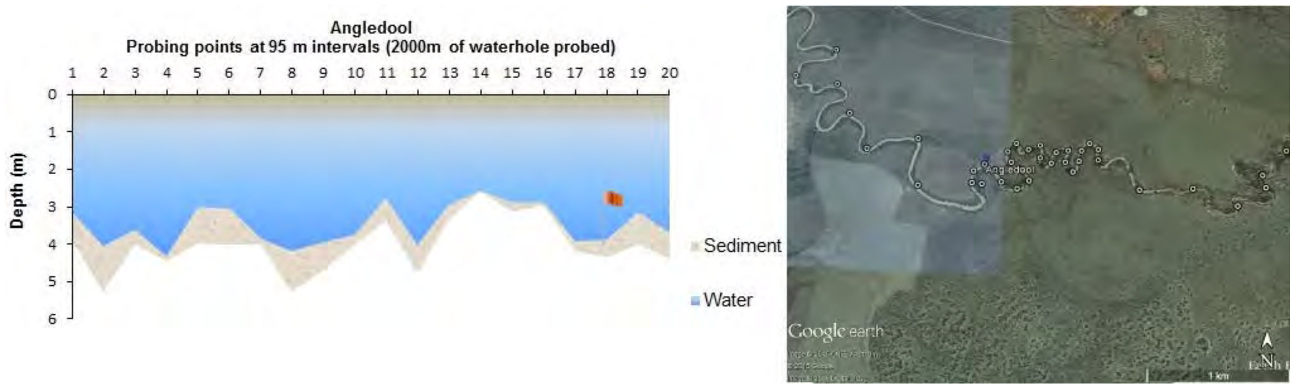

Figure A.20. Sediment depth profile along Angledool Waterhole. Google Image © 2015 DigitalGlobe/CNES/Astrium.

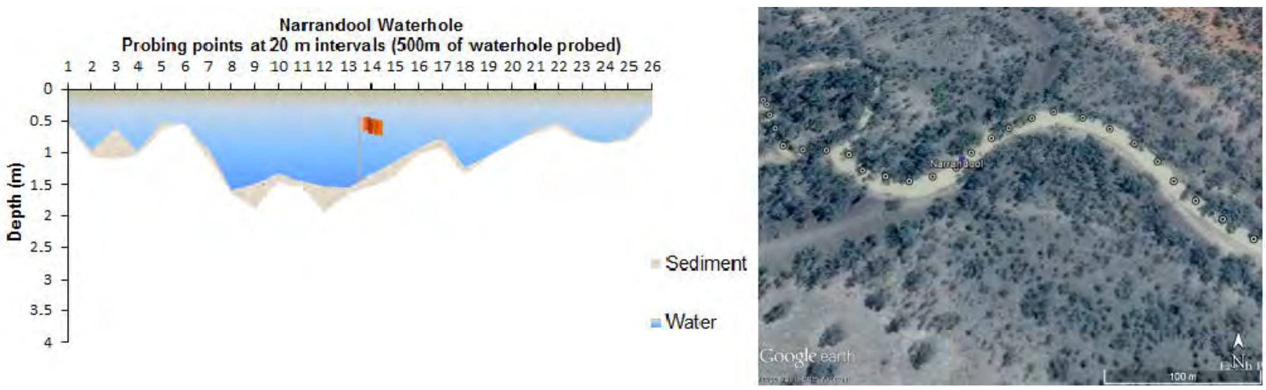

Figure A.21. Sediment depth profile along Narrandool Waterhole. Google Image © 2015 CNES/Astrium.

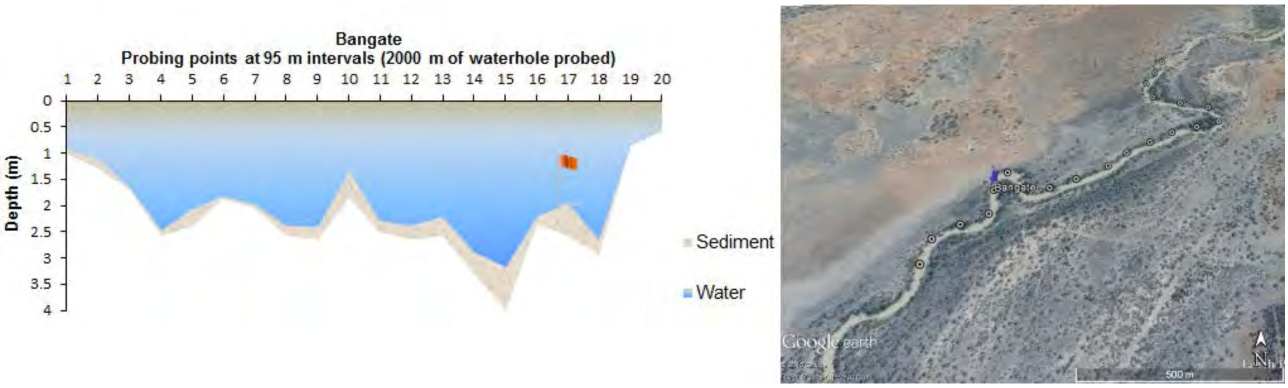

Figure A.22. Sediment depth profile along Bangate (Sorrento Hole) Waterhole. Google Image © 2015 CNES/Astrium.

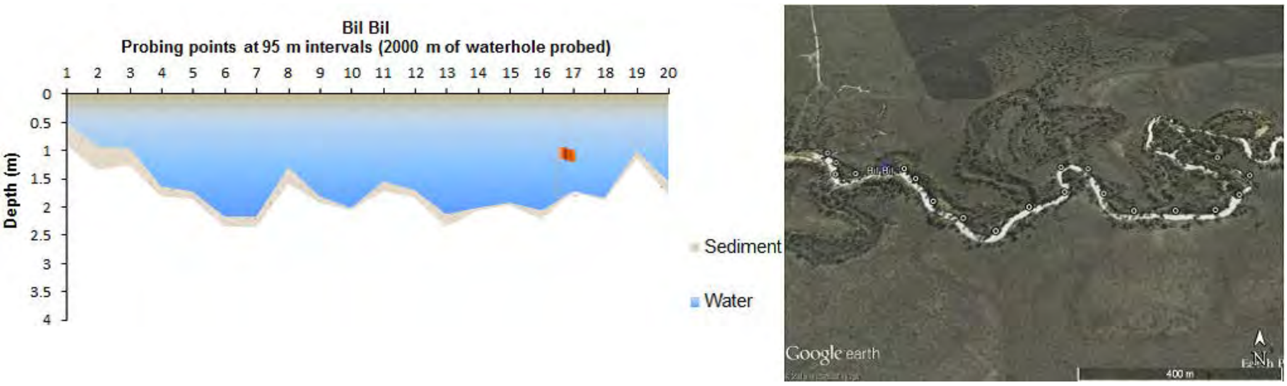

Figure A.23. Sediment depth profile along Bil Bil Waterhole. Google Image © 2015 CNES/Spot Image.

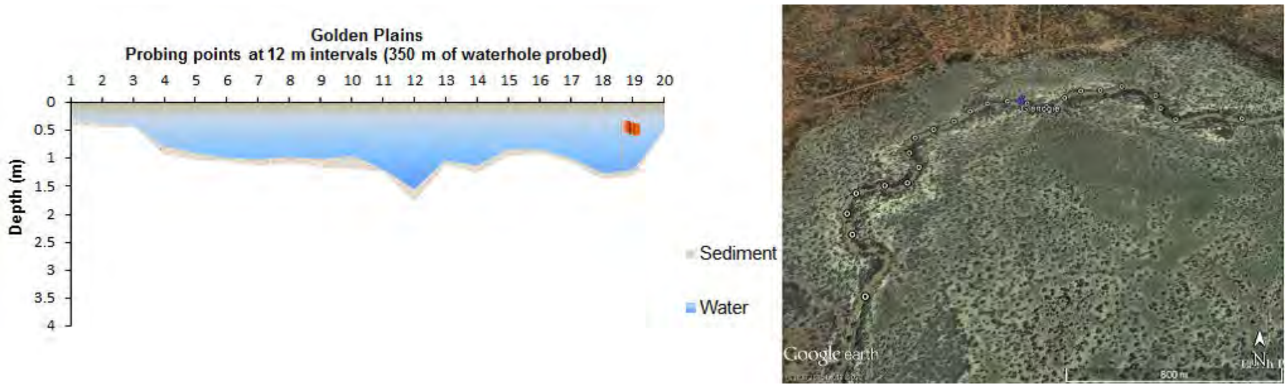

Figure A.24. Sediment depth profile along Golden Plains Waterhole. Google Image © 2015 CNES/Spot Image.

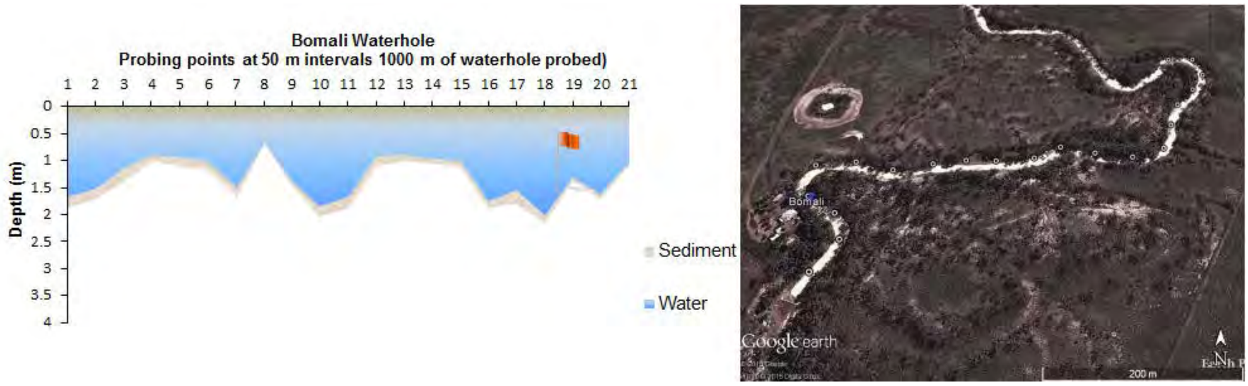

Figure A.25. Sediment depth profile along Bomali Waterhole. Google Image © 2015 DigitalGlobe.

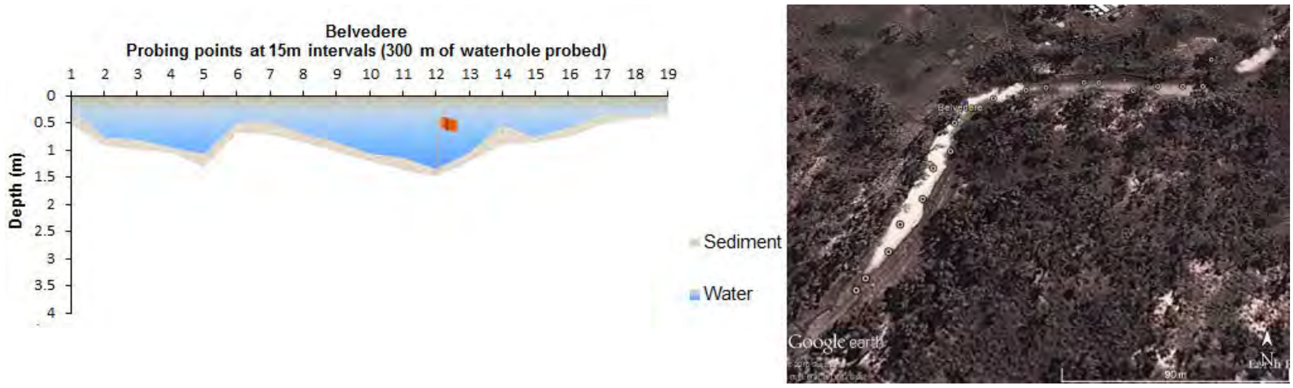

Figure A.26. Sediment depth profile along Belvedere Waterhole. Google Image © 2015 DigitalGlobe.

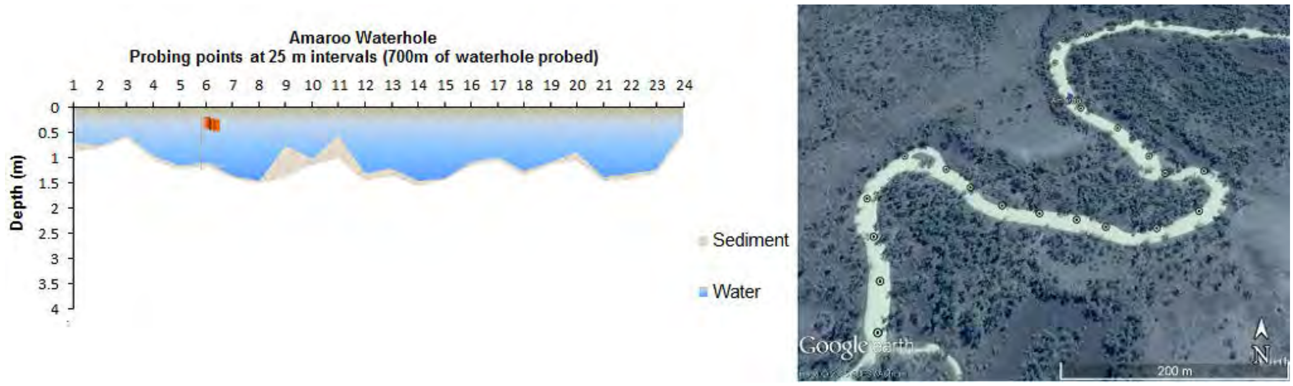

Figure A.27. Sediment depth profile along Amaroo Waterhole. Google Image © 2015 CNES/Astrium.

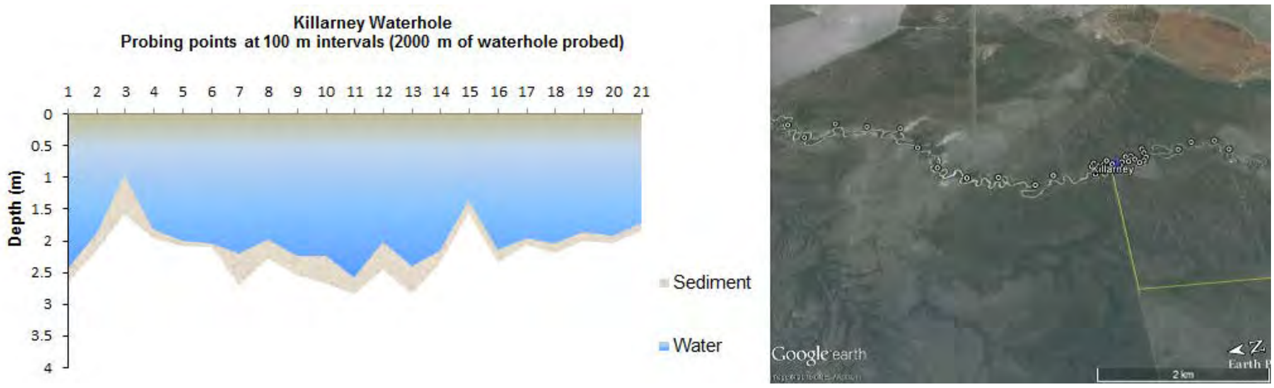

Figure A.28. Sediment depth profile along Killarney Waterhole. Google Image © 2015 CNES/Astrium.

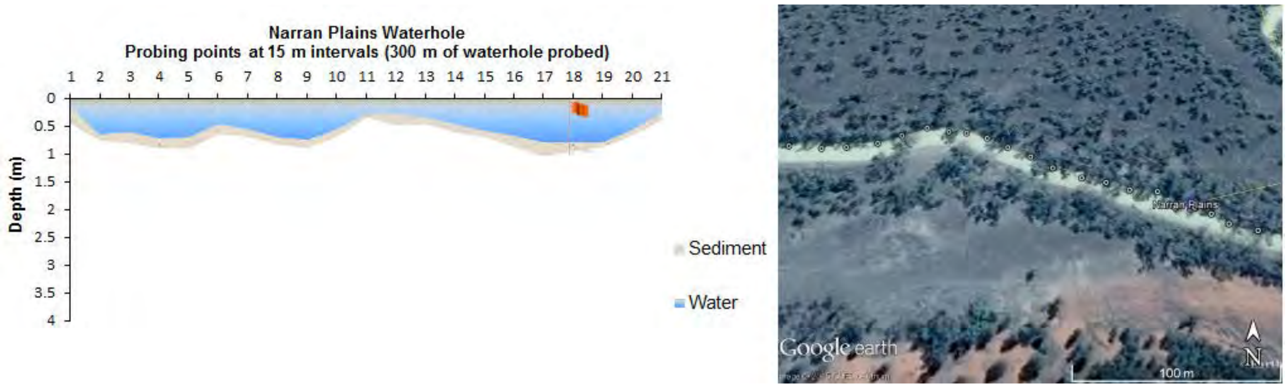

Figure A.29. Sediment depth profile along Narran Plains Waterhole. Google Image © 2015 CNES/Astrium.

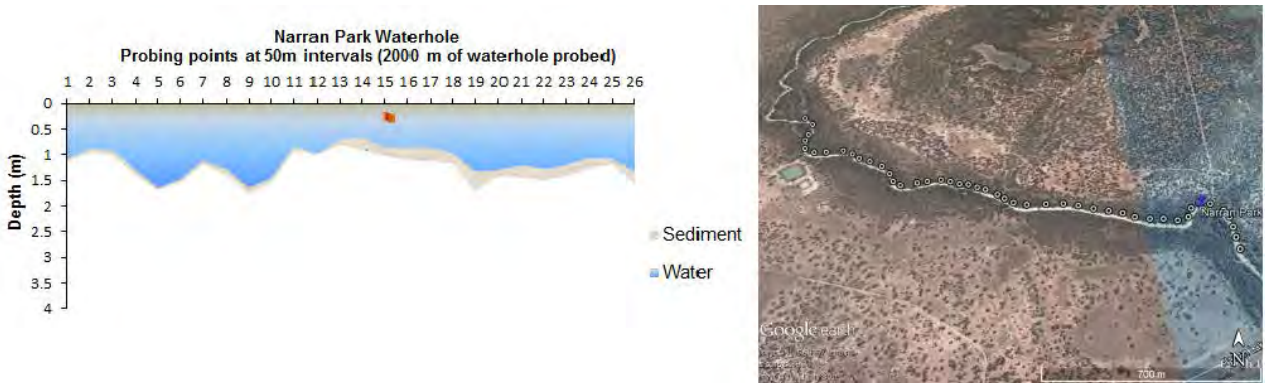

Figure A.30. Sediment depth profile along Narran Park Waterhole. Google Image © 2015 DigitalGlobe/CNES/Astrium.

Depth profiles - Barwon–Darling River

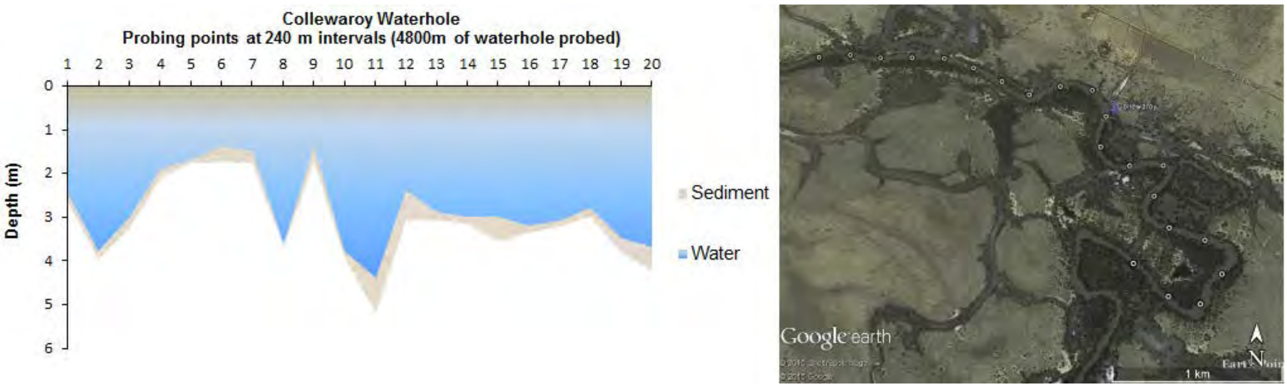

Figure A.31. Sediment depth profile along Collewaroy Waterhole. Google Image © 2015 CNES/Spot Image.

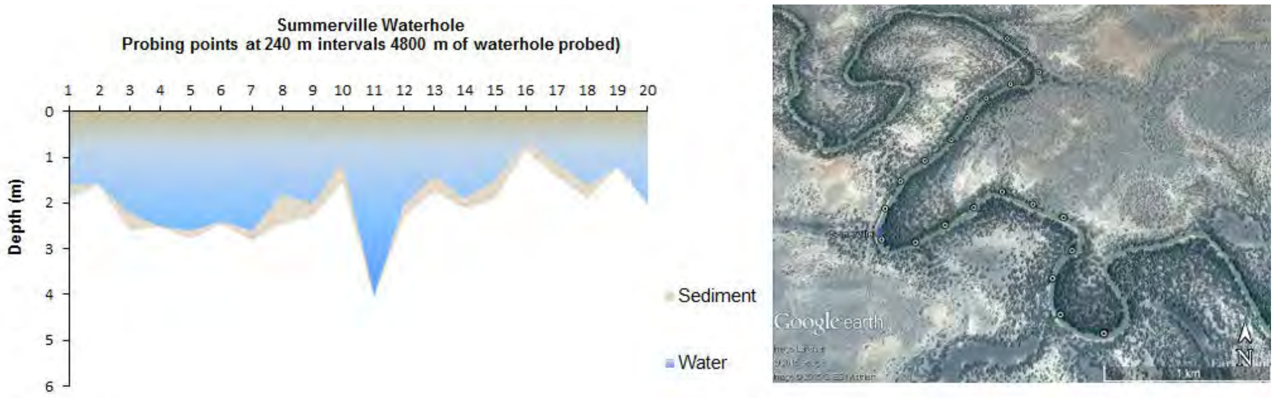

Figure A.32. Sediment depth profile along Summerville Waterhole. Google Image © 2015 Landsat/CNES/Astrium.

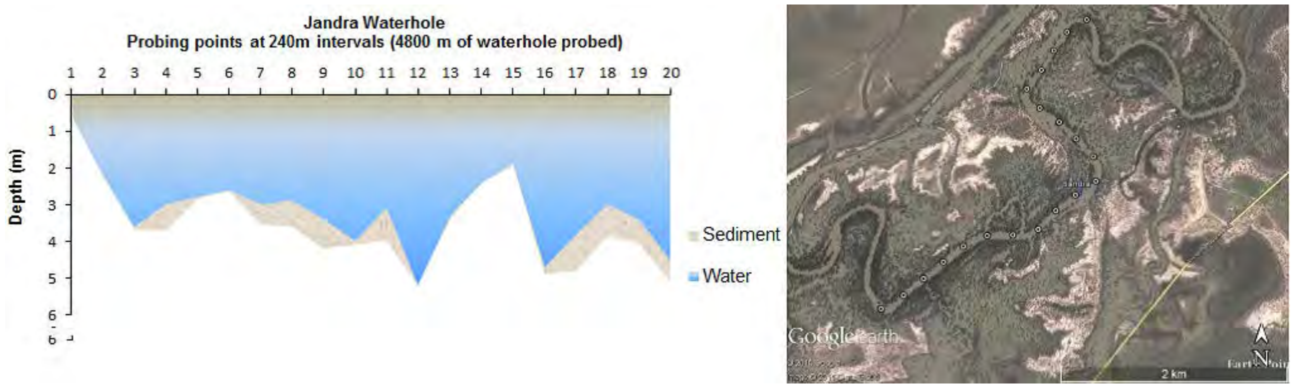

Figure A.33. Sediment depth profile along Jandra Waterhole. Google Image © 2015 DigitalGlobe.

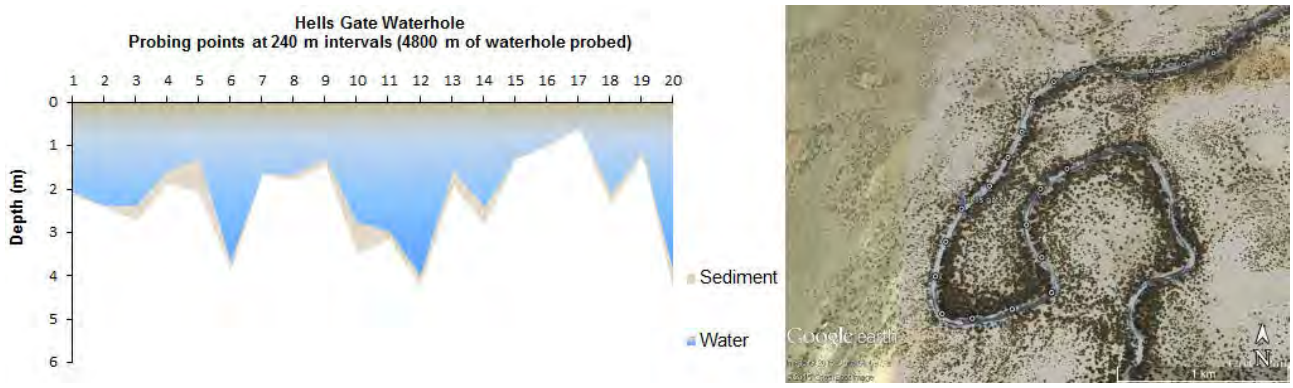

Figure A.34. Sediment depth profile along Hell's Gate Waterhole. Google Image © 2015 DigitalGlobe/CNES/Spot Image.

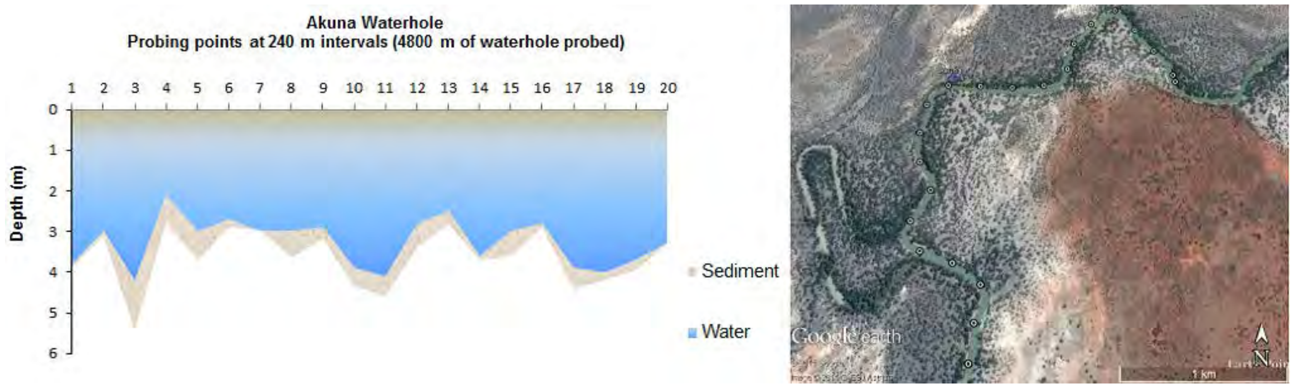

Figure A.35. Sediment depth profile along Akuna Waterhole. Google Image © 2015 CNES/Astrium.

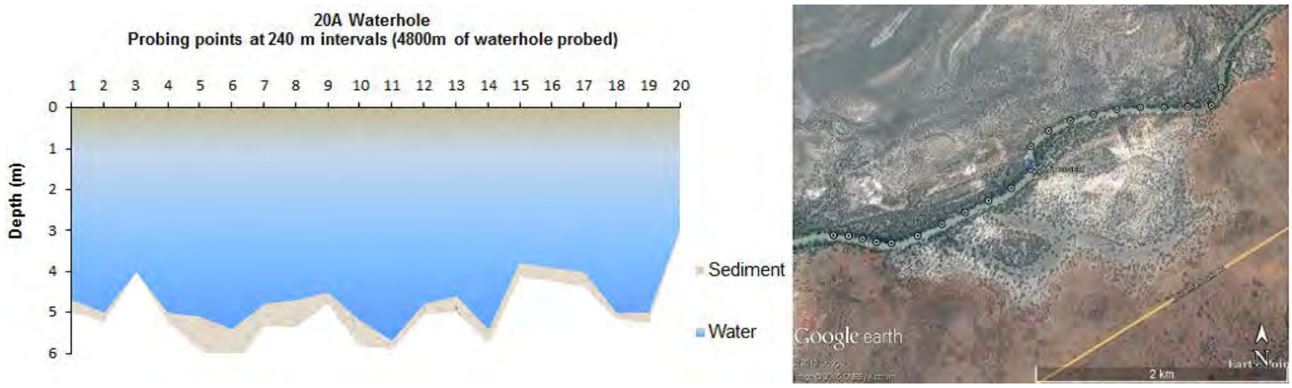

Figure A.36. Sediment depth profile along 20A Waterhole. Google Image © 2015 CNES/Astrium.

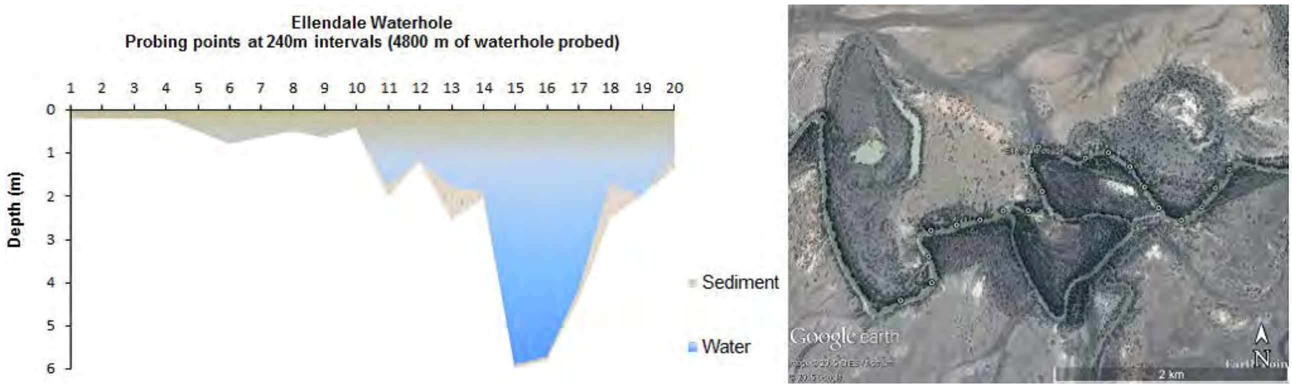

Figure A.37. Sediment depth profile along Ellendale Waterhole. Google Image © 2015 CNES/Astrium.

Appendix B – Waterhole Maps

Lower Balonne

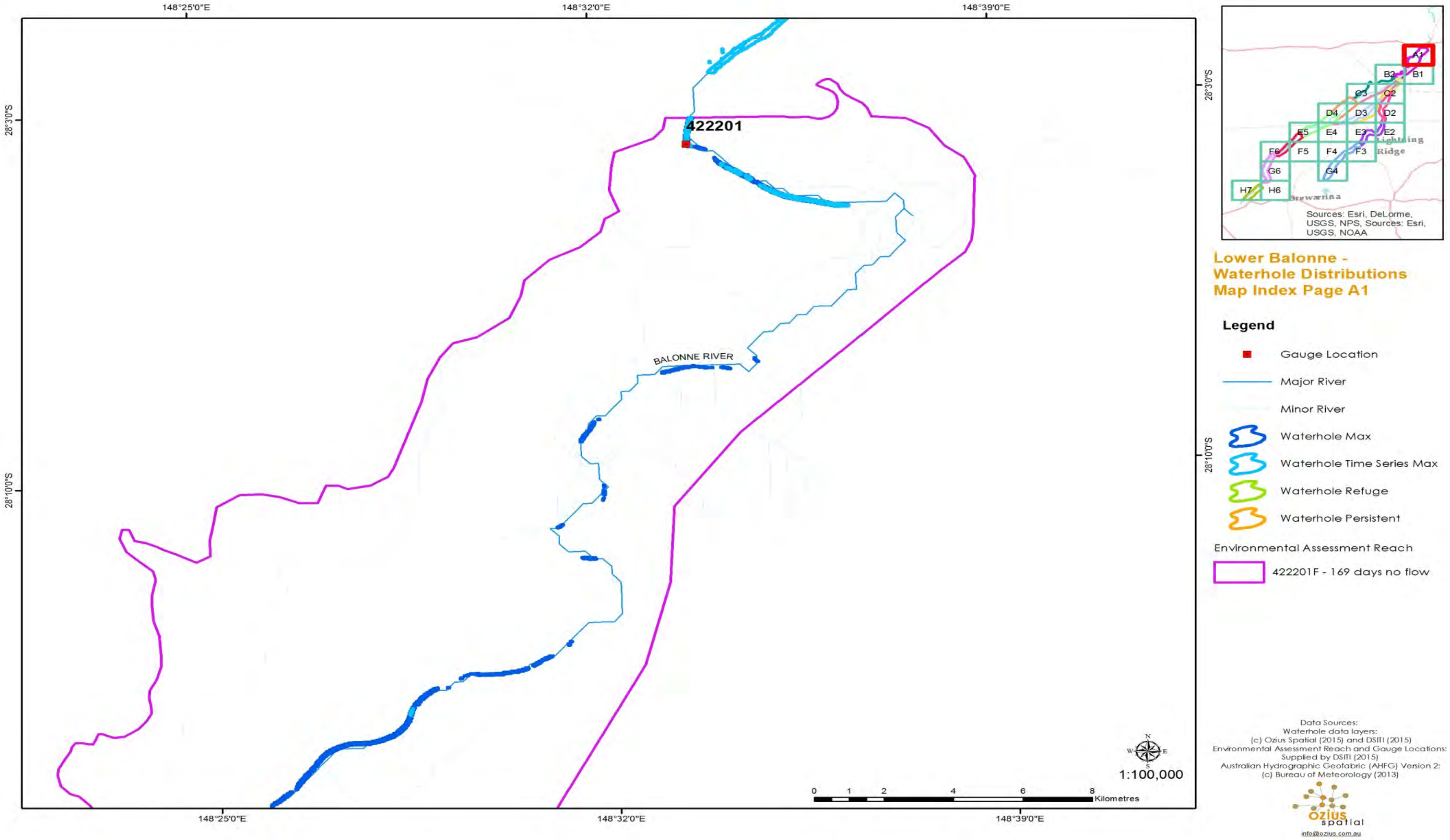

Figure B.1. Waterhole Distributions in Lower Balonne Page A1

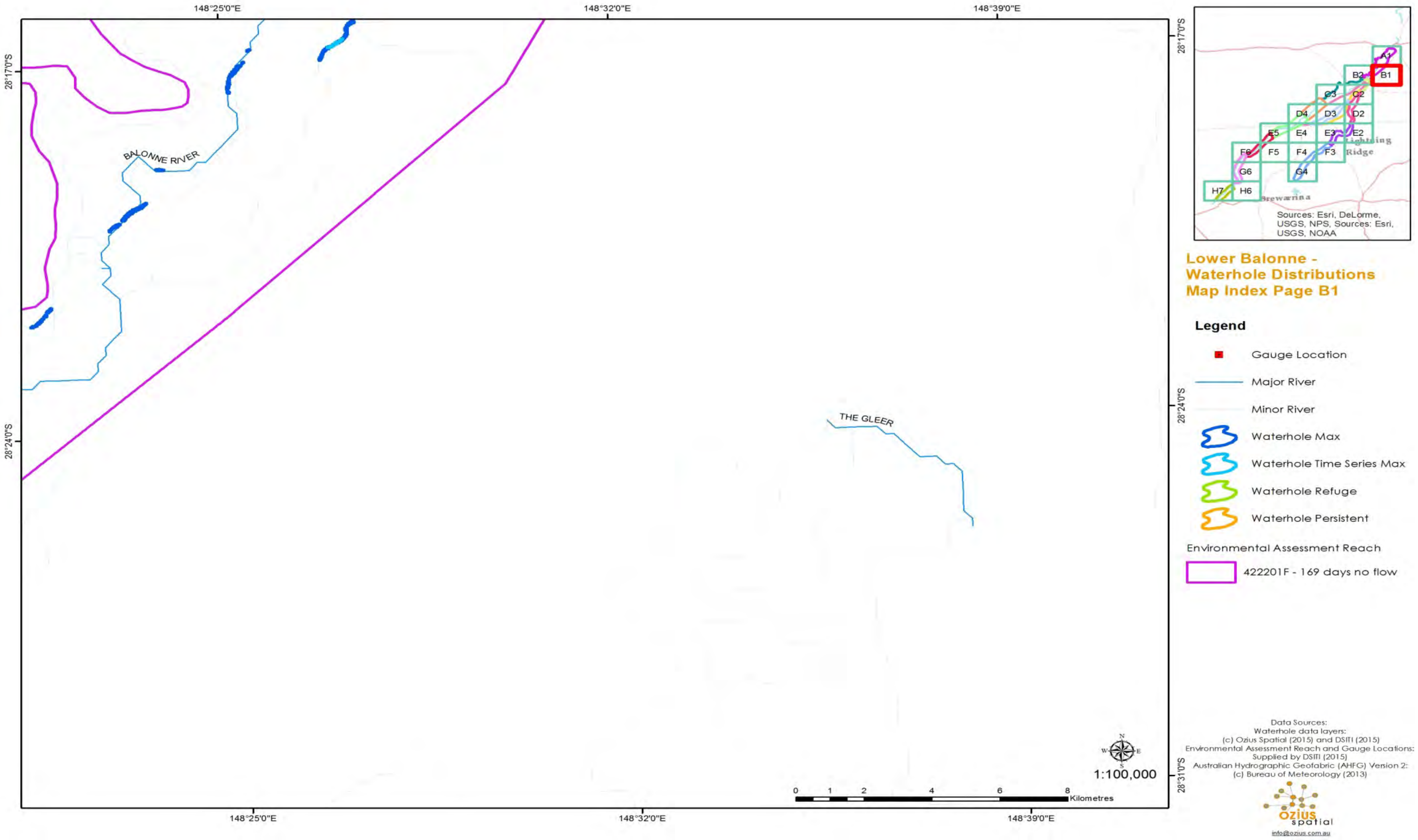

Figure B.2. Waterhole Distributions in Lower Balonne Page B1

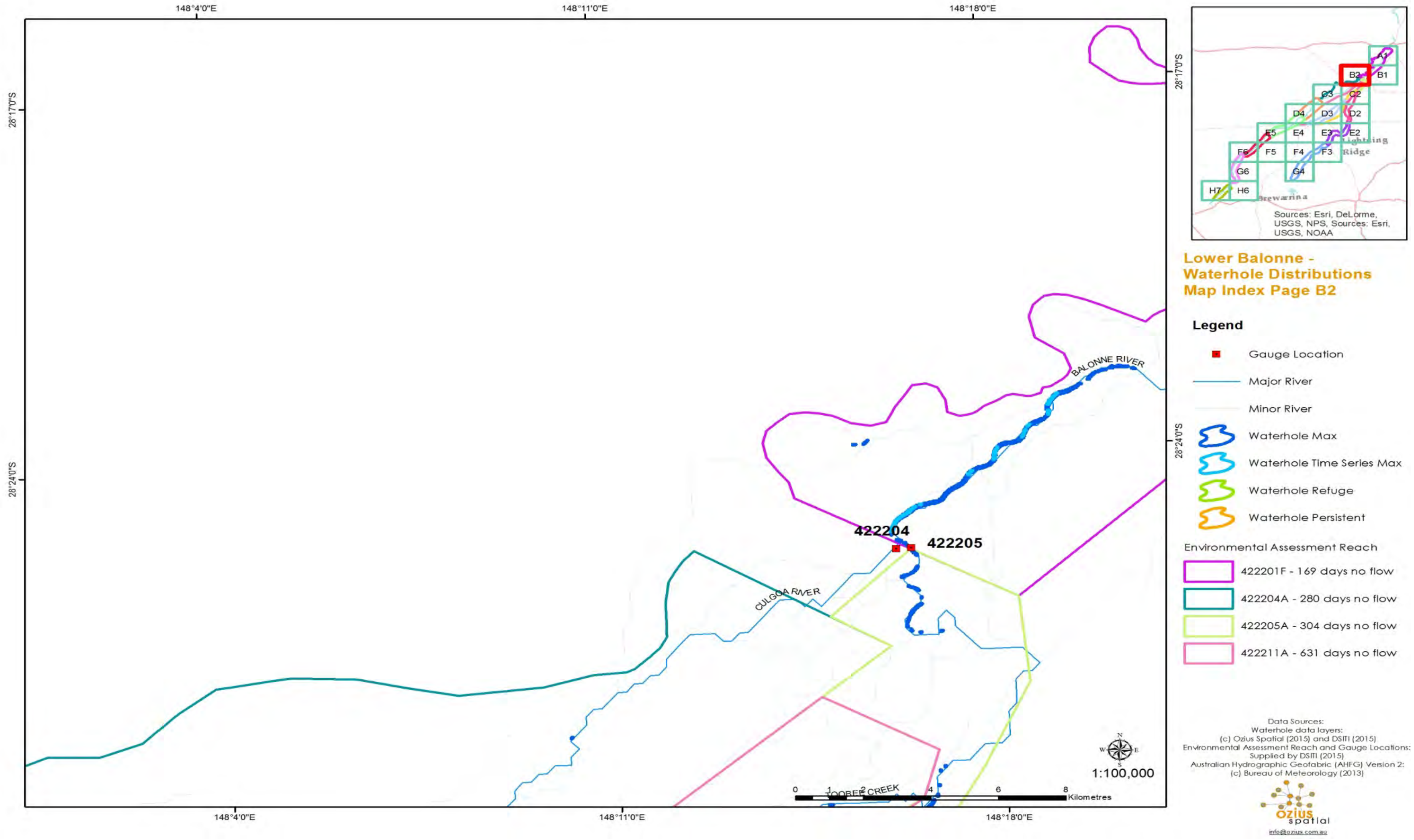

Figure B.3. Waterhole Distributions in Lower Balonne Page B2

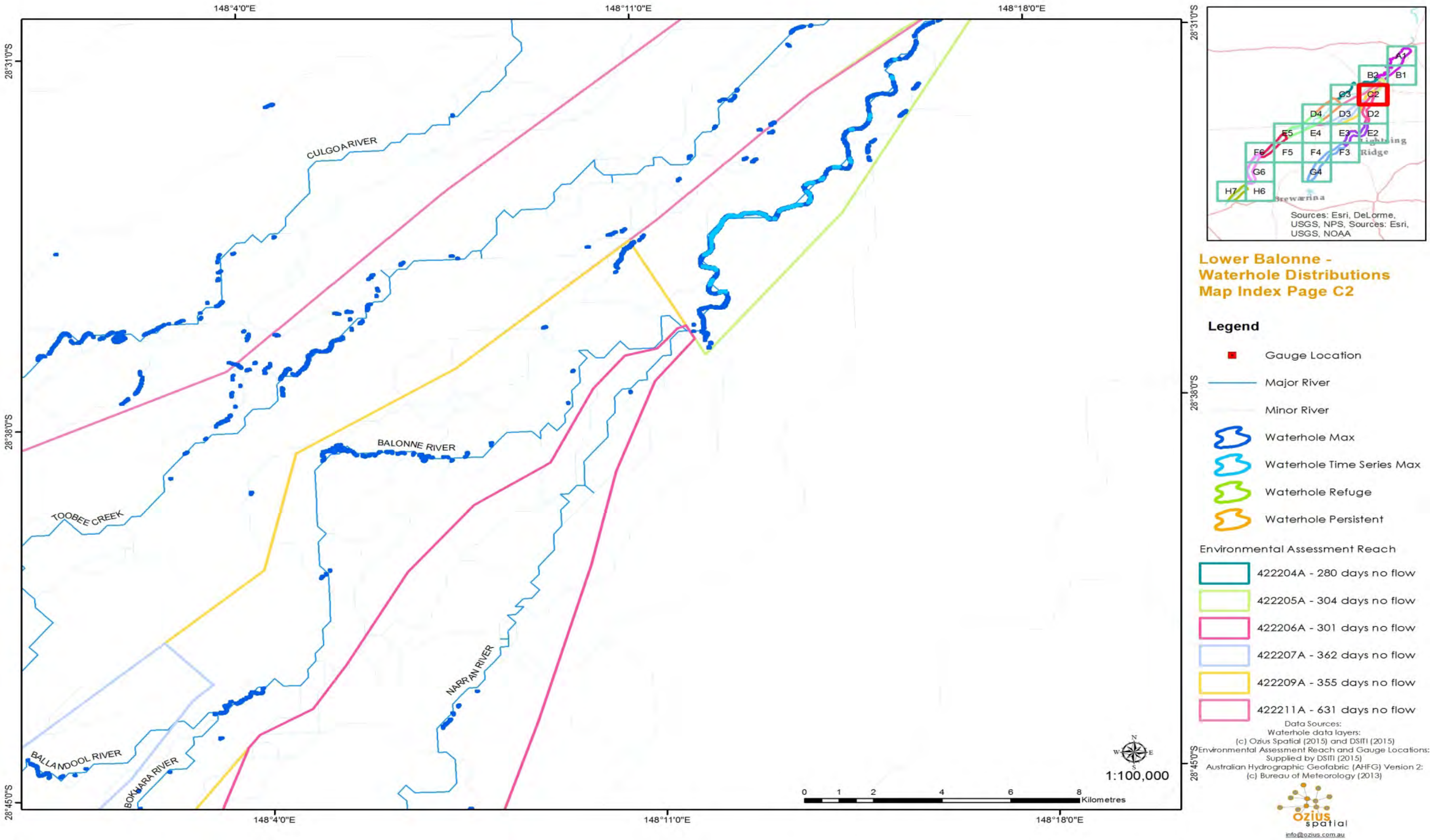

Figure B.4. Waterhole Distributions in Lower Balonne Page C2

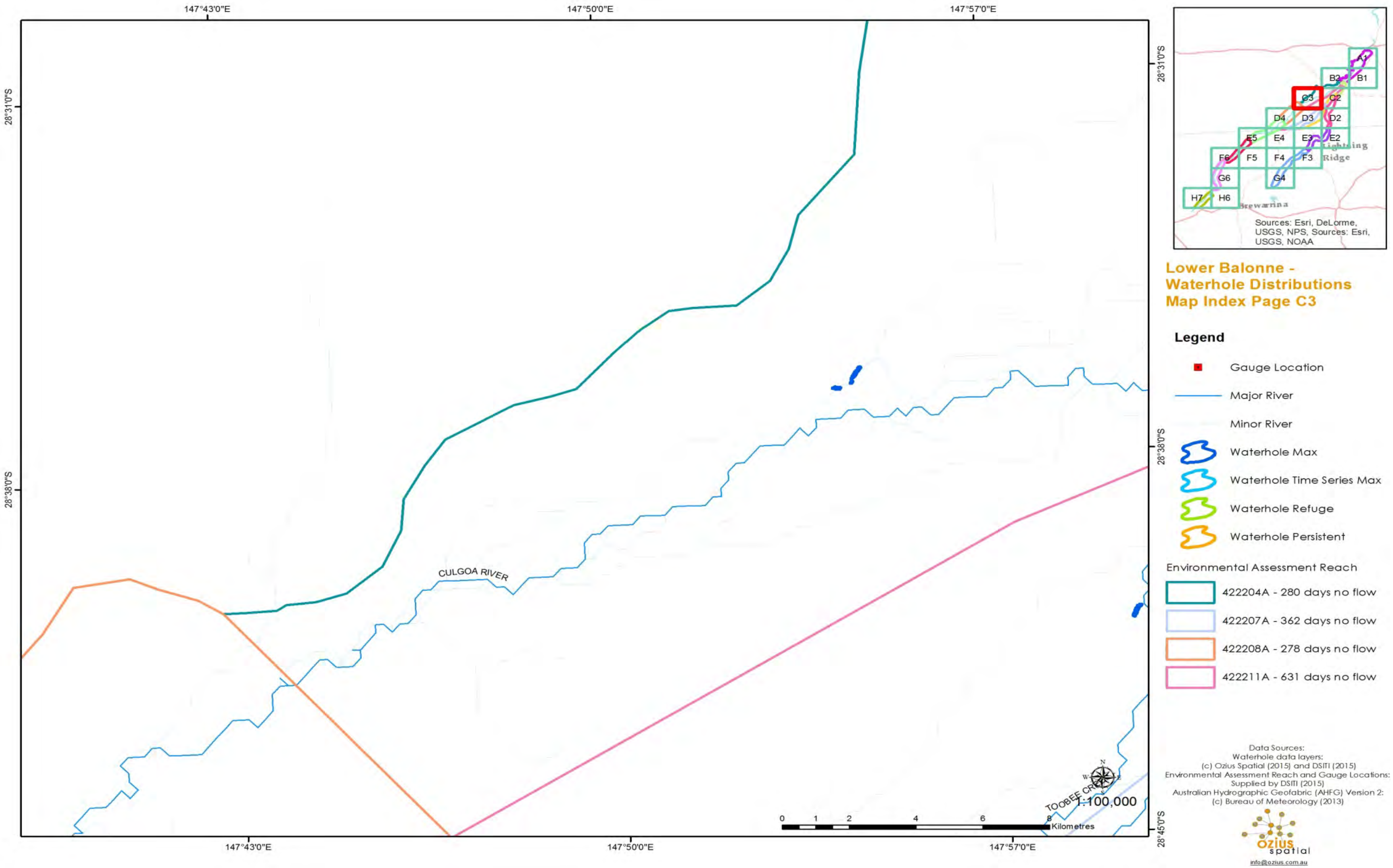

Figure B.5. Waterhole Distributions in Lower Balonne Page C3

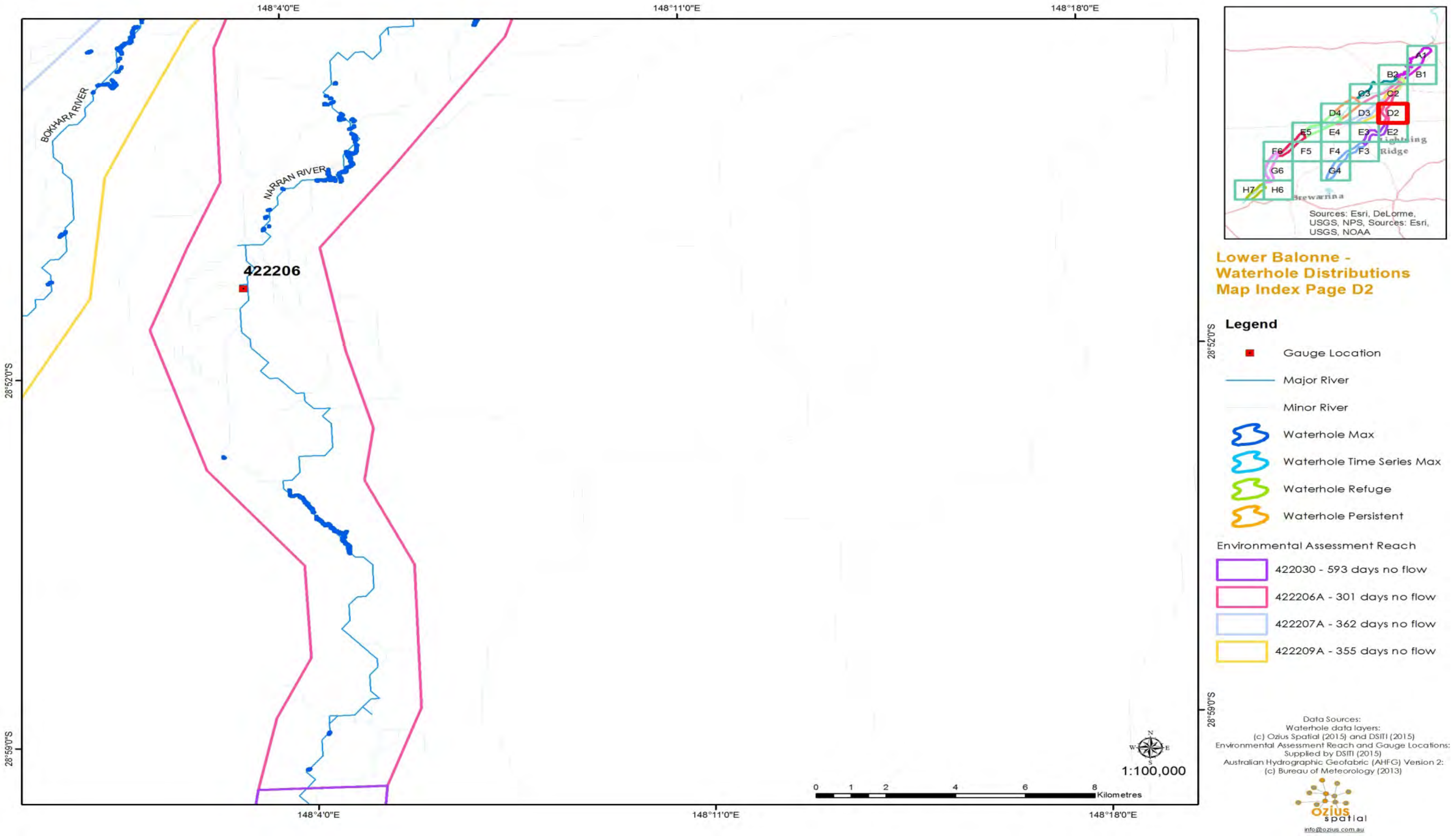

Figure B.6. Waterhole Distributions in Lower Balonne Page D2

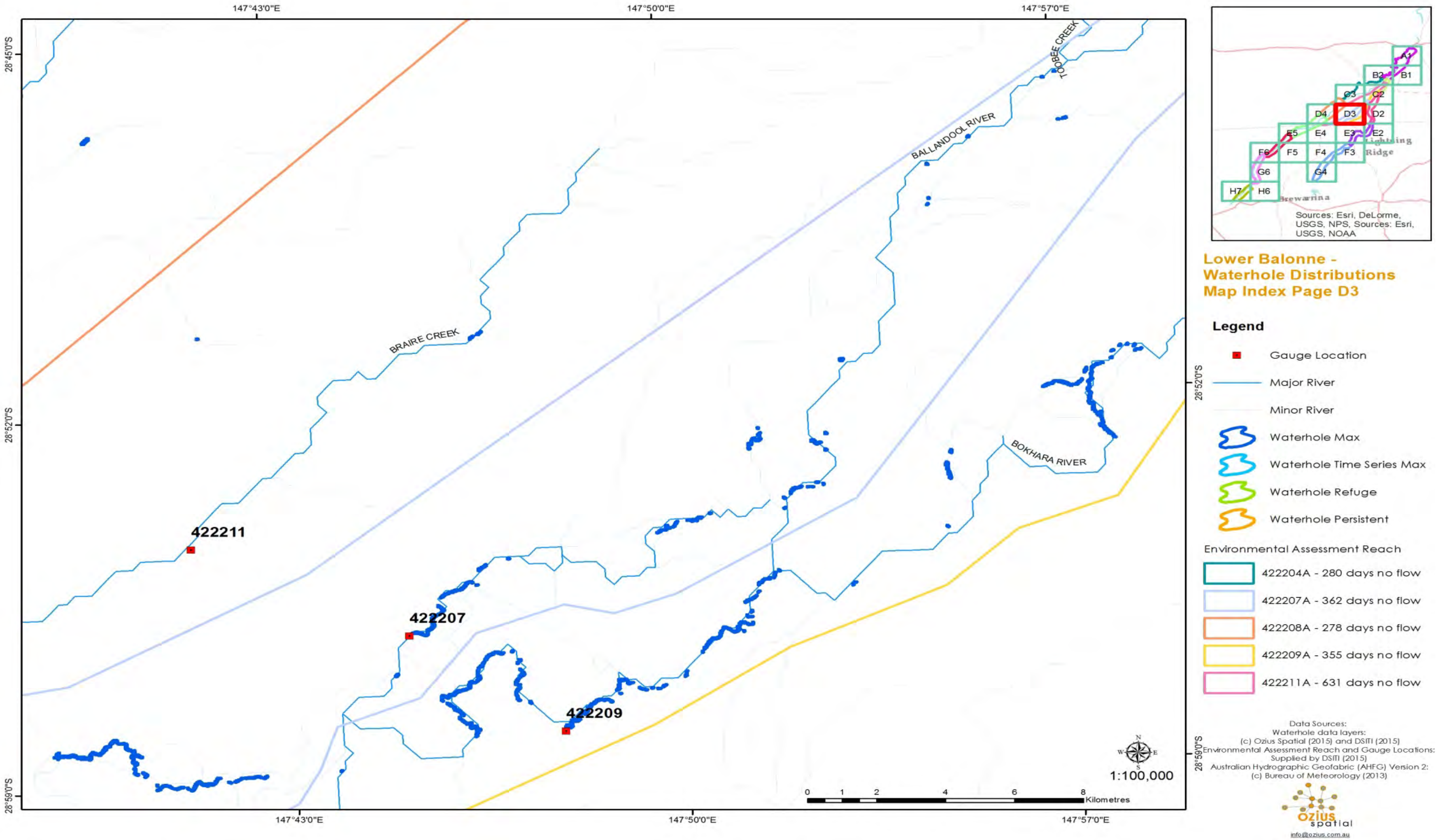

Figure B.7. Waterhole Distributions in Lower Balonne Page D3

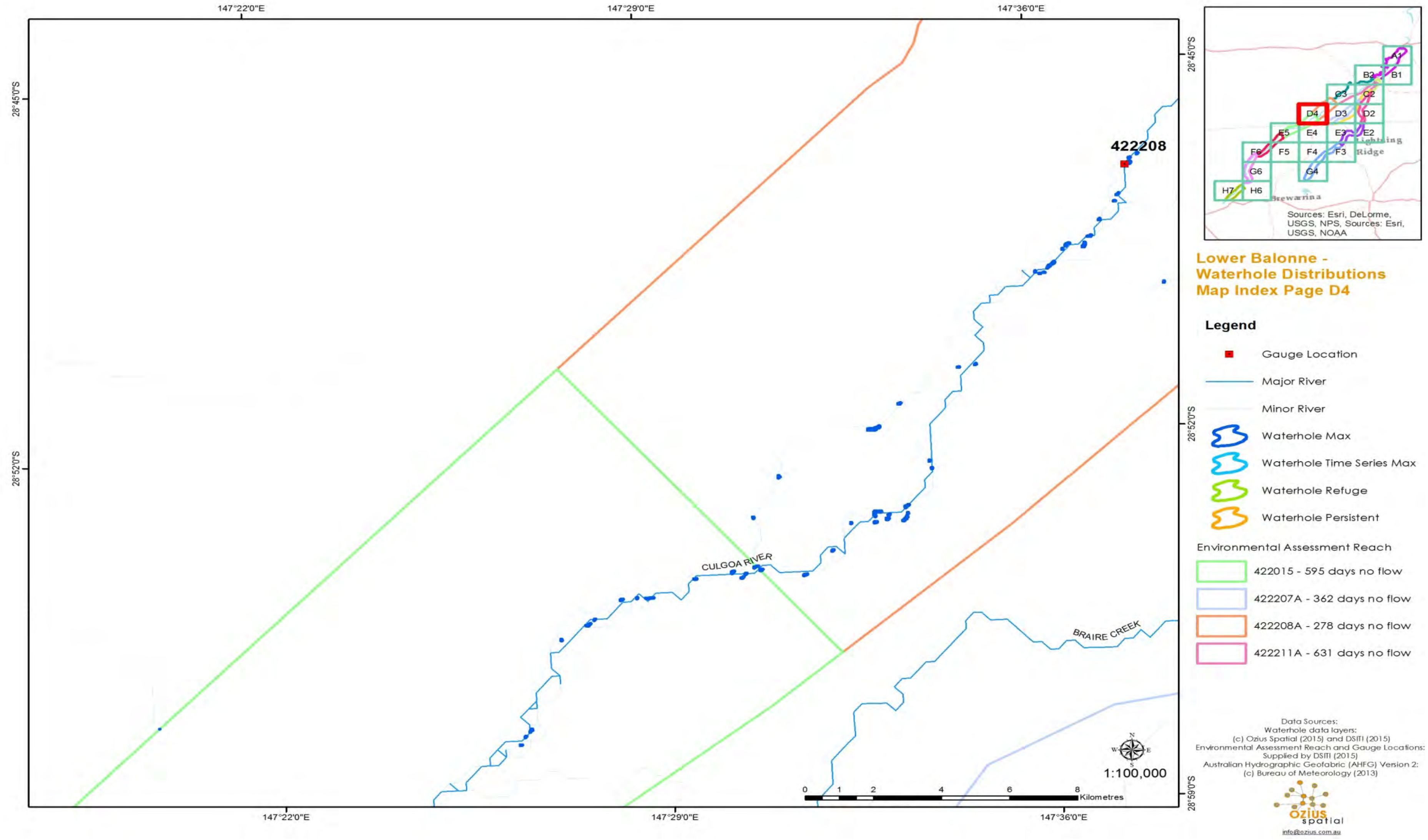

Figure B.8. Waterhole Distributions in Lower Balonne Page D4

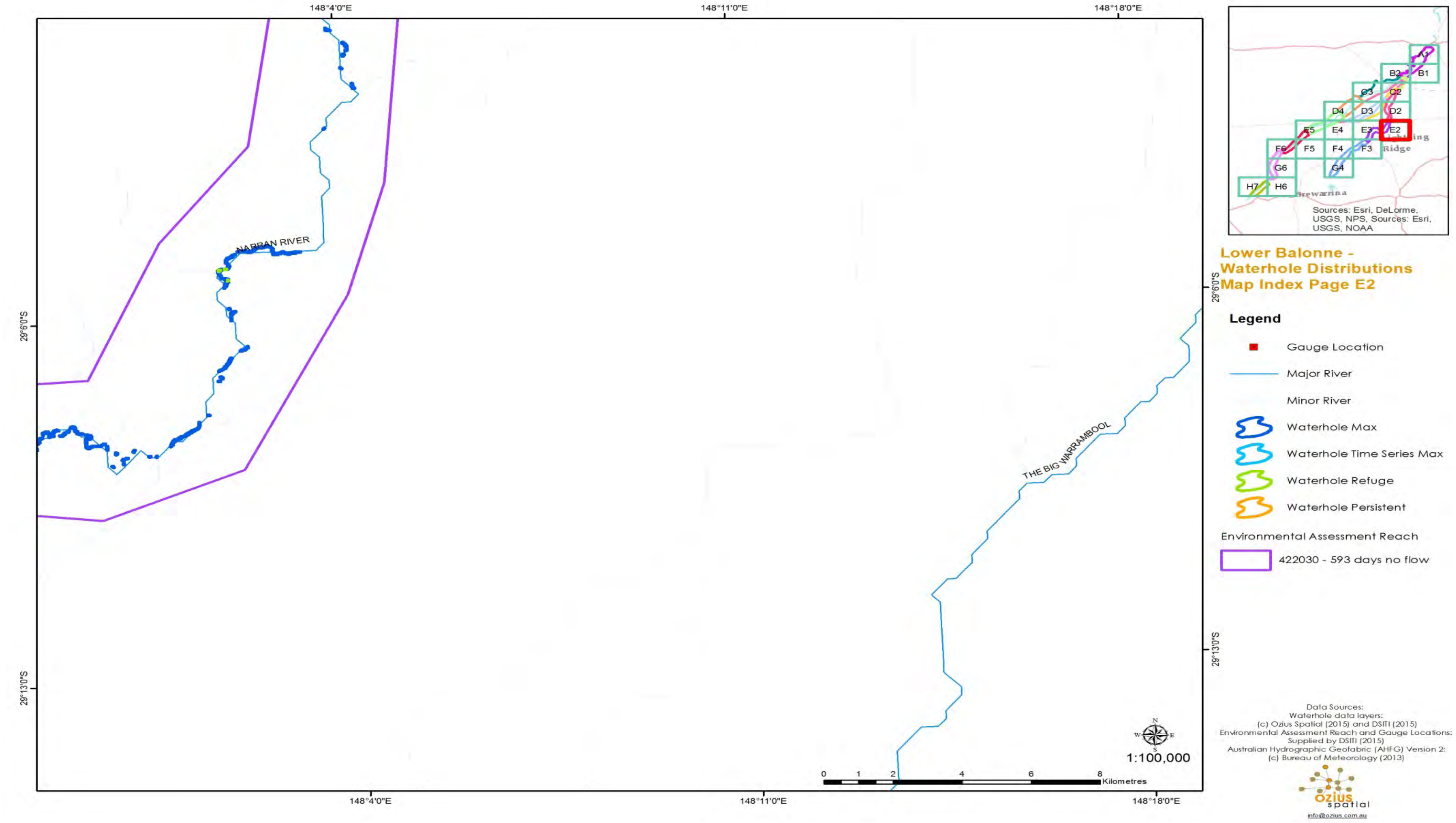

Figure B.9. Waterhole Distributions in Lower Balonne Page E2

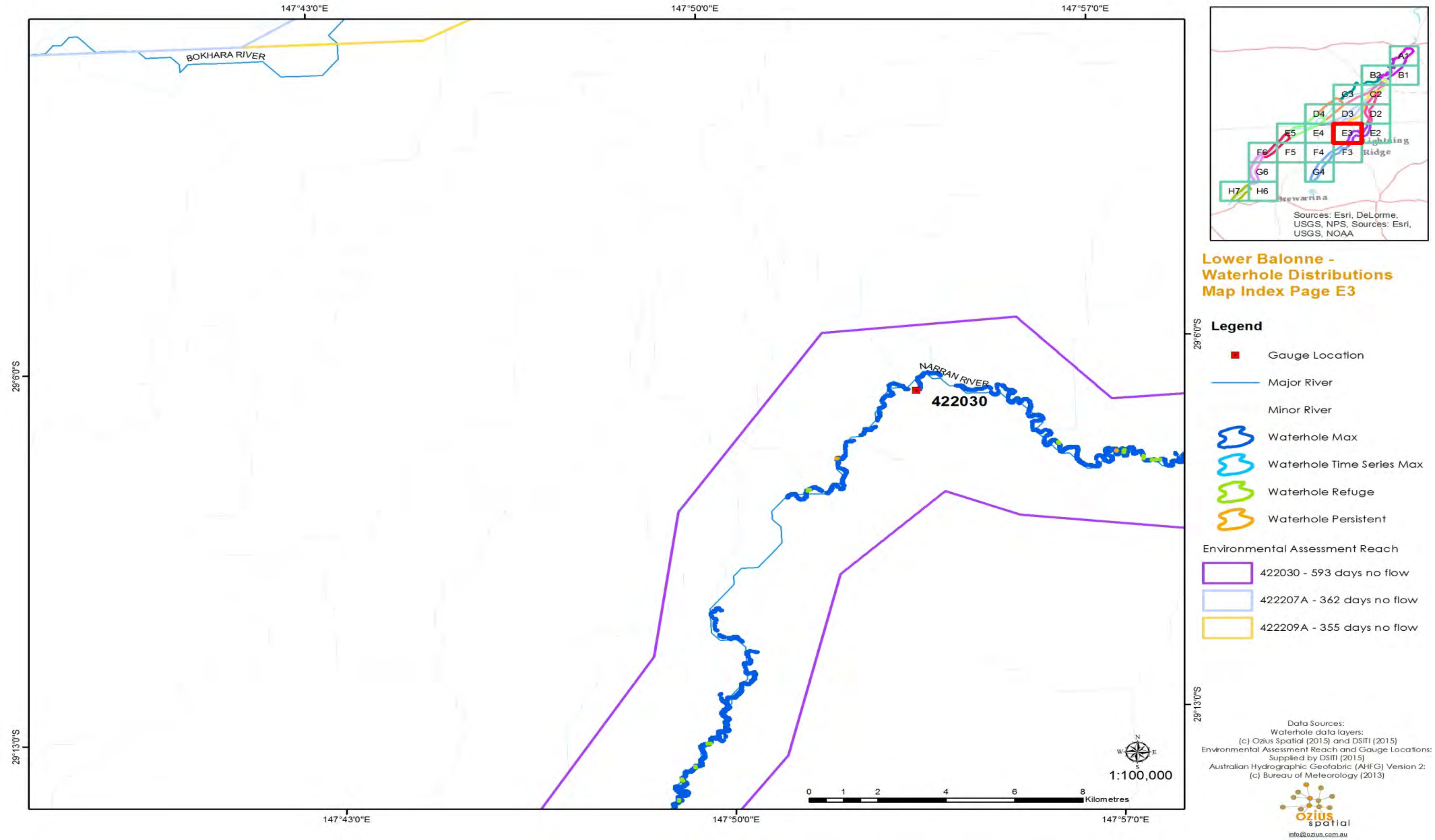

Figure B.10. Waterhole Distributions in Lower Balonne Page E3

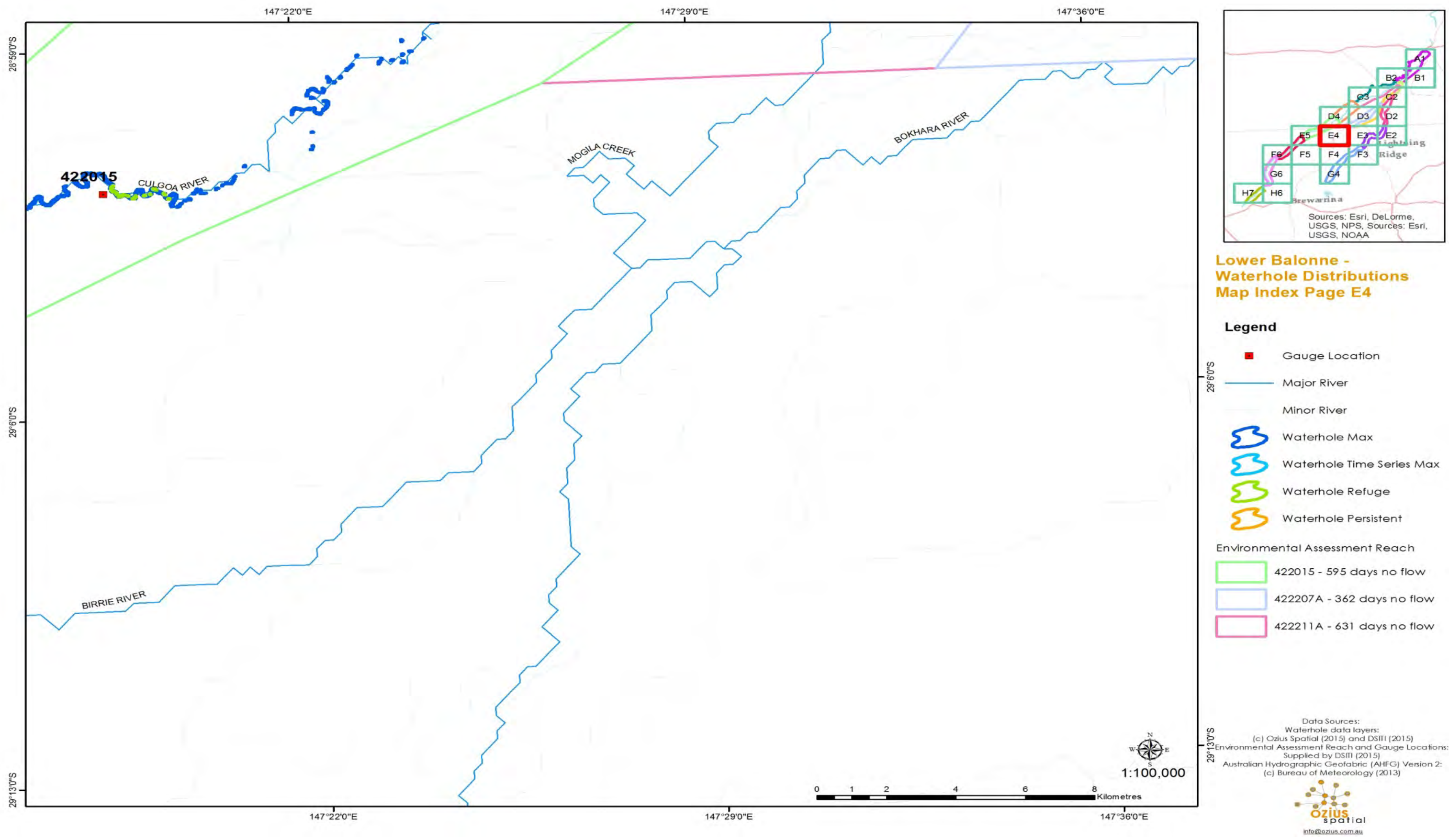

Figure B.11. Waterhole Distributions in Lower Balonne Page E4

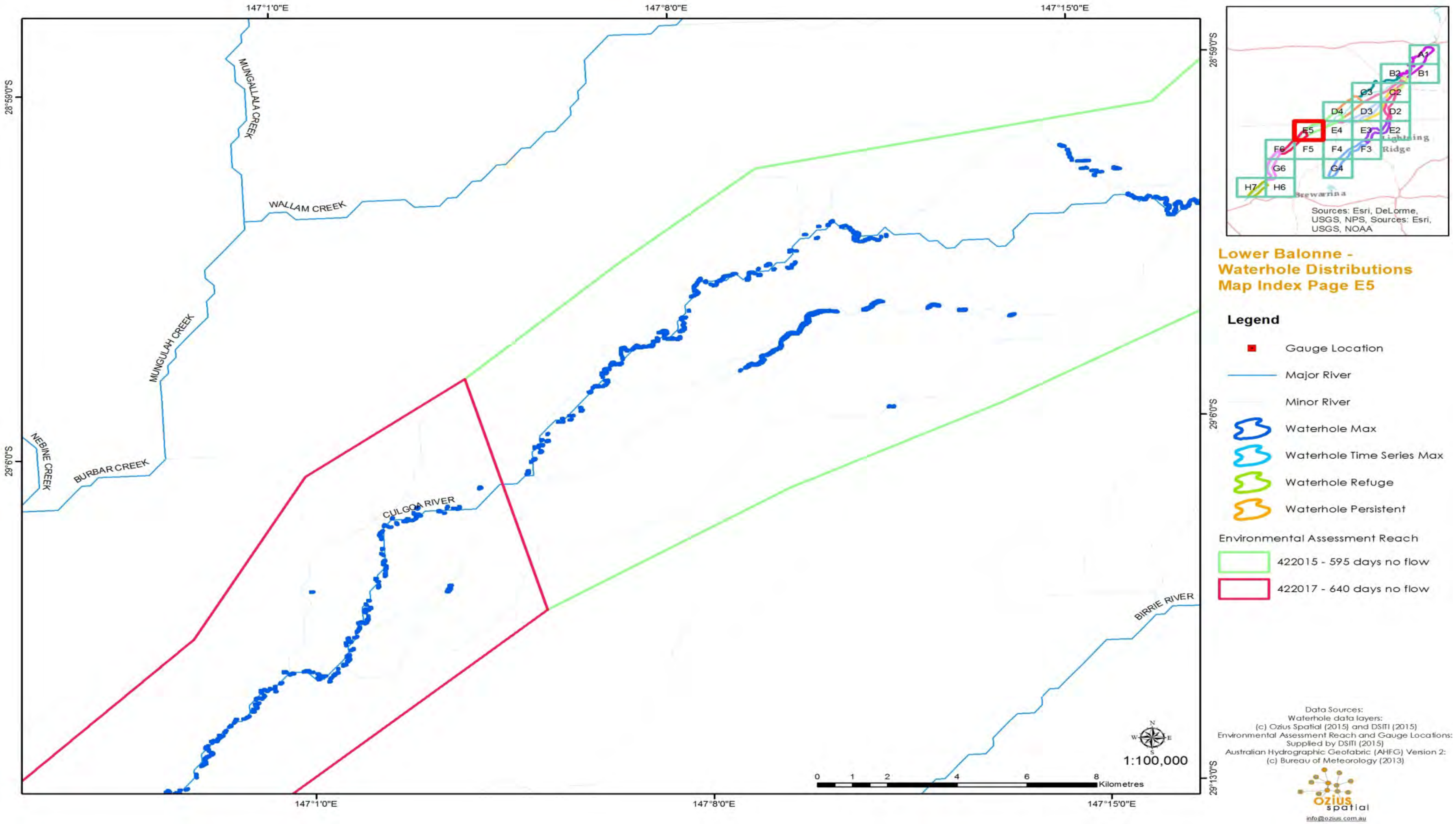

Figure B.12. Waterhole Distributions in Lower Balonne Page E5

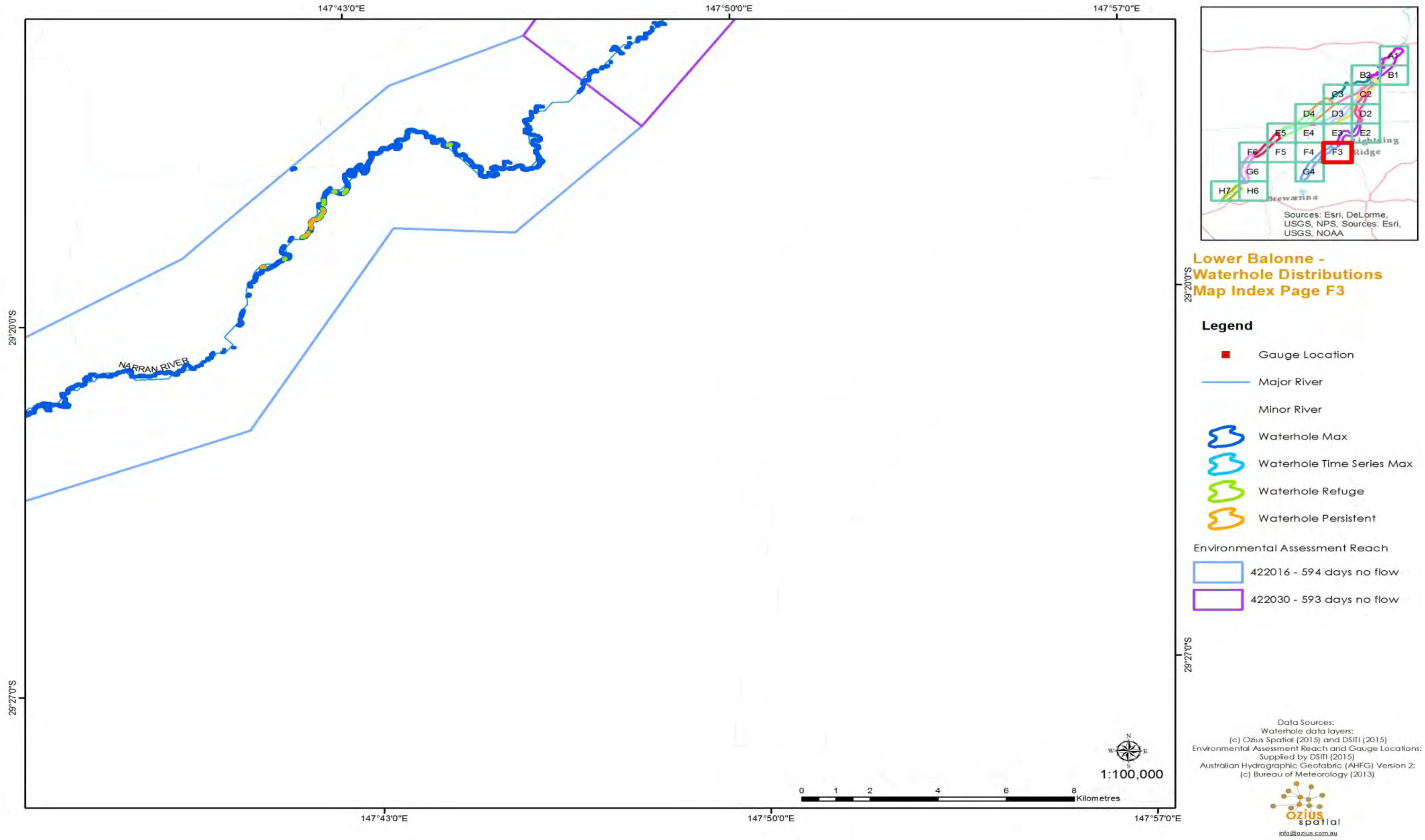

Figure B.13. Waterhole Distributions in Lower Balonne Page F3

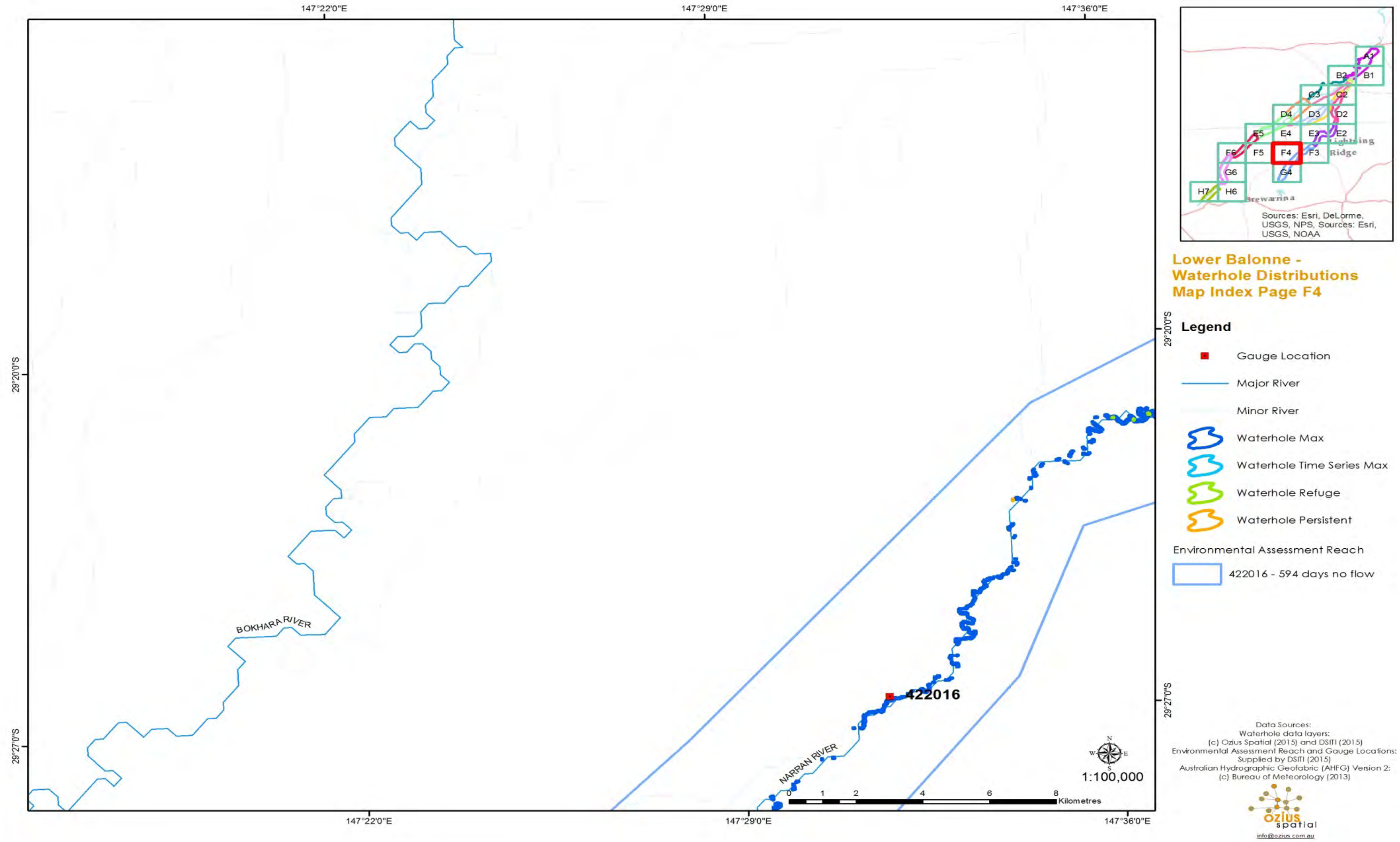

Figure B.14. Waterhole Distributions in Lower Balonne Page F4

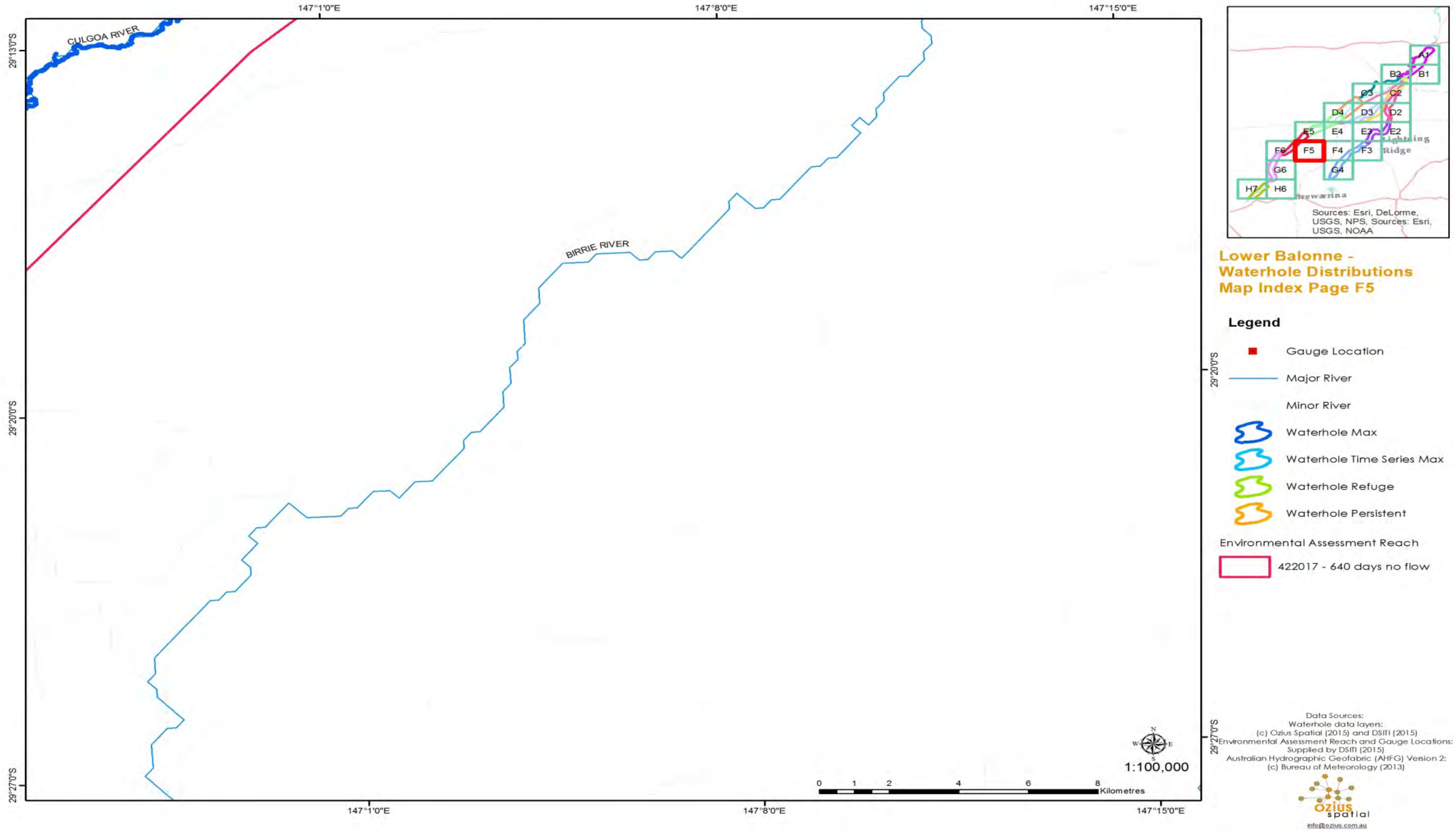

Figure B.15. Waterhole Distributions in Lower Balonne Page F5

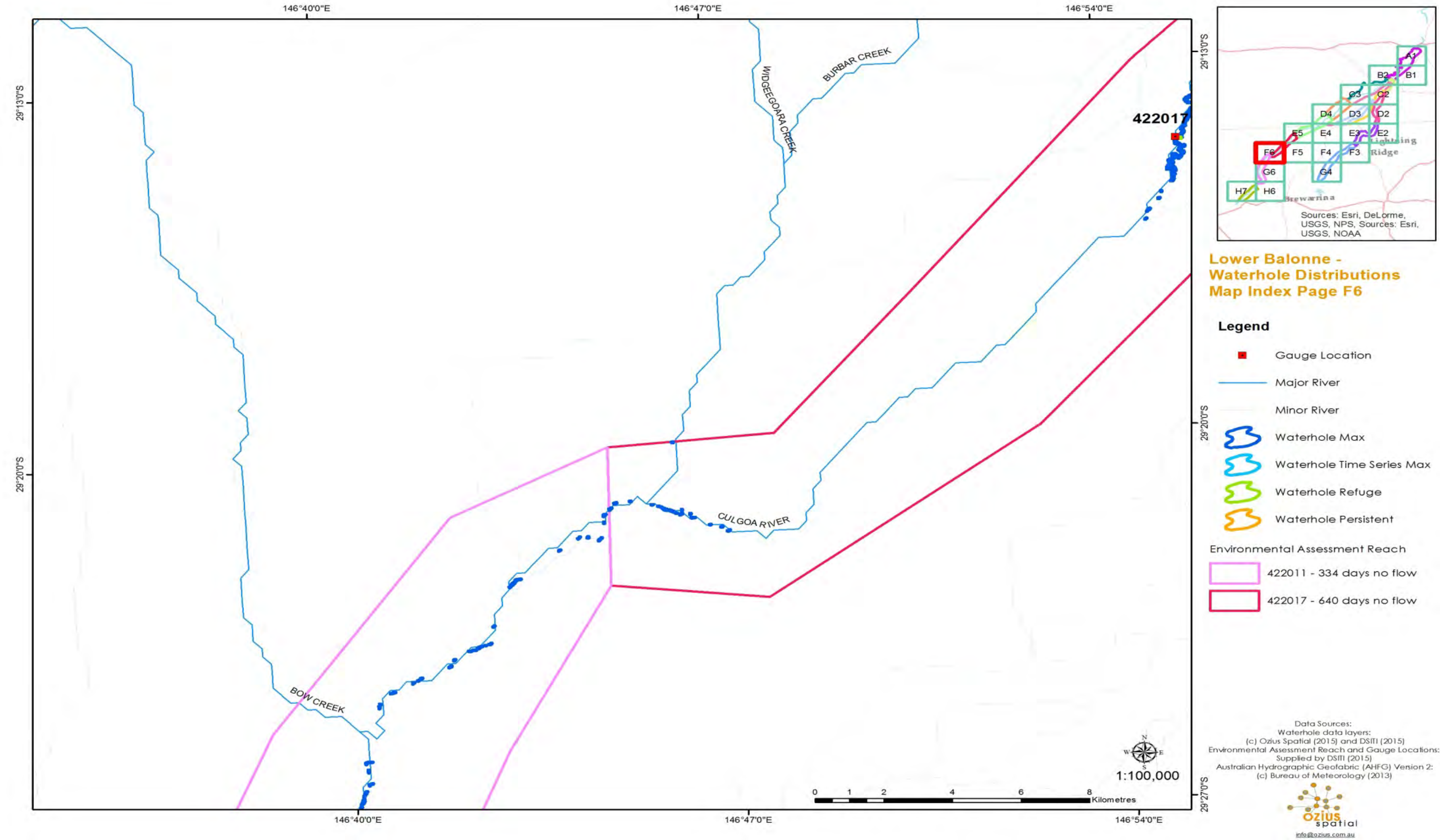

Figure B.16. Waterhole Distributions in Lower Balonne Page F6

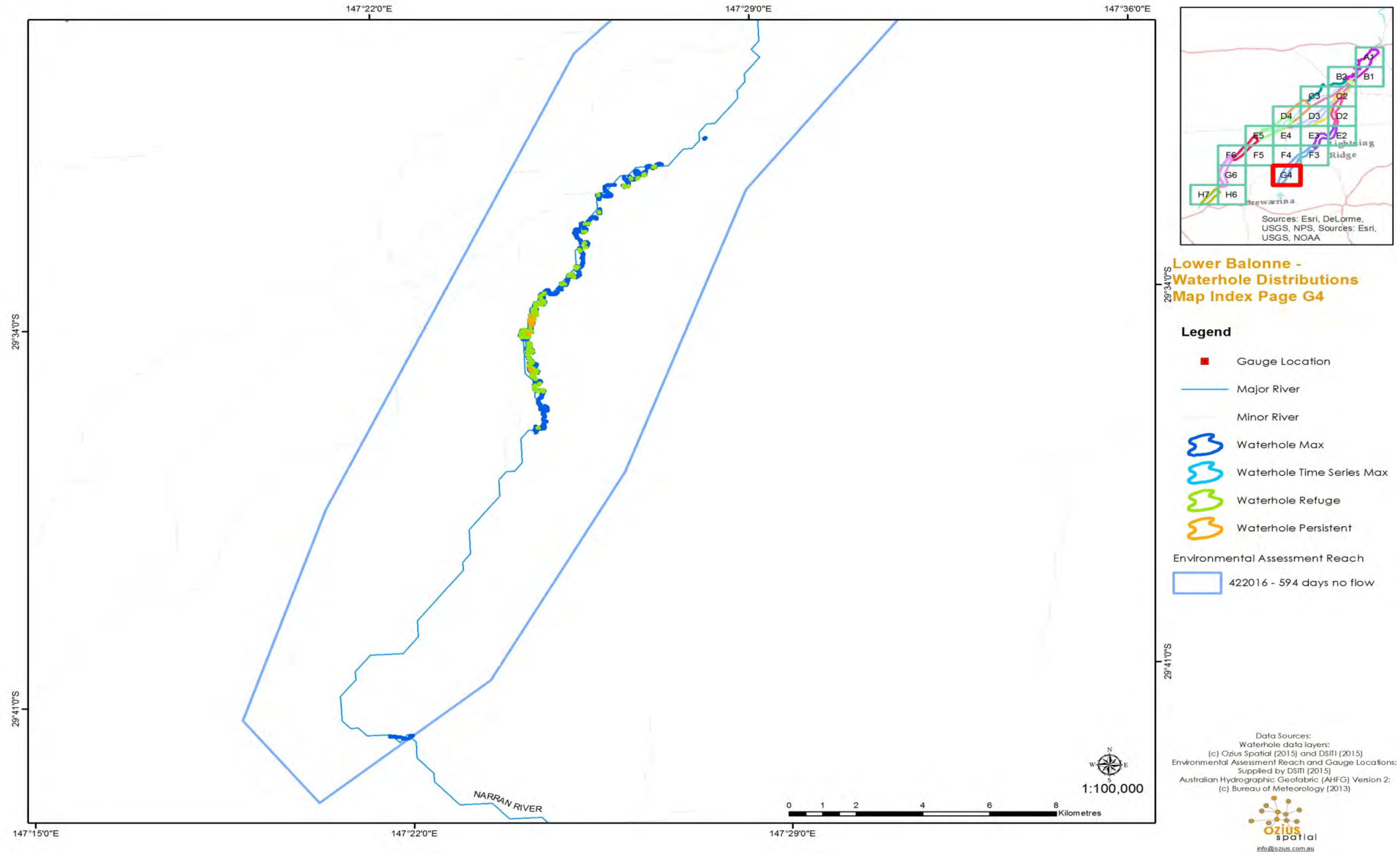

Figure B.17. Waterhole Distributions in Lower Balonne Page G4

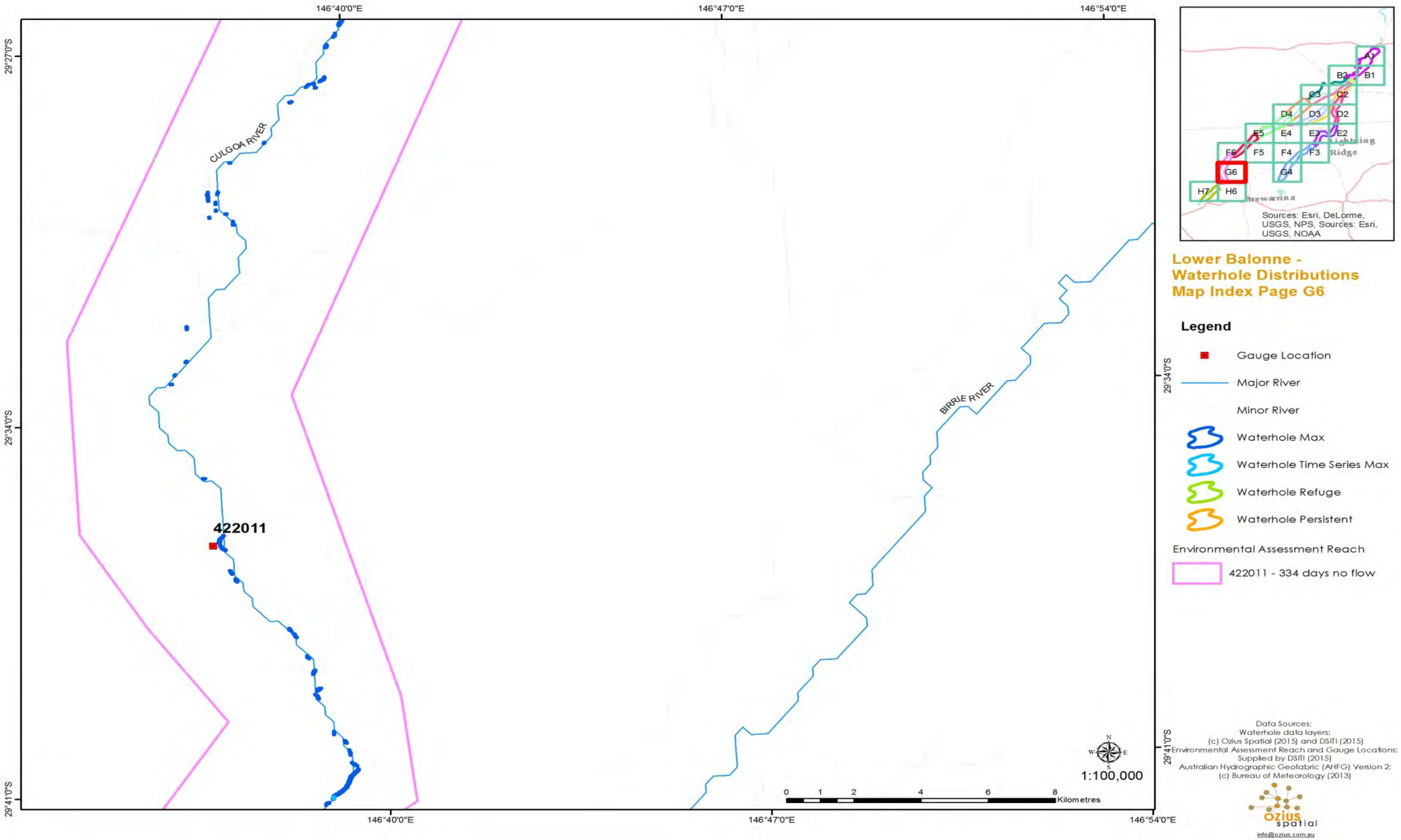

Figure B.18. Waterhole Distributions in Lower Balonne Page G6

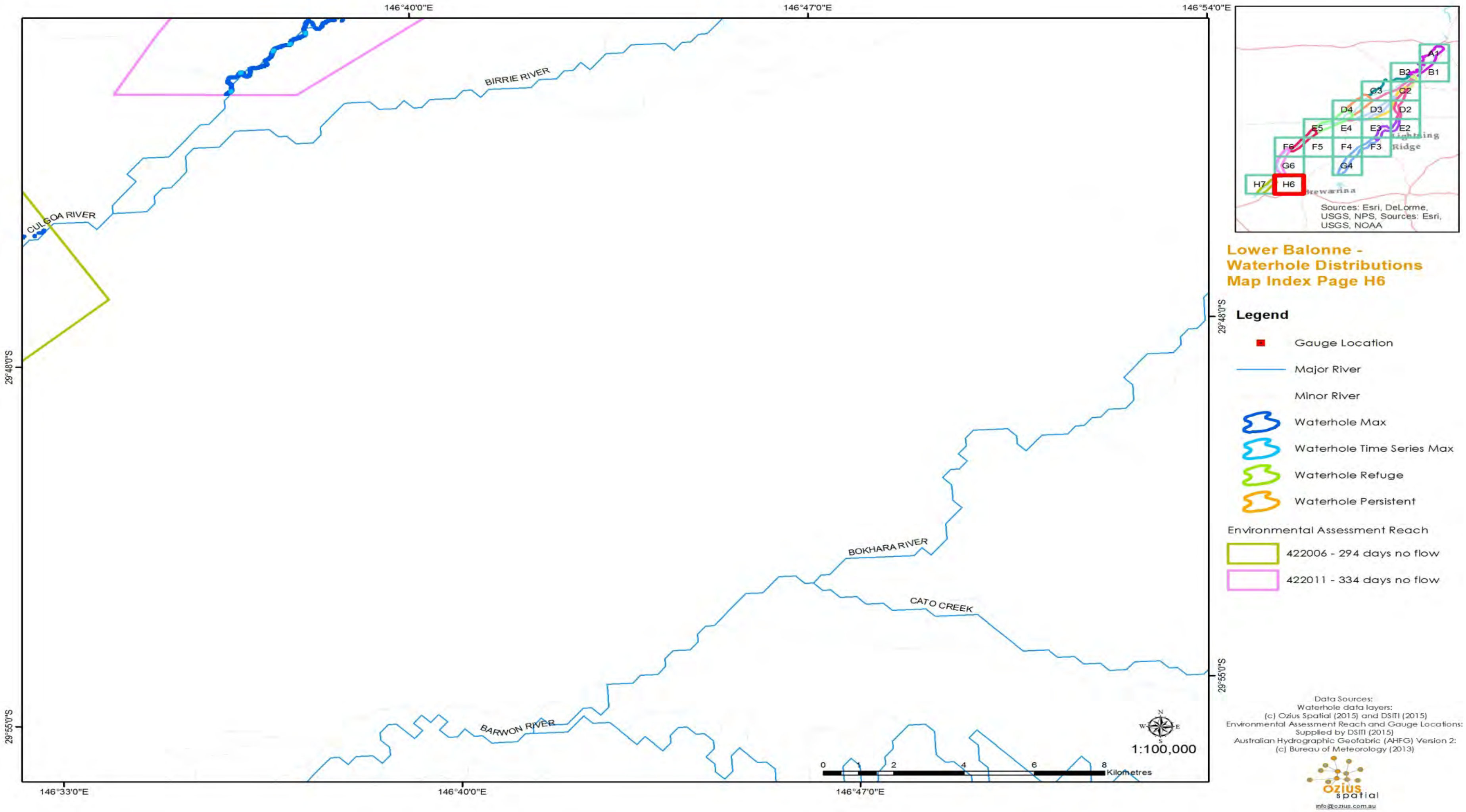

Figure B.19. Waterhole Distributions in Lower Balonne Page H6

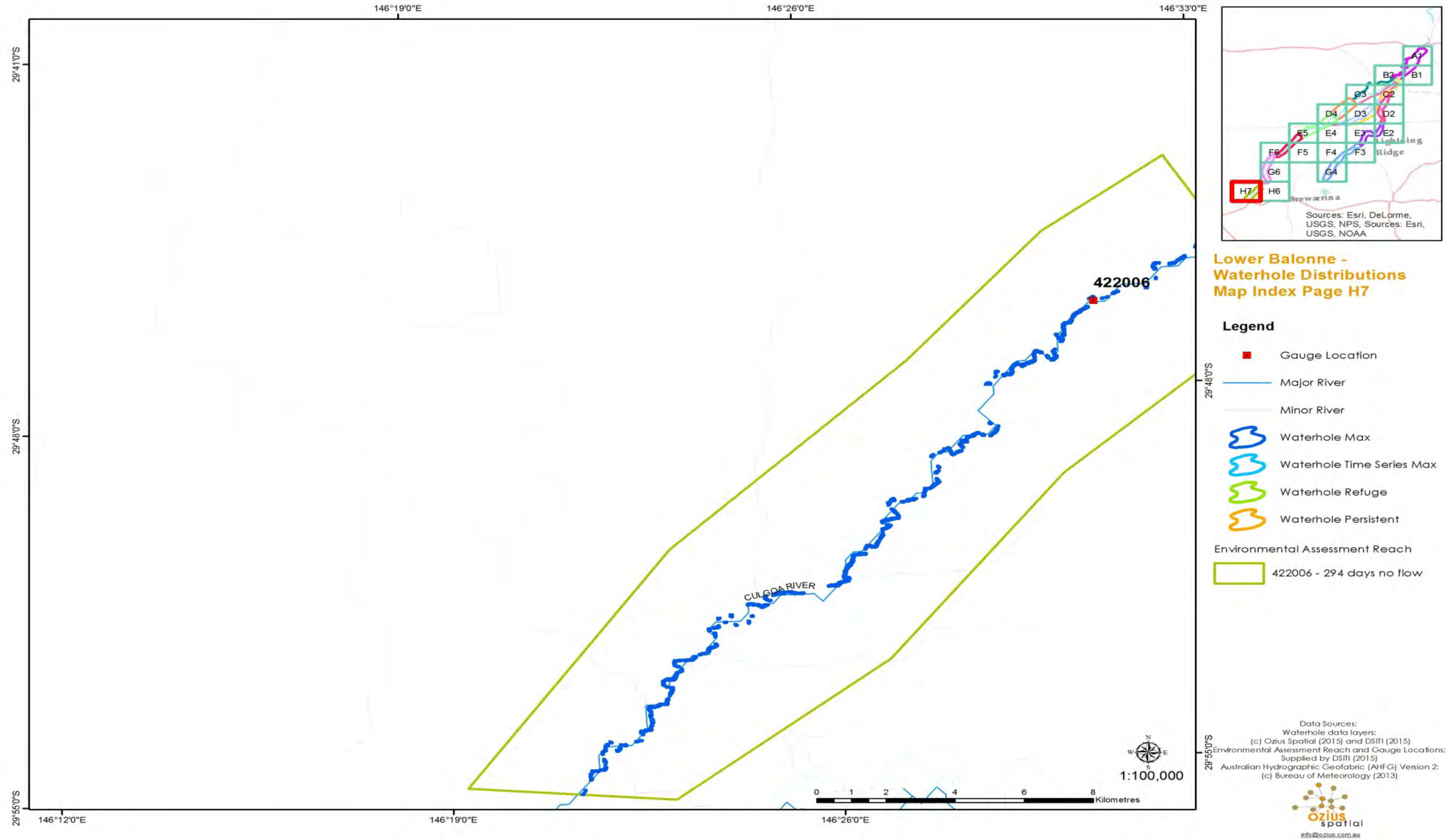

Figure B.20. Waterhole Distributions in Lower Balonne Page H7

Barwon–Darling

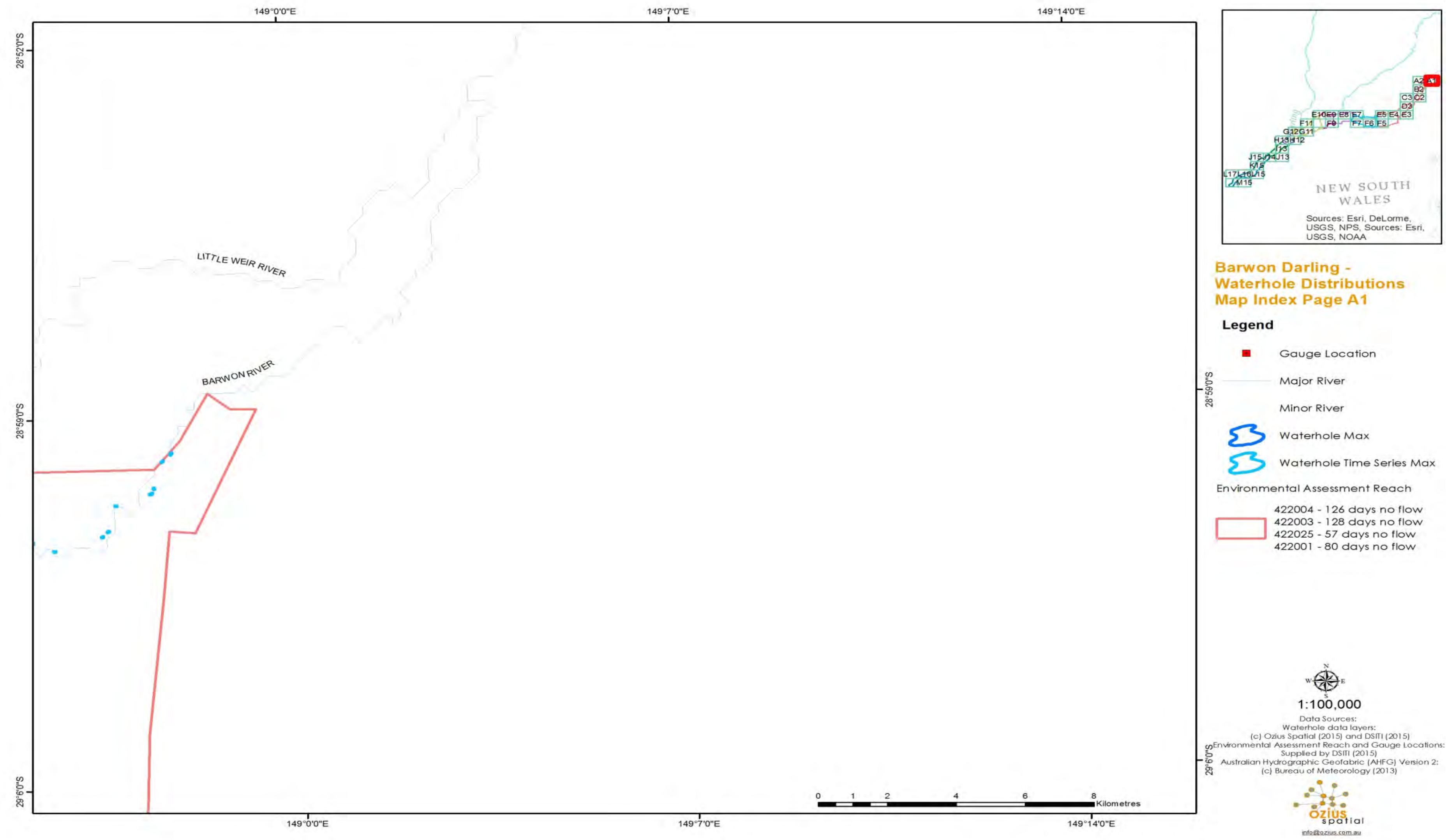

Figure B.21. Waterhole Distributions in Barwon–Darling Page A1

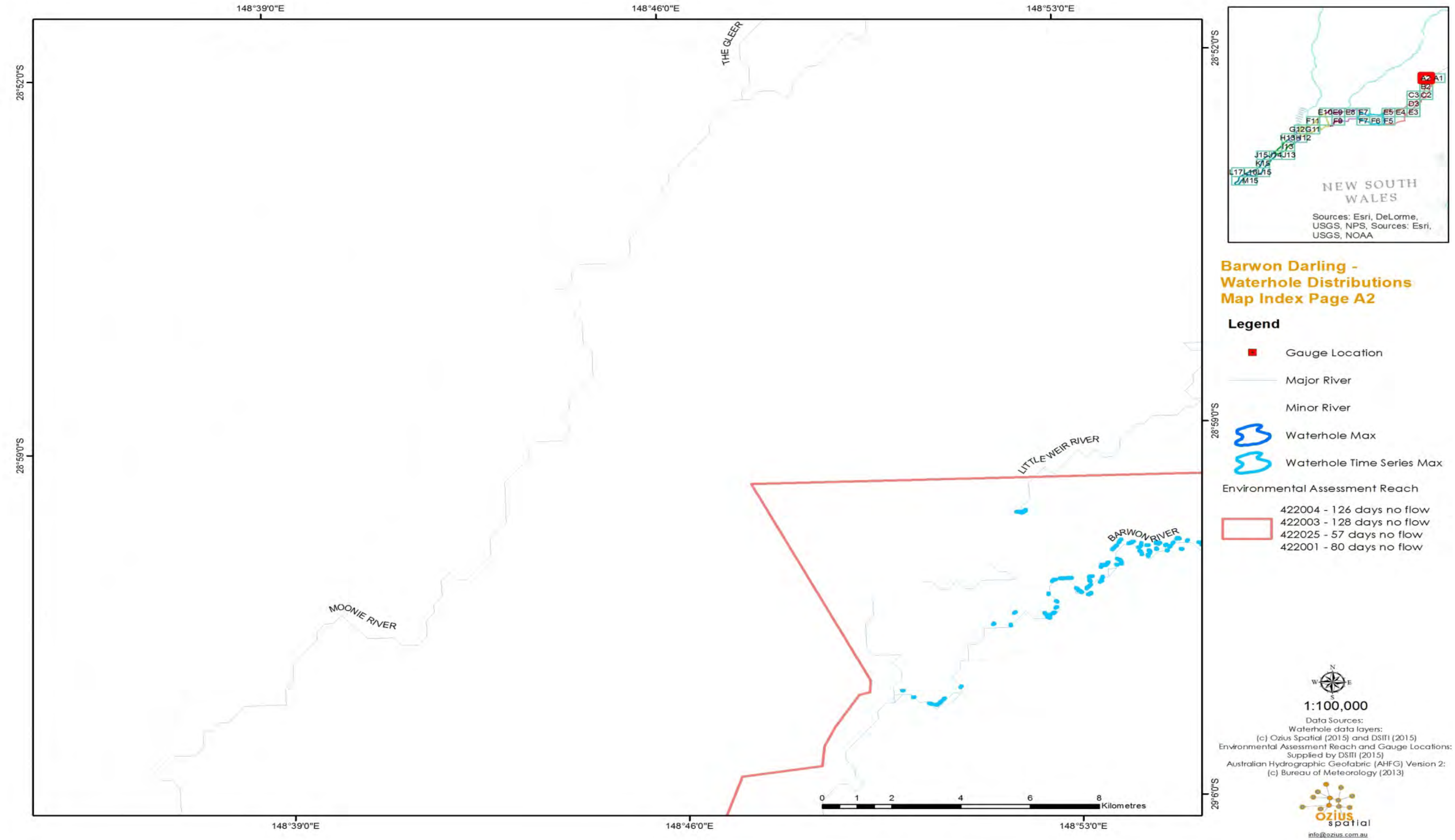

Figure B.22. Waterhole Distributions in Barwon–Darling Page A2

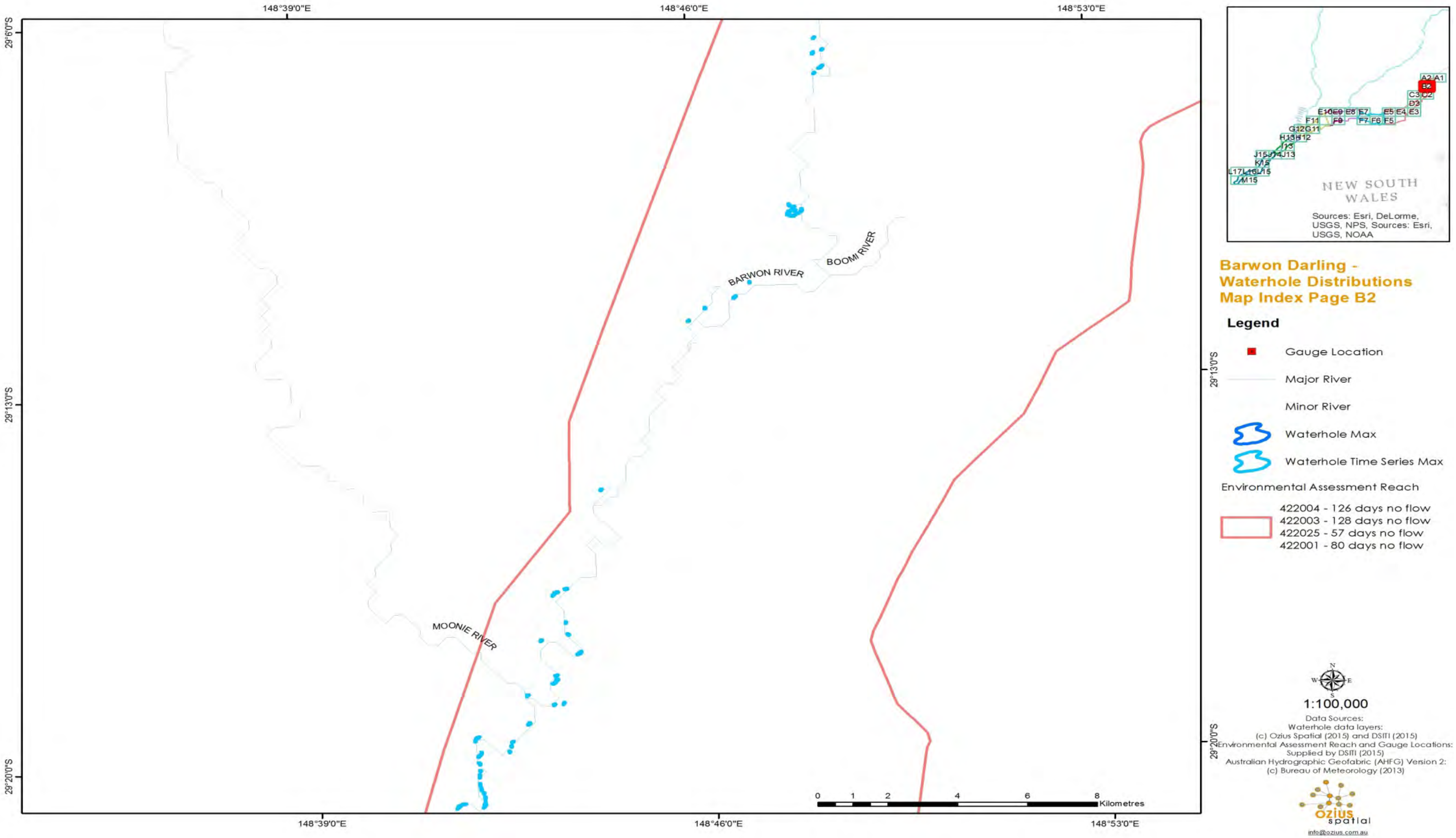

Figure B.23. Waterhole Distributions in Barwon–Darling Page B2

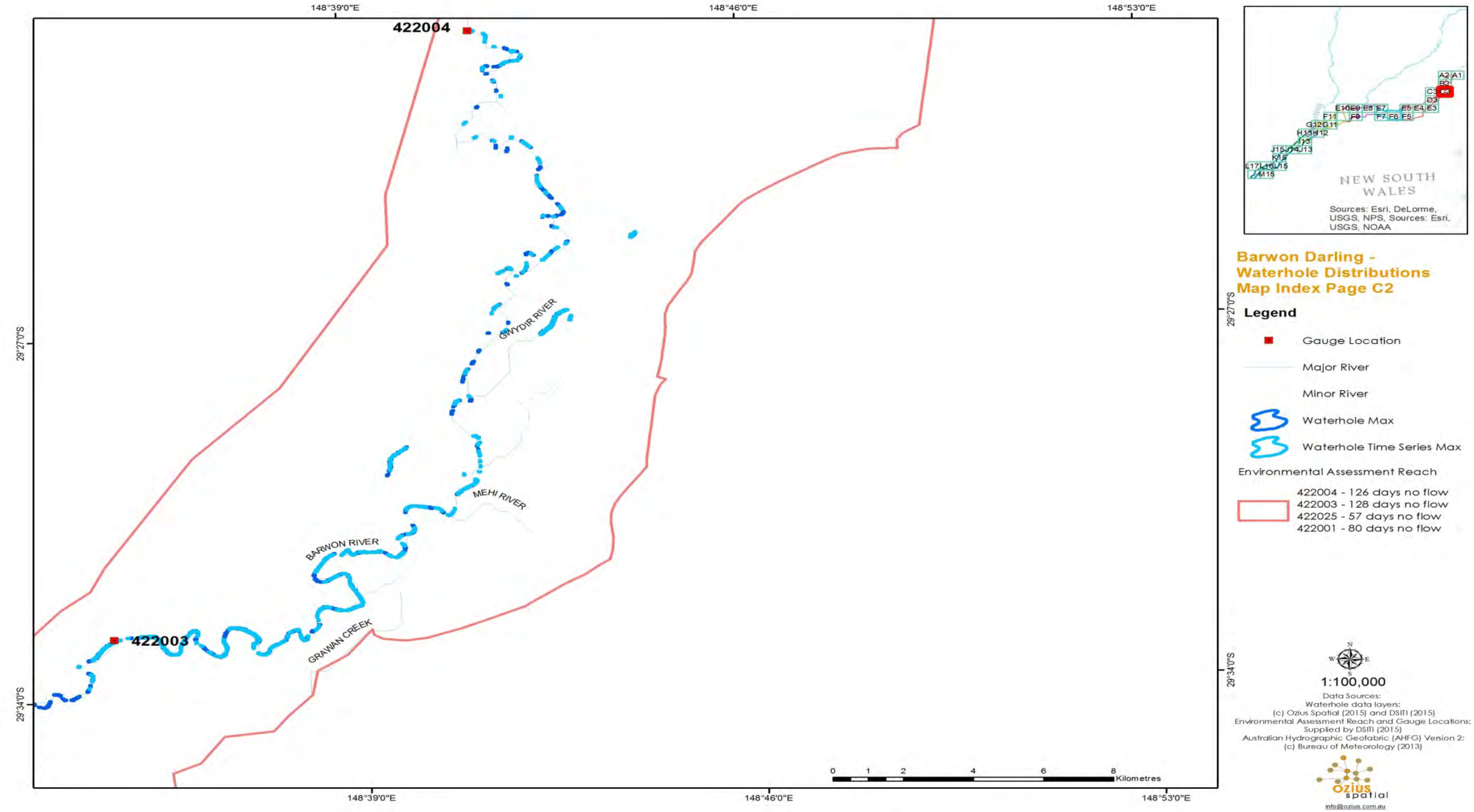

Figure B.24. Waterhole Distributions in Barwon–Darling Page C2

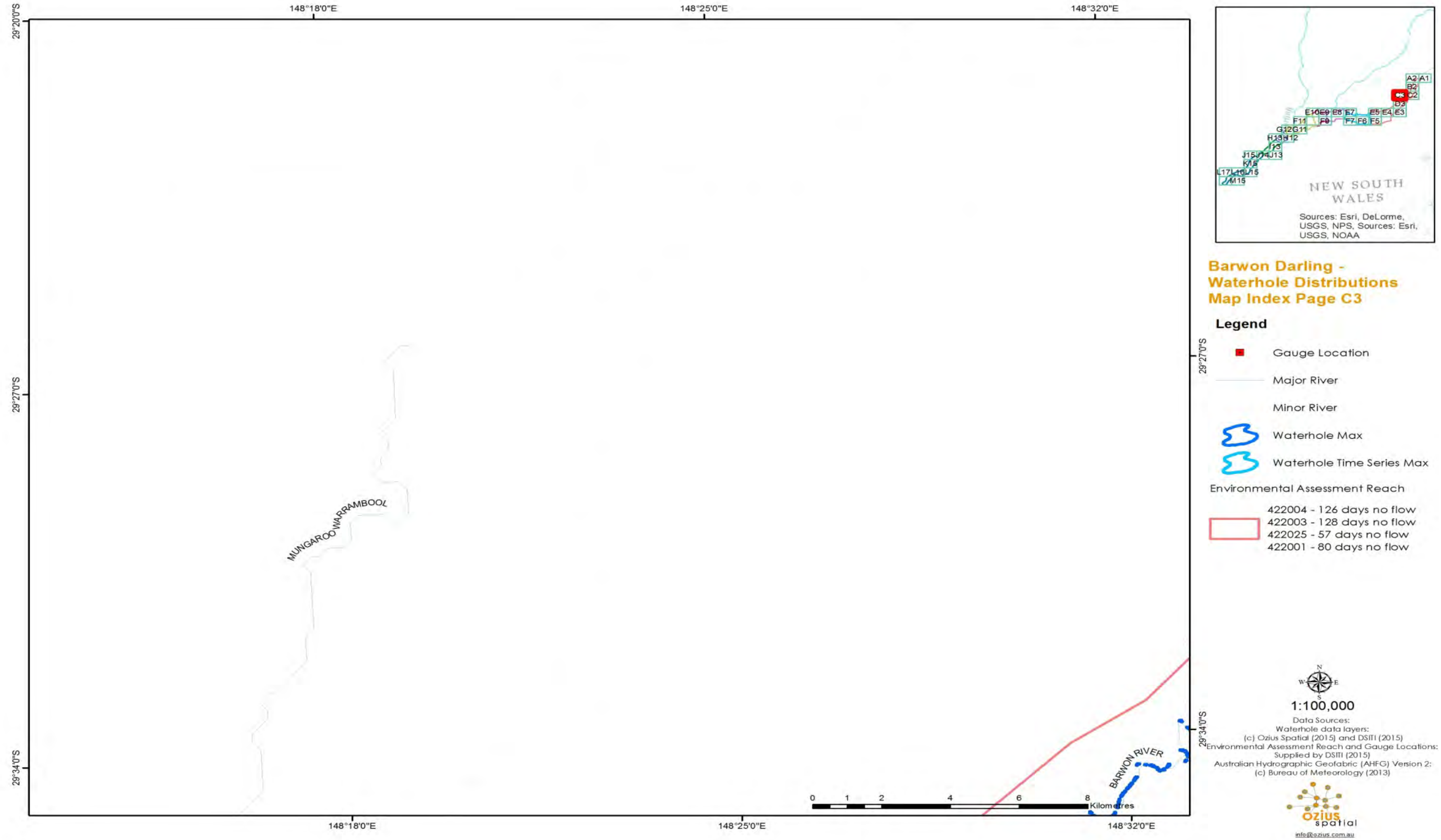

Figure B.25. Waterhole Distributions in Barwon–Darling Page C3

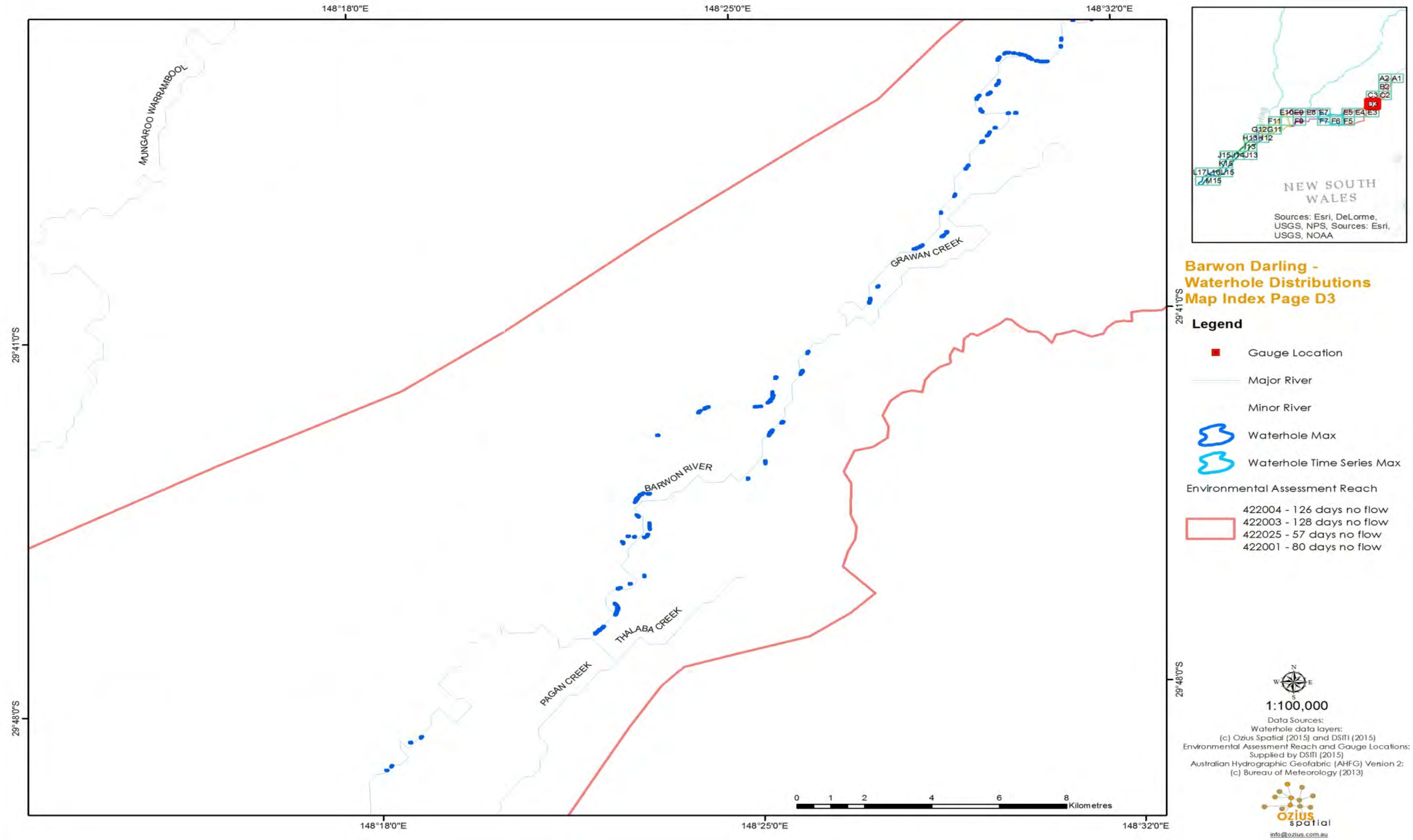

Figure B.26. Waterhole Distributions in Barwon–Darling Page D3

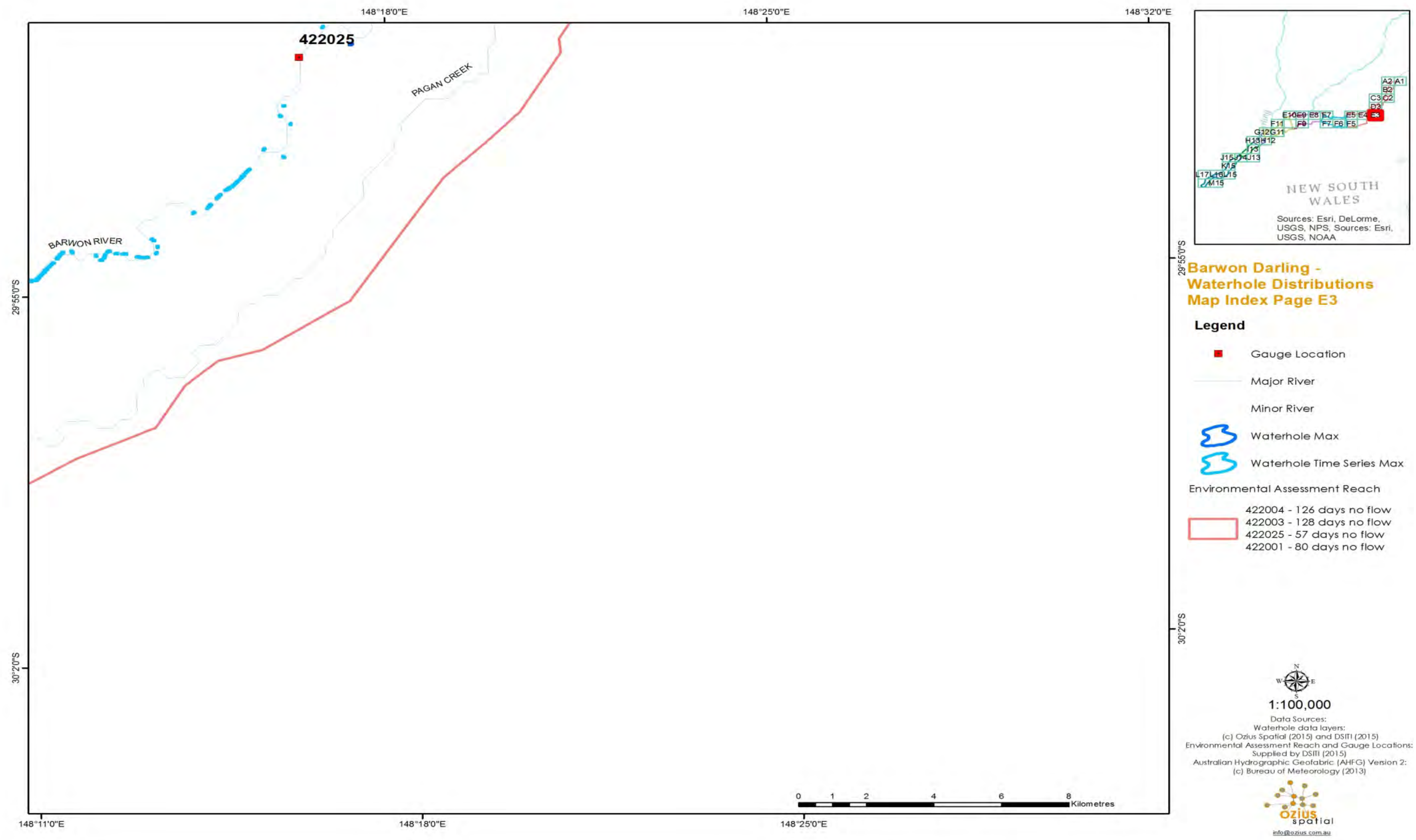

Figure B.27. Waterhole Distributions in Barwon–Darling Page E3

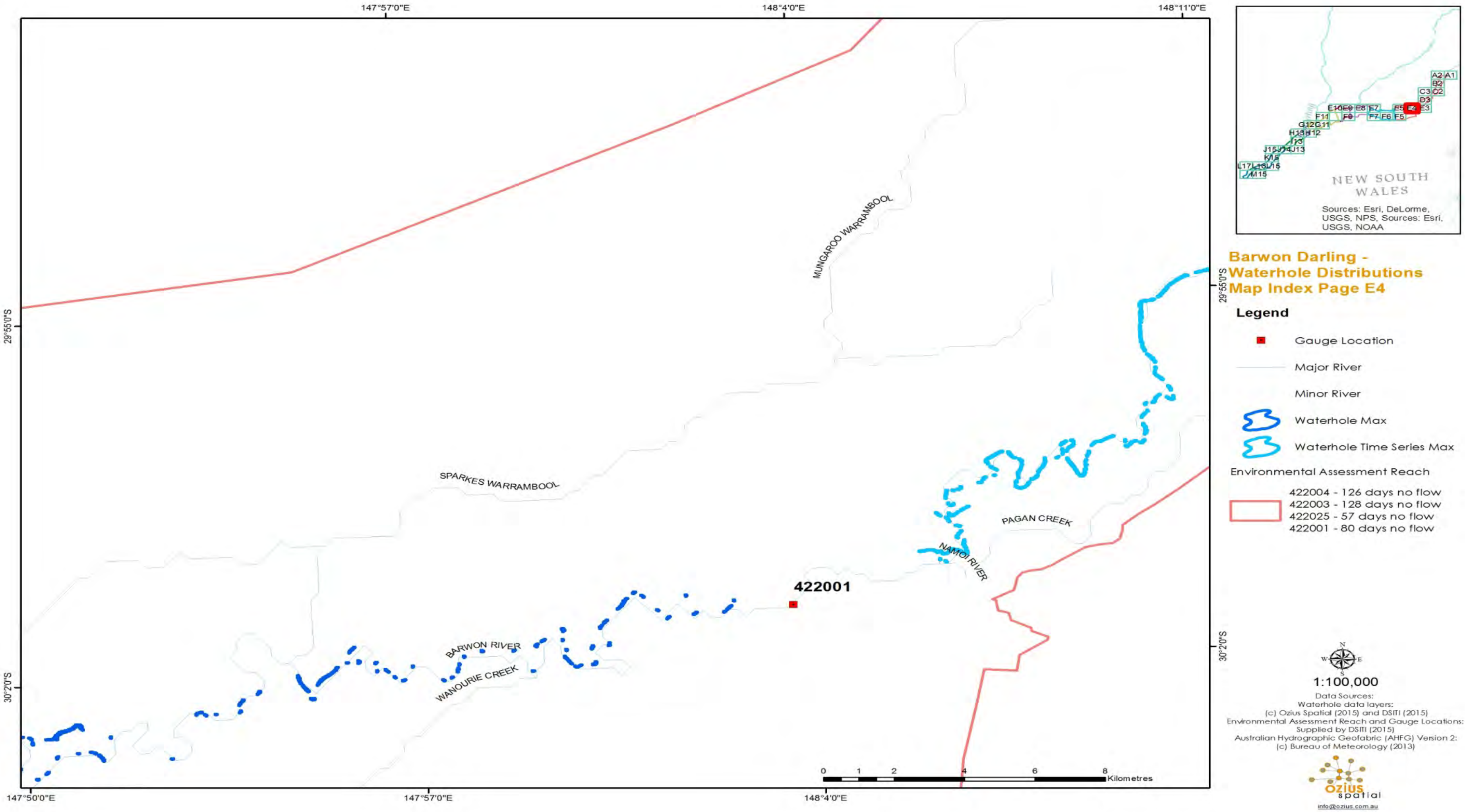

Figure B.28. Waterhole Distributions in Barwon–Darling Page E4

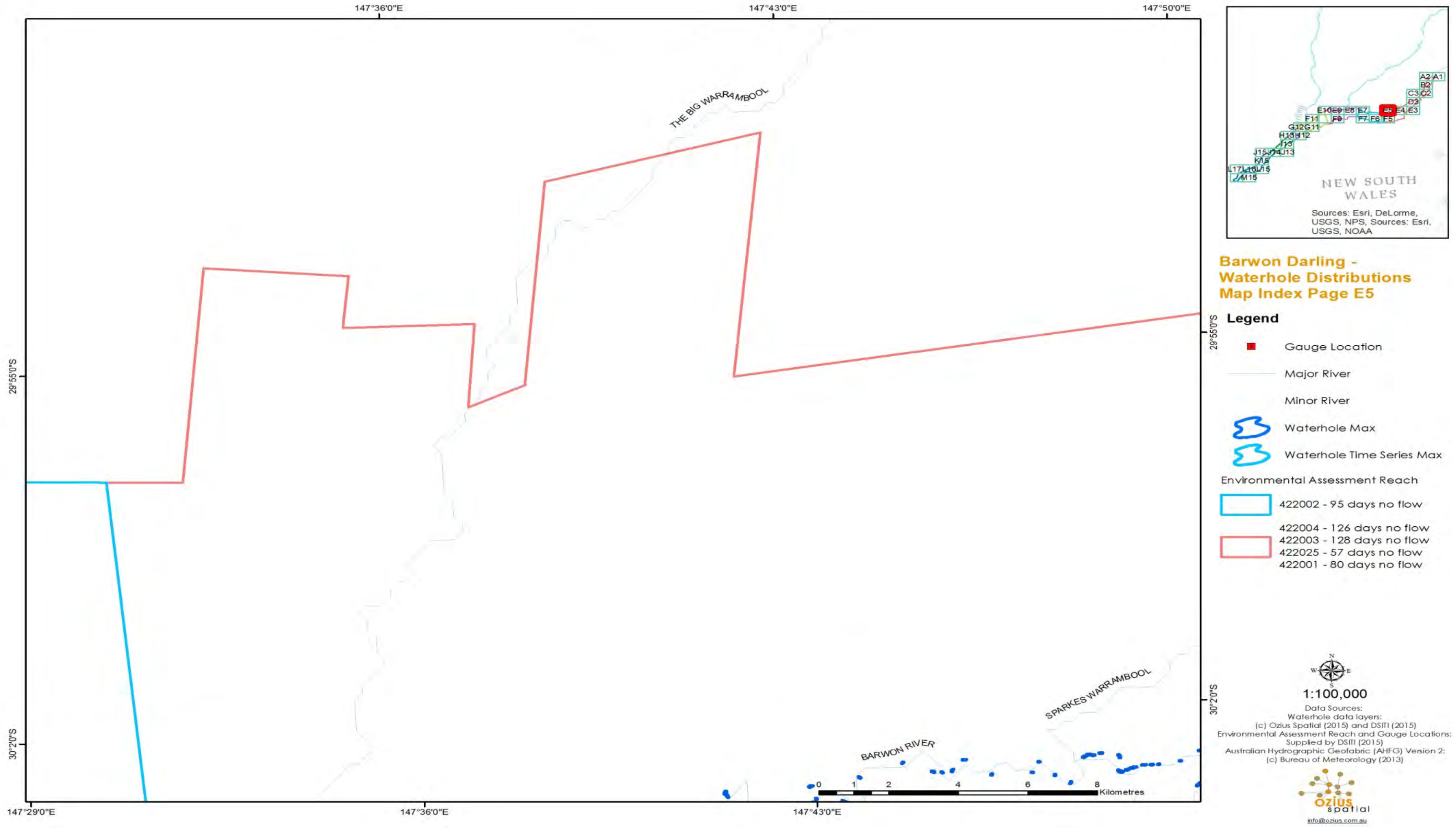

Figure B.29. Waterhole Distributions in Barwon–Darling Page E5

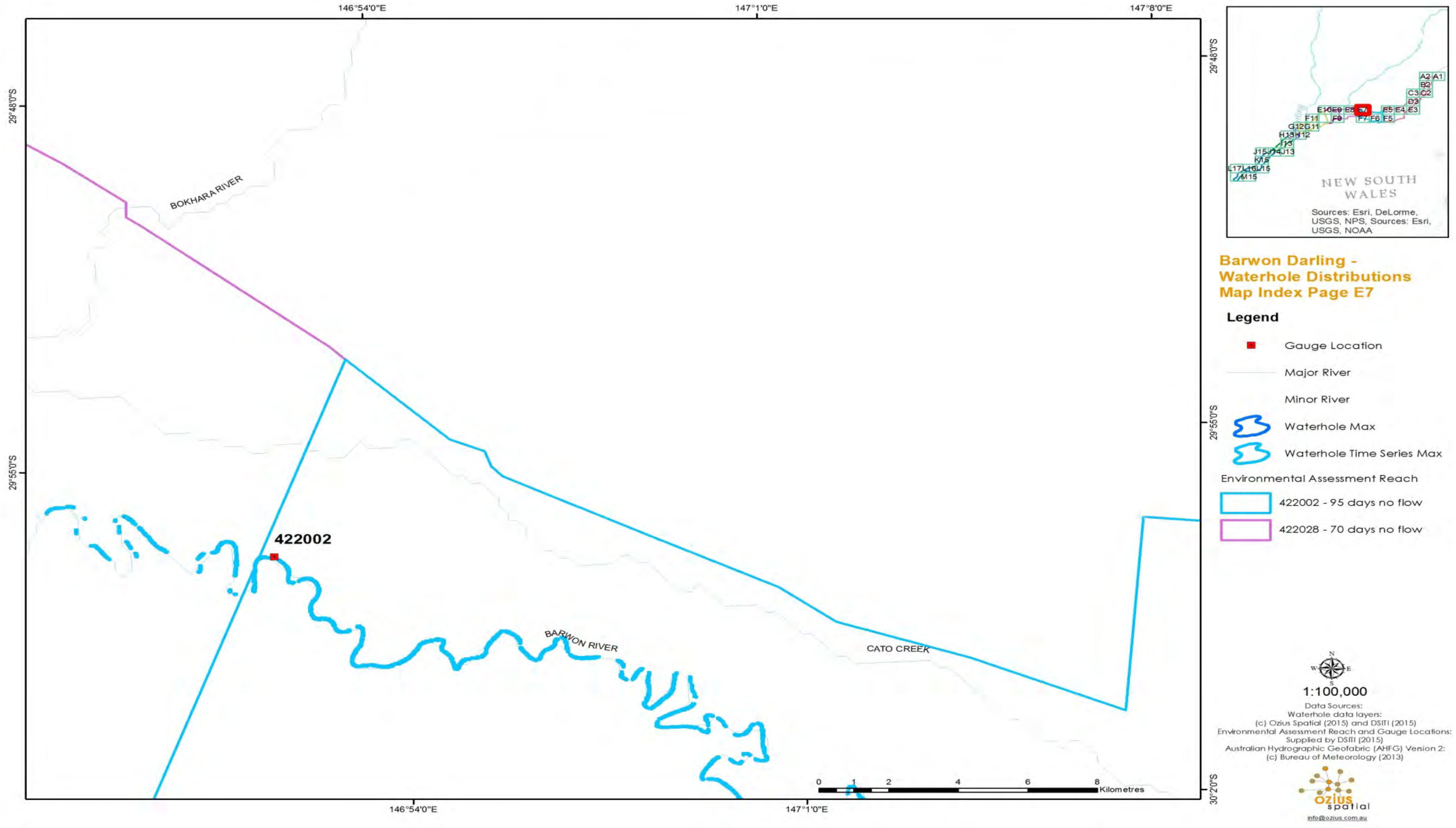

Figure B.30. Waterhole Distributions in Barwon–Darling Page E7

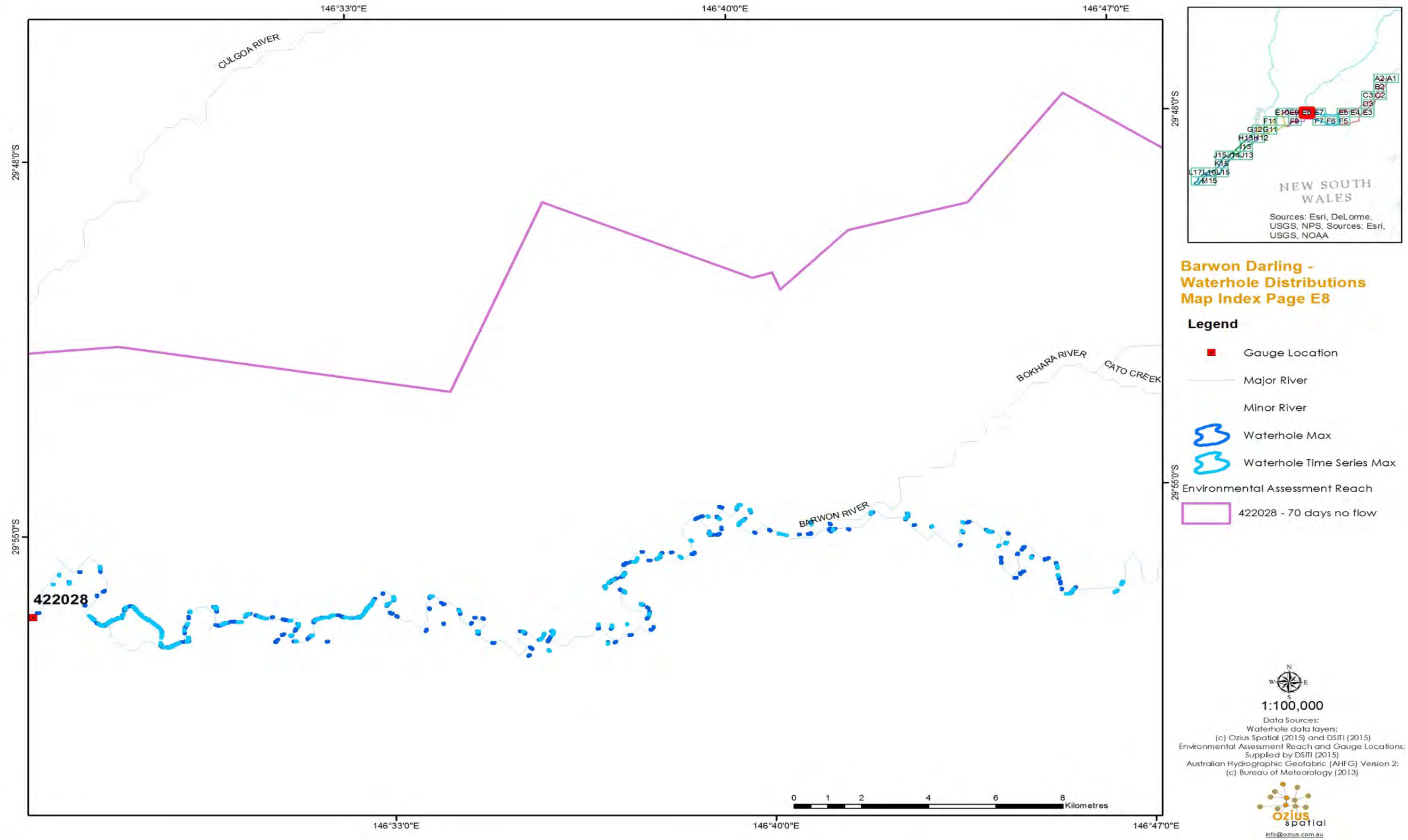

Figure B.31. Waterhole Distributions in Barwon–Darling Page E8

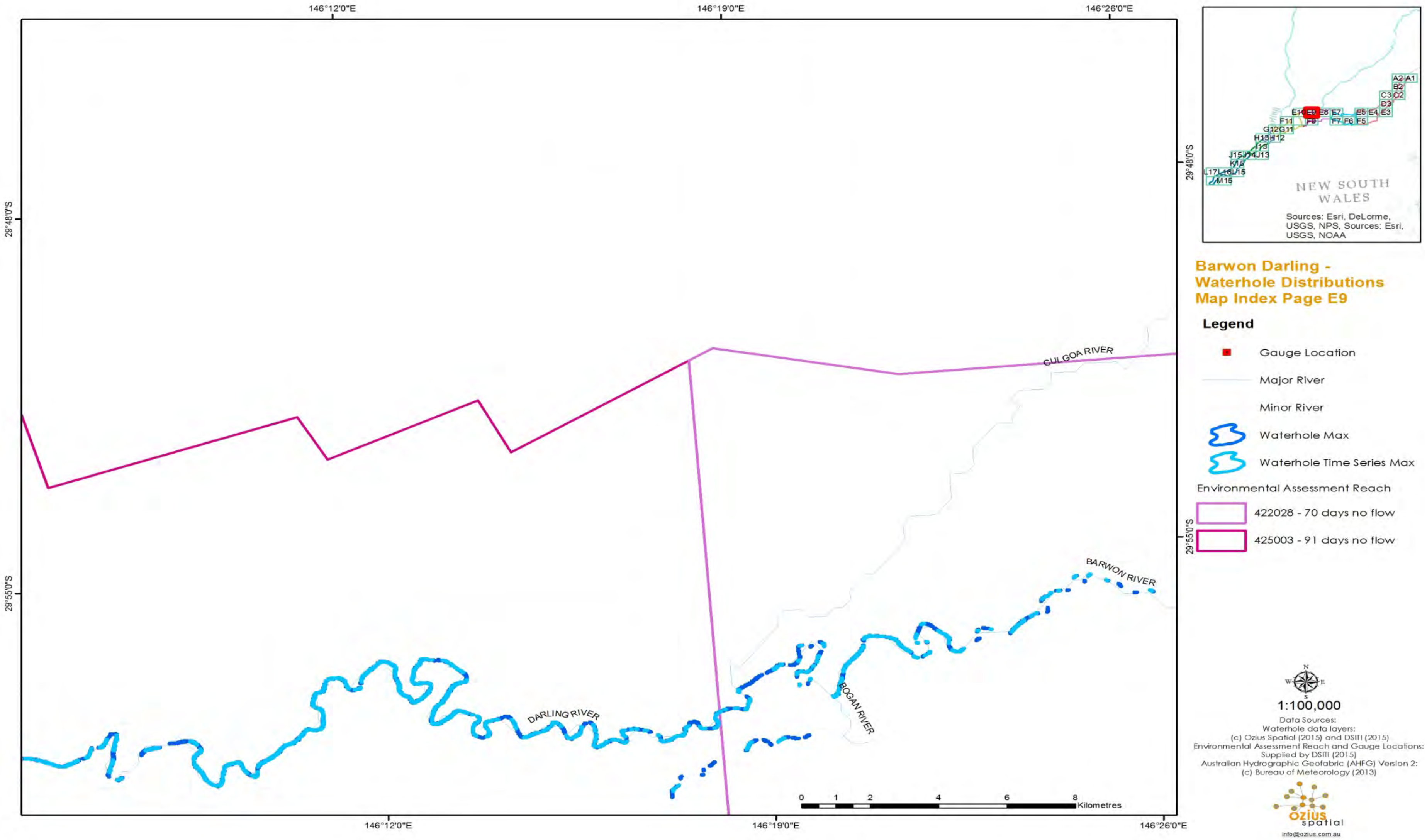

Figure B.32. Waterhole Distributions in Barwon–Darling Page E9

Figure B.33. Waterhole Distributions in Barwon–Darling Page E10

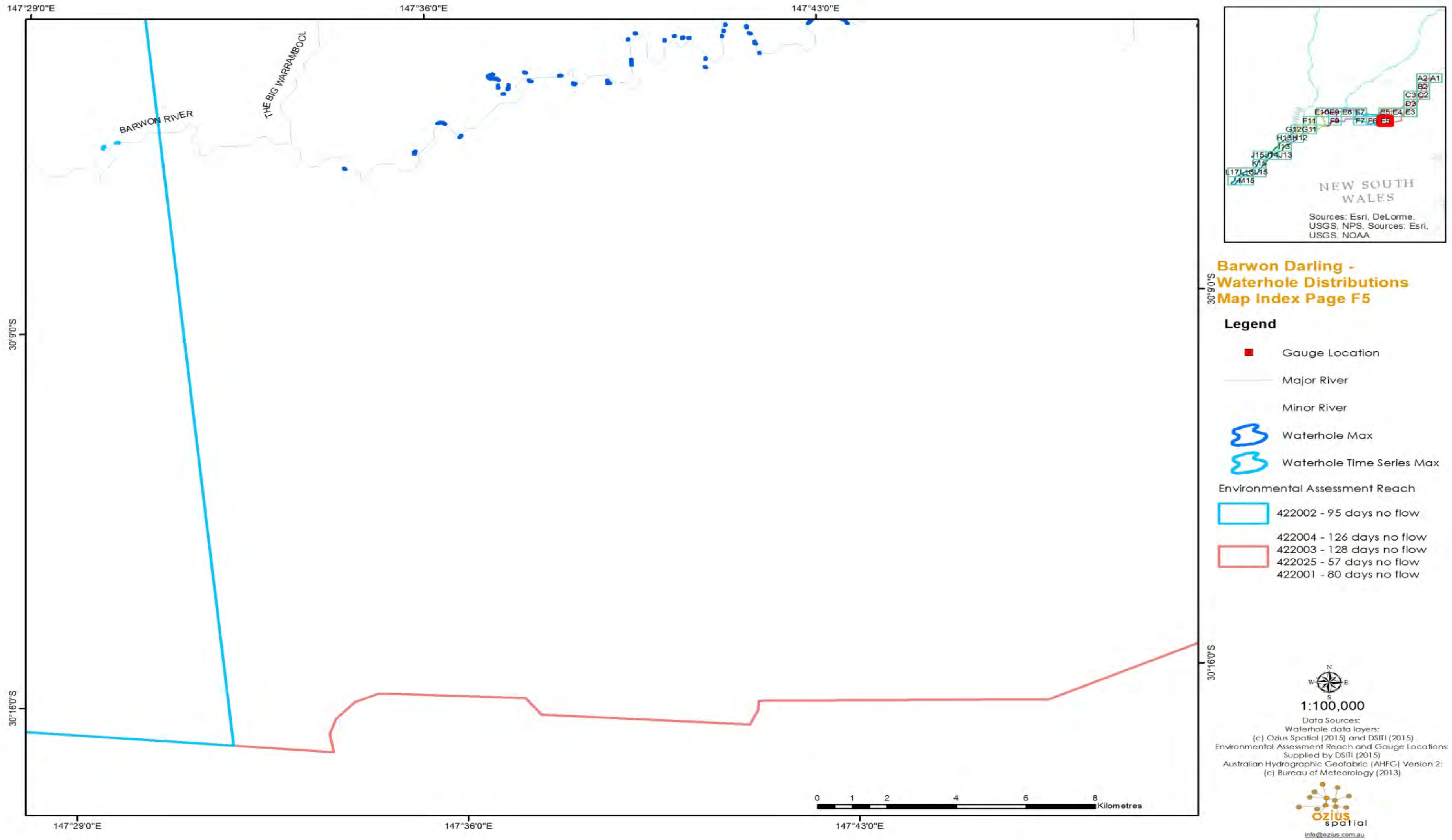

Figure B.34. Waterhole Distributions in Barwon–Darling Page F5

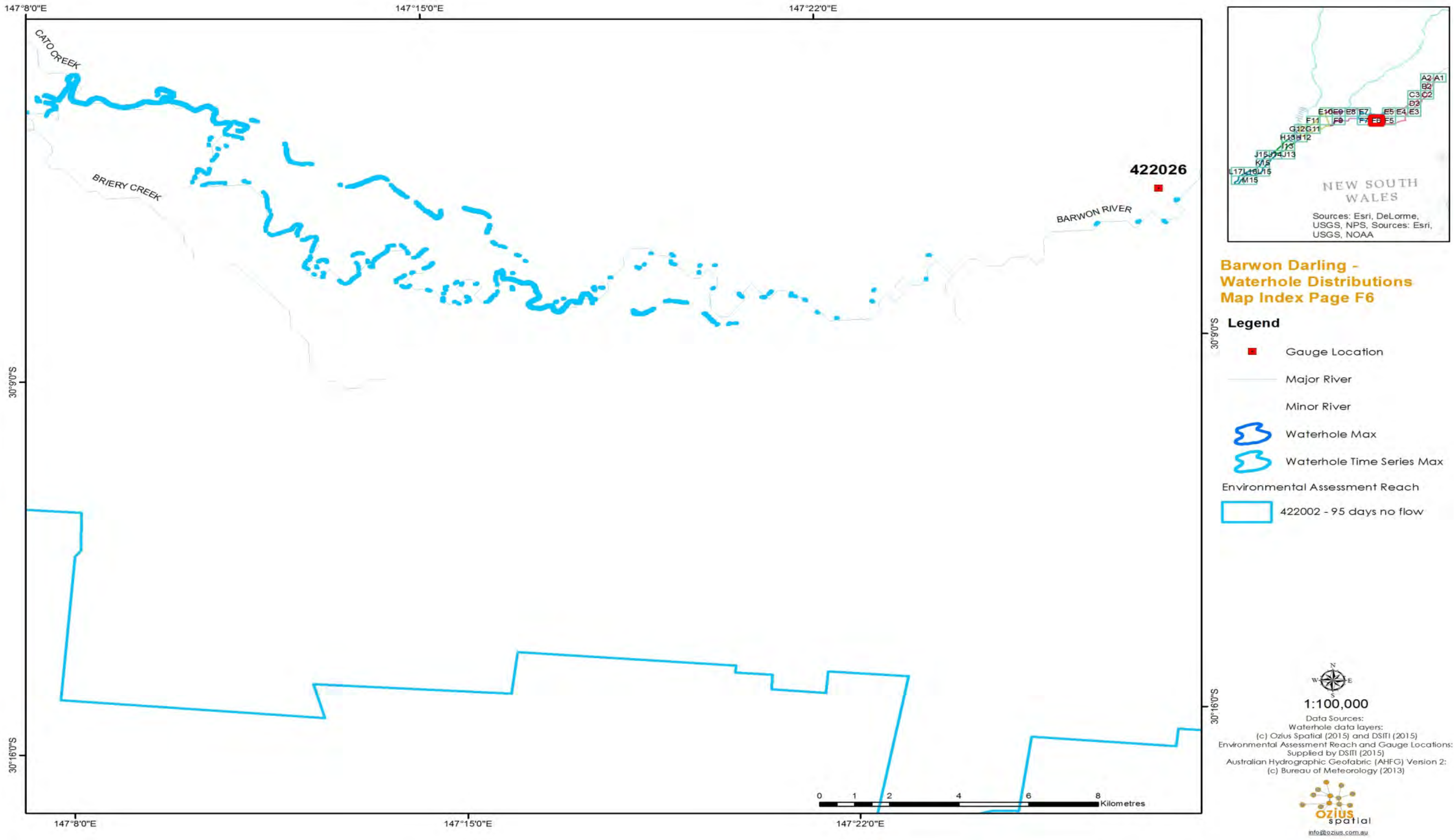

Figure B.35. Waterhole Distributions in Barwon–Darling Page F6

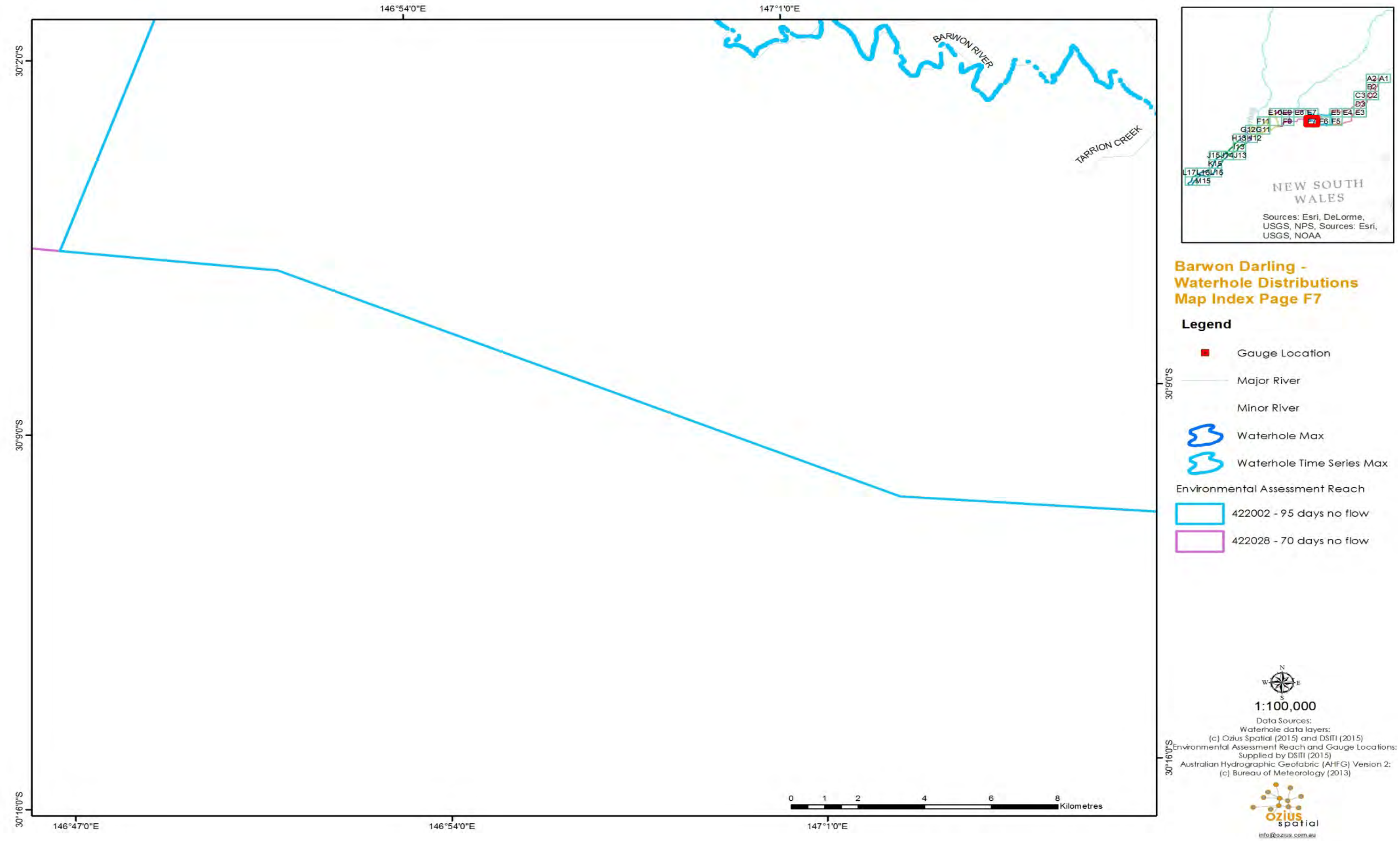

Figure B.36. Waterhole Distributions in Barwon–Darling Page F7

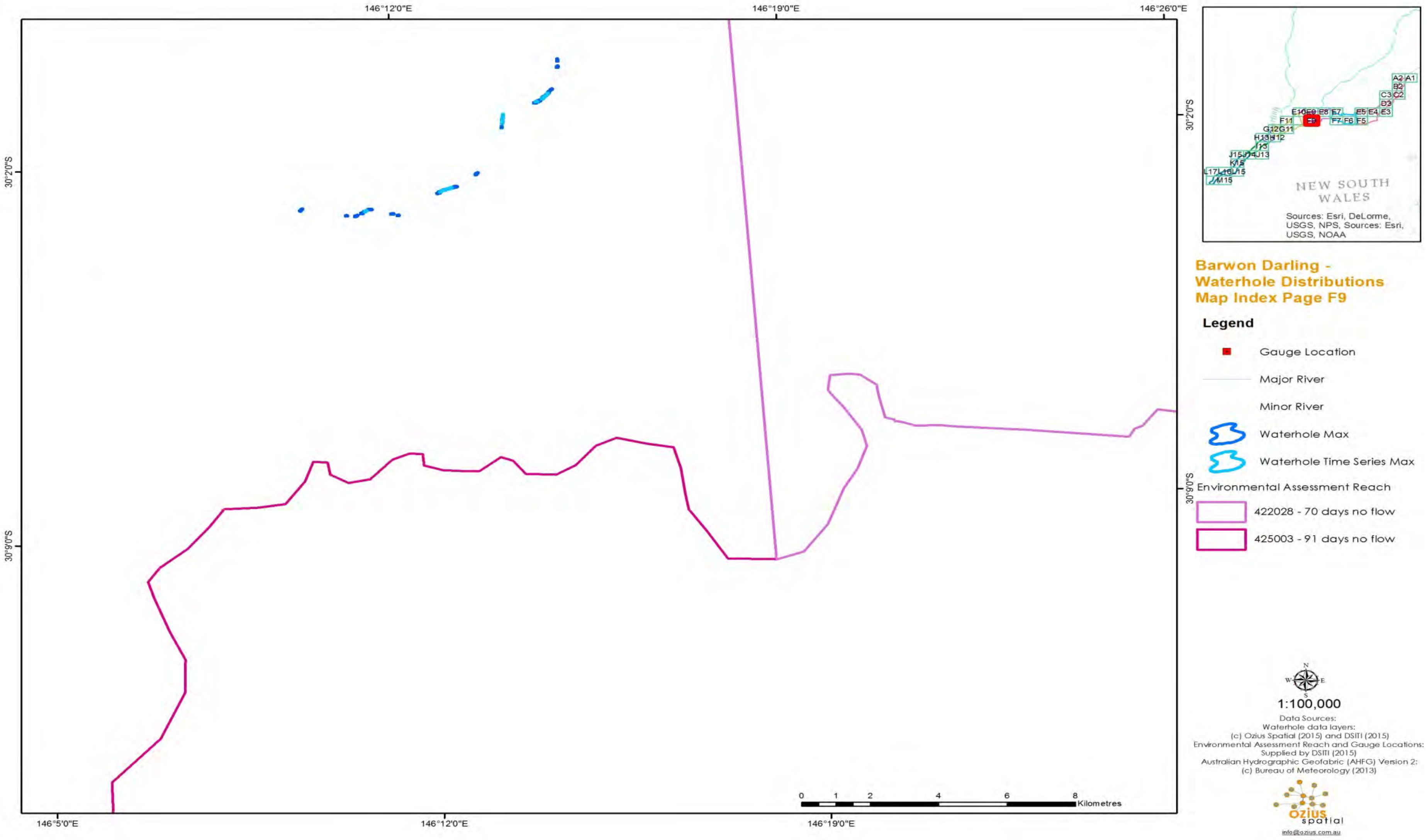

Figure B.37. Waterhole Distributions in Barwon–Darling Page F9

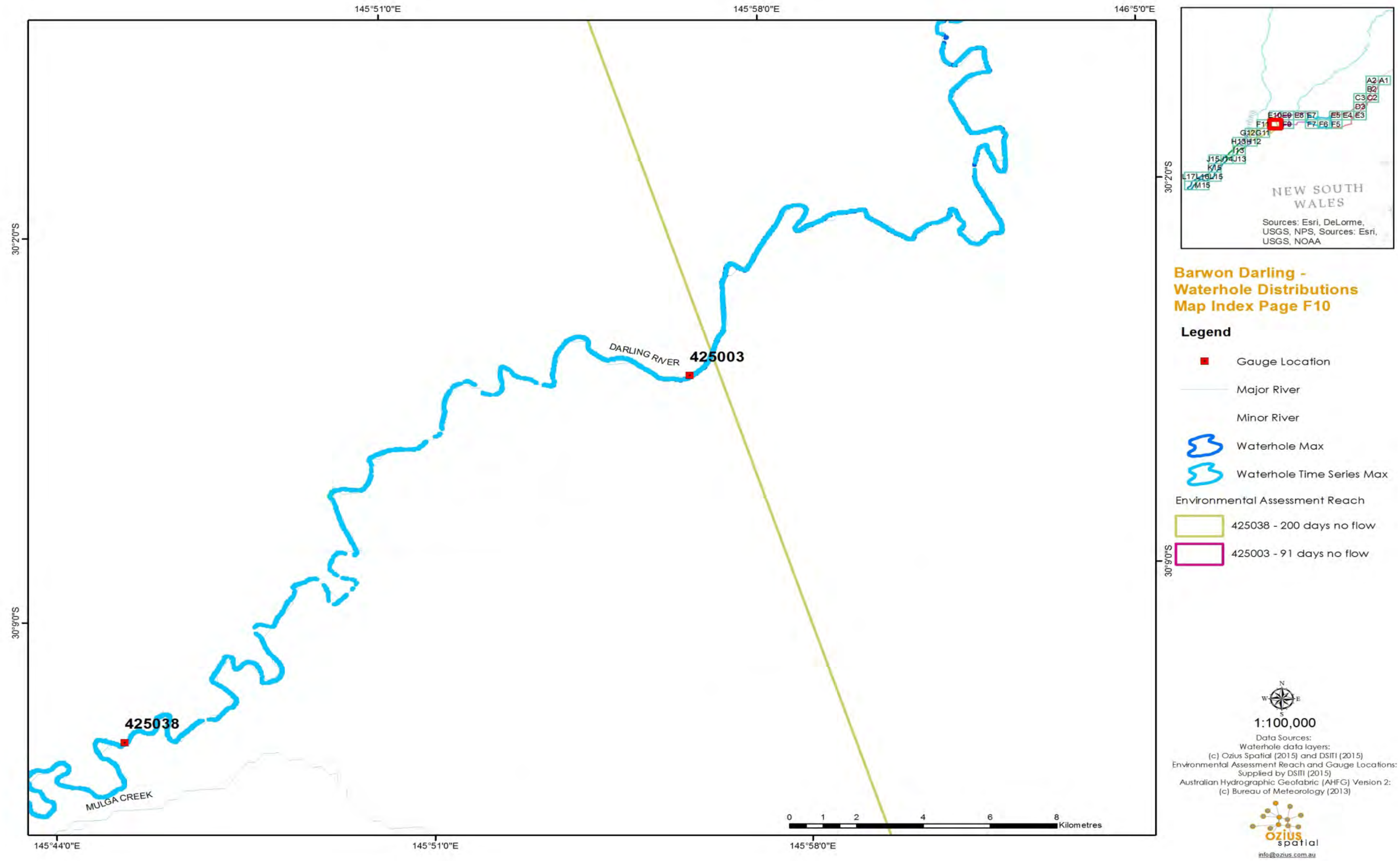

Figure B.38. Waterhole Distributions in Barwon–Darling Page F10

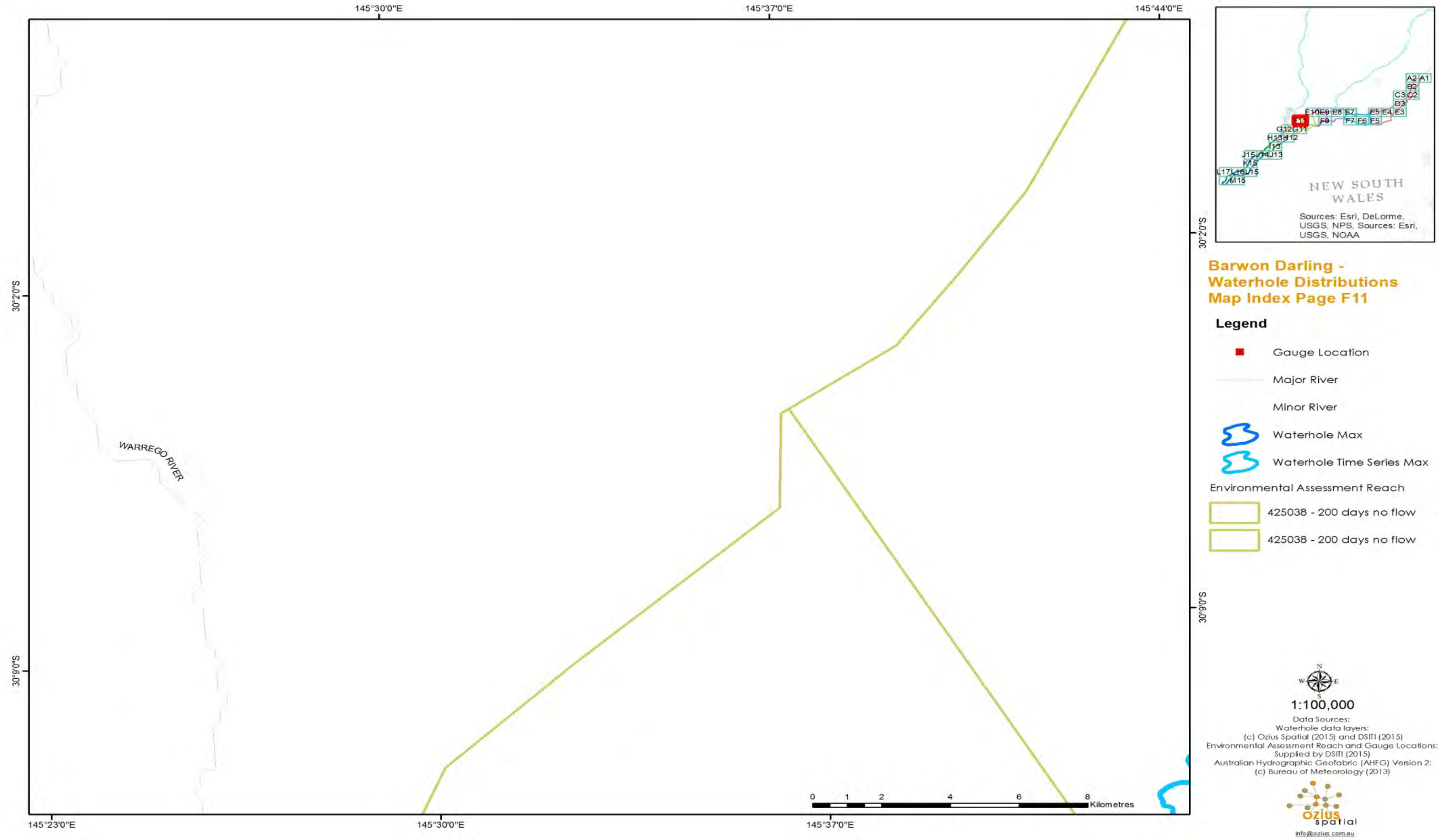

Figure B.39. Waterhole Distributions in Barwon–Darling Page F11

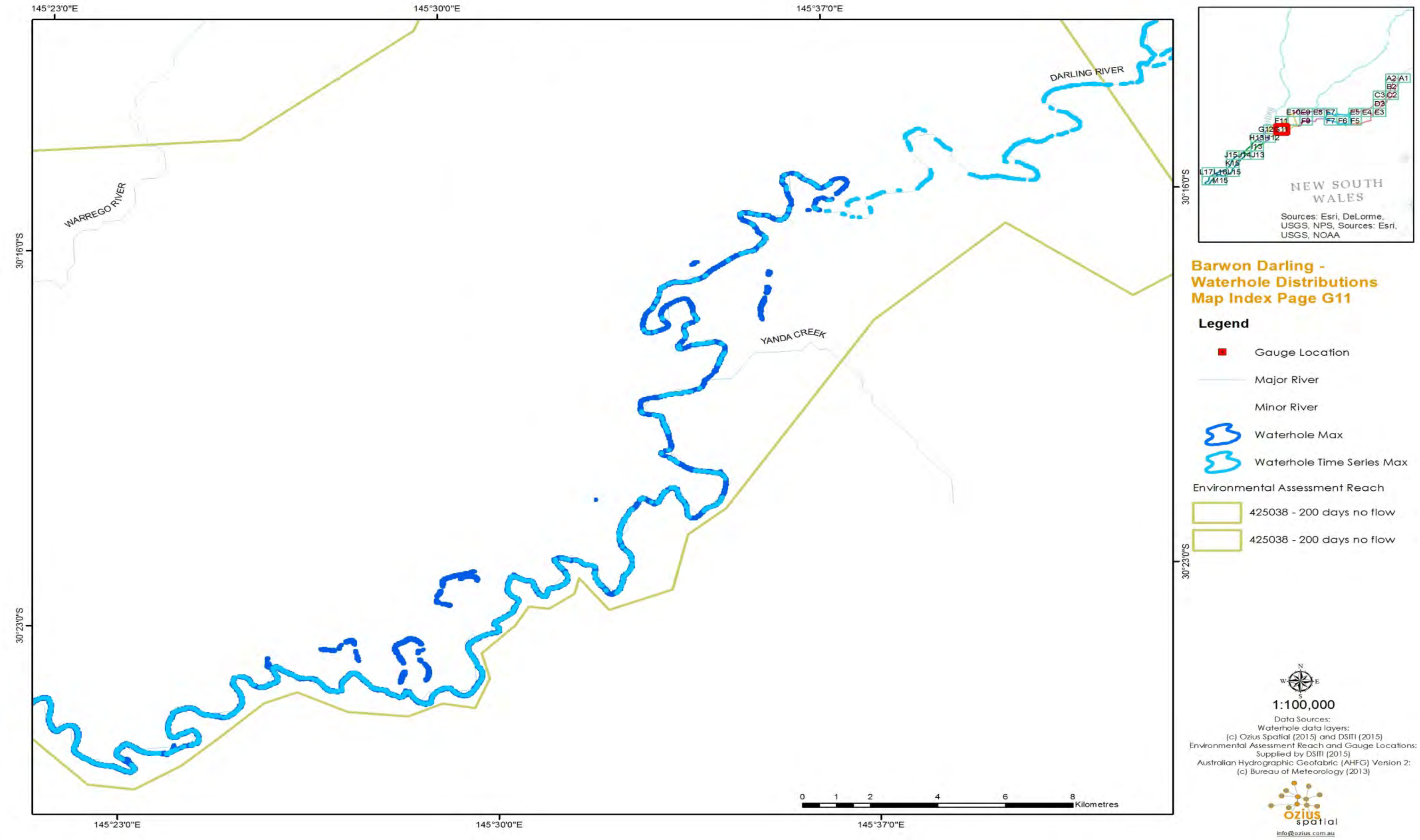

Figure B.40. Waterhole Distributions in Barwon–Darling Page G11

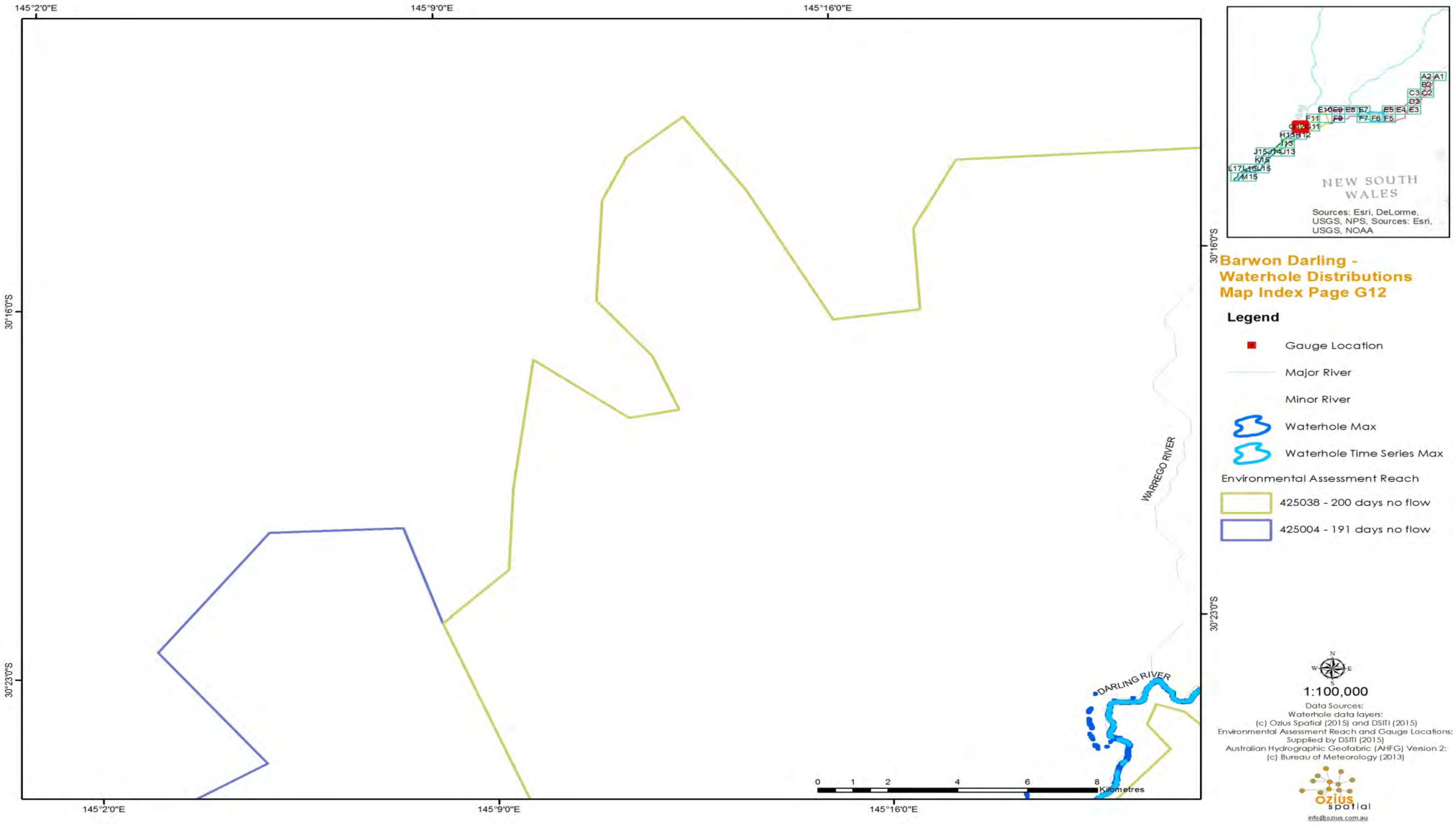

Figure B.41. Waterhole Distributions in Barwon–Darling Page G12

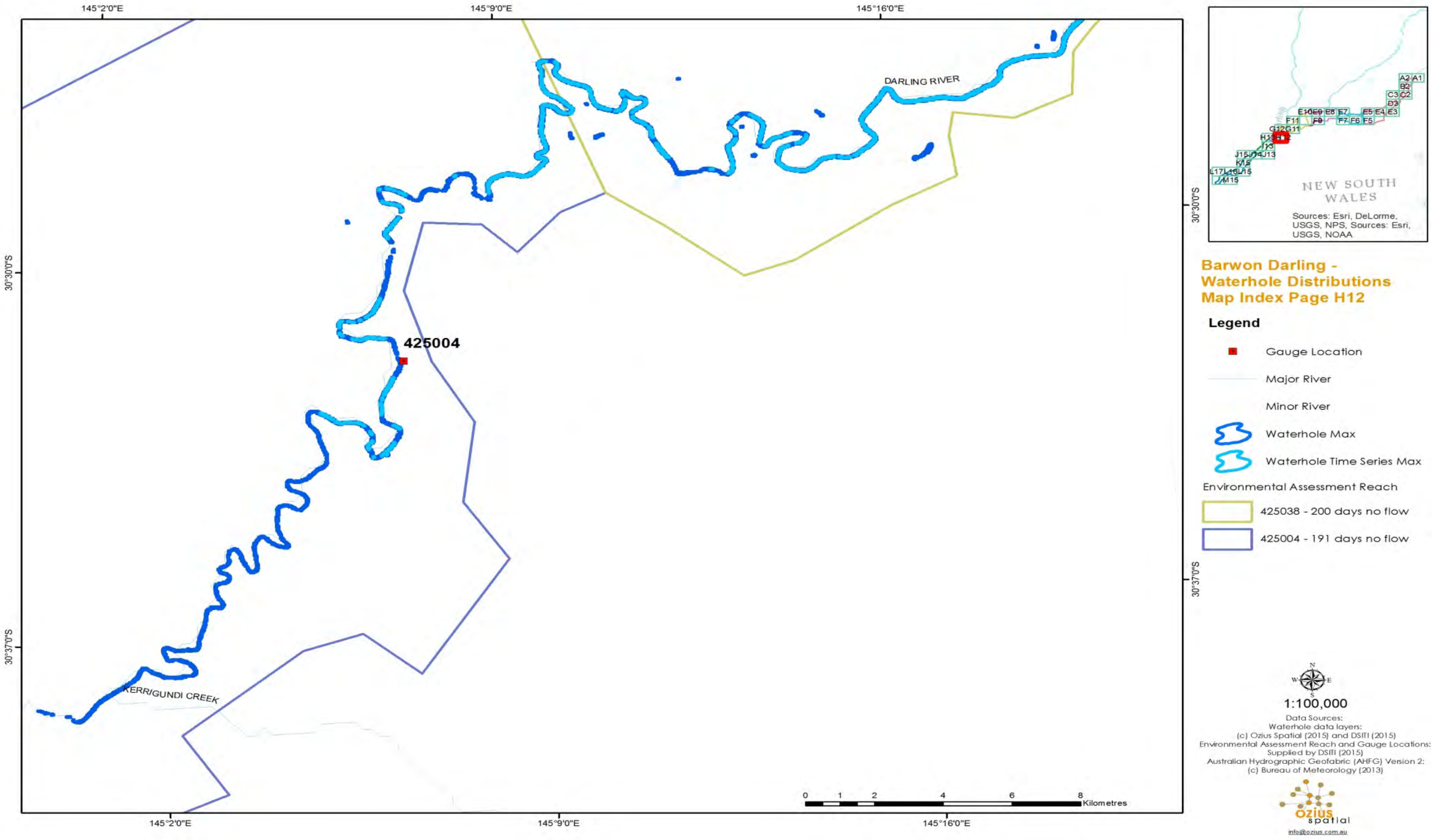

Figure B.42. Waterhole Distributions in Barwon–Darling Page H12

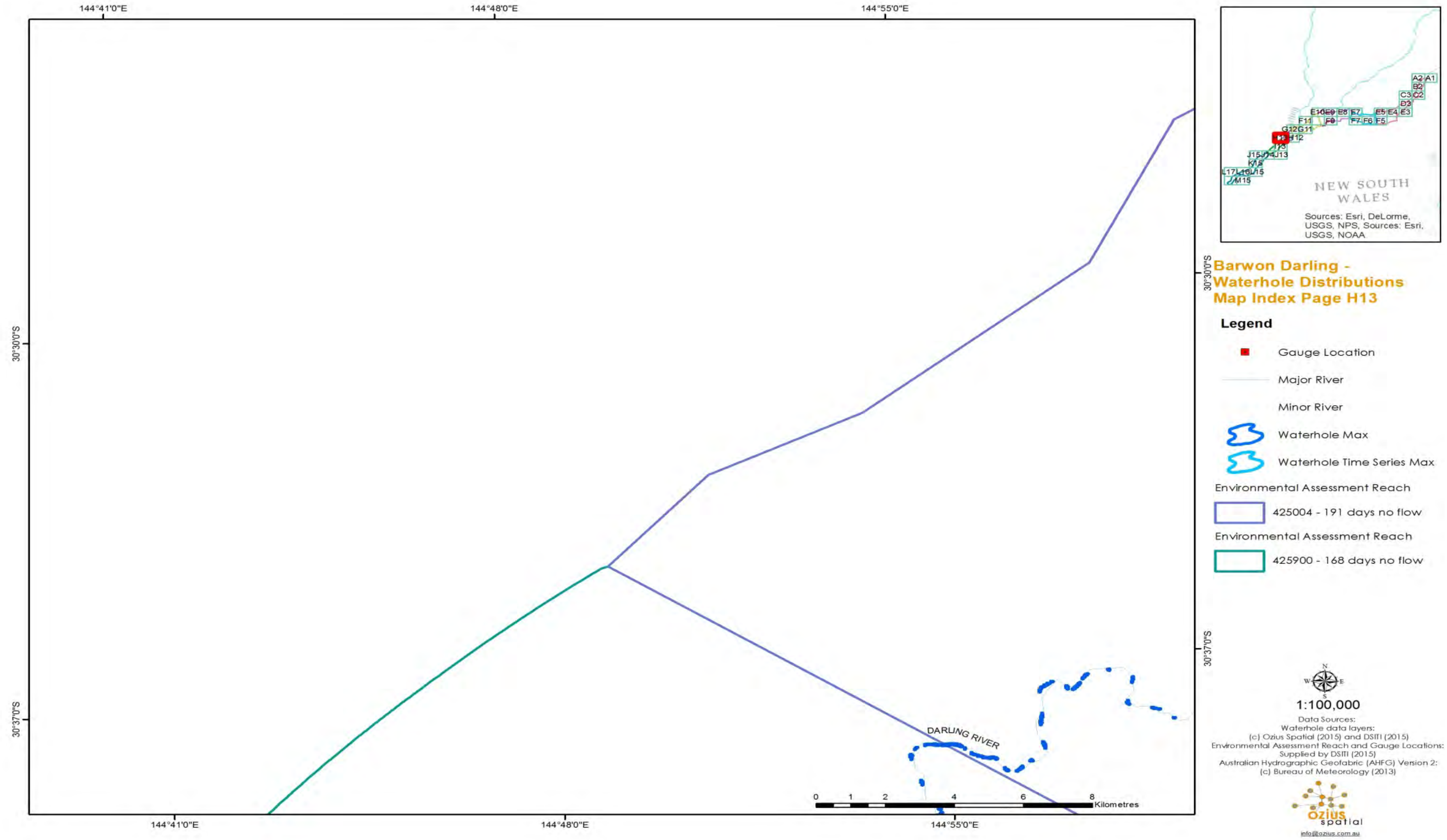

Figure B.43. Waterhole Distributions in Barwon–Darling Page H13

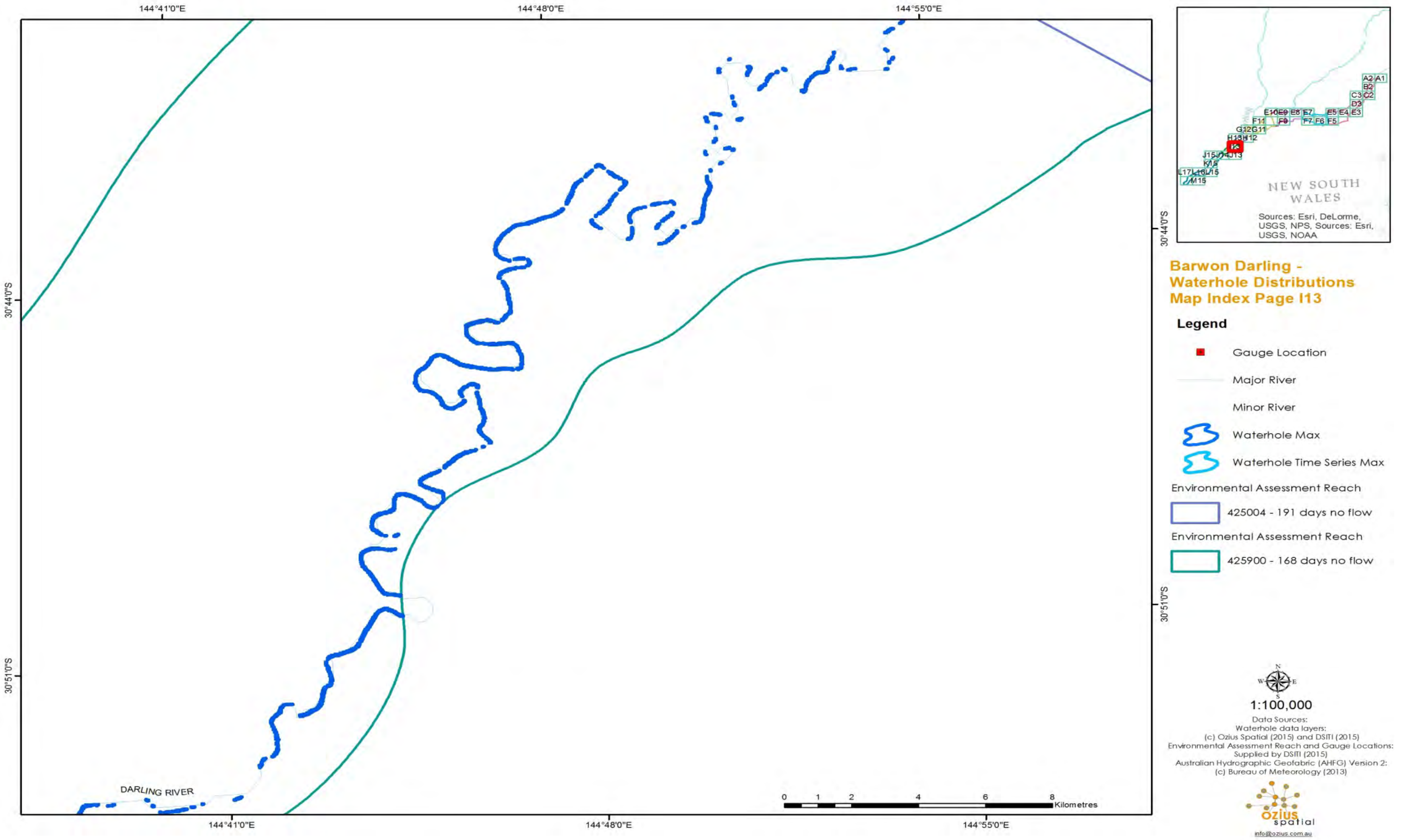

Figure B.44. Waterhole Distributions in Barwon–Darling Page I13

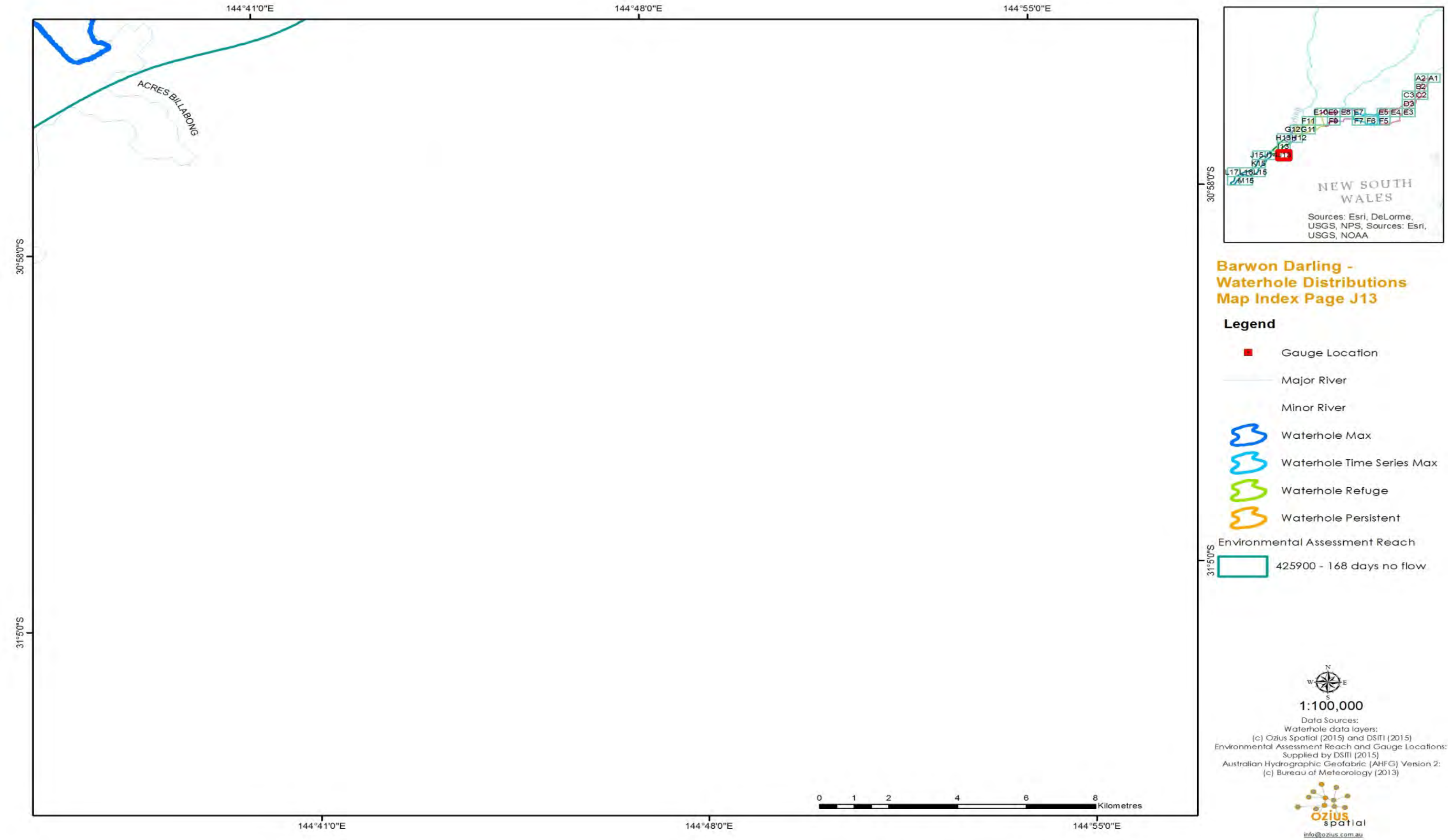

Figure B.45. Waterhole Distributions in Barwon–Darling Page J13

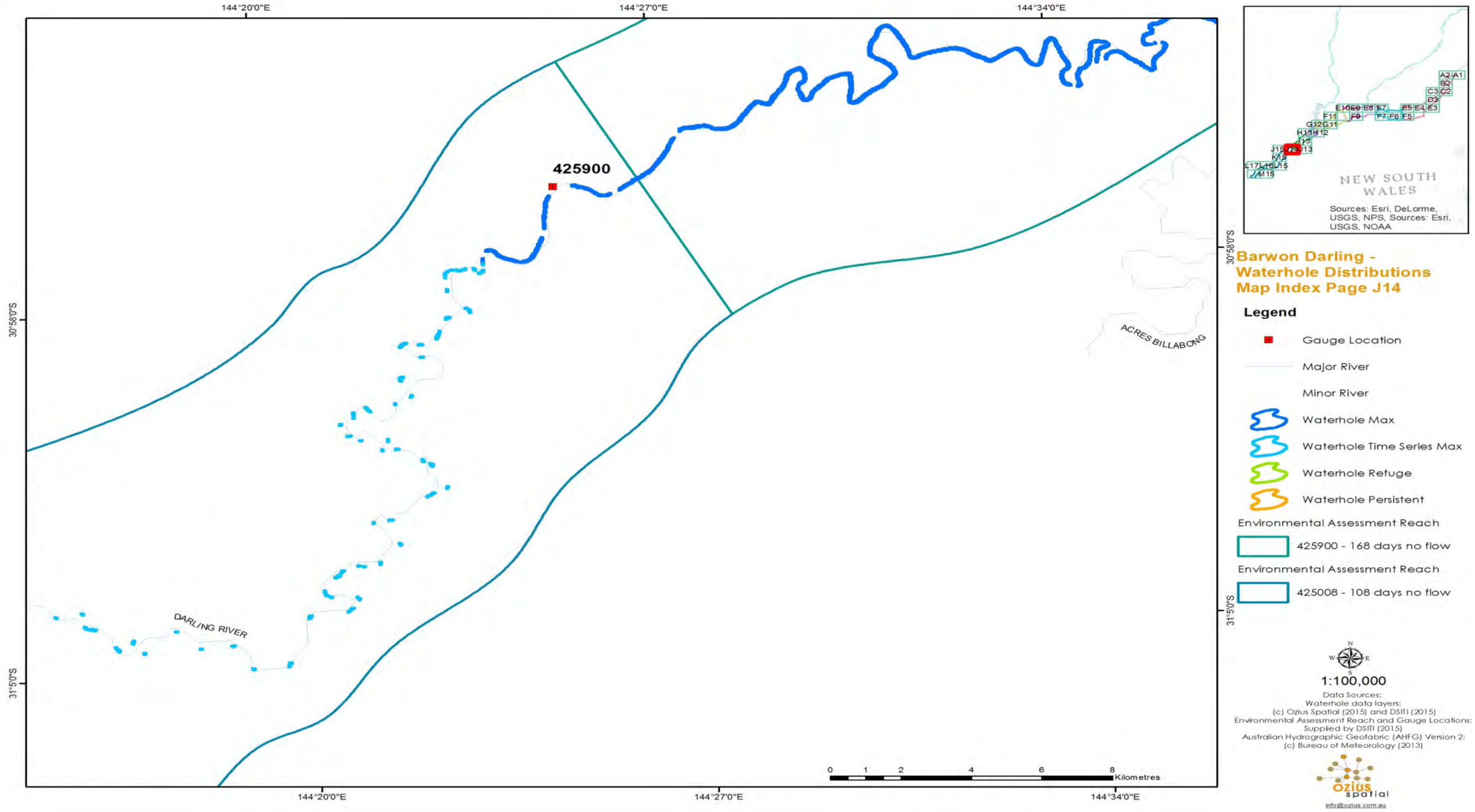

Figure B.46. Waterhole Distributions in Barwon–Darling Page J14

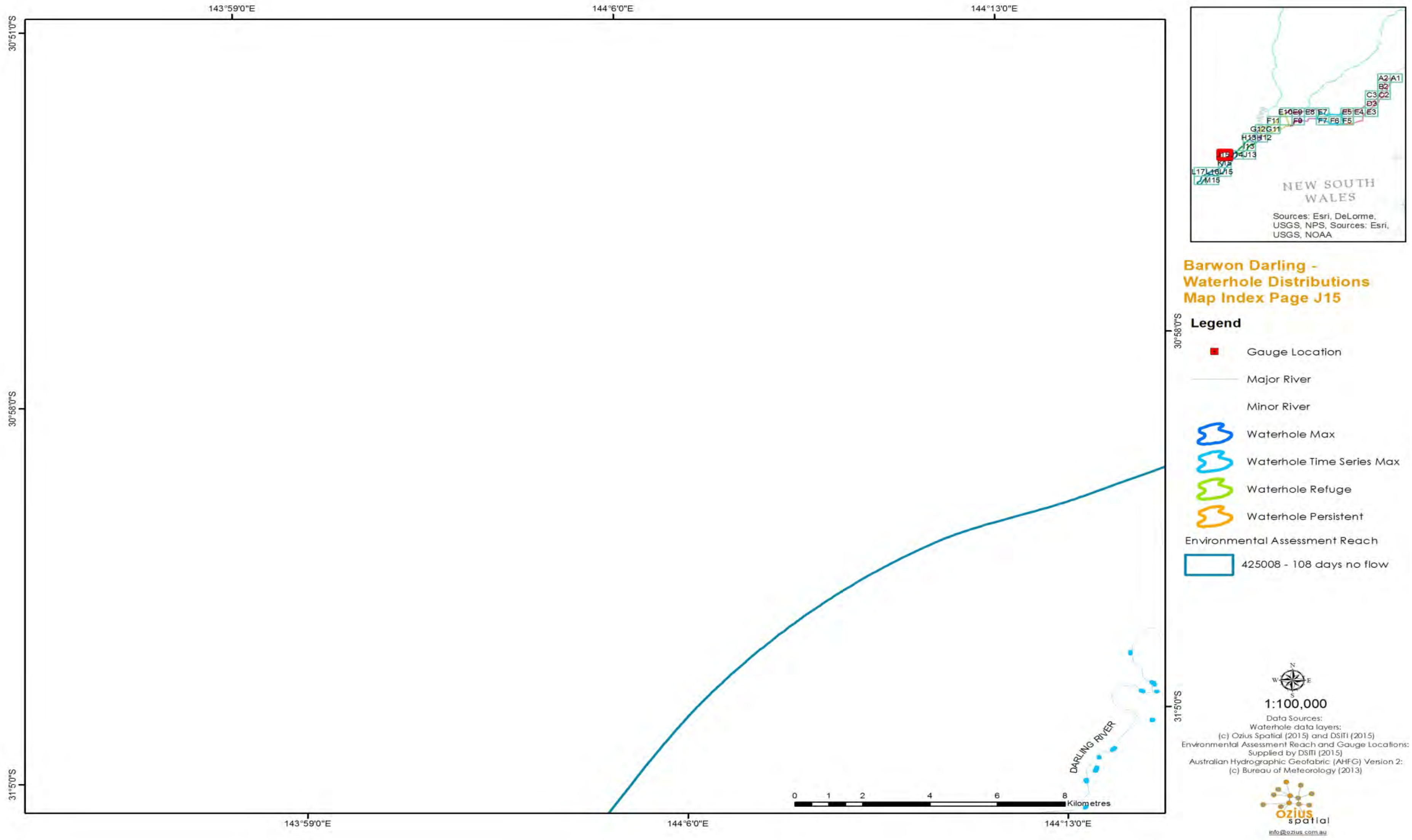

Figure B.47. Waterhole Distributions in Barwon–Darling Page J15

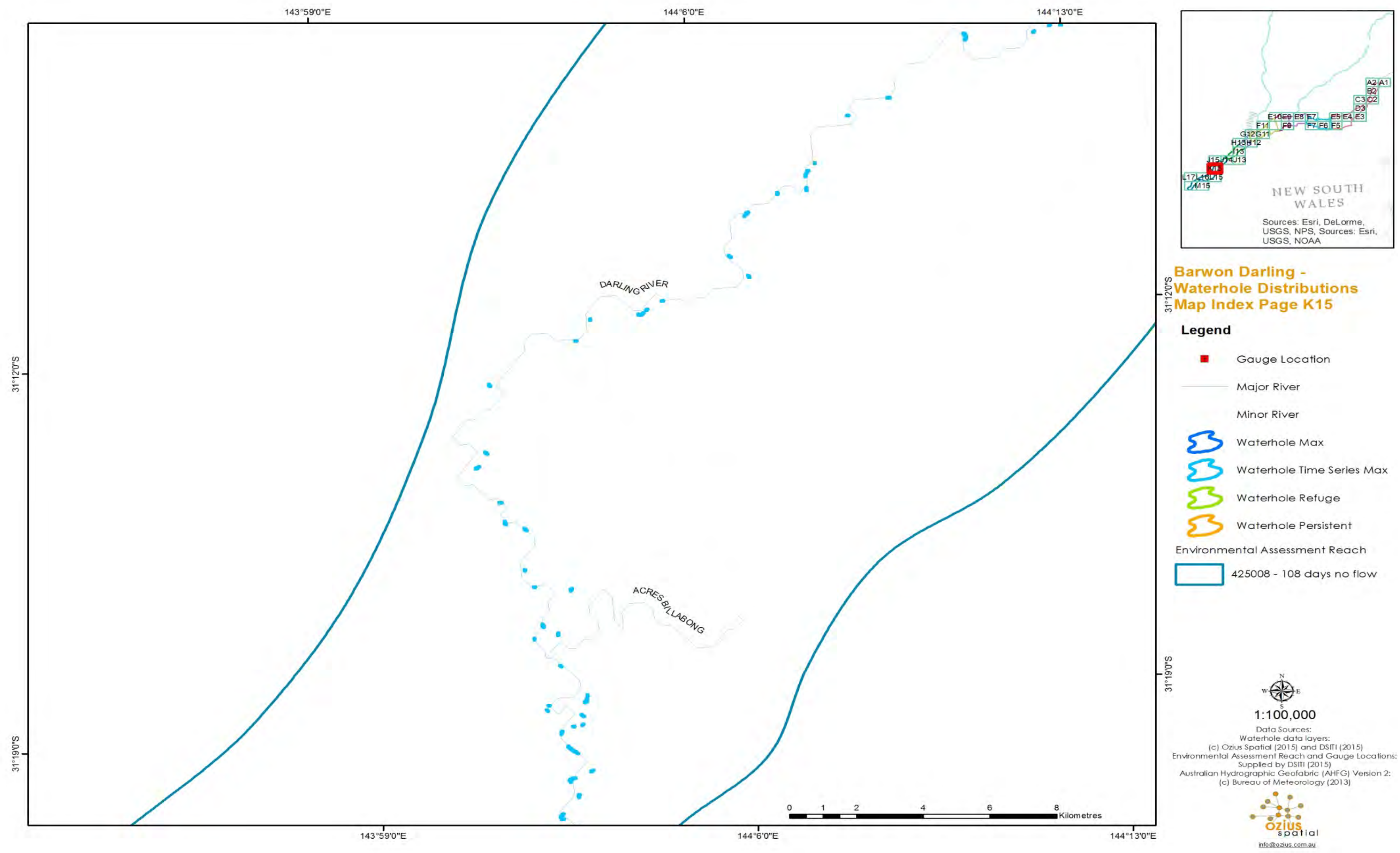

Figure B.48. Waterhole Distributions in Barwon–Darling Page K15

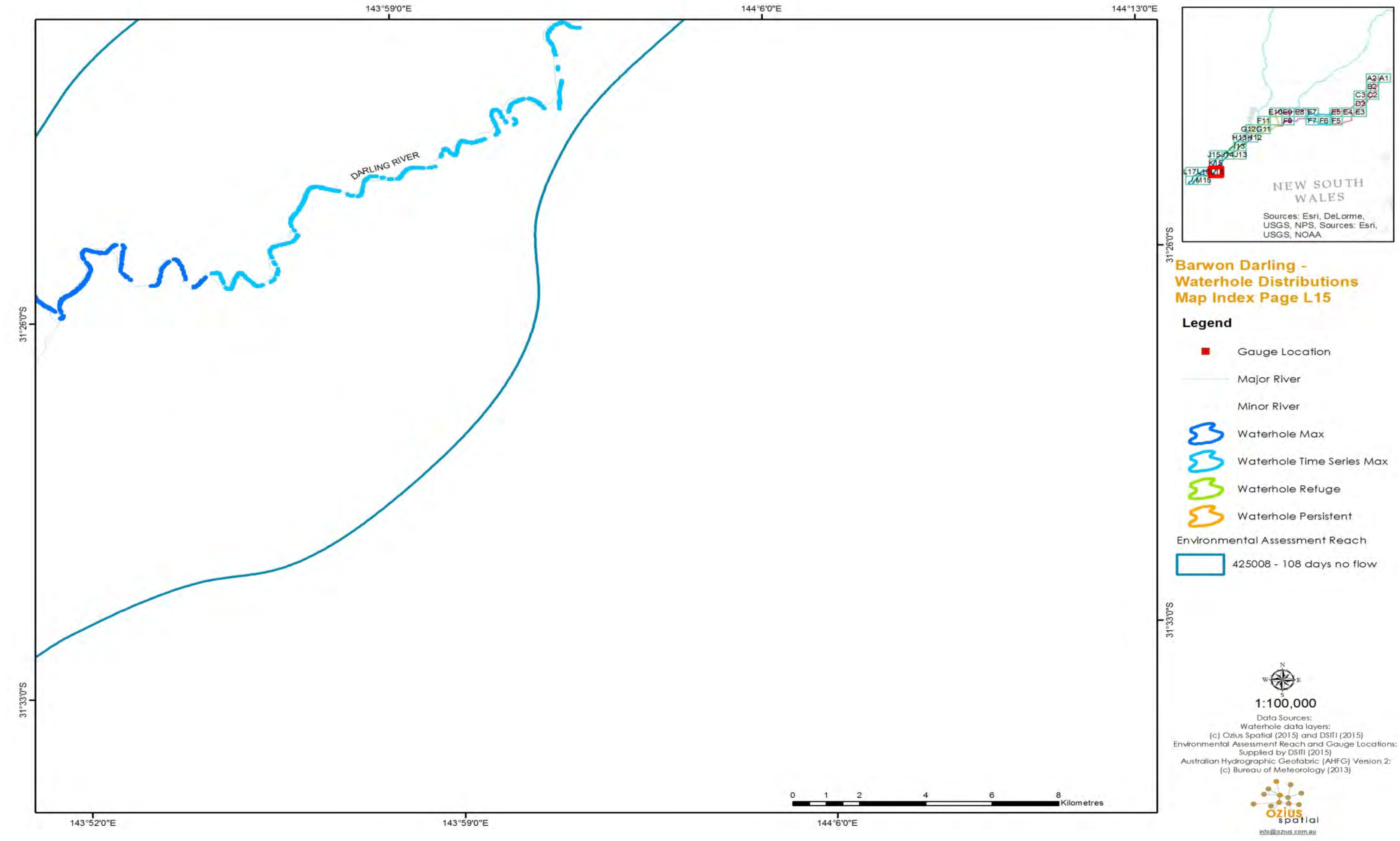

Figure B.49. Waterhole Distributions in Barwon–Darling Page L15

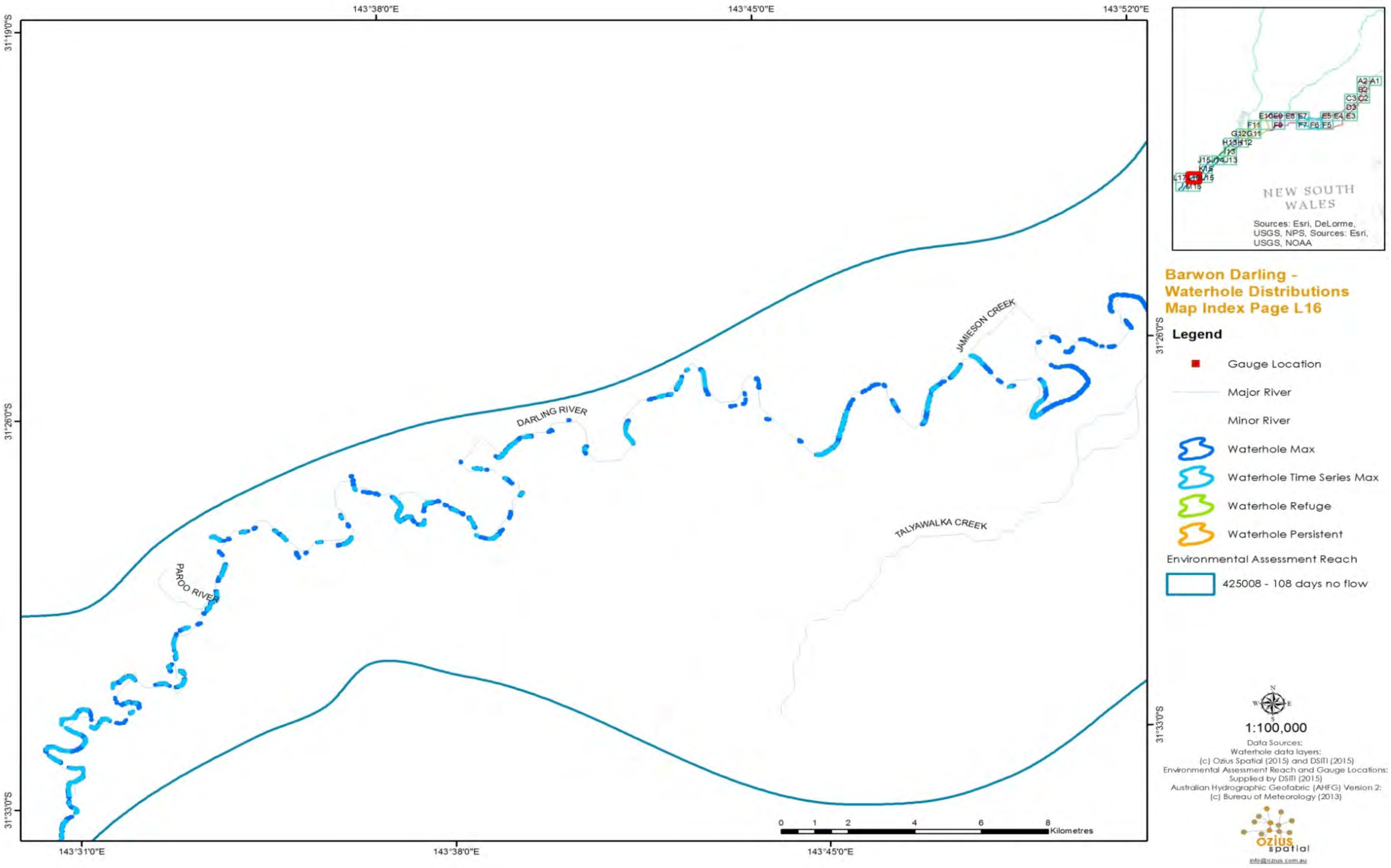

Figure B.50. Waterhole Distributions in Barwon–Darling Page L16

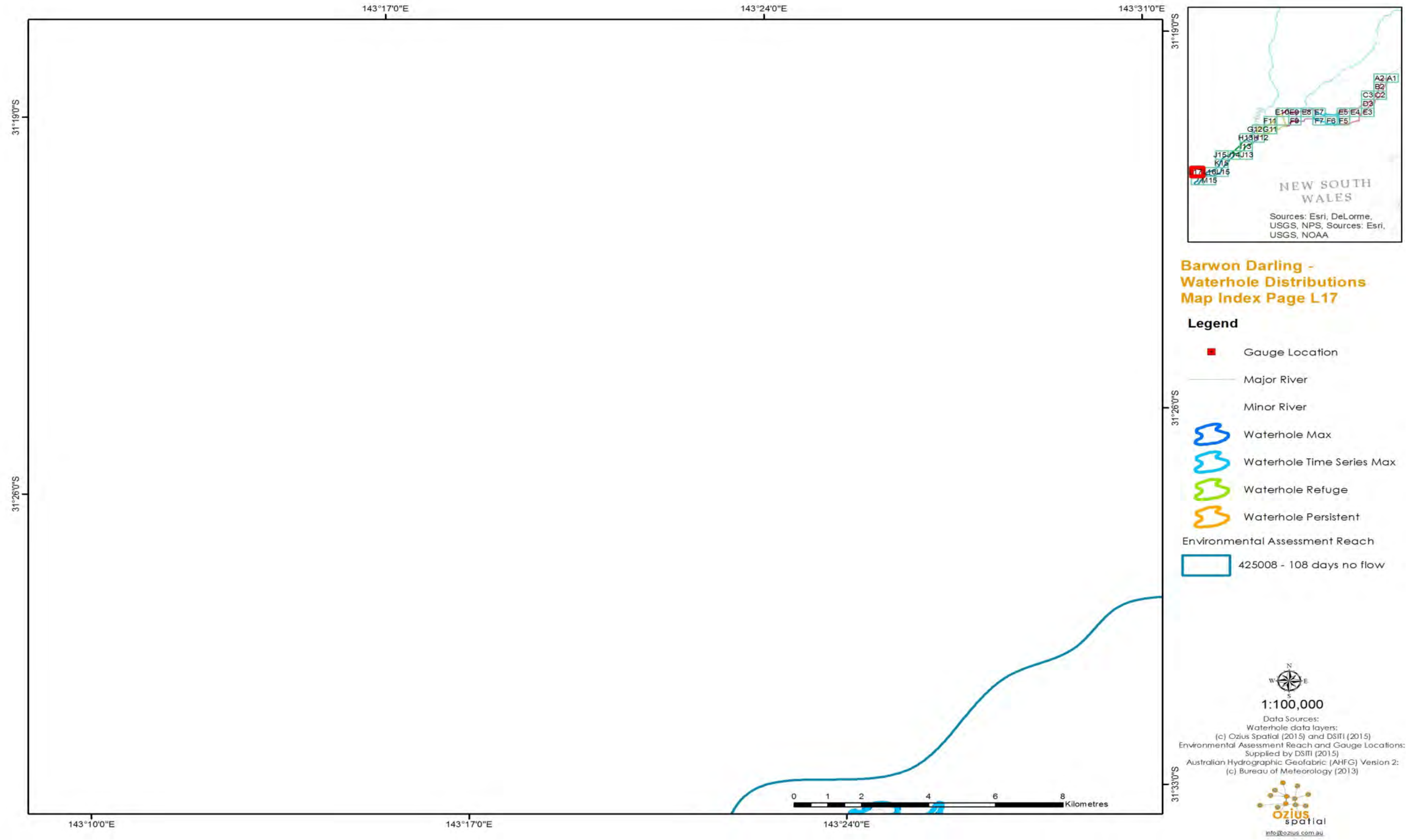

Figure B.51. Waterhole Distributions in Barwon–Darling Page L17

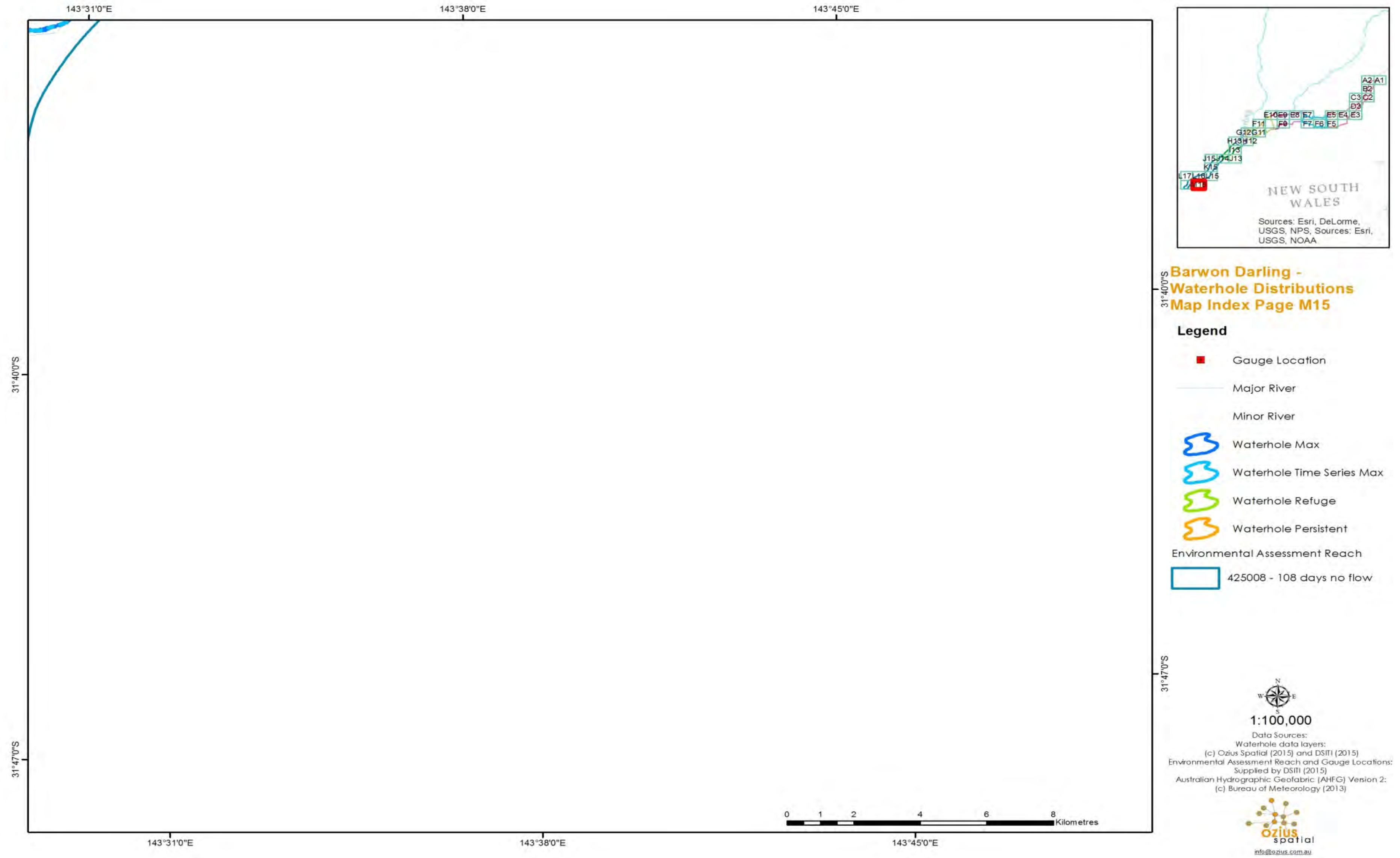

Figure B.52. Waterhole Distributions in Barwon–Darling Page M15

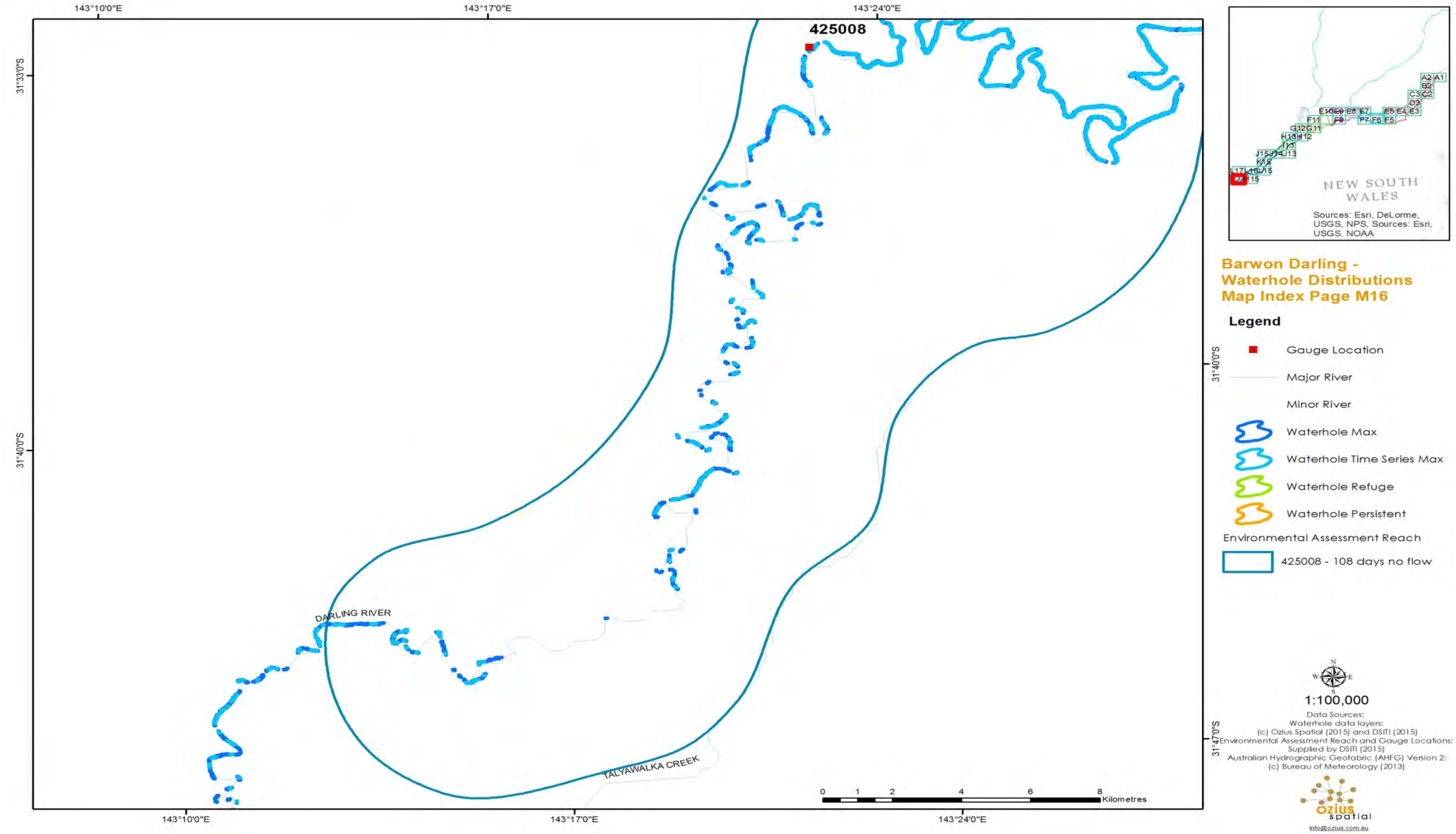

Figure B.53. Waterhole Distributions in Barwon–Darling Page M16

Appendix C – Modelling

Digital Elevation Models (DEMs)

The following figures are the Digital Elevation Models (DEMs) for each of the waterholes showing a map of depth as derived from the bathymetric mapping surveys. The DEM for each waterhole was used to derive the surface area and volume at 1cm depth intervals.

Culgoa River

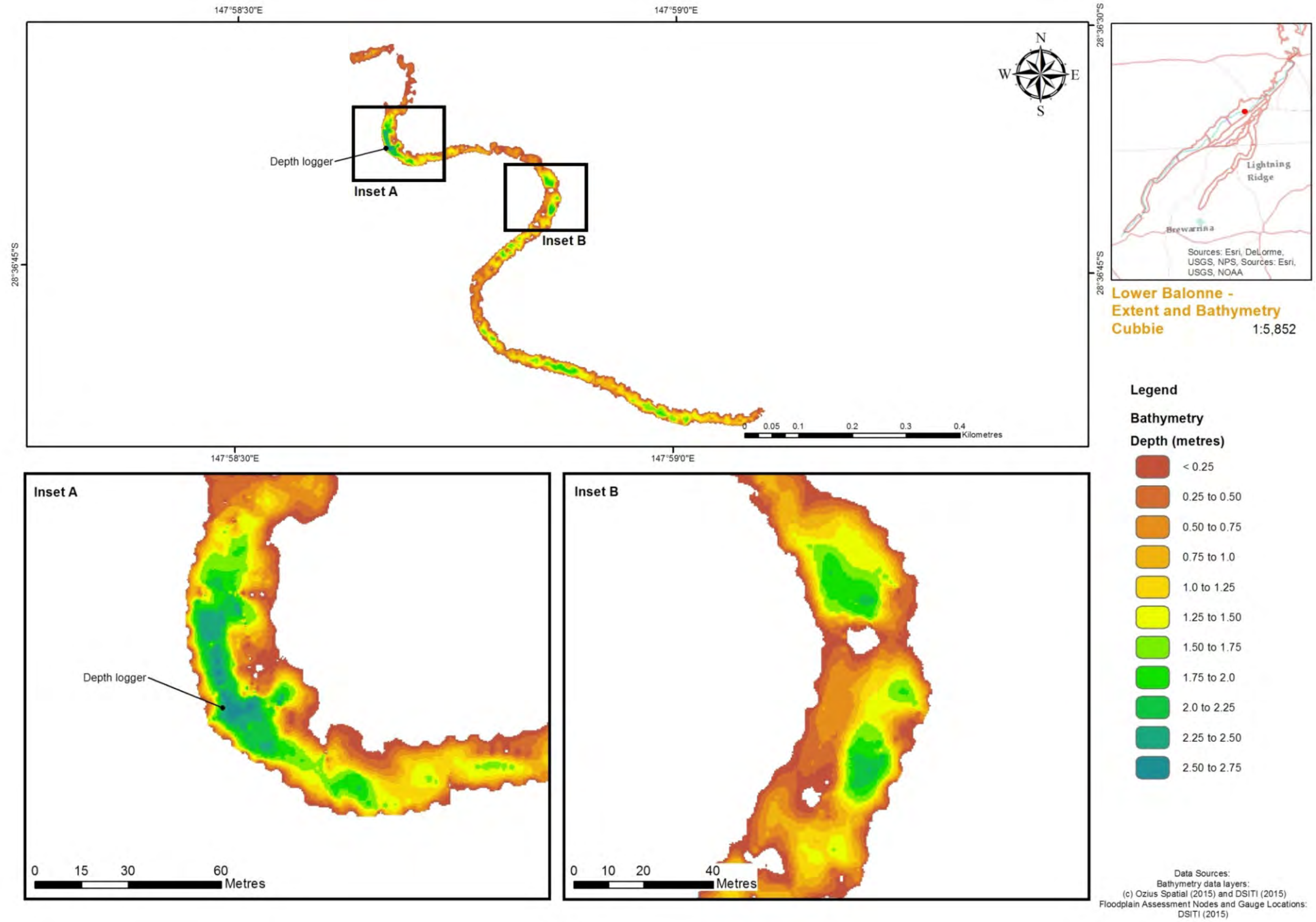

Figure C.1. Digital Elevation Model of Cubbie Waterhole.

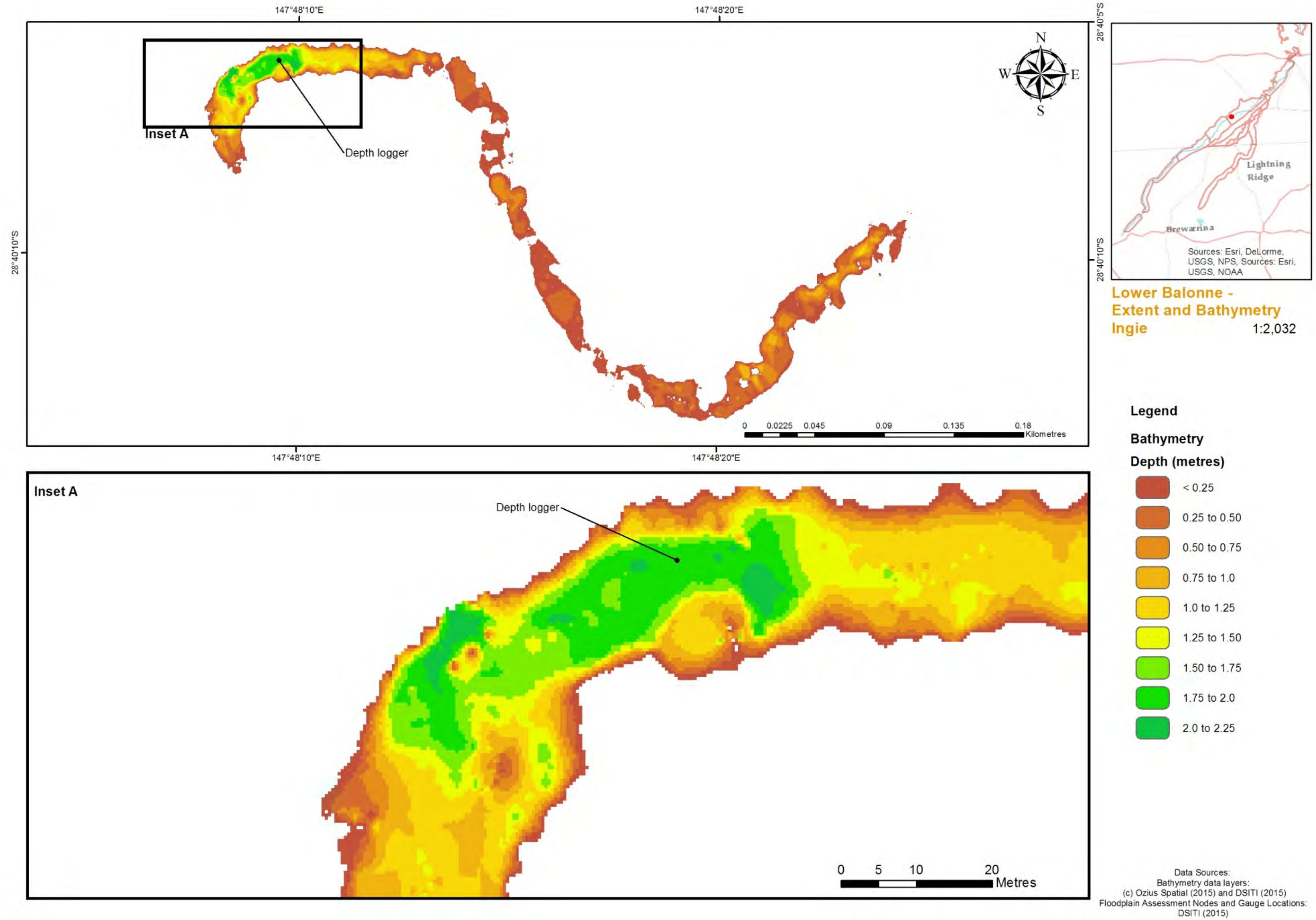

Figure C.2. Digital Elevation Model of Ingie Waterhole.

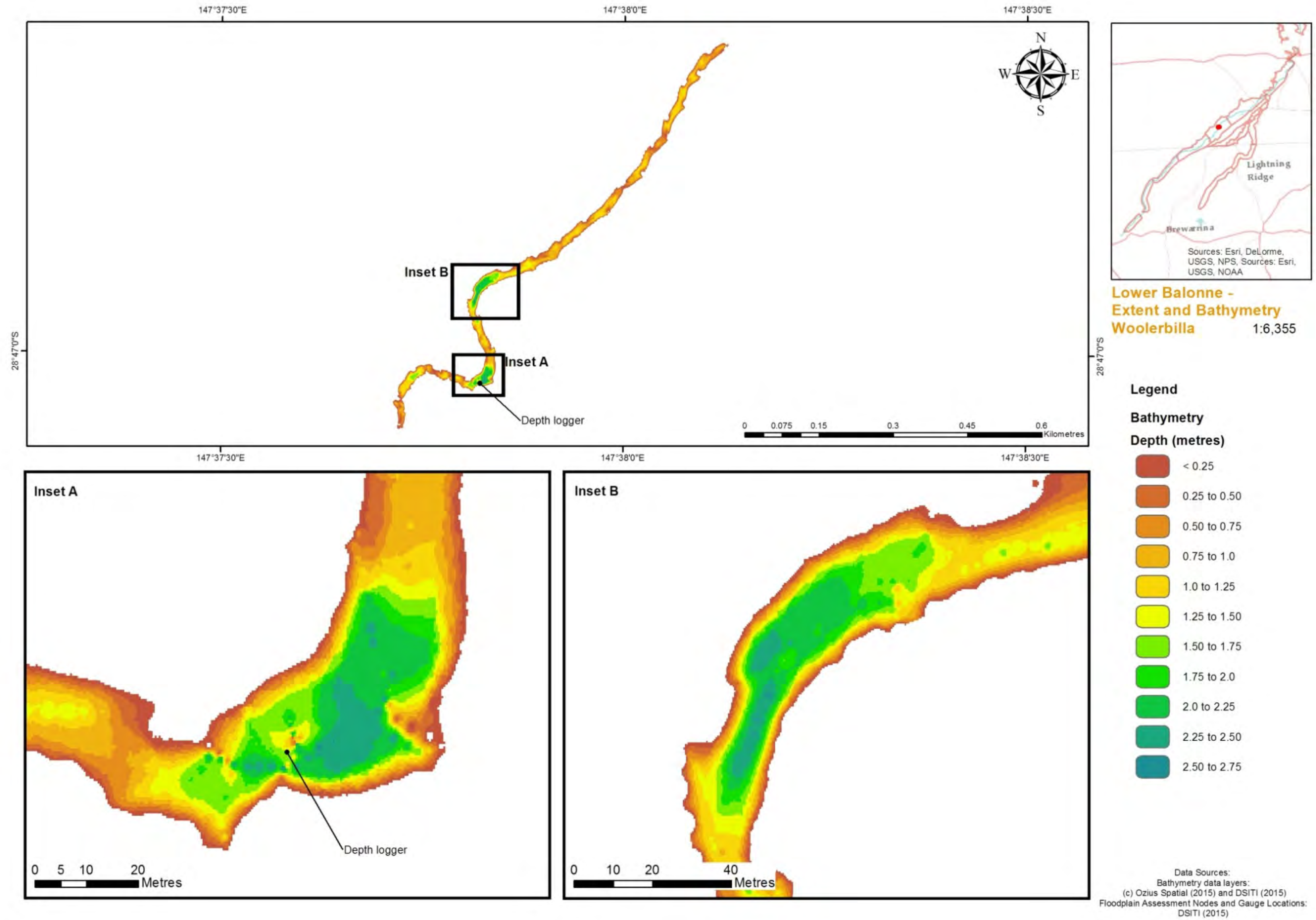

Figure C.3. Digital Elevation Model of Woolerbilla Waterhole.

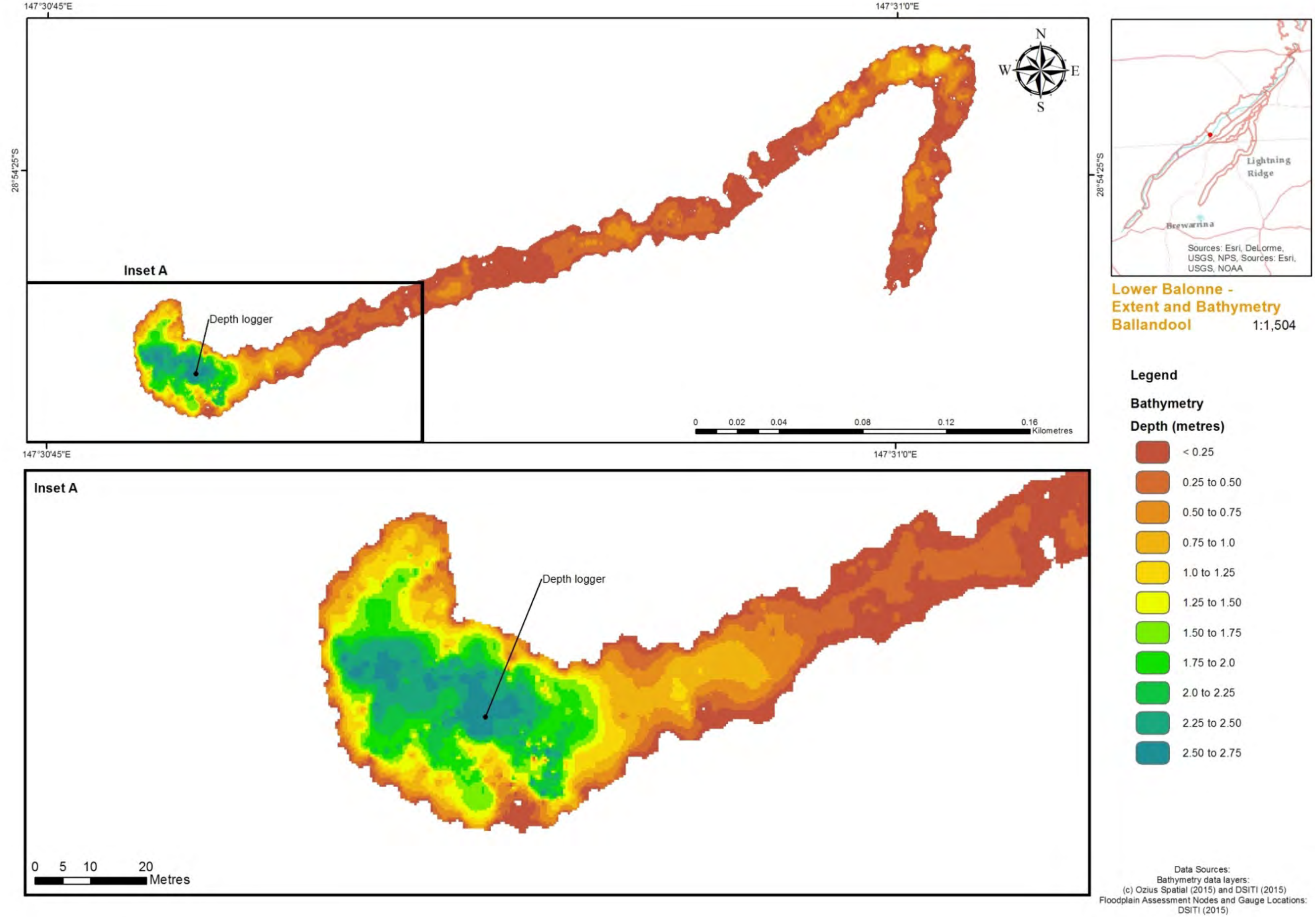

Figure C.4. Digital Elevation Model of Ballandool Waterhole.

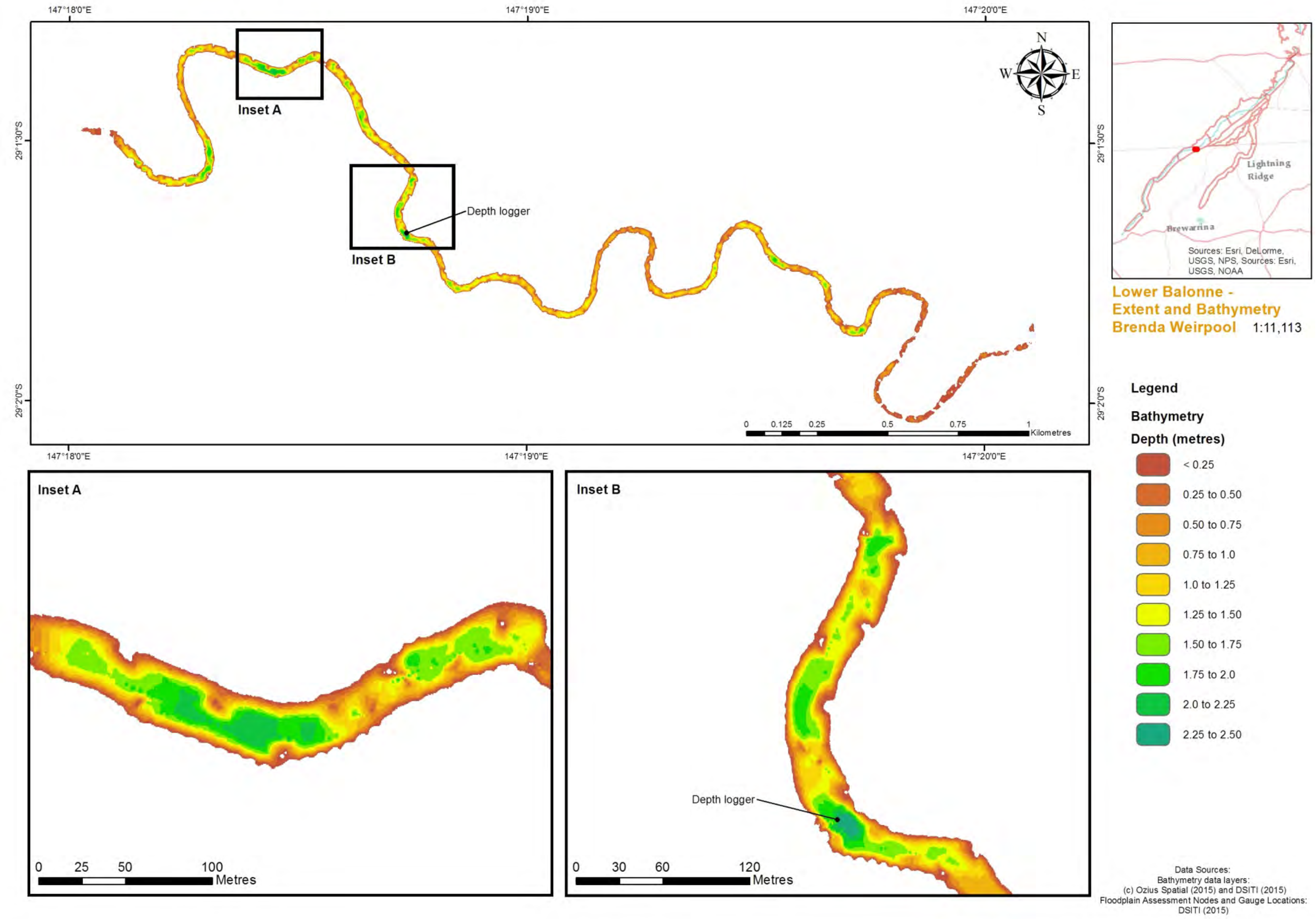

Figure C.5. Digital Elevation Model of Brenda Weir Waterhole.

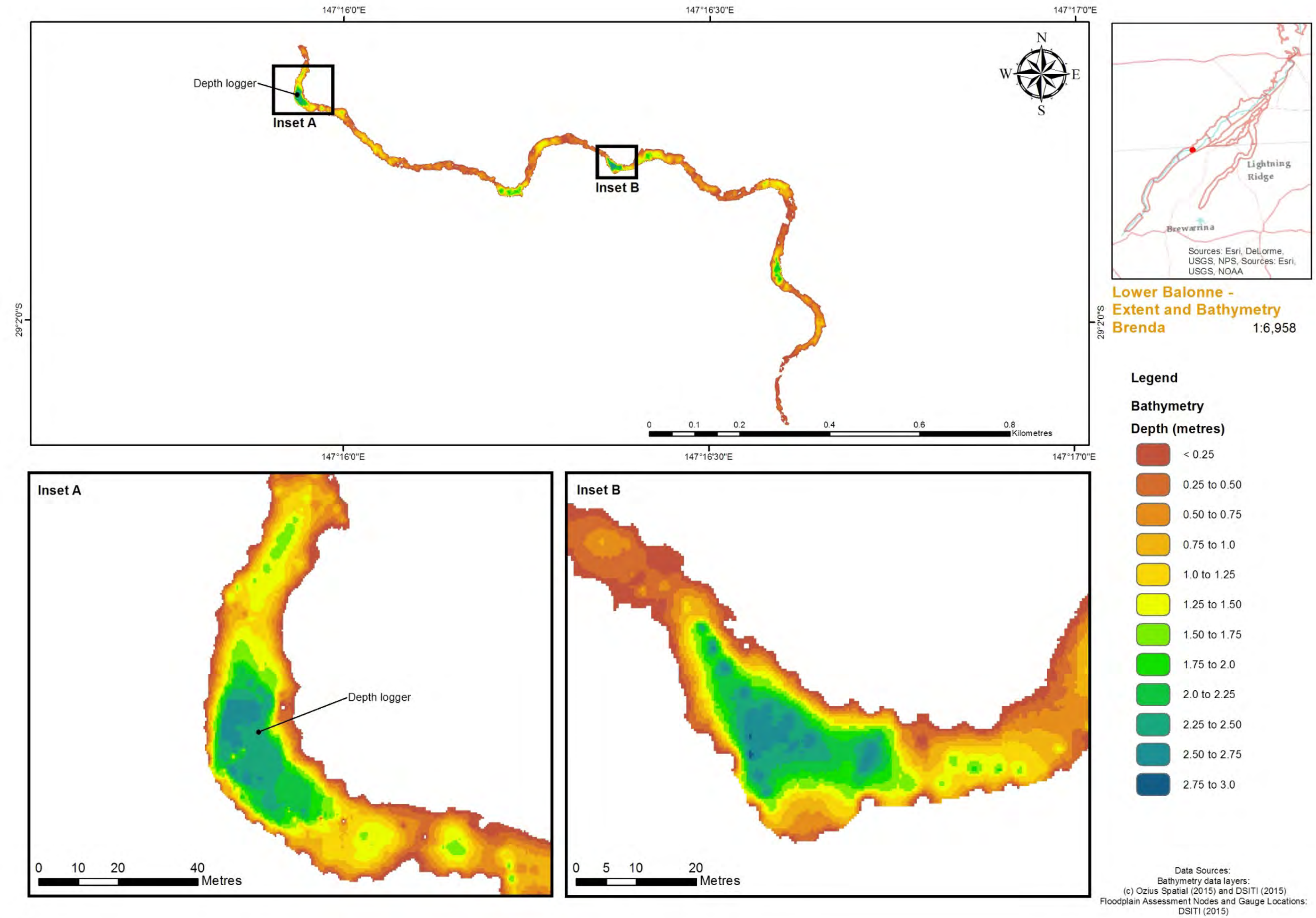

Figure C.6. Digital Elevation Model of Brenda Waterhole.

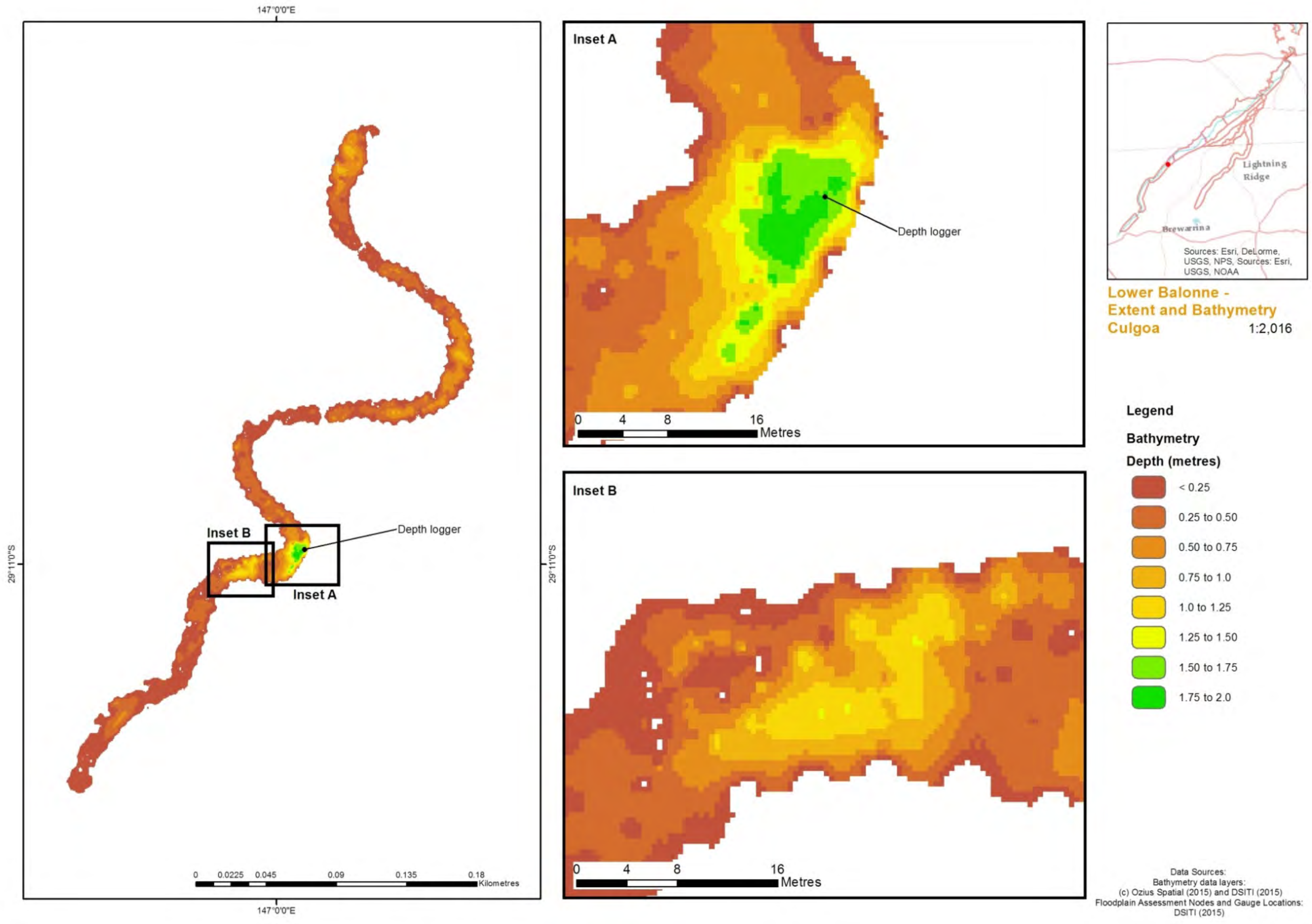

Figure C.7. Digital Elevation Model of Culgoa National Park Waterhole.

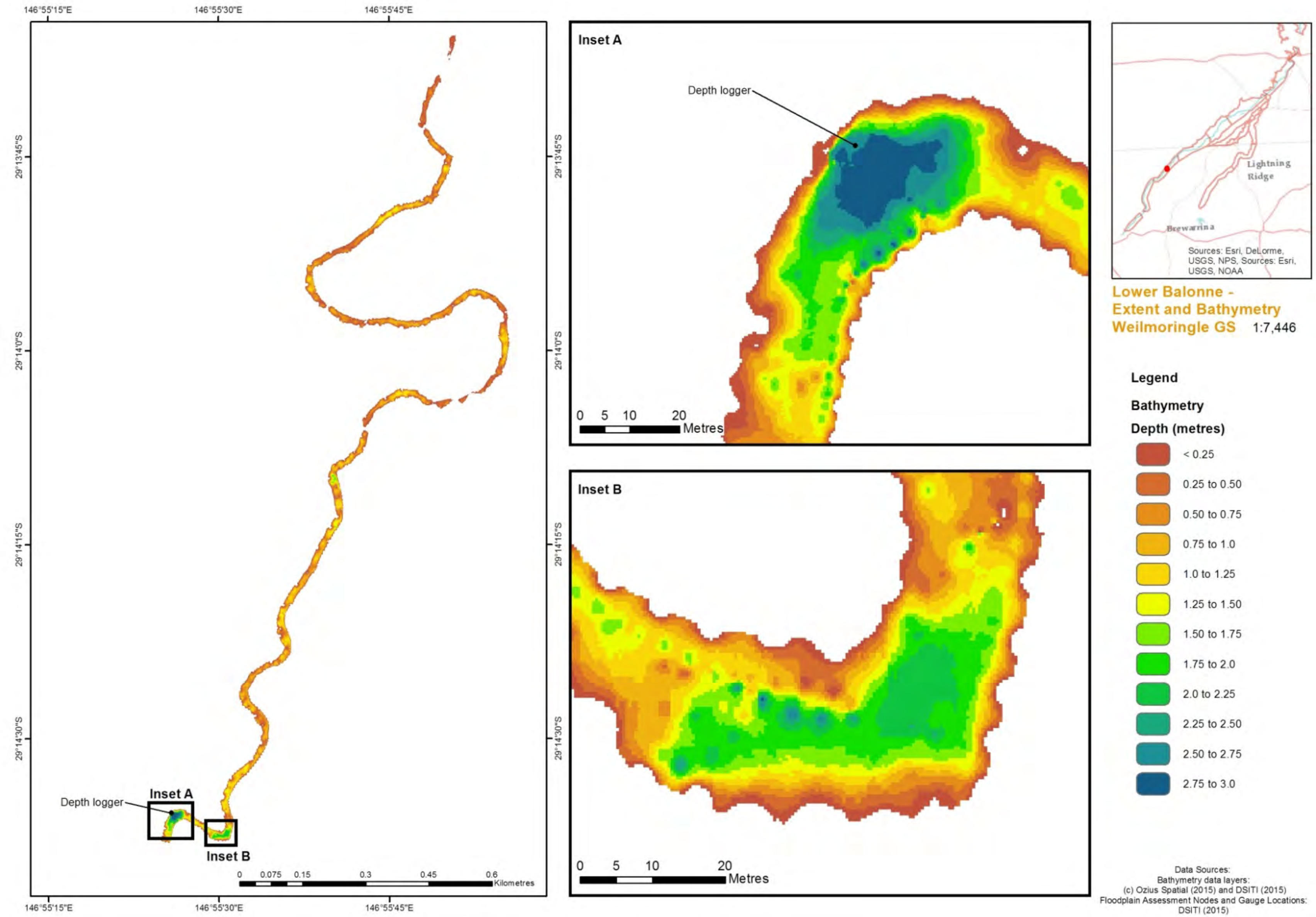

Figure C.8. Digital Elevation Model of Weilmoringle GS Waterhole.

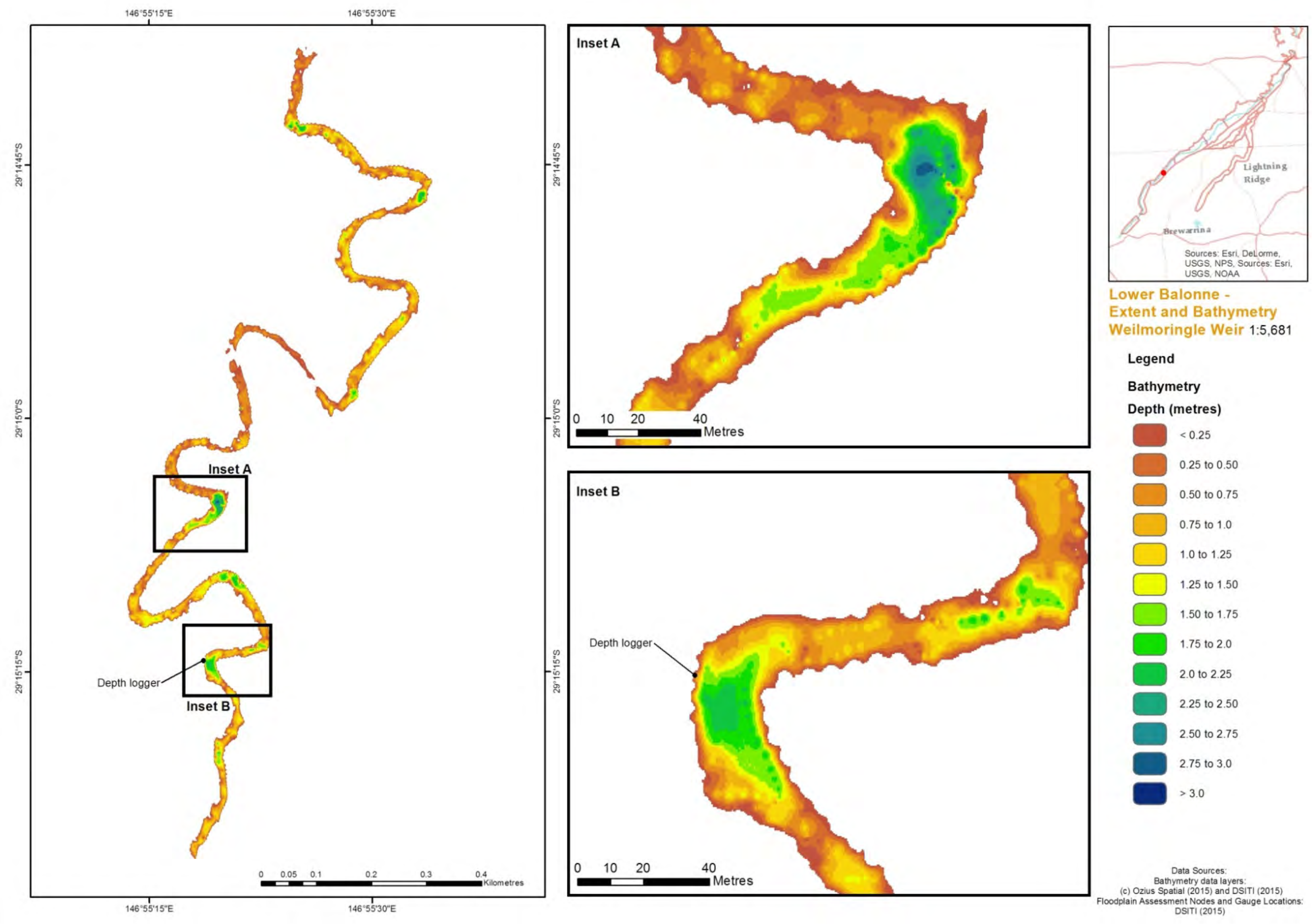

Figure C.9. Digital Elevation Model of Weilmoringle Weir Waterhole.

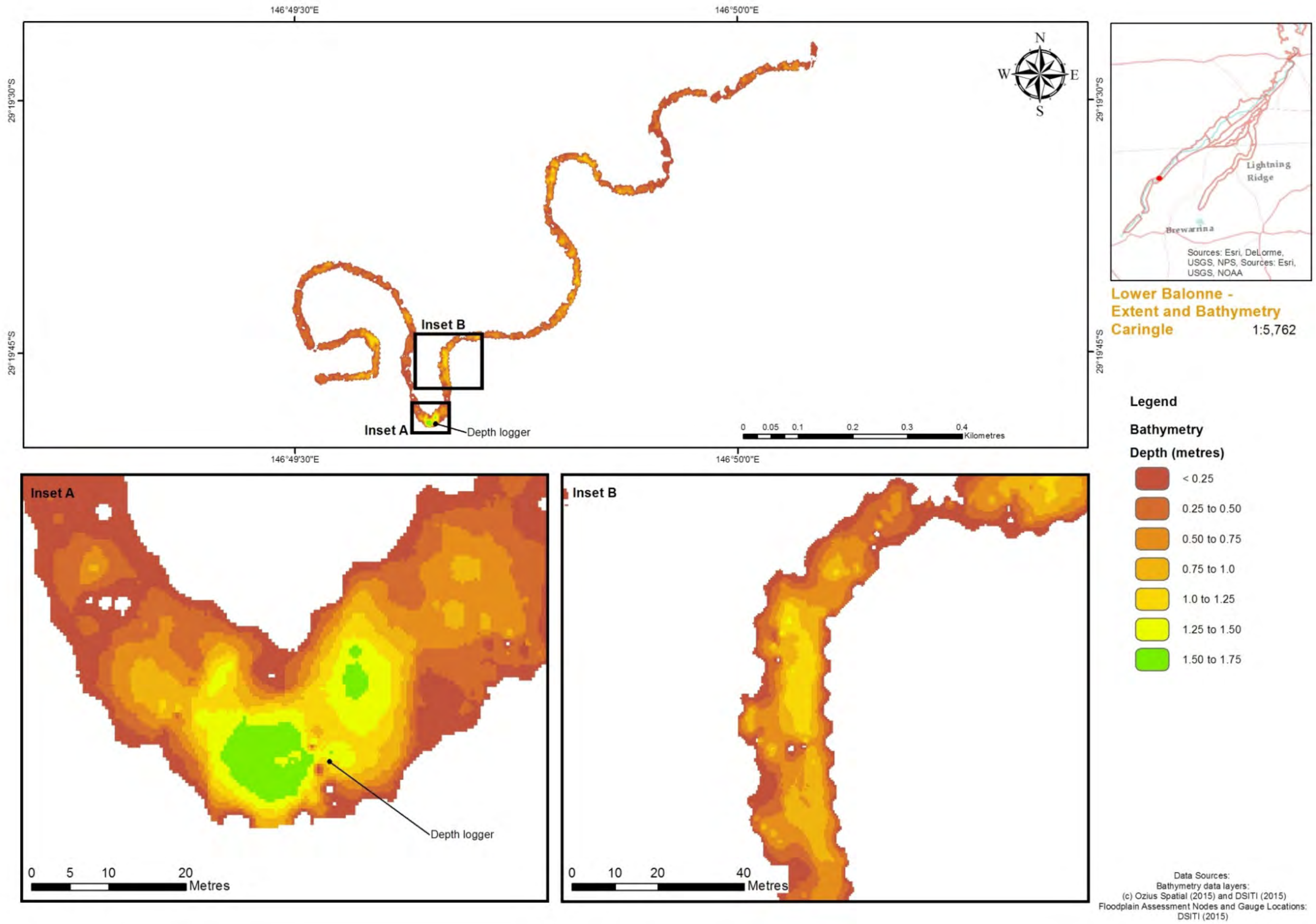

Figure C.10. Digital Elevation Model of Caringle Waterhole.

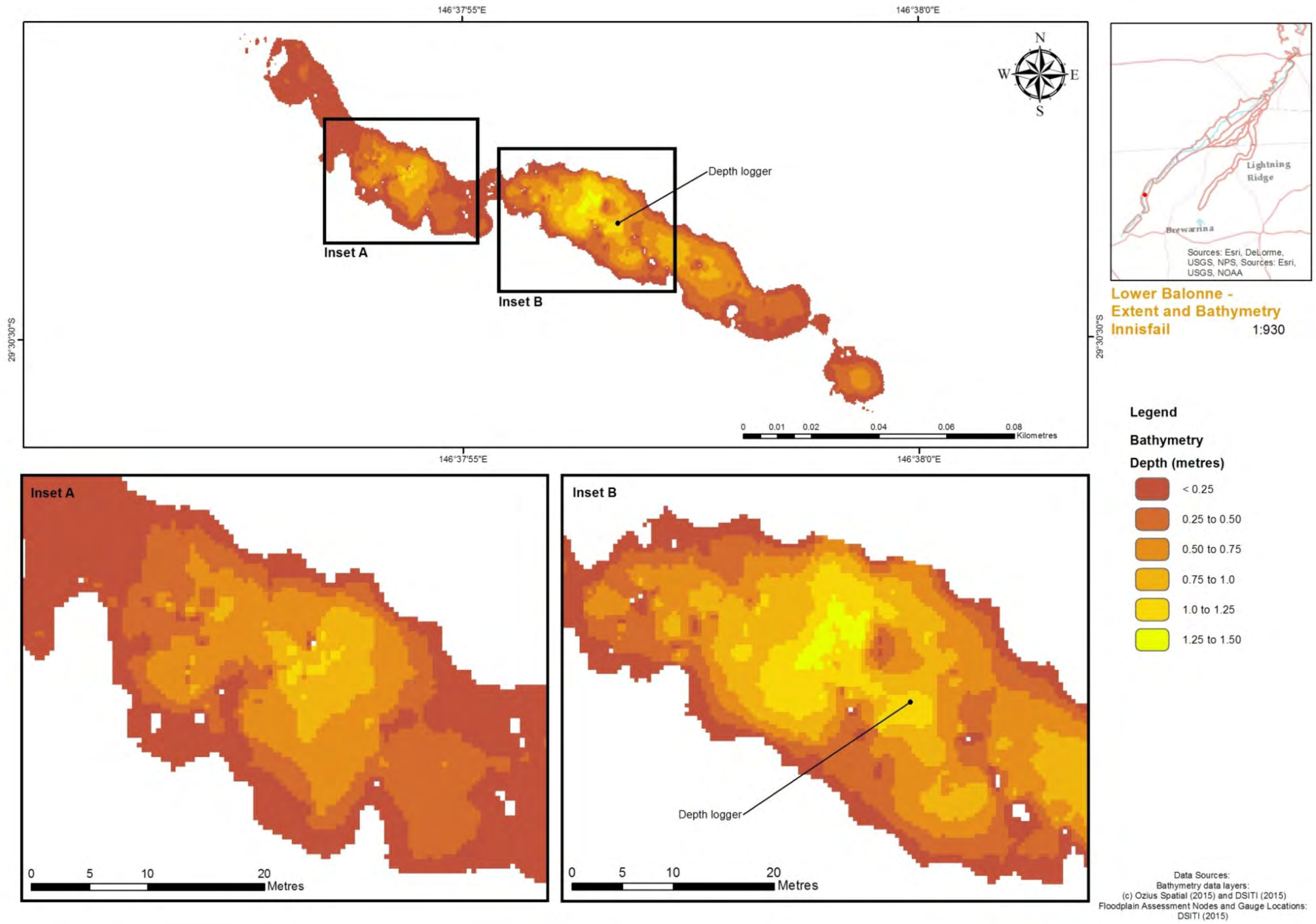

Figure C.11. Digital Elevation Model of Innisfail Waterhole.

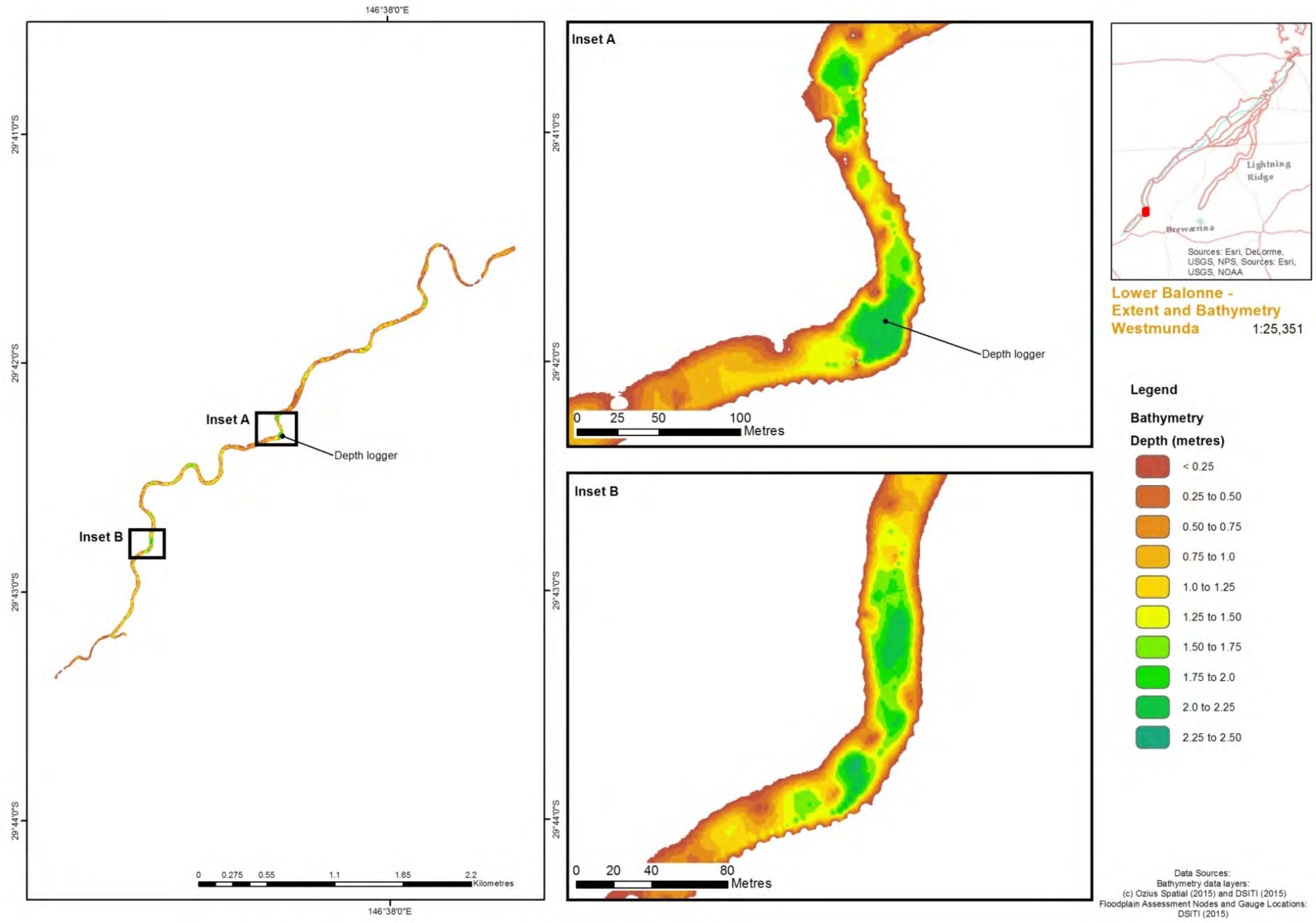

Figure C.12. Digital Elevation Model of Westmunda (Grogan's Hole) Waterhole.

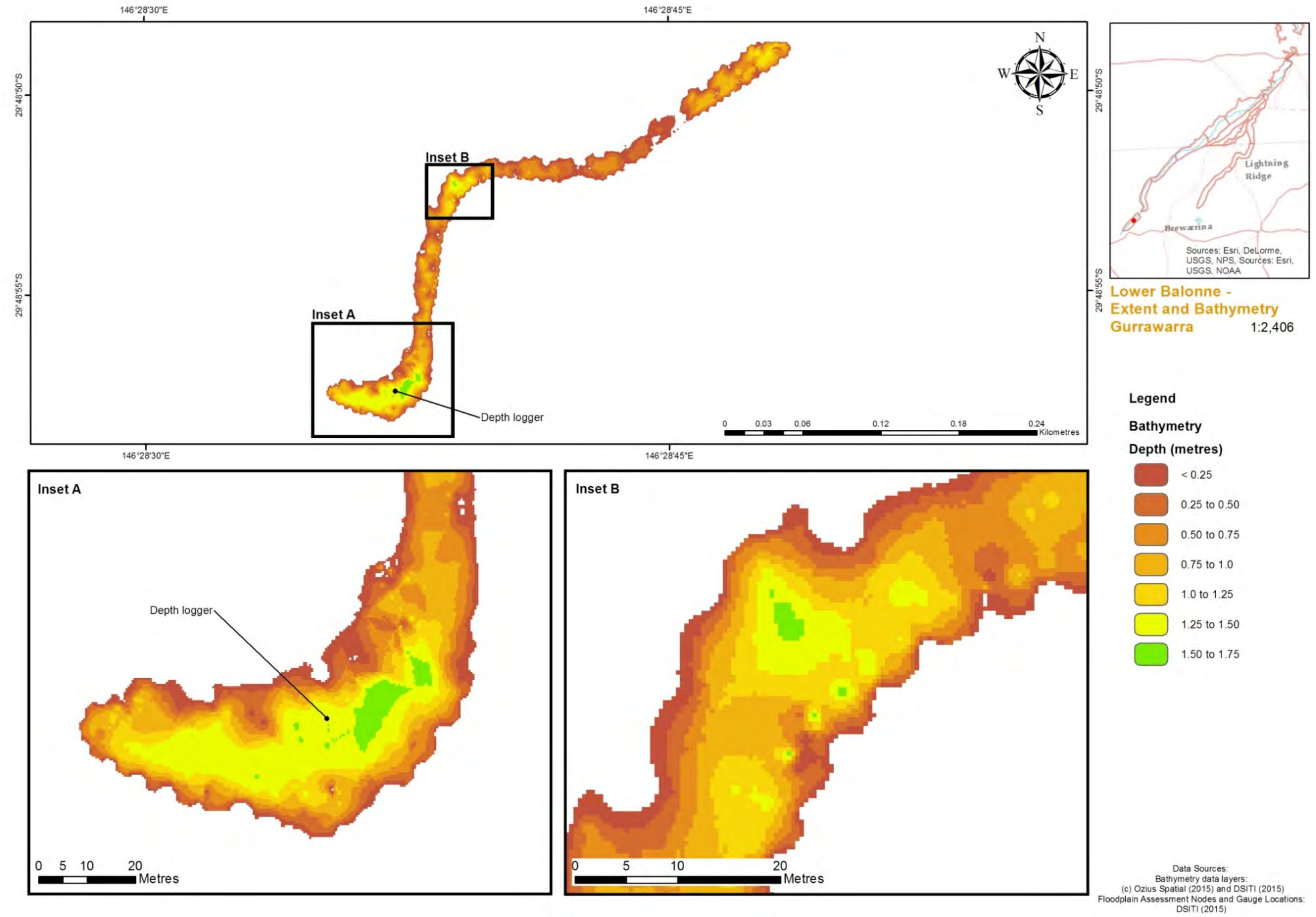

Figure C.13. Digital Elevation Model of Gurrawarra Waterhole.

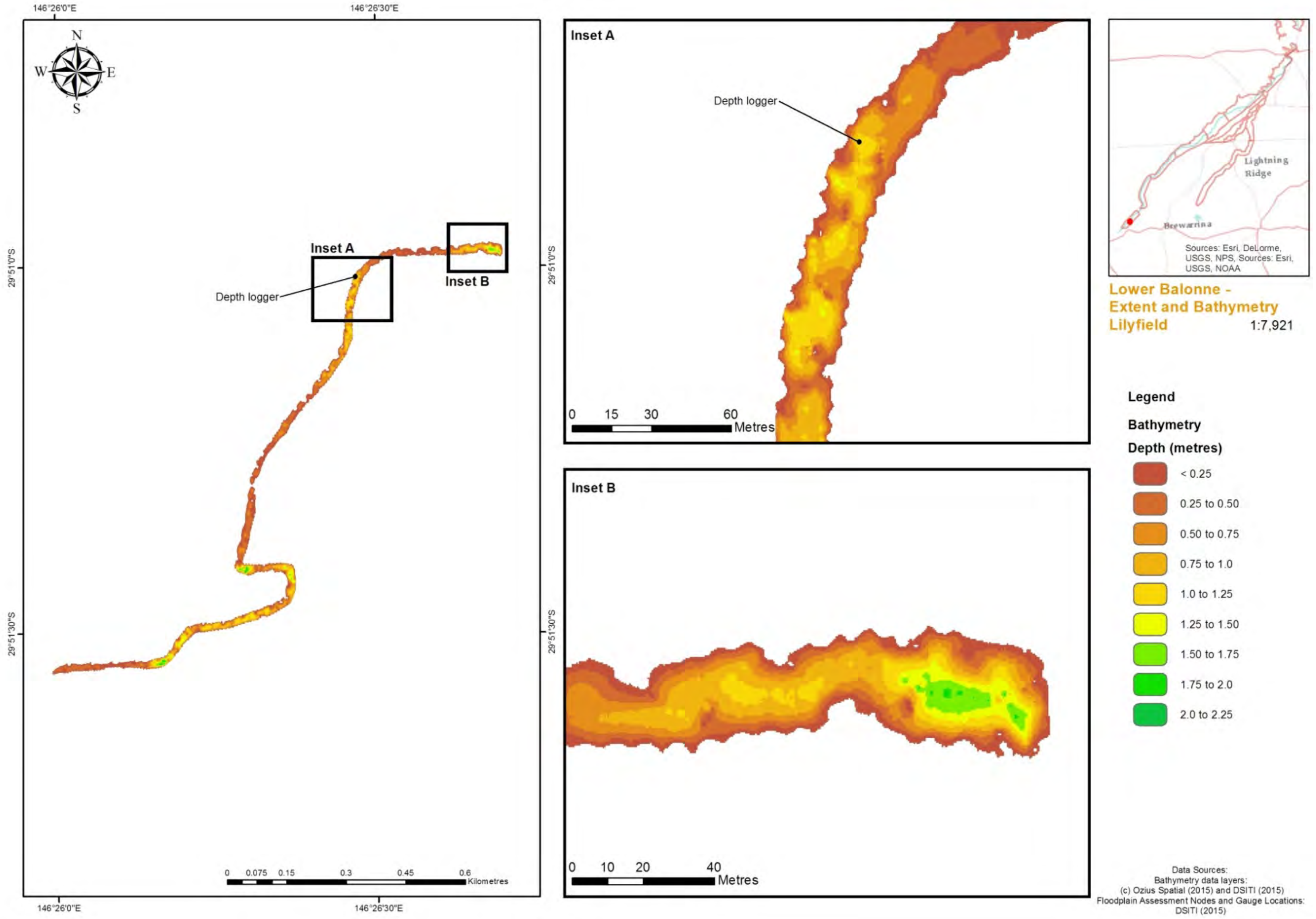

Figure C.14. Digital Elevation Model of Lilyfield Waterhole.

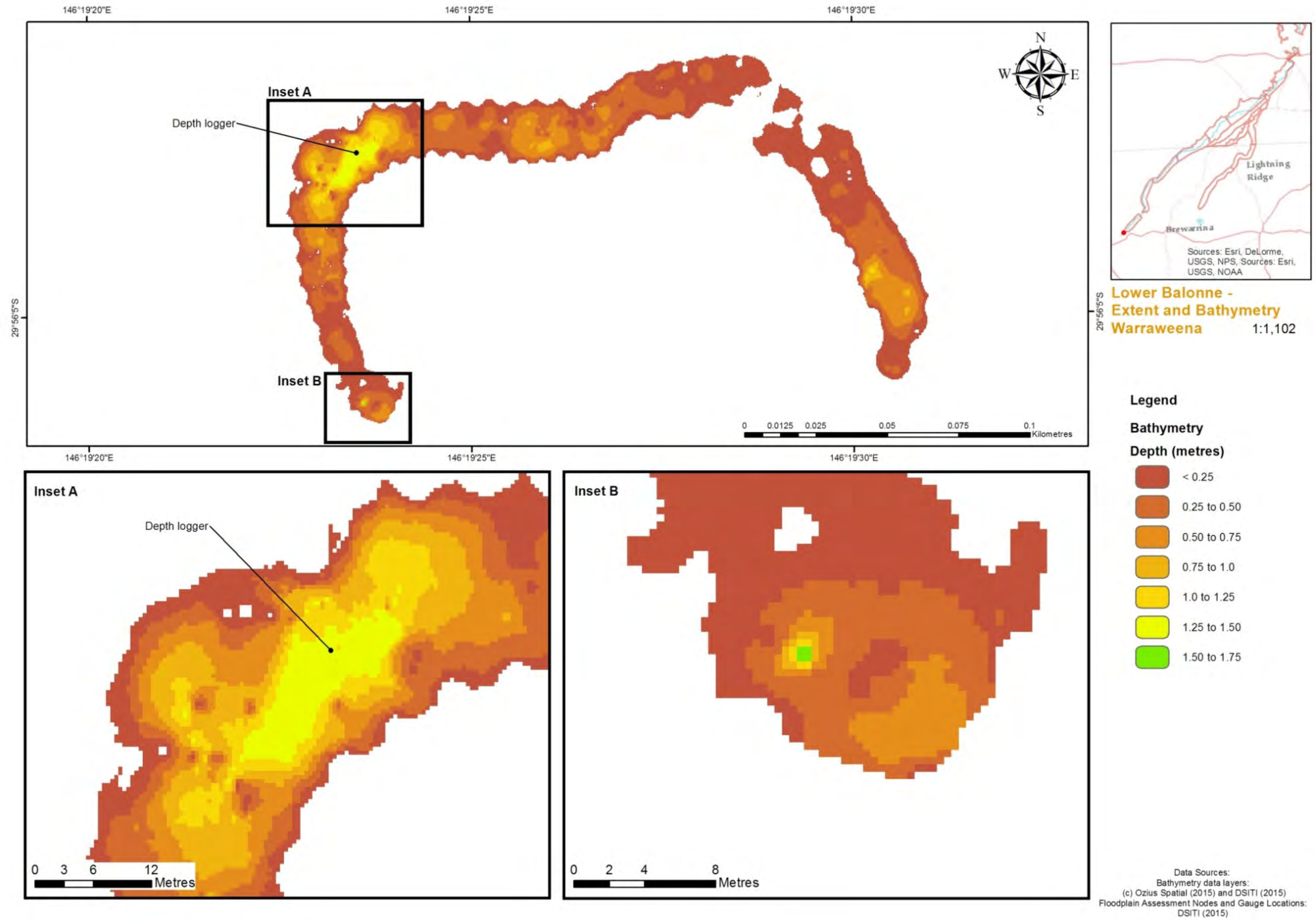

Figure C.15. Digital Elevation Model of Warraweena Waterhole.

Narran River

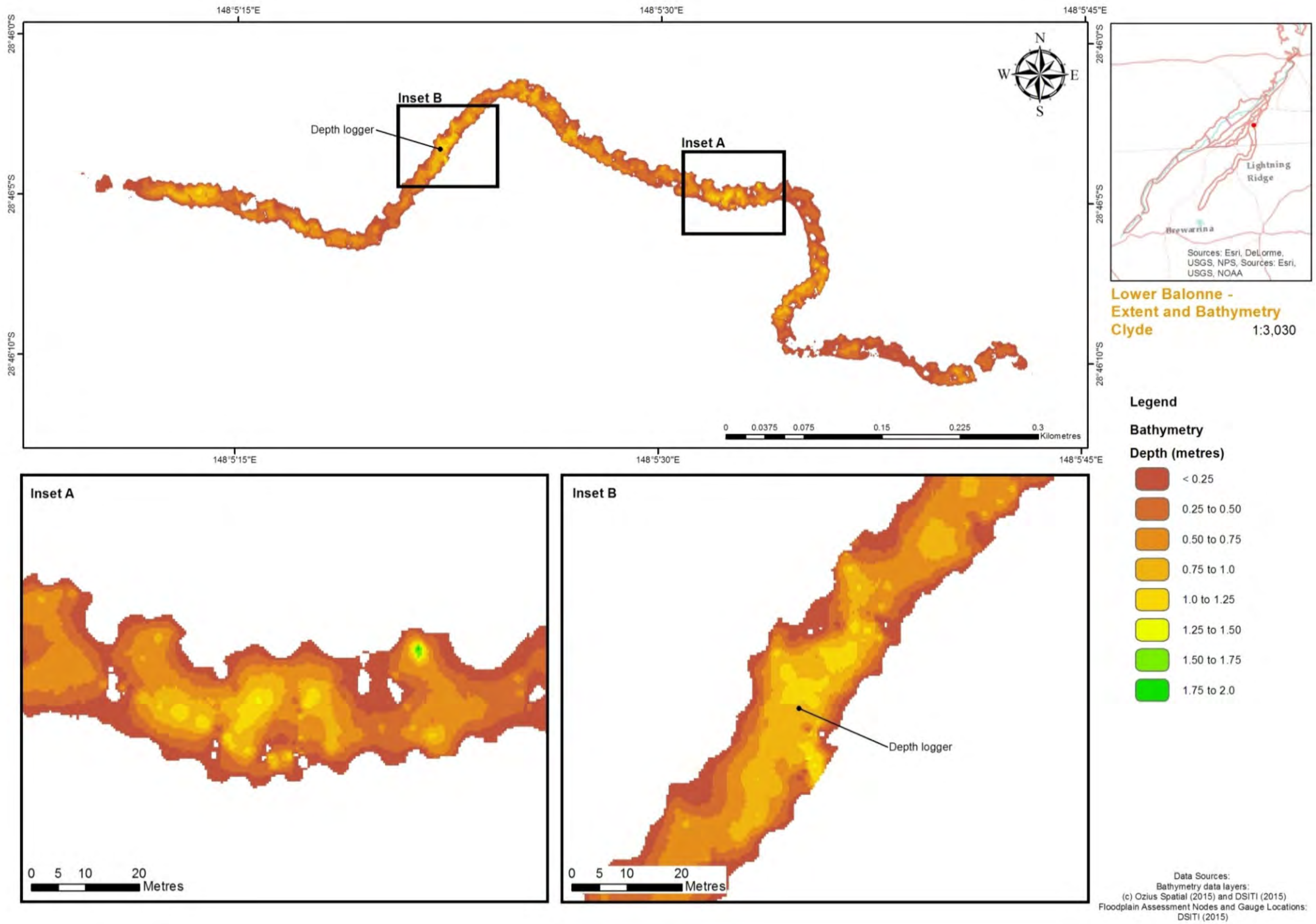

Figure C.16. Digital Elevation Model of Clyde Waterhole.

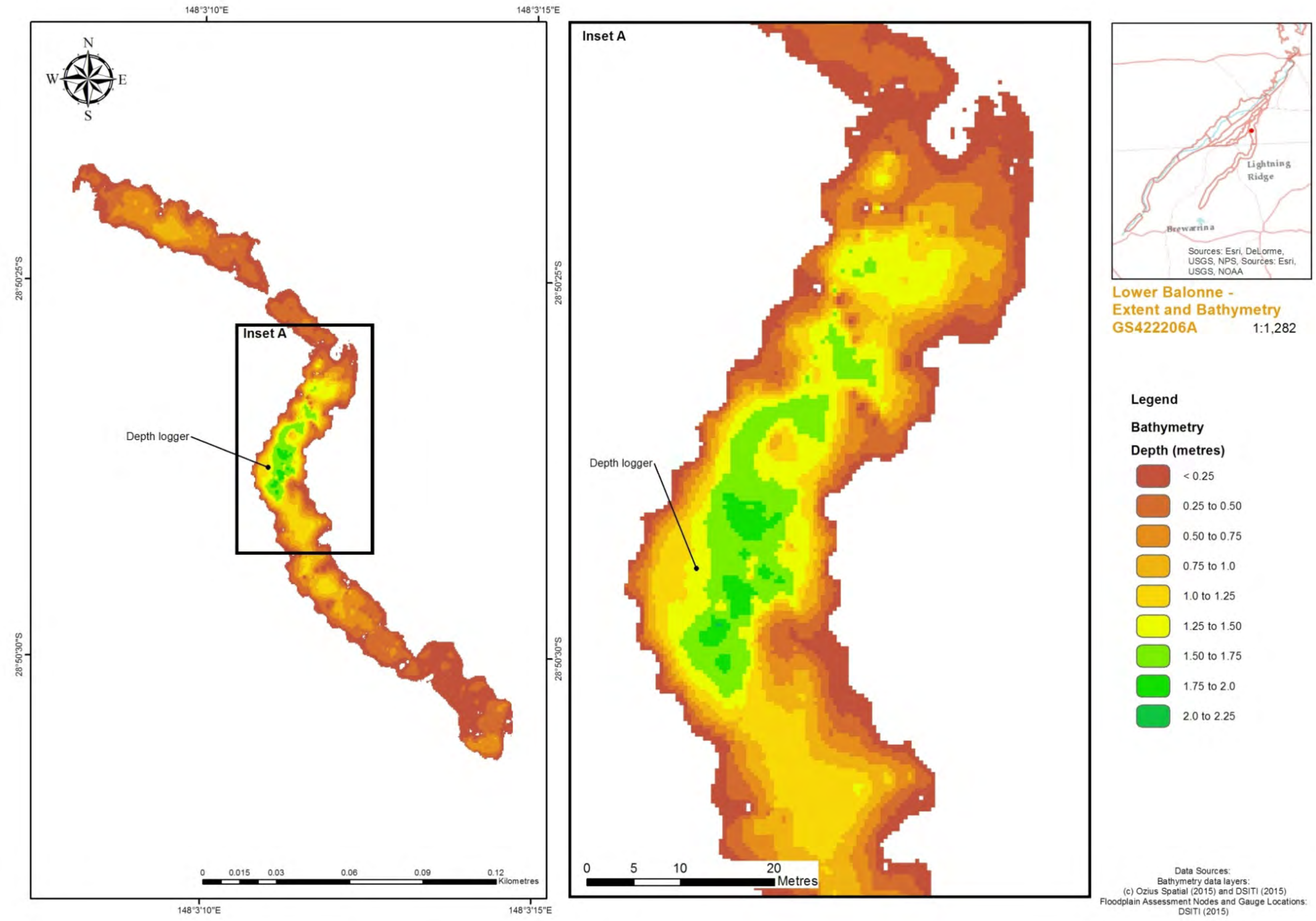

Figure C.17. Digital Elevation Model of GS422206A Waterhole.

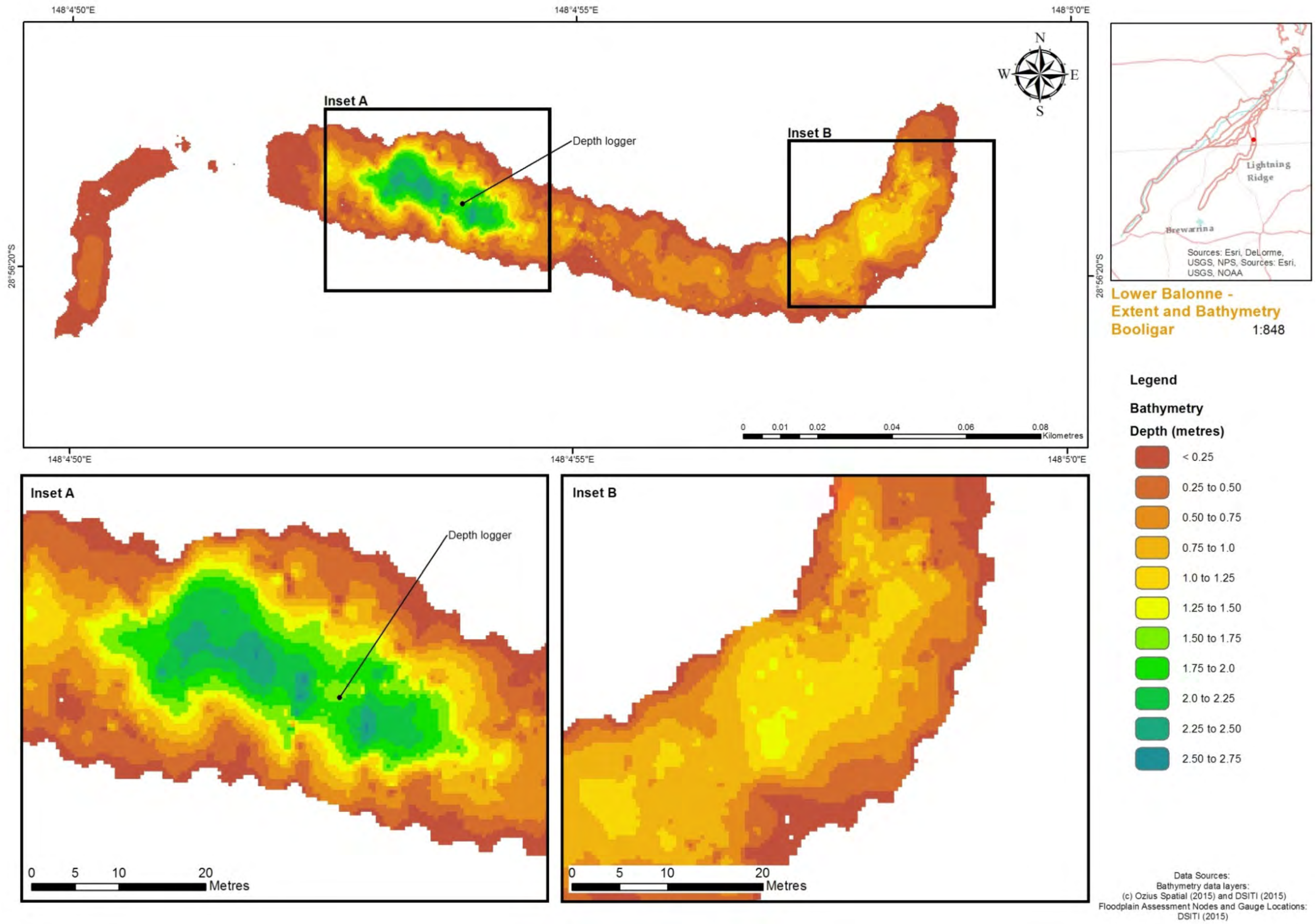

Figure C.18. Digital Elevation Model of Booligar Waterhole.

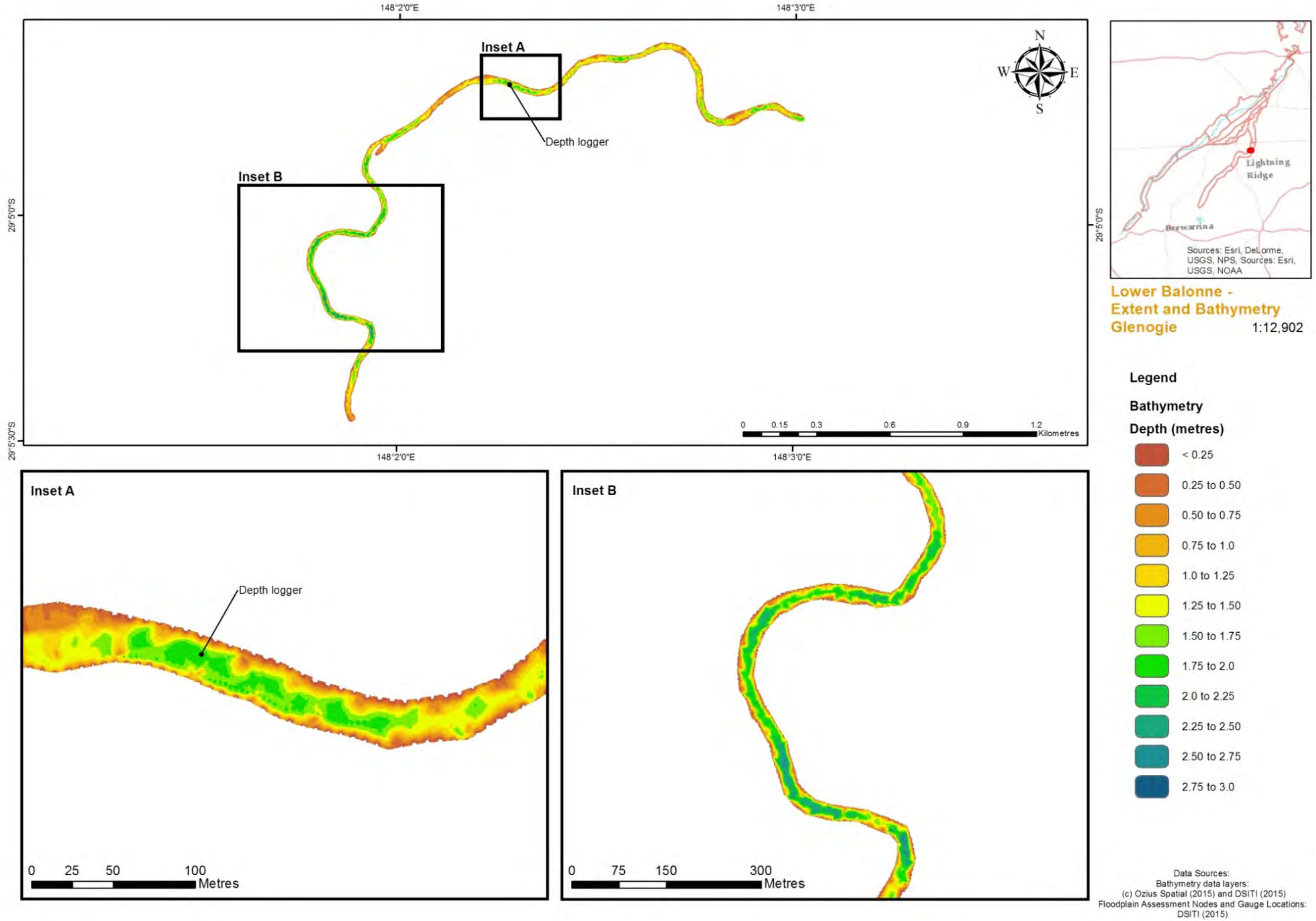

Figure C.19. Digital Elevation Model of Glenogie Waterhole.

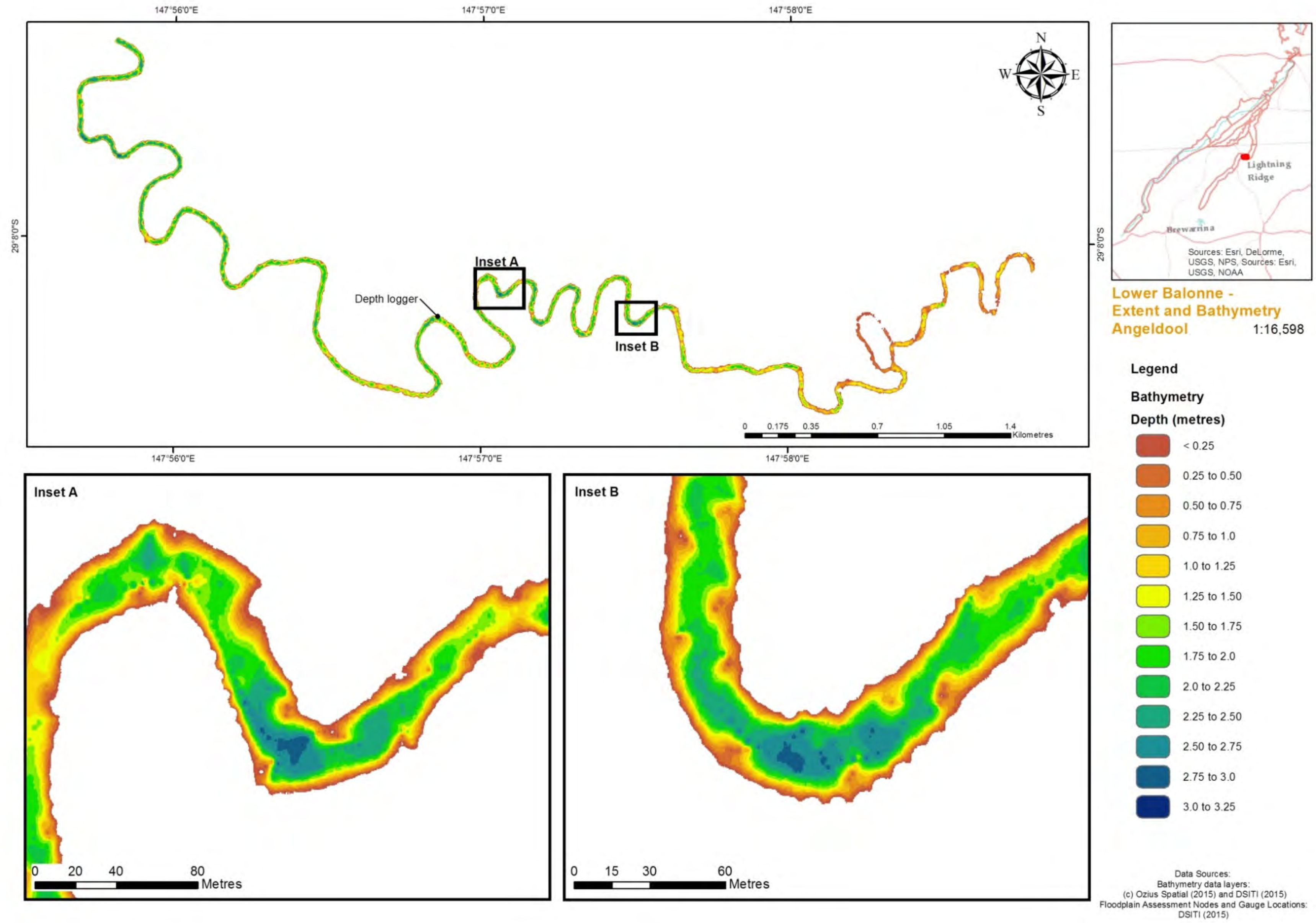

Figure C.20. Digital Elevation Model of Angledool Waterhole.

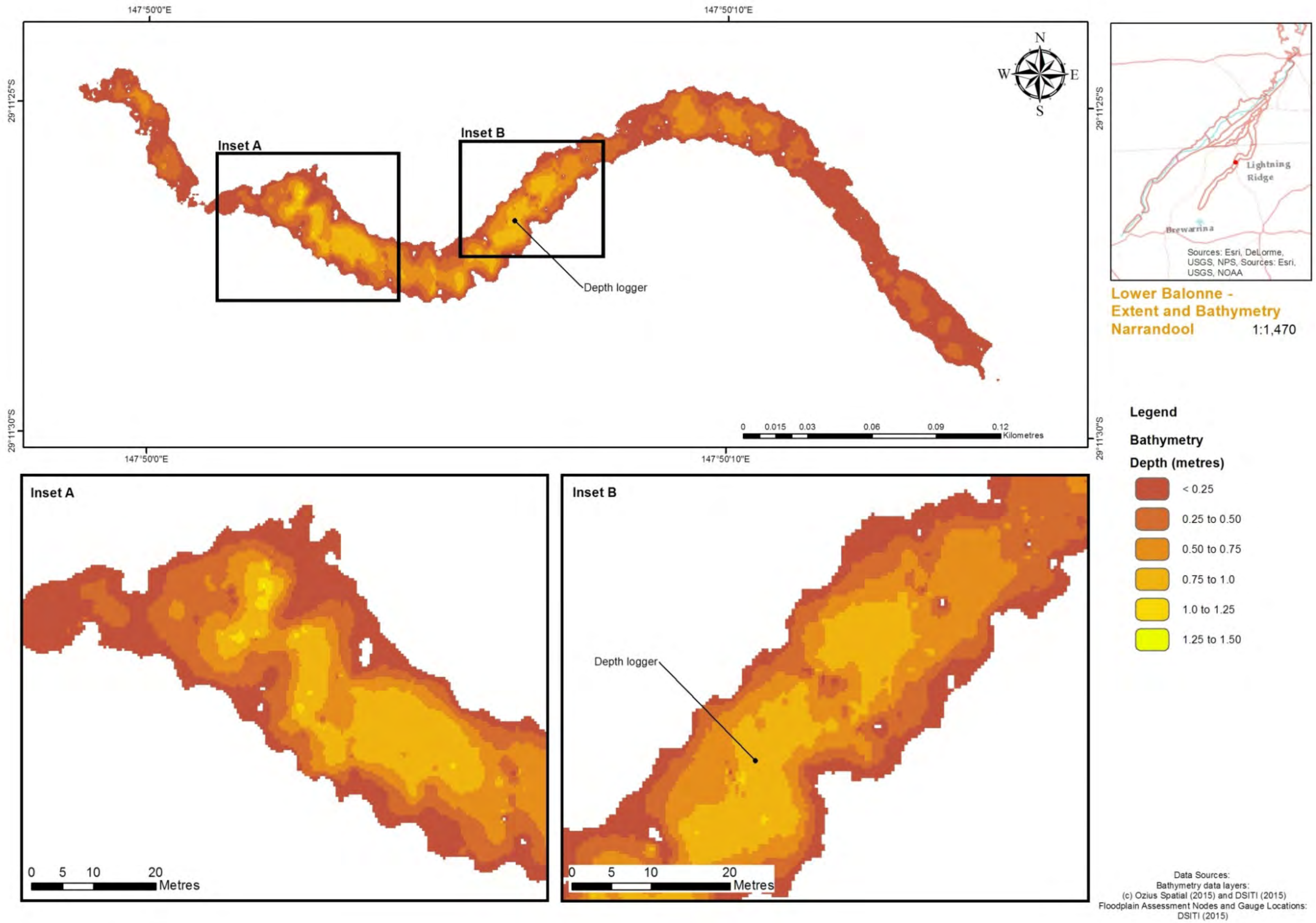

Figure C.21. Digital Elevation Model of Narrandool Waterhole.

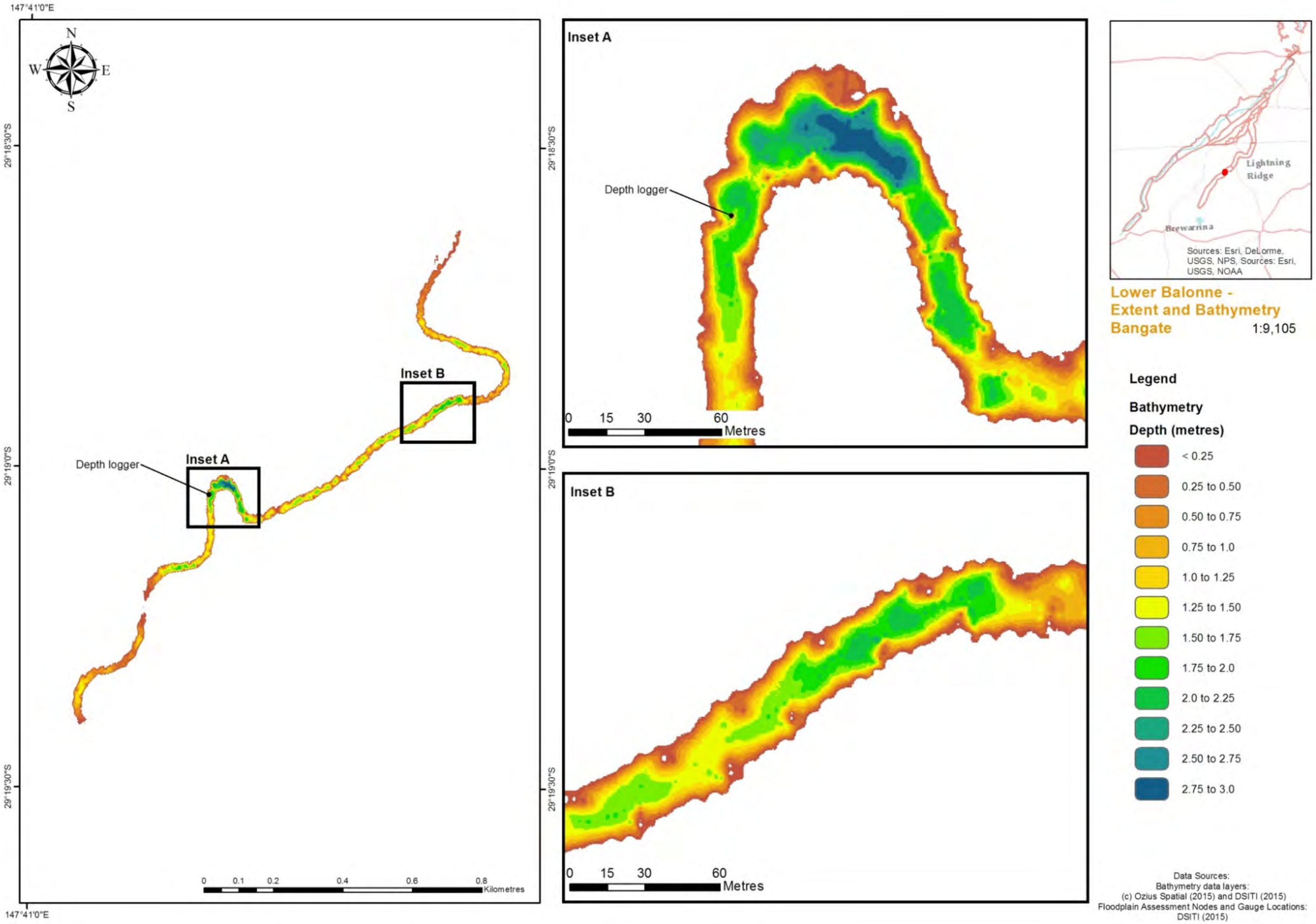

Figure C.22. Digital Elevation Model of Bangate (Sorrento Hole) Waterhole.

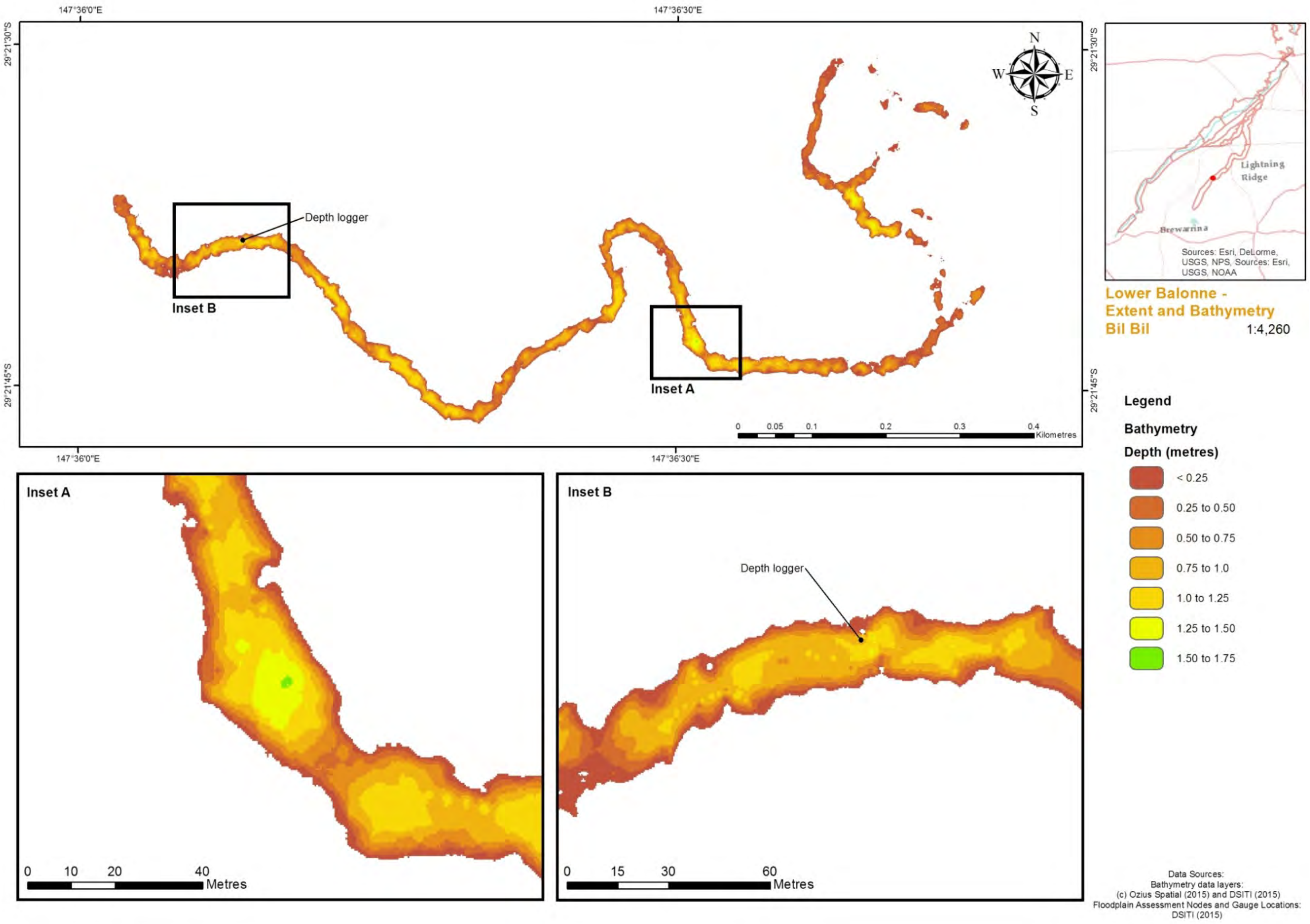

Figure C.23. Digital Elevation Model of Bil Bil Waterhole.

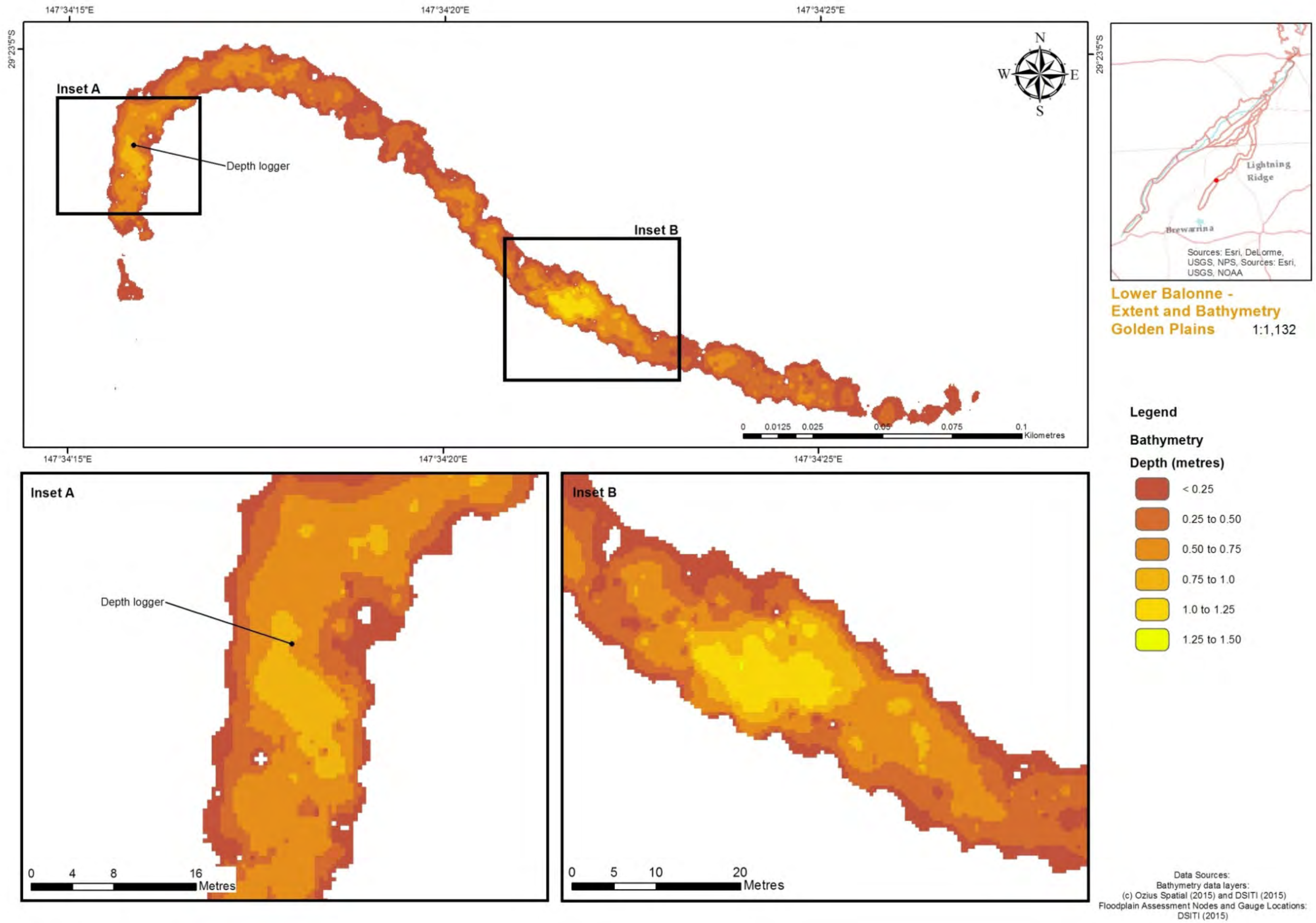

Figure C.24. Digital Elevation Model of Golden Plains Waterhole.

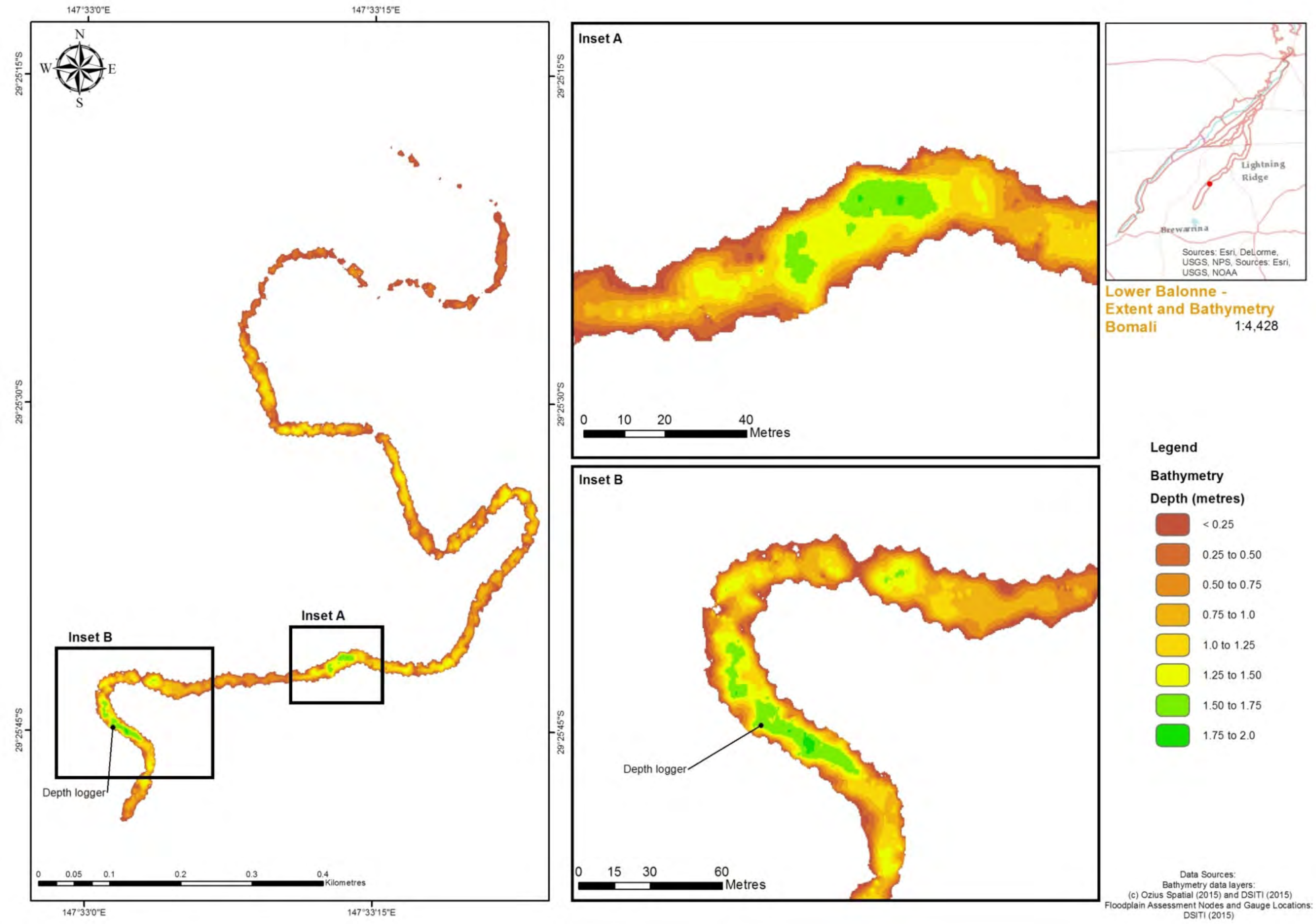

Figure C.25. Digital Elevation Model of Bomali Waterhole.

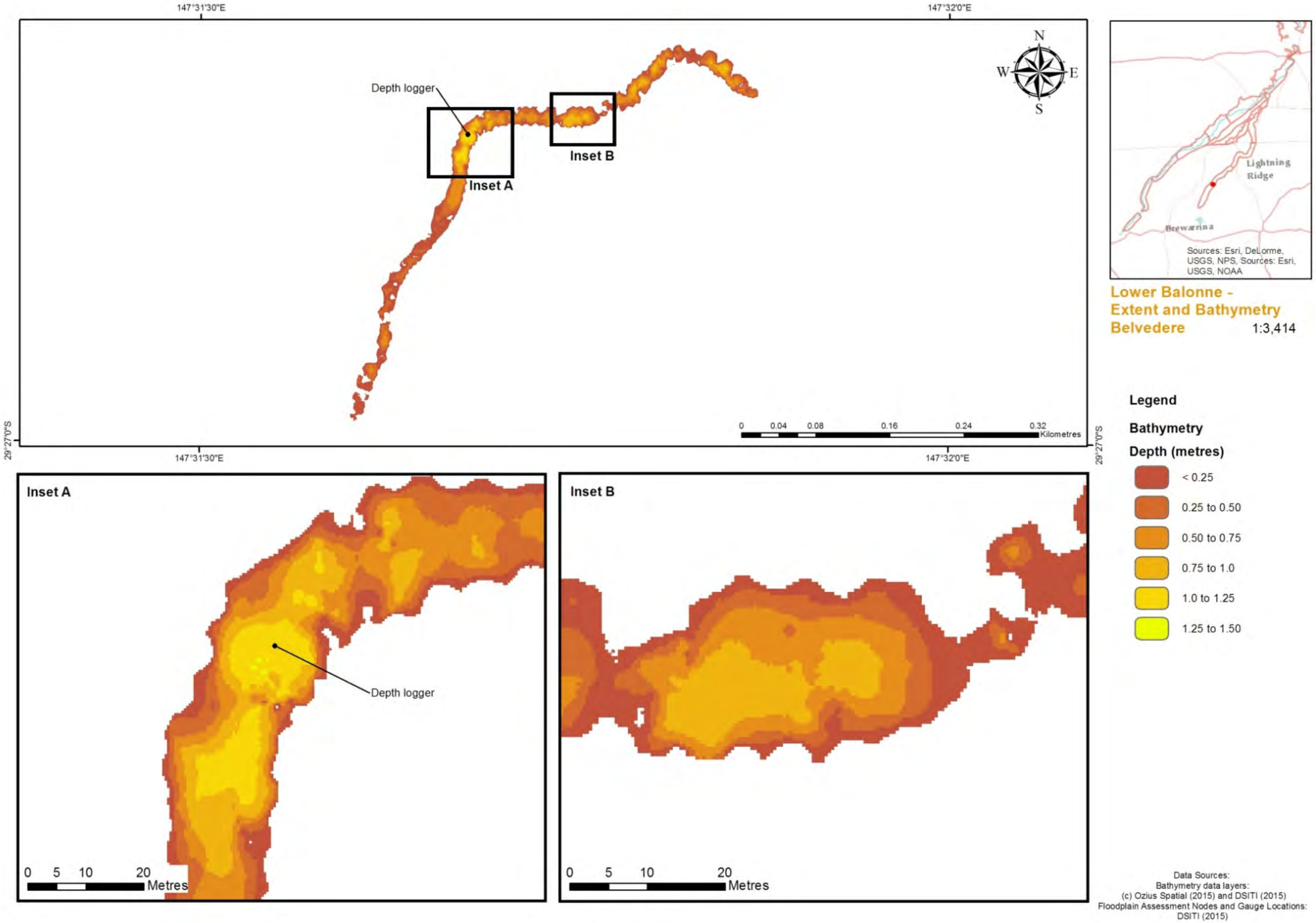

Figure C.26. Digital Elevation Model of Belvedere Waterhole.

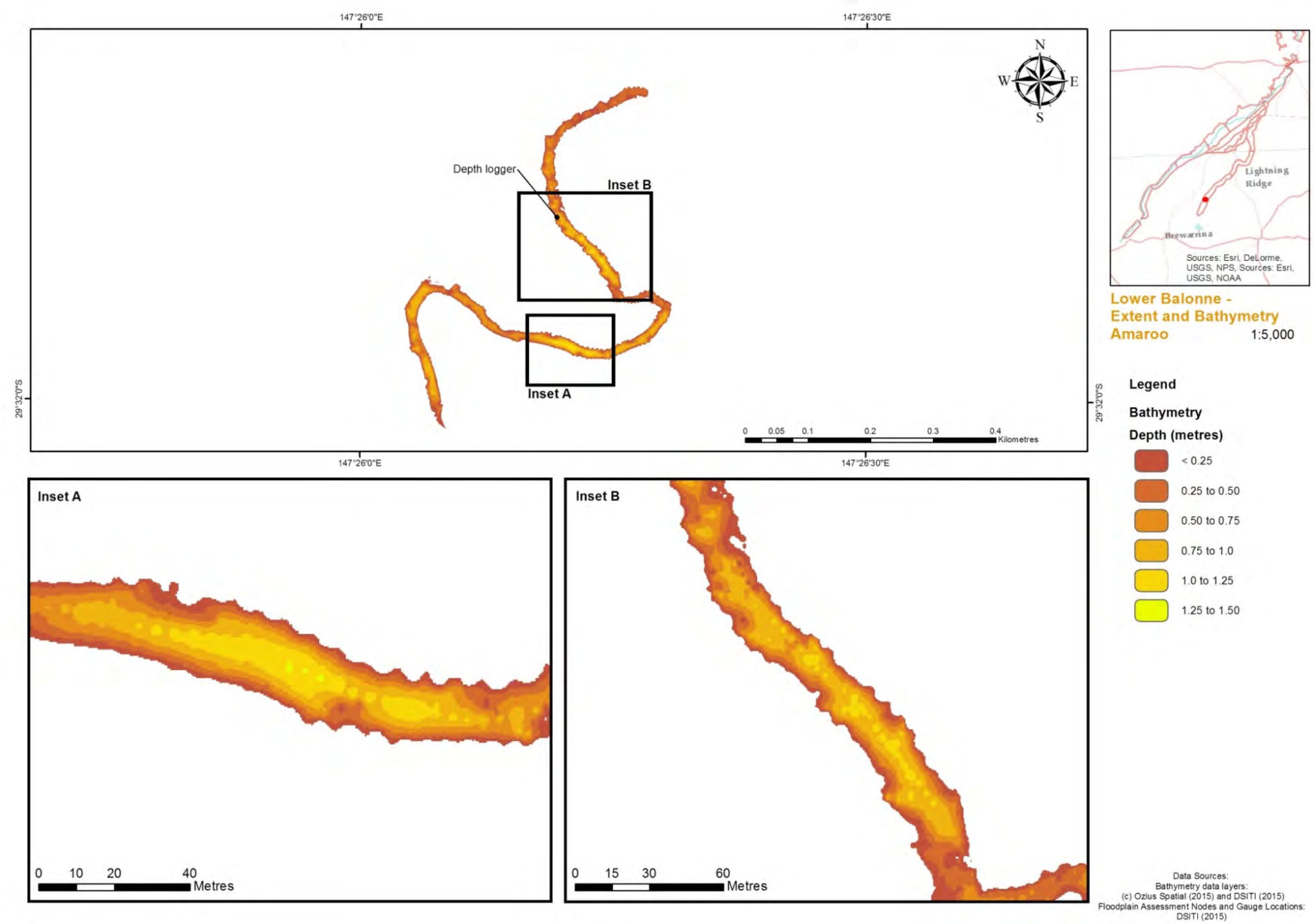

Figure C.27. Digital Elevation Model of Amaroo Waterhole.

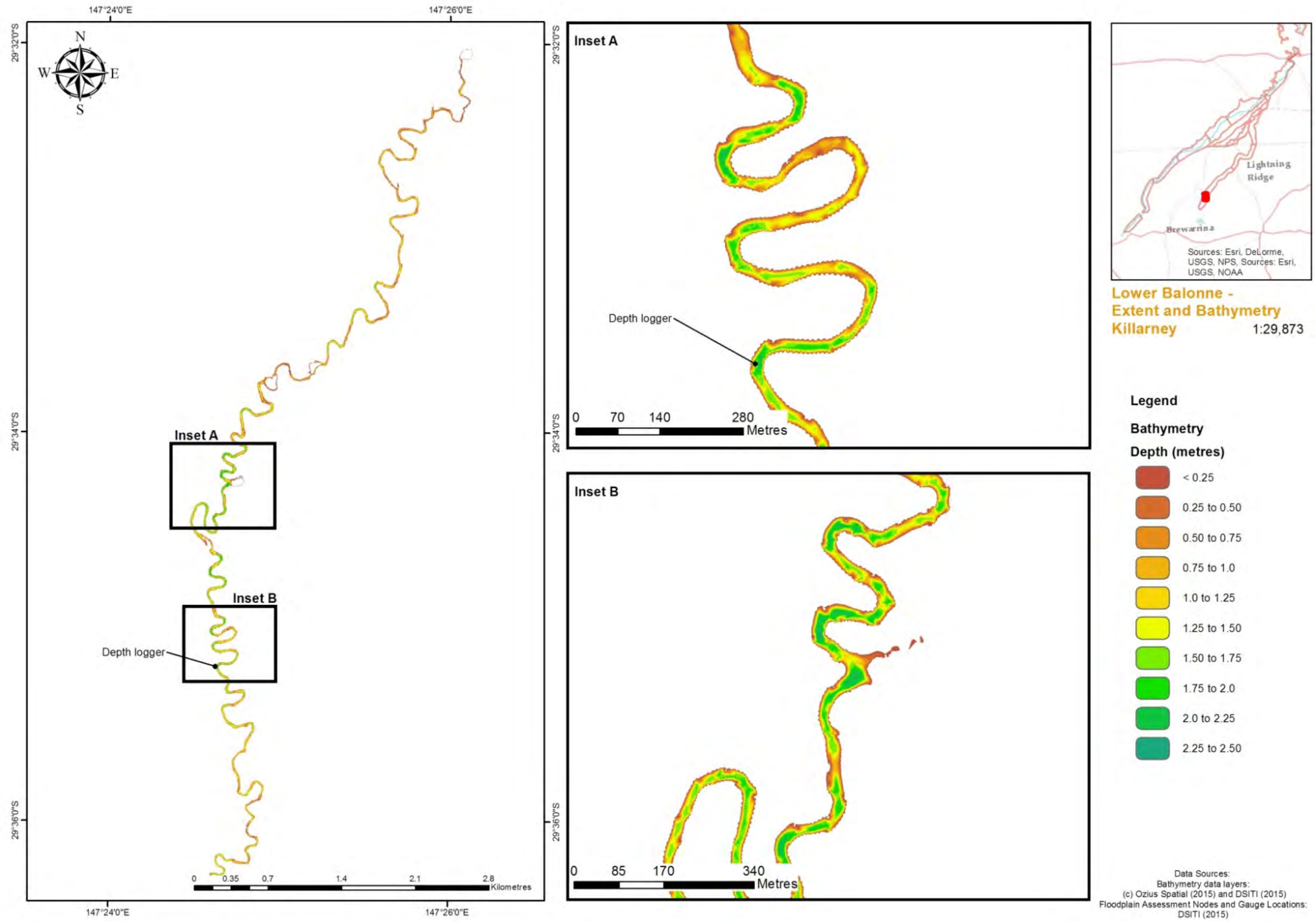

Figure C.28. Digital Elevation Model of Killarney Waterhole.

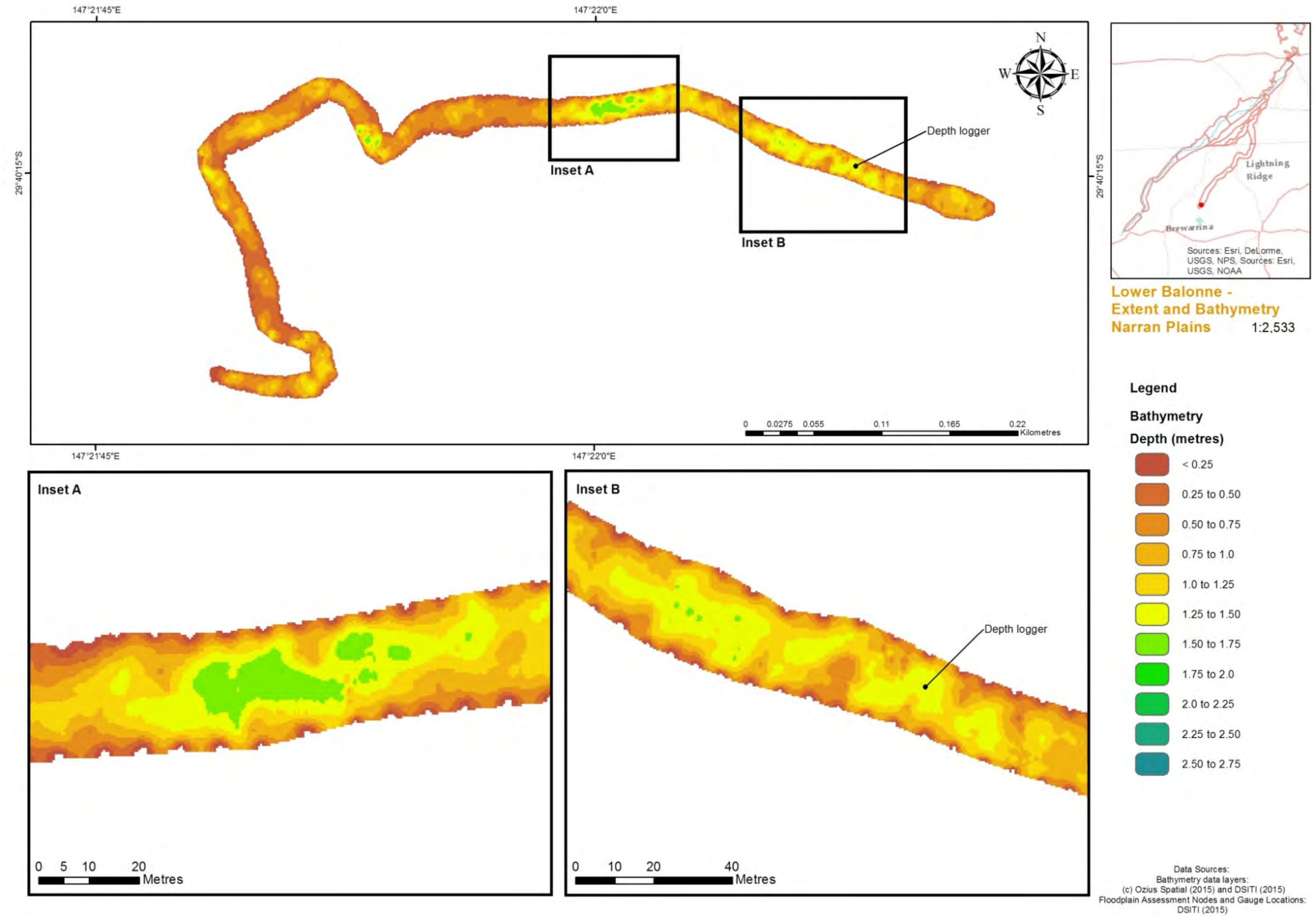

Figure C.29. Digital Elevation Model of Narran Plains Waterhole.

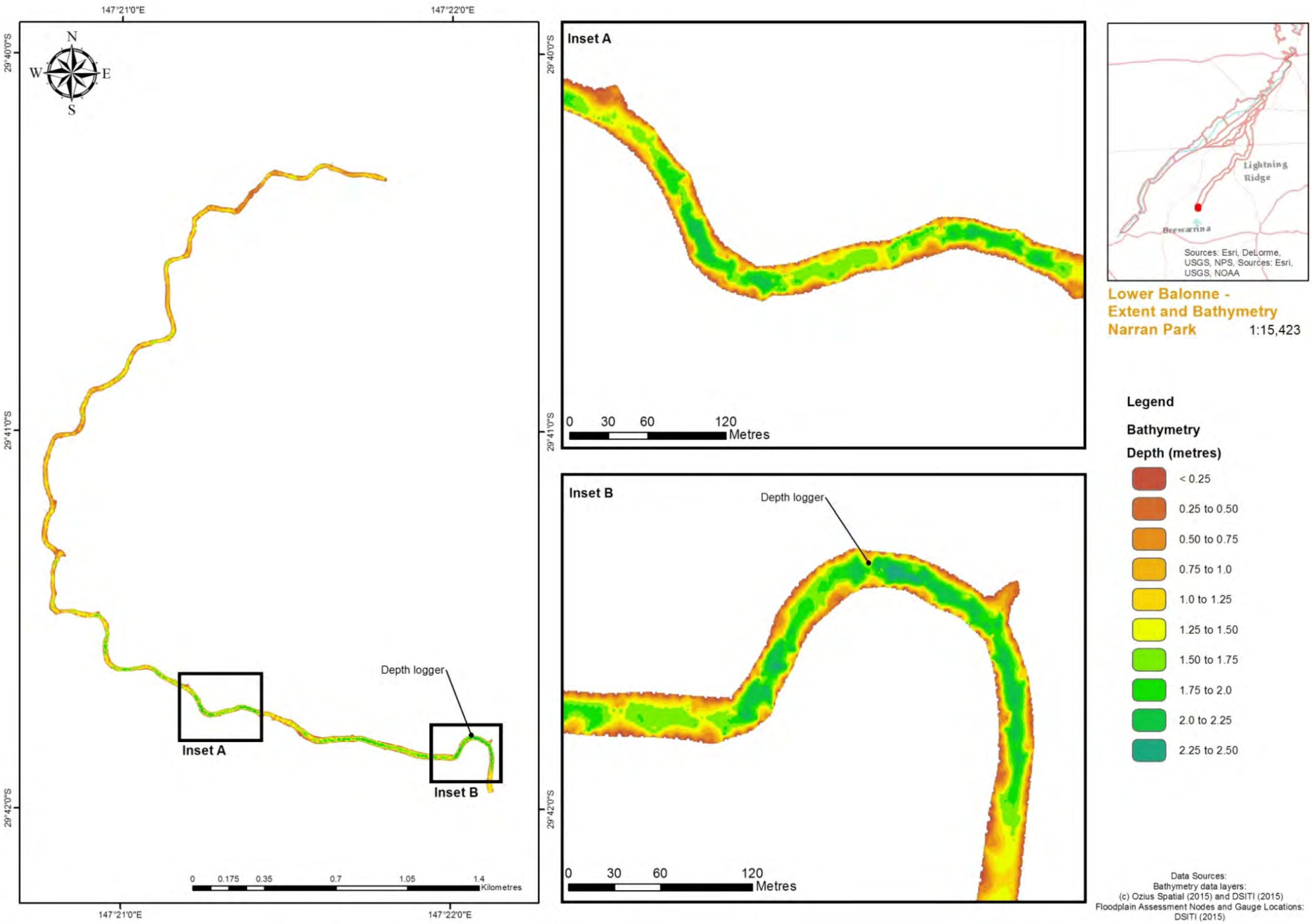

Figure C.30. Digital Elevation Model of Narran Park Waterhole.

Barwon–Darling River

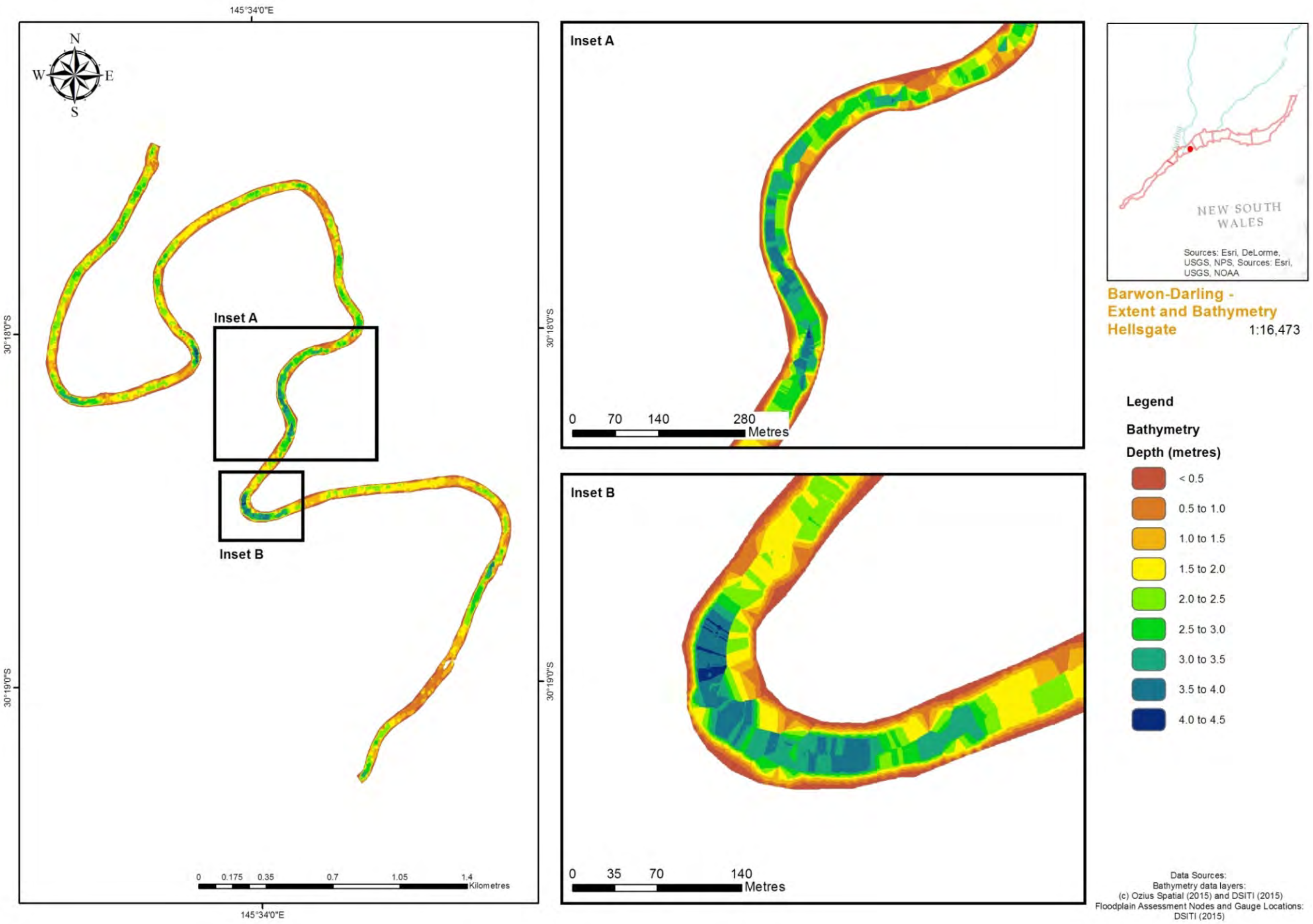

Figure C.31. Digital Elevation Model of Hell's Gate Waterhole.

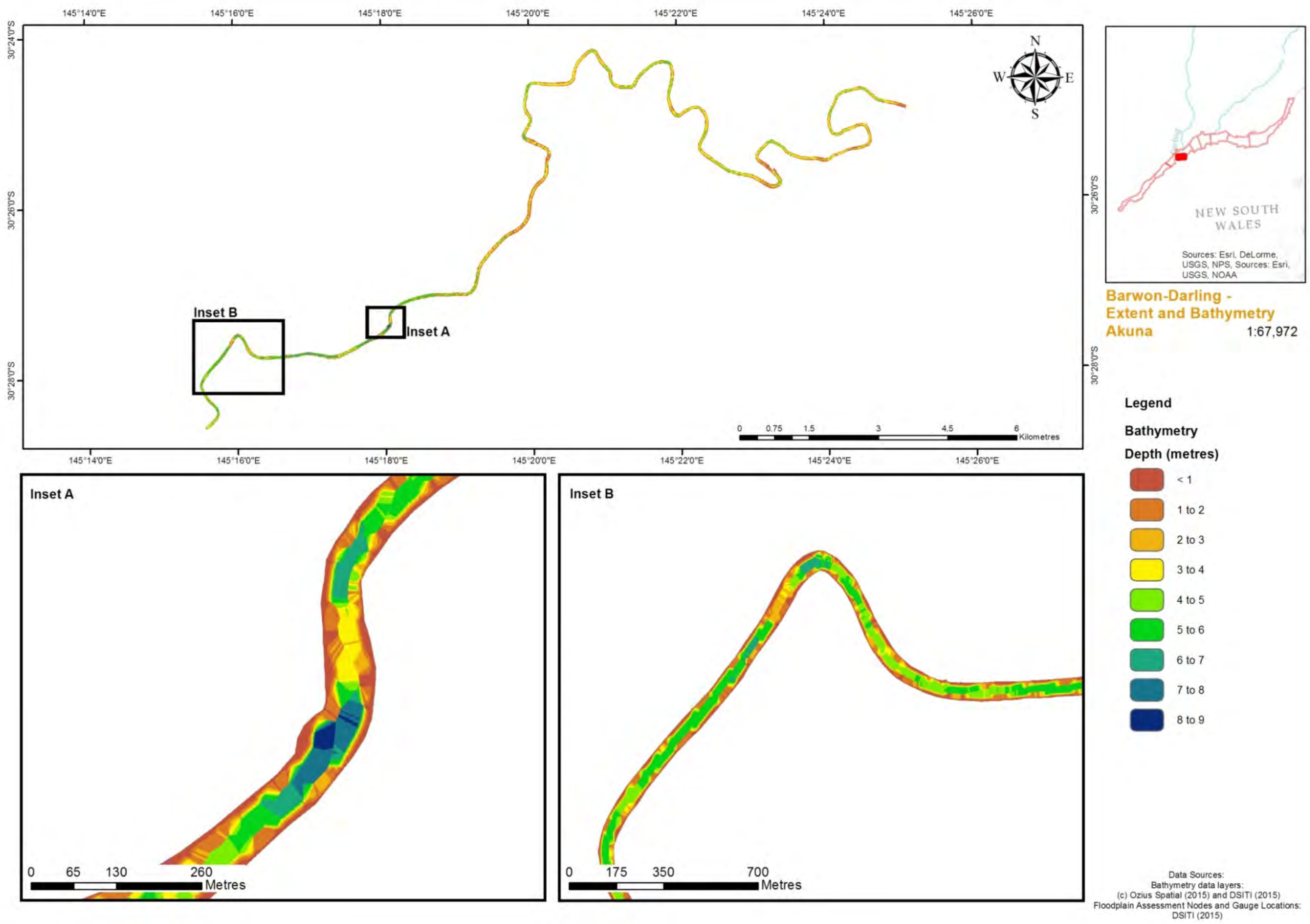

Figure C.32. Digital Elevation Model of Akuna-20A Waterhole. The two sites were merged for modelling due to their proximity and likely connectivity.

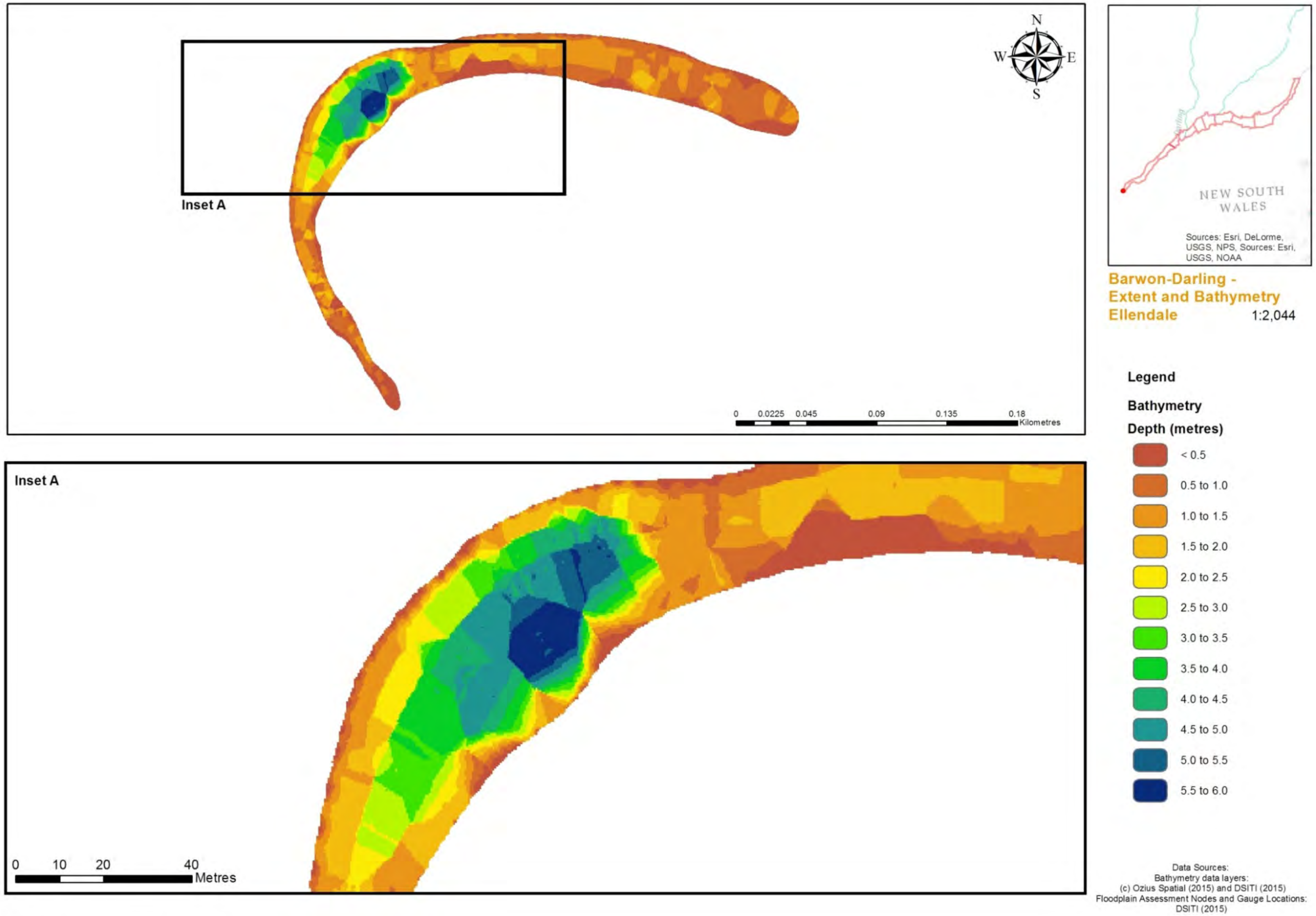

Figure C.33. Digital Elevation Model of Ellendale Waterhole.

Calibration Parameters

Using Eco Modeller, there are a wide range of adjustments that can be applied to the input data:

- **Calibration start/end date** – Sets the range of data to be used in the calibration. Useful if the depth logger data contains a sudden unexpected change (e.g. from water extraction) or to exclude extrapolations/interpolations in data.
- **Flow Lag** – Shifts when flow will impact the waterhole; can be negative or positive to account for a gauge upstream or downstream respectively. Useful when the closest gauging station is a long distance from the waterhole and flow transmission times are long.
- **Evaporation Scaling** – Changes the impact of evaporation; adds a multiplication factor to evaporation, values greater than 1 increase the impact of evaporation and values less than 1 reduce it. Useful to account for waterhole micro-climate.
- **Seepage Rate –** Adds a daily depth loss in mm/day. Useful when manipulation of the evaporation rate cannot explain a higher loss rate than expected; losses can be attributed to groundwater seepage or another loss that operates consistently throughout drying.
- **Local Catchment Area** – Increases the surface area for calculation of gain from rainfall. Useful for when rain events have a greater impact on observed data than model data, likely attributable to runoff from the surrounding area.
- **Maximum Daily Infiltration** – Sets the threshold of a rainfall event beyond which all rain enters the waterhole. This is particularly relevant in areas with a large catchment to account for a certain amount of rain which must first penetrate the soil before rain makes it to the waterhole. Useful when only larger rainfall events seem to have a significant impact on water levels.
- **Local Groundwater Catchment** – Sets the size of the larger area around the waterhole in which water can be temporarily stored following a rain event, gradually contributing to the waterhole over a period following that event. The volume of water stored is equal to the catchment area multiplied by the depth of the waterhole multiplied by 0.4 (the relative proportion of the volume which is water as opposed to soil). The amount of water reaching the groundwater catchment set by the maximum daily infiltration (above).
- **Inflow to Waterhole** – Percentage of the groundwater that reaches the waterhole.
- **Lost to deep drainage** – Percentage of the groundwater that is lost to deep drainage rather than reaching the waterhole.

Model Calibrations

The following figures show the observed and modelled data for the calibration period of each site that was modelled. For each calibration period the calculated Root Mean Square Error (RMSE) is displayed; this figure represents the difference between the observed and modelled data where a lower figure represents less error.

Culgoa River

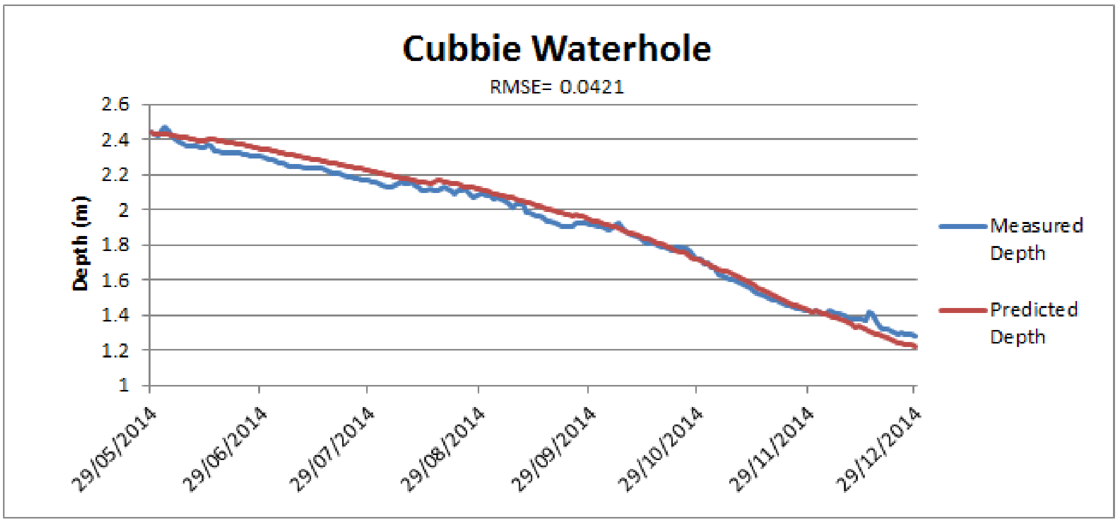

Figure C.34. Observed and modelled data for Cubbie Waterhole for the Calibration Period.

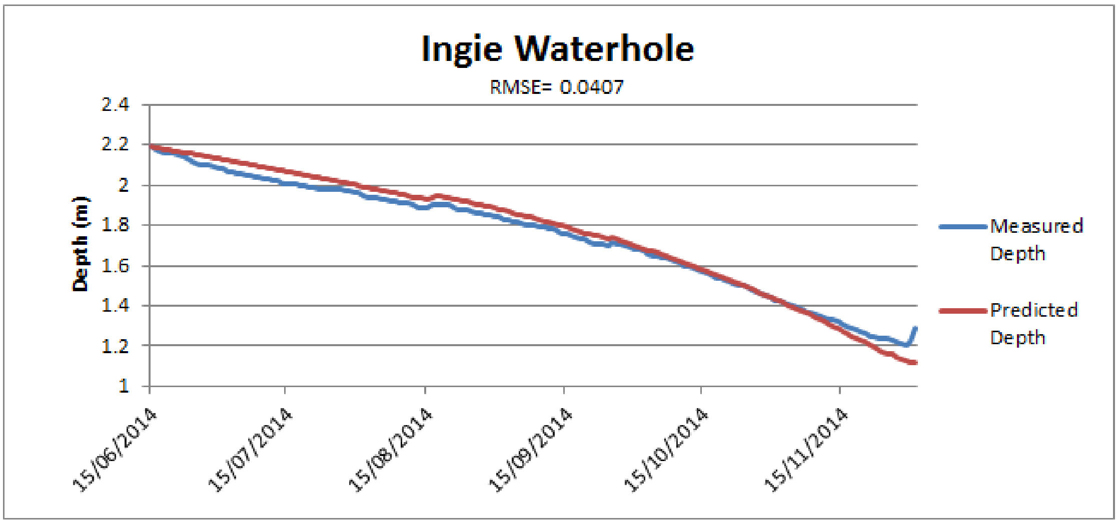

Figure C.35. Observed and modelled data for Ingie Waterhole for the Calibration Period.

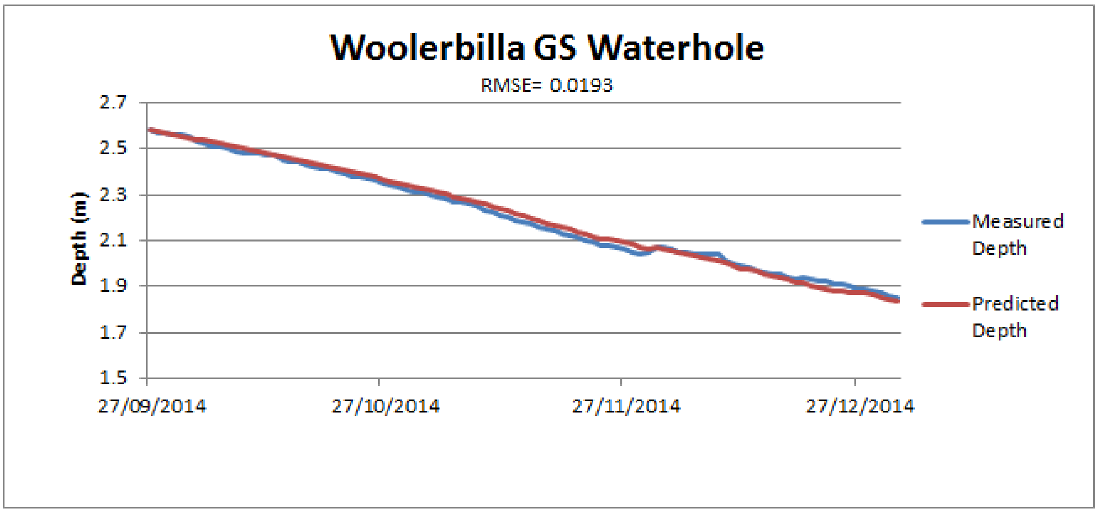

Figure C.36. Observed and modelled data for Woolerbilla Waterhole for the Calibration Period.

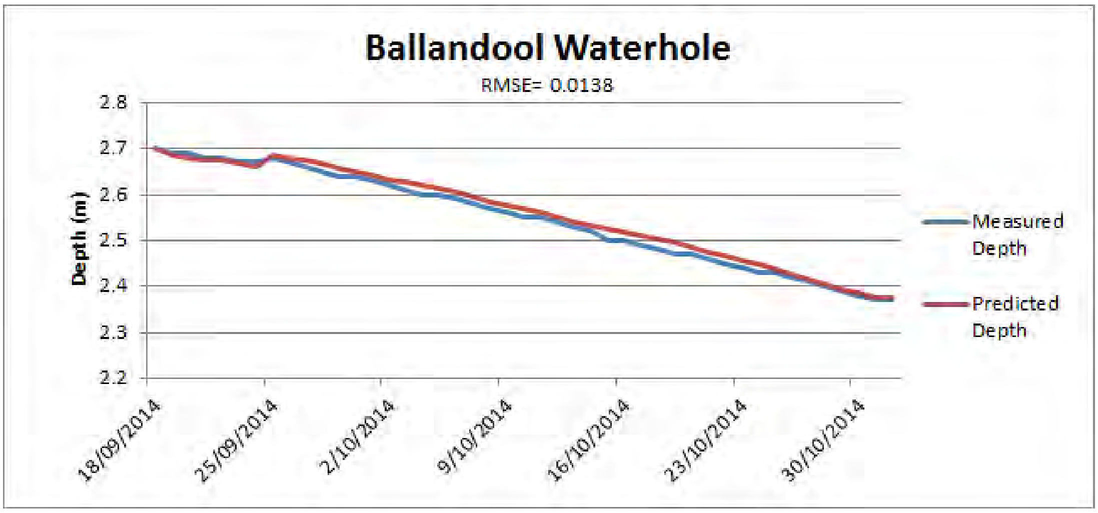

Figure C.37. Observed and modelled data for Ballandool Waterhole for the Calibration Period.

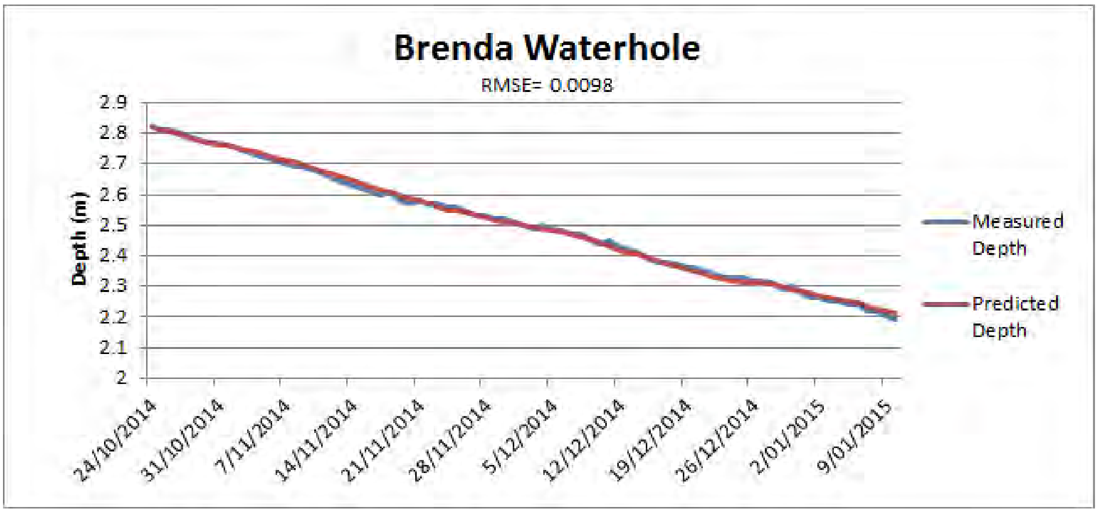

Figure C.38. Observed and modelled data for Brenda Waterhole for the Calibration Period.

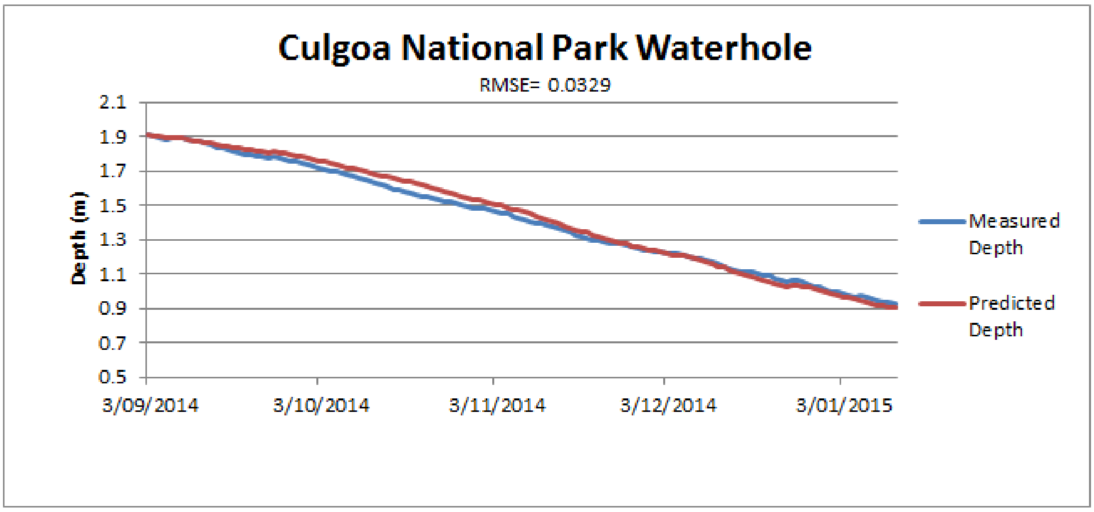

Figure C.39. Observed and modelled data for Culgoa National Park Waterhole for the Calibration Period.

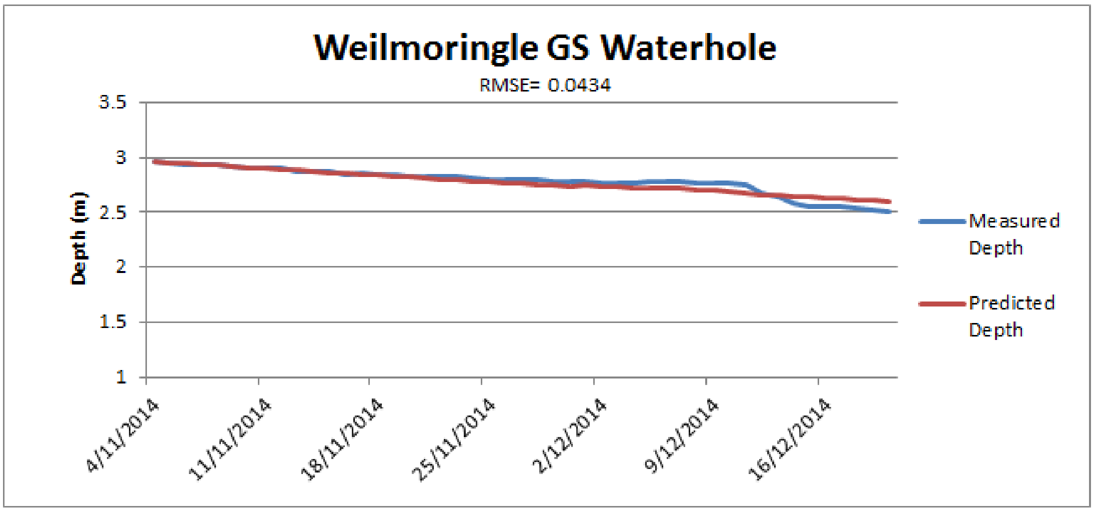

Figure C.40. Observed and modelled data for Weilmoringle GS Waterhole for the Calibration Period.

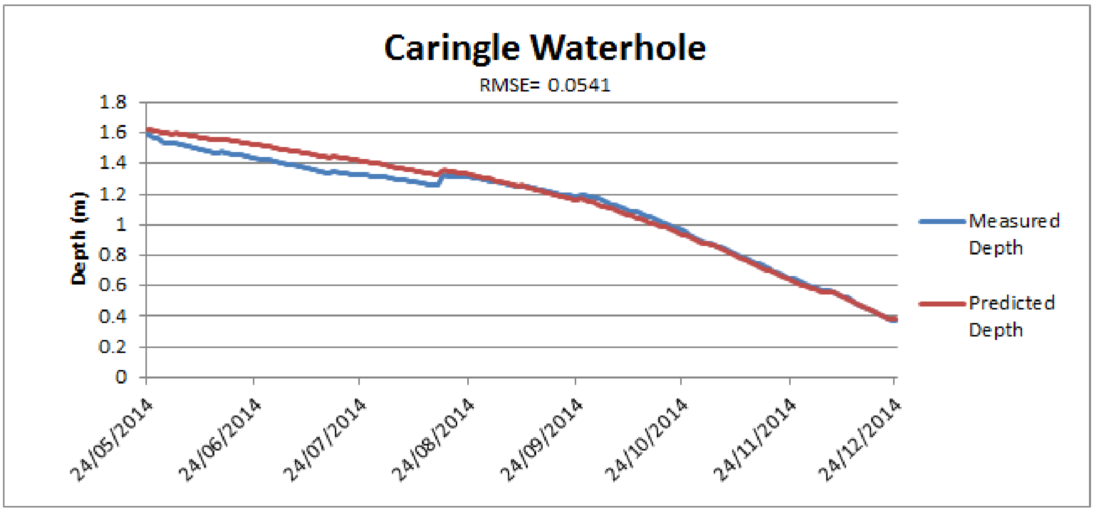

Figure C.41. Observed and modelled data for Caringle Waterhole for the Calibration Period.

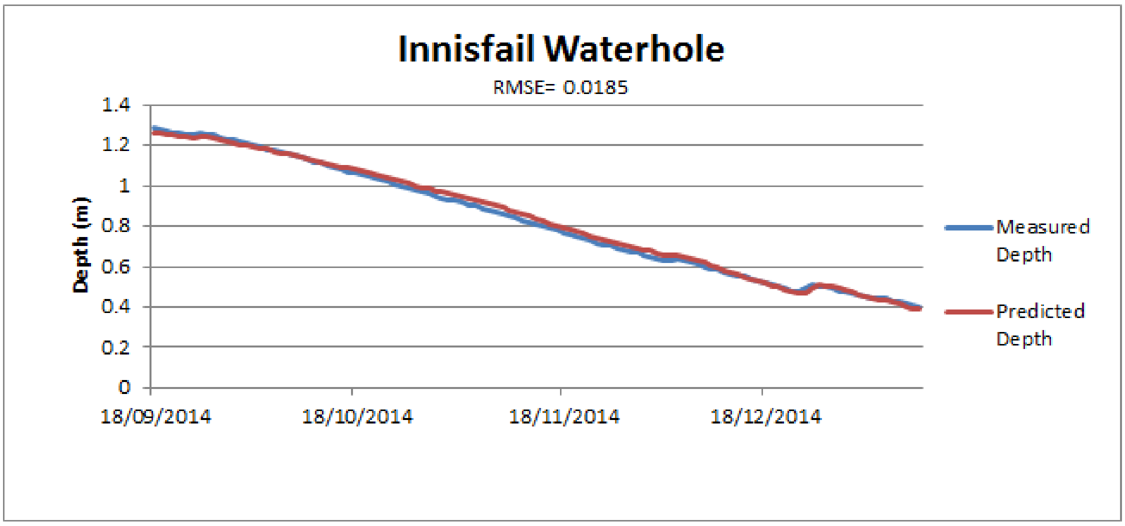

Figure C.42. Observed and modelled data for Innisfail Waterhole for the Calibration Period.

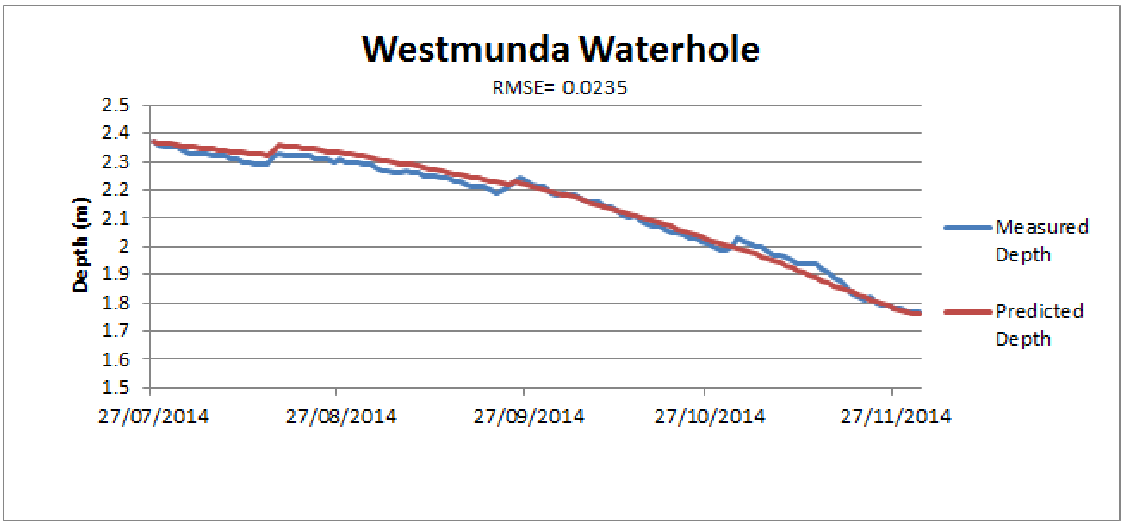

Figure C.43. Observed and modelled data for Westmunda (Grogan's Hole) Waterhole for the Calibration Period.

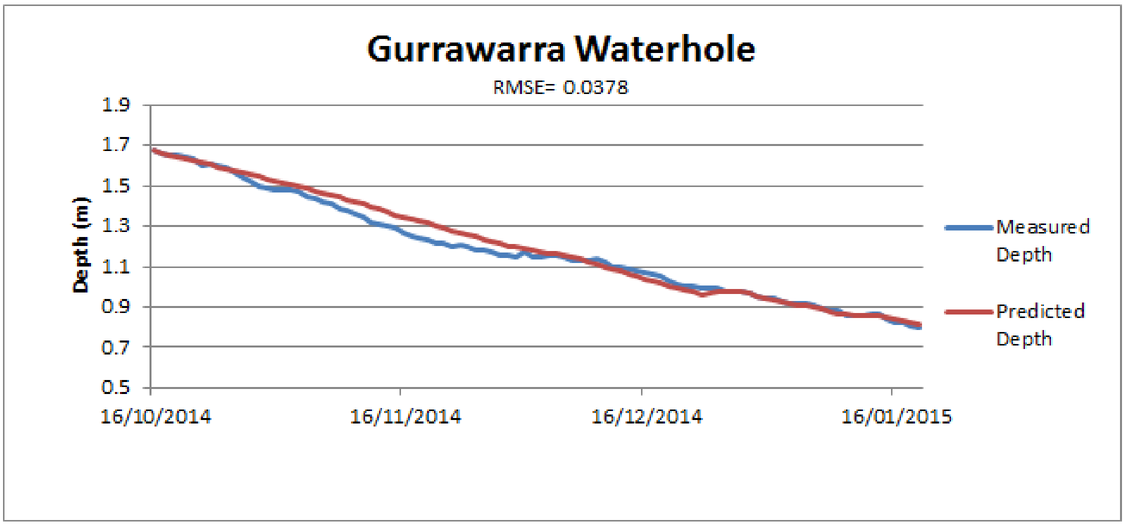

Figure C.44. Observed and modelled data for Gurrawarra Waterhole for the Calibration Period.

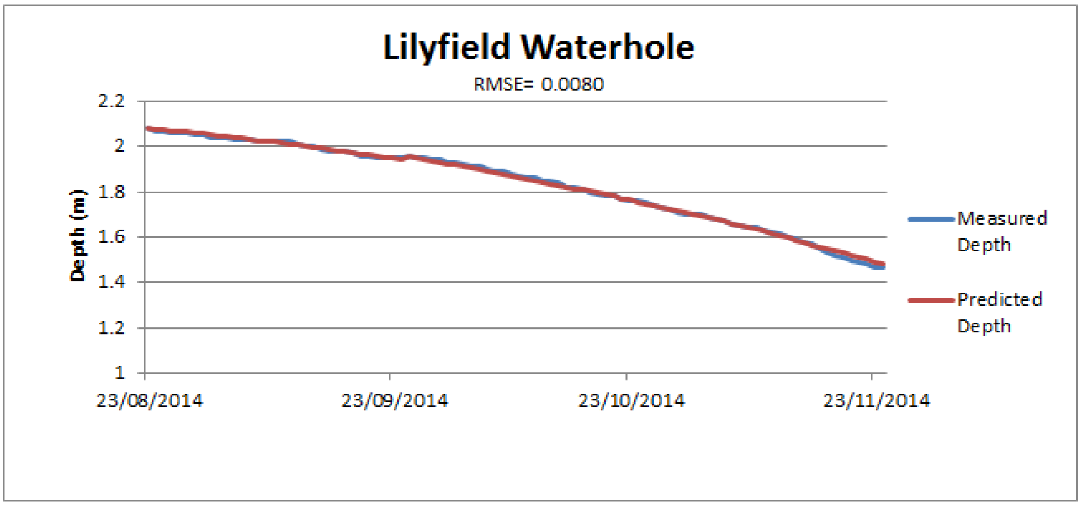

Figure C.45. Observed and modelled data for Lilyfield Waterhole for the Calibration Period.

Narran River

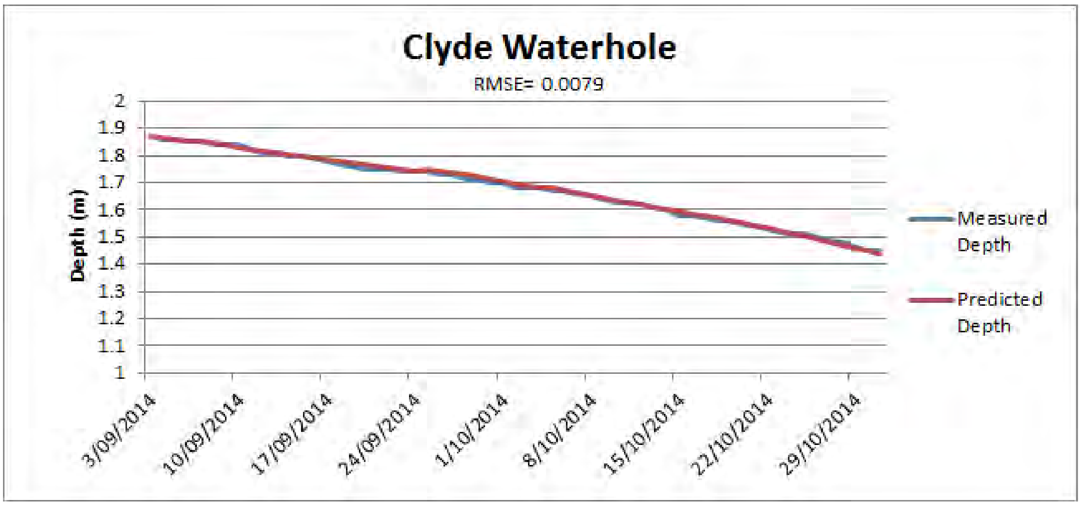

Figure C.46. Observed and modelled data for Clyde Waterhole for the Calibration Period.

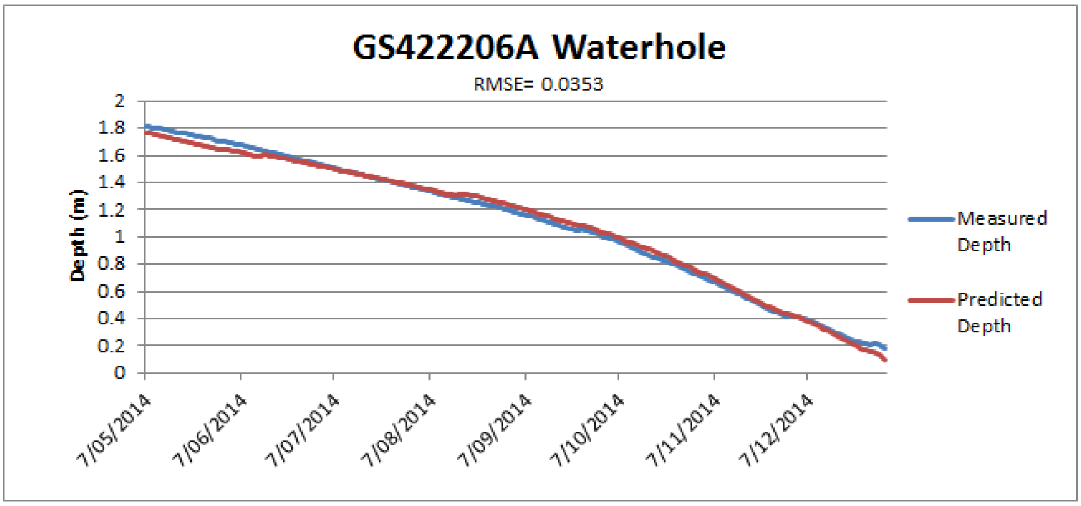

Figure C.47. Observed and modelled data for GS422206A Waterhole for the Calibration Period.

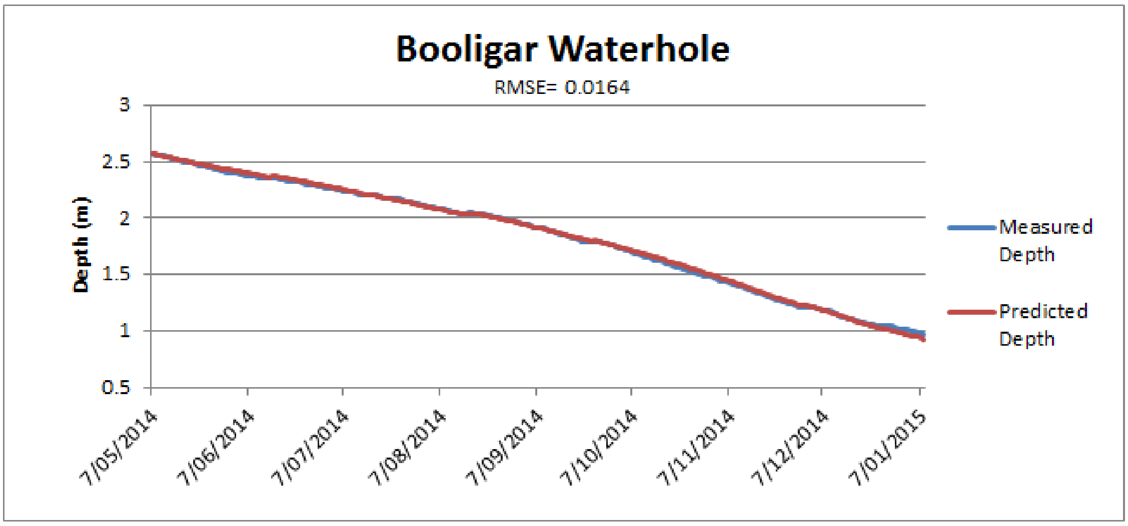

Figure C.48. Observed and modelled data for Booligar Waterhole for the Calibration Period.

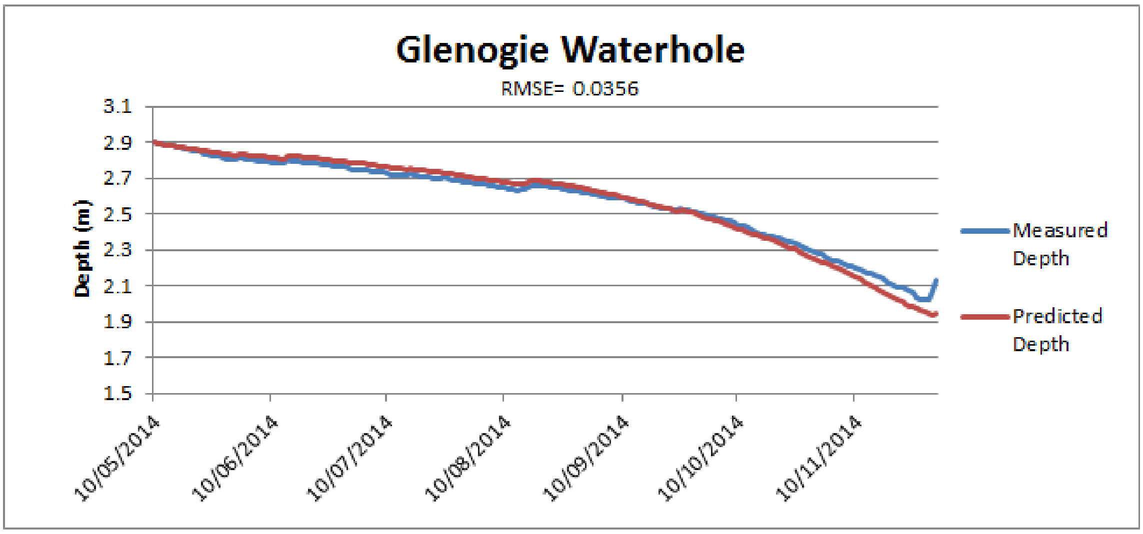

Figure C.49. Observed and modelled data for Glenogie Waterhole for the Calibration Period.

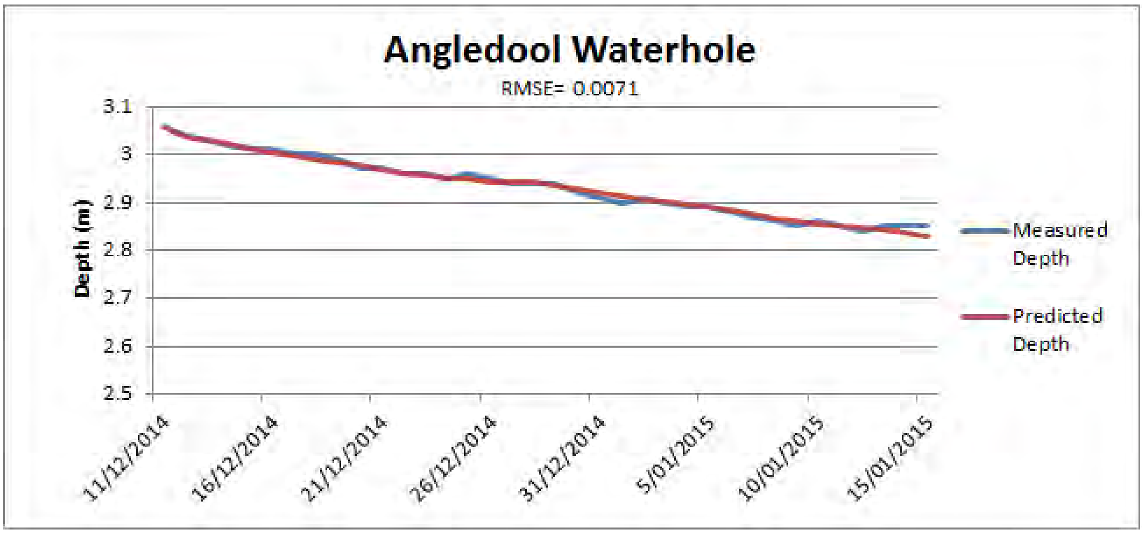

Figure C.50. Observed and modelled data for Angledool Waterhole for the Calibration Period.

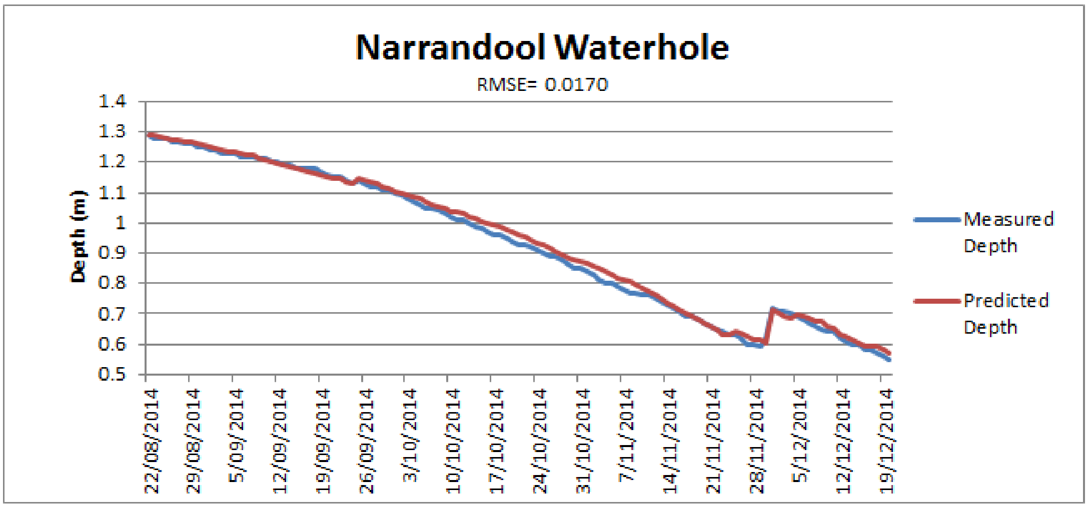

Figure C.51. Observed and modelled data for Narrandool Waterhole for the Calibration Period.

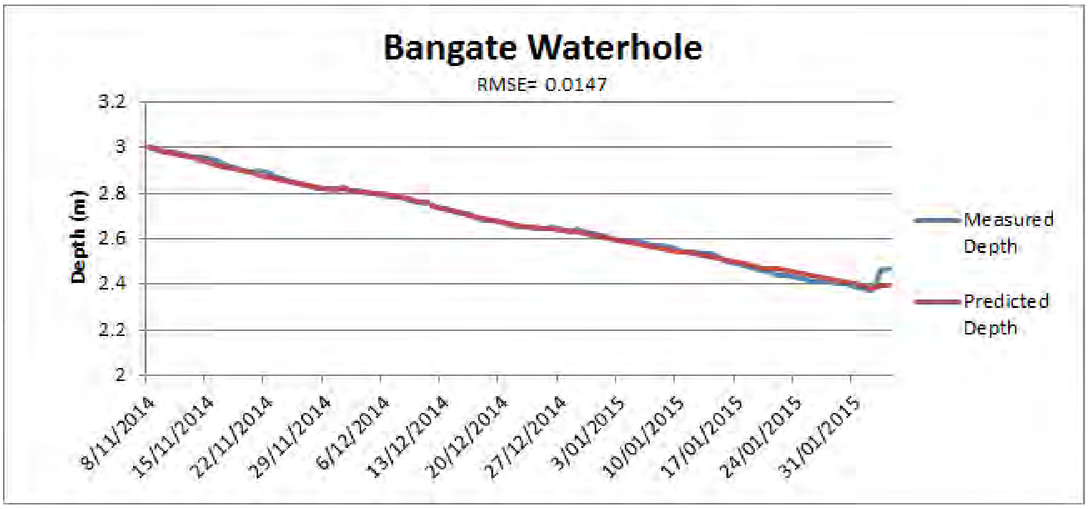

Figure C.52. Observed and modelled data for Bangate (Sorrento Hole) Waterhole for the Calibration Period.

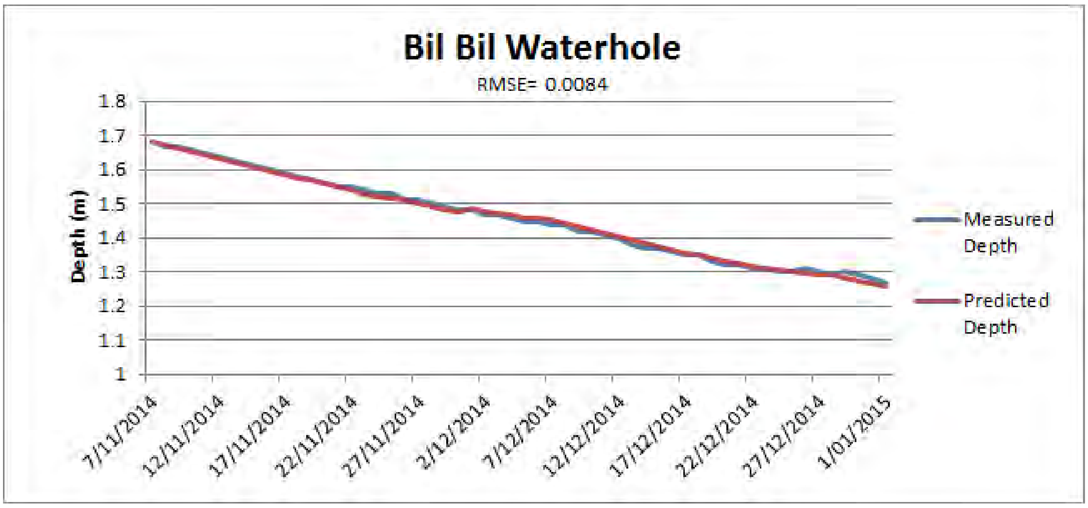

Figure C.53. Observed and modelled data for Bil Bil Waterhole for the Calibration Period.

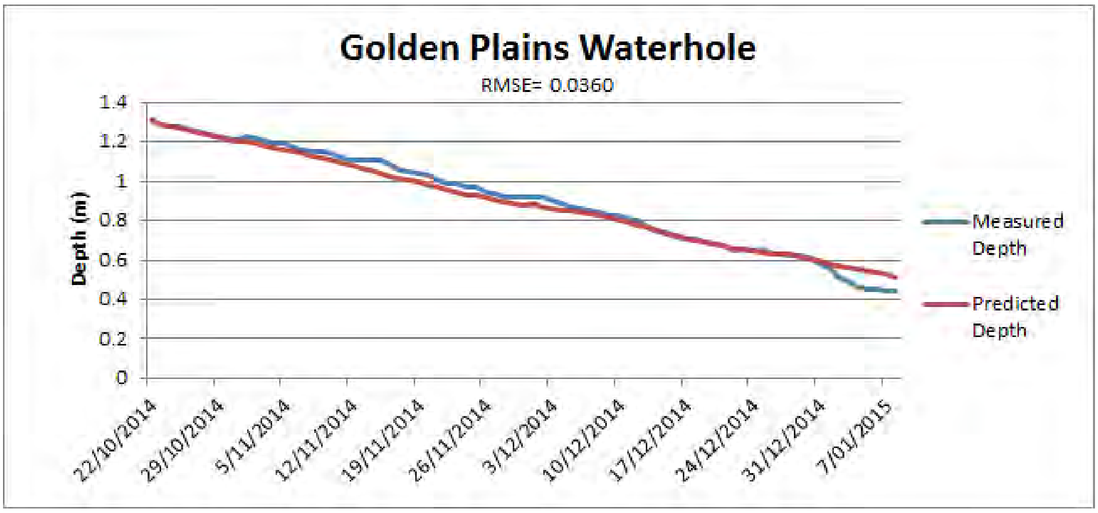

Figure C.54. Observed and modelled data for Golden Plains Waterhole for the Calibration Period.

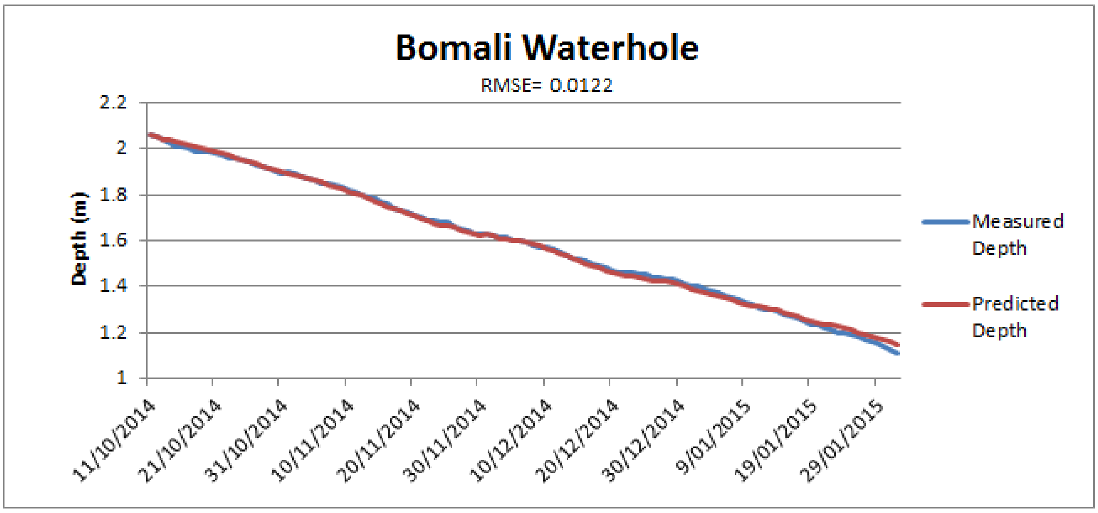

Figure C.55. Observed and modelled data for Bomali Waterhole for the Calibration Period.

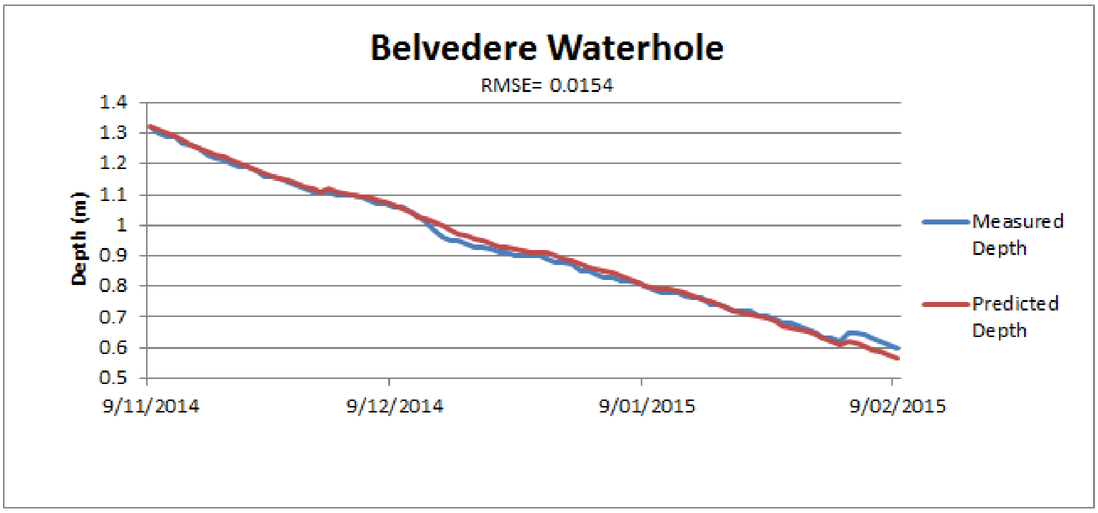

Figure C.56. Observed and modelled data for Belvedere Waterhole for the Calibration Period.

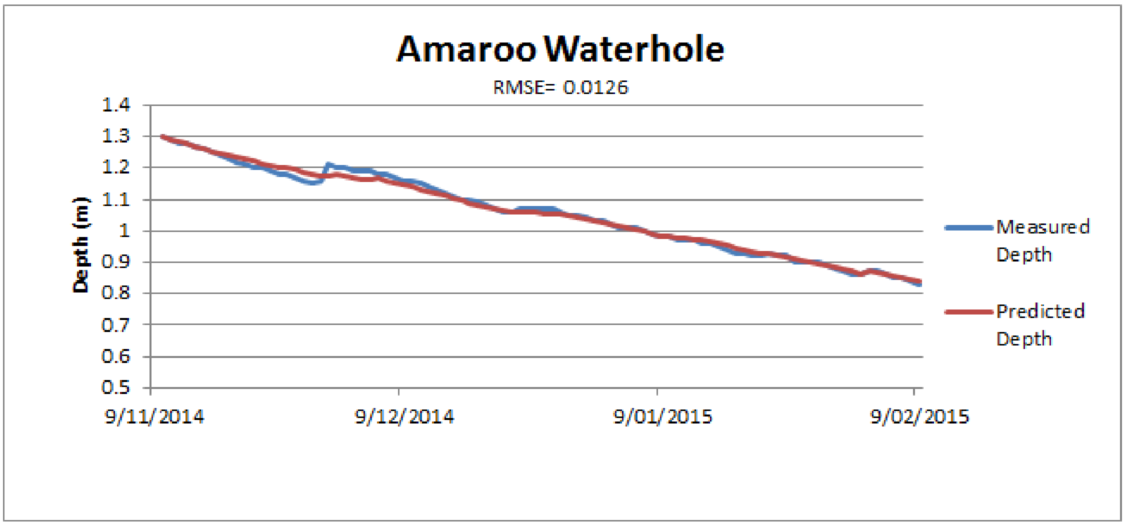

Figure C.57. Observed and modelled data for Amaroo Waterhole for the Calibration Period.

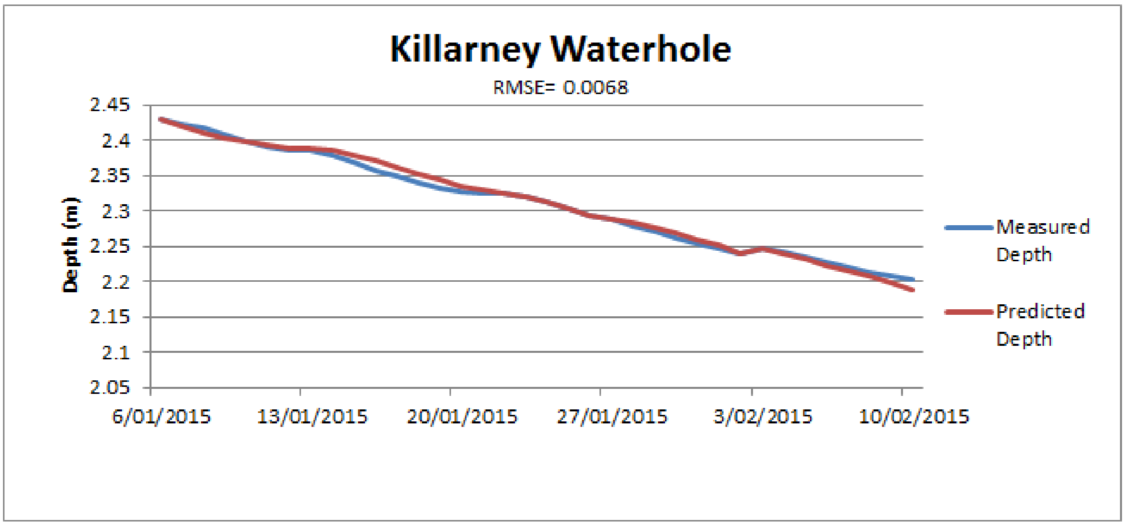

Figure C.58. Observed and modelled data for Killarney Waterhole for the Calibration Period.

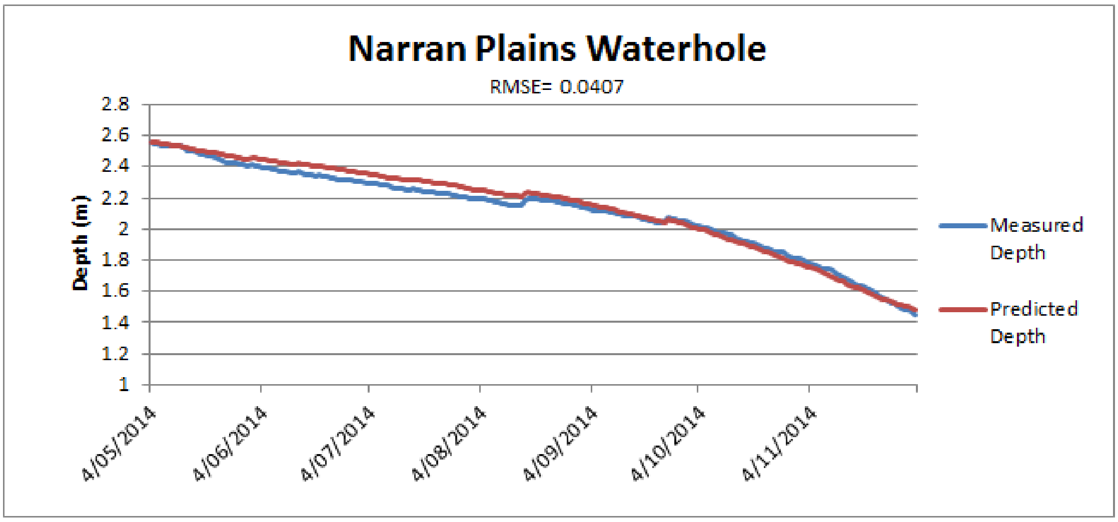

Figure C.59. Observed and modelled data for Narran Plains Waterhole for the Calibration Period.

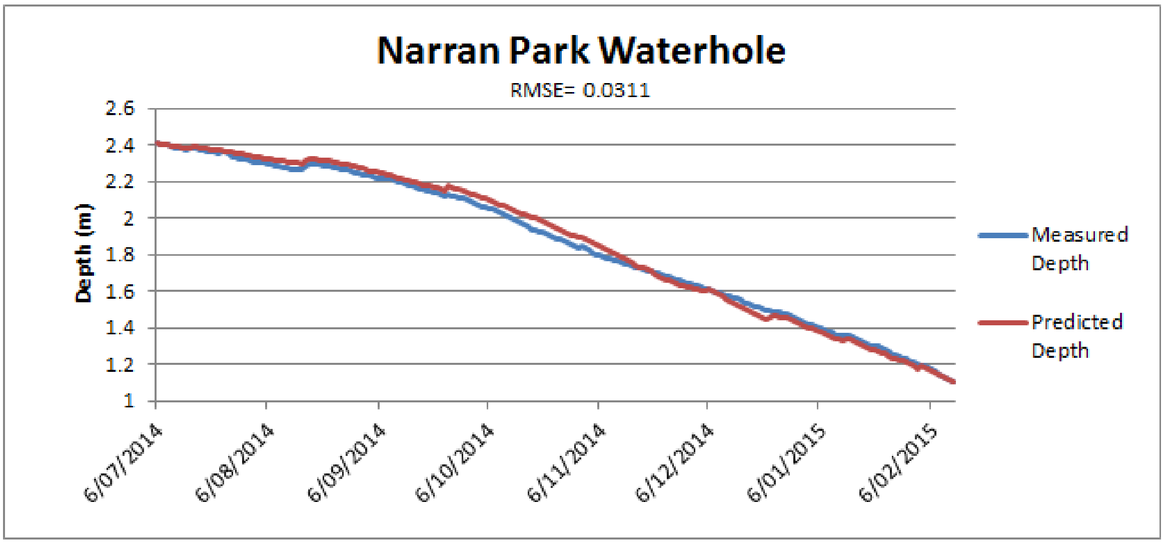

Figure C.60. Observed and modelled data for Narran Park Waterhole for the Calibration Period.

Appendix D – Groundwater Interactions

Table D.1 and D.2 - 100 Samples were taken in total and were analysed for $\delta^{18}O$ and $\delta^{2}H$. 33 samples were taken during the bathymetry survey (February/March 2015) and only EC and $\delta^{18}O$ and $\delta^{2}H$ was determined while the remaining 67 were also measured for Radon.

Table D.1 – Results from Radon analysis and EC measurements for waterholes of the Culgoa River.

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18O} permil	d^{2}H permil
Ballandool	sw	Culgoa	12/06/2015	133.33	151.4	-0.07	0.15
Ballandool	sw	Culgoa	10/03/2015	N/A	139.4	-0.19	-2.84
Brenda	sw	Culgoa	10/03/2015	N/A	140.0	-0.31	-3.45
Brenda Waterhole	sw	Culgoa	13/06/2005	174.43	162.8	0.73	3.12
Brenda Waterhole-1	sw	Culgoa	12/06/2015	158.74	109.8	0.52	-0.63
Brenda Waterhole-2	sw	Culgoa	12/06/2015	169.34	135.9	0.31	1.14
Brenda Waterhole-3	sw	Culgoa	12/06/2015	156.33	131.8	0.20	0.32
Brenda Waterhole-4	sw	Culgoa	12/06/2015	159.64	105.9	0.22	-0.05
Brenda Waterhole-5	sw	Culgoa	12/06/2015	166.40	105.2	0.21	-0.22
Brenda Waterhole-6	sw	Culgoa	12/06/2015	205.38	106.5	0.20	0.13
Brenda Waterhole-7	sw	Culgoa	12/06/2015	177.30	96.8	0.19	-0.95
Brenda Waterhole-8	sw	Culgoa	12/06/2015	182.01	125.5	0.05	0.81

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18O} permil	d^{2}H permil
Brenda Weirpool	sw	Culgoa	11/02/2015	N/A	137.7	-0.63	-4.19
Caringle	sw	Culgoa	26/02/2015	N/A	126.5	-1.73	-10.16
Cubbie	sw	Culgoa	10/06/2015	158.55	147.6	-0.56	-1.42
Cubbie	sw	Culgoa	18/02/2015	N/A	107.5	-2.24	-10.13
Culgoa	sw	Culgoa	12/03/2015	N/A	150.5	0.03	-3.68
CulgoaNP-1	sw	Culgoa	13/06/2015	128.64	167.8	2.53	8.60
CulgoaNP-2	sw	Culgoa	13/06/2015	169.21	172.5	2.51	7.66
CulgoaNP-3	sw	Culgoa	13/06/2015	200.61	143.7	2.55	7.78
CulgoaNP-4	sw	Culgoa	13/06/2015	172.33	142.3	2.63	9.96
Gurrawarra	sw	Culgoa	15/03/2015	N/A	203.0	1.74	4.30
Ingie	sw	Culgoa	17/02/2015	N/A	108.0	-2.36	-10.12
Ingie-1	sw	Culgoa	26/05/2015	40.13	112.0	-0.43	-2.75
Ingie-2	sw	Culgoa	26/05/2015	42.74	124.0	-0.43	-2.16
Ingie-3	sw	Culgoa	26/05/2015	76.97	123.0	-0.45	-0.55
Ingie-3	sw	Culgoa	26/05/2015	59.96	217.0	-0.43	-3.22

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18}O permil	d^{2}H permil
Innisfal	sw	Culgoa	14/03/2015	N/A	125.6	-0.06	-0.47
Innisfall-1	sw	Culgoa	29/05/2015	66.25	96.0	-3.09	-14.84
Innisfall-2	sw	Culgoa	29/05/2015	76.47	84.0	-3.18	-16.28
Innisfall-3	sw	Culgoa	29/05/2015	69.94	85.0	-3.07	-15.32
Innisfall-4	sw	Culgoa	29/05/2015	53.75	87.0	-3.08	-16.12
Lillyfield	sw	Culgoa	15/03/2015	N/A	201.0	1.79	3.81
Lilyfield-1	sw	Culgoa	29/05/2015	53.75	79.0	-2.68	-15.05
Lilyfield-2	sw	Culgoa	29/05/2015	90.83	77.0	N/A	N/A
Lilyfield-3	sw	Culgoa	29/05/2015	71.89	79.0	N/A	N/A
Lilyfield-4	sw	Culgoa	29/05/2015	48.21	78.0	-2.75	-14.93
Warraweena	sw	Culgoa	15/03/2015	N/A	198.8	1.62	3.45
Weilmoringie Weir	sw	Culgoa	12/03/2015	N/A	150.4	-0.31	-3.04
Weilmoringle Weir-1	sw	Culgoa	14/06/2015	124.10	122.9	2.13	4.16
Weilmoringle Weir-2	sw	Culgoa	14/06/2015	165.61	142.8	N/A	N/A
Weilmoringle Weir-3	sw	Culgoa	14/06/2015	119.08	140.8	2.65	8.93

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18O} permil	d^{2}H permil
Weilmoringie Weir-4	sw	Culgoa	13/06/2015	234.81	195.2	2.16	6.38
Weilmoringle Station	sw	Culgoa	12/03/2015	N/A	146.7	-0.01	-3.28
Westmunda	sw	Culgoa	13/06/2015	114.72	97.8	-2.26	-12.19
Westmunda	sw	Culgoa	14/03/2015	N/A	143.0	0.19	-1.60
Woolerbilla	sw	Culgoa	17/02/2015	N/A	110.1	-2.38	-10.46
Woolerbilla-1	sw	Culgoa	13/06/2015	N/A	161.1	-0.34	-1.43
Woolerbilla-2	sw	Culgoa	13/06/2015	N/A	163.3	-0.29	-0.38
Woolerbilla-3	sw	Culgoa	13/06/2015	N/A	164.3	-0.24	-0.74

Table D.2 – Results from Radon analysis and EC measurements for waterholes of the Narran River.

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18O} permil	d^{2}H permil
Amaroo	sw	Narran	13/05/2015	N/A	156.8	2.04	6.18
Amaroo-1	sw	Narran	28/05/2015	114.86	274.0	4.79	19.32
Amaroo-14	sw	Narran	28/05/2015	84.86	290.0	4.82	18.39
Amaroo-15	sw	Narran	28/05/2015	79.44	289.0	4.81	18.29

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18}O permil	d^{2}H permil
Amaroo-17	sw	Narran	28/05/2015	114.44	283.0	4.79	18.86
Amaroo-2	sw	Narran	28/05/2015	78.33	285.0	4.75	18.57
Amaroo-20	sw	Narran	28/05/2015	115.14	292.0	4.79	18.48
Bangate	sw	Narran	21/02/2015	N/A	150.1	-0.52	-0.48
Belvedere	sw	Narran	22/02/2015	N/A	164.8	0.04	1.19
BilBil	sw	Narran	21/02/2015	N/A	158.5	-0.23	0.24
Bomali	sw	Narran	22/02/2015	N/A	170.9	0.03	0.02
Bomali-2	sw	Narran	16/06/2015	225.54	191.8	1.96	8.04
Bomali-3	sw	Narran	16/06/2015	201.95	194.8	4.03	14.02
Booligar	sw	Narran	13/06/2015	116.27	156.7	0.35	1.37
Booligar	sw	Narran	20/02/2015	N/A	119.5	-2.05	-10.99
Clyde	sw	Narran	19/02/2015	N/A	101.6	-2.22	-11.00
Clyde 1	sw	Narran	11/06/2015	176.42	104.6	-0.06	-1.80
Clyde 2	sw	Narran	11/06/2015	170.87	101.2	-0.22	-2.48
Clyde 3	sw	Narran	11/06/2015	155.99	101.1	-0.22	-2.51

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18O} permil	d^{2}H permil
Glenogie	sw	Narran	20/02/2015	N/A	124.0	-1.84	-11.00
GoldenPlains	sw	Narran	24/02/2015	N/A	165.9	-0.09	-1.36
GSA22206A	sw	Narran	19/02/2015	N/A	107.6	-2.16	-12.13
GSA22206A-1	sw	Narran	26/05/2015	40.13	122.0	-0.57	-2.53
GSA22206A-2	sw	Narran	26/05/2015	110.97	119.0	-0.49	-2.68
GSA22206A-3	sw	Narran	27/05/2015	135.97	115.0	-0.61	-3.30
GSA22206A-4	sw	Narran	26/05/2015	57.28	114.0	-0.59	-2.11
Killarney	sw	Narran	13/03/2015	N/A	200.0	1.59	6.84
Killarney-10	sw	Narran	15/06/2015	203.77	165.7	3.55	13.95
Killarney-12	sw	Narran	15/06/2015	203.22	211.0	3.54	14.03
Killarney-13	sw	Narran	15/06/2015	142.18	213.0	3.62	14.93
Killarney-5	sw	Narran	15/06/2015	215.23	211.0	4.40	17.01
Killarney-6	sw	Narran	15/06/2015	269.79	190.2	4.12	16.10
Killarney-7	sw	Narran	15/06/2015	207.73	164.2	3.82	15.14
Killarney-8	sw	Narran	15/06/2015	238.00	213.0	3.55	14.15

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18}O permil	d^{2}H permil
Killarney-8	sw	Narran	15/06/2015	142.08	N/A	N/A	N/A
Killarney-9	sw	Narran	15/06/2015	225.29	165.2	3.53	14.11
Narran Park 7	sw	Narran	27/05/2015	N/A	250.0	N/A	N/A
Narran Park 8	sw	Narran	27/05/2015	93.19	253.0	4.59	18.29
Narran Park 9	sw	Narran	27/05/2015	101.53	247.0	4.29	18.50
Narran Park 10	sw	Narran	27/05/2015	79.96	251.0	4.24	16.80
Narran Park 12	sw	Narran	27/05/2015	81.90	248.0	4.21	17.06
Narran Park 13	sw	Narran	27/05/2015	95.28	244.0	4.42	18.44
Narran Park-bank	gw	Narran	27/05/2015	2779.17	10600.0	4.22	16.53
Narran Plains	sw	Narran	15/06/2015	234.98	233.0	5.14	18.27
Narrandool	sw	Narran	24/02/2015	N/A	141.2	-0.95	-6.04
Narrandool-1	sw	Narran	14/06/2015	187.04	184.6	1.99	6.51
Narrandool-2	sw	Narran	14/06/2015	182.22	125.7	2.12	4.49
Narrandool-3	sw	Narran	14/06/2015	208.59	127.5	N/A	N/A
Narran Park	sw	Narran	23/02/2015	N/A	185.6	0.64	4.97

Sample	Type	River	Date	Radon (Bq/m^3)	EC (microS/cm)	d^{18O} permil	d^{2}H permil
Narran Plains	sw	Narran	23/02/2015	N/A	184.1	0.57	-5.57
Goodooga_Rain	rain	Rain	26/05/2015	N/A	81.0	-2.63	-9.51

Table D.3 - Data obtained from 12 surface water samples and 8 groundwater samples along the Darling River from Brewarrina to West of Tilpa.

Sample	Type	Date	EC (microS/cm)	T°C	DO (mg/L)	Radon (Bq/m3)	d^{18O} permil	d^{2}H permil
Summerville	sw	28/09/15 12:00	395	20.3	8.9	56.1	-1.67	-13.28
Jandra	sw	28/09/15 14:00	347	22.7	10.12	47.7	-2.95	-19.12
Hell’s Gate	sw	28/09/15 17:00	499	21.7	10	73.5	-2.60	-18.63
Hell’s Gate	sw	28/09/15 17:00	504	20.2	9.72	65.9	-2.57	-18.24
Akuna	sw	29/09/15 07:40	474	17.9	6.99	102.2	-1.32	-8.62
Weir 20A	sw	29/09/15 08:30	453	18.3	7	83.8	-1.62	-10.21
Winbar	sw	29/09/15 11:20	495	18.8	8.68	37.1	-1.12	-8.78
Nangara Bend	sw	29/09/15 12:00	459	20.5	8.9	22.1	-0.81	-7.90
Trevallyn	sw	29/09/15 14:00	350	21	8.4	43.4	-1.14	-7.84
Wilga	sw	29/09/15 14:40	348	19.6	8.02	38.3	-1.10	-7.43
Weir 19A downstream	sw	10/01/15 08:00	309	18.1	9.37	23.8	-2.84	-19.64
Weir 19A upstream	sw	10/01/15 08:00	310	17.7	6.84	28.2	-2.95	-19.88
B36842-1	gw	29/09/15 16:00	541	23.3	0.14	5343.8	-3.54	-28.48
B36842-2	gw	29/09/15 16:00	1976	23.2	0.4	74.5	-3.64	-29.24

Sample	Type	Date	EC (microS/cm)	T°C	DO (mg/L)	Radon (Bq/m3)	d^{18O} permil	d^{2}H permil
B36852-1	gw	30/09/15 09:30	34570	23.9	0.38	6739.6	-4.04	-31.45
B36852-2	gw	30/09/15 09:30	35120	24	3.7	4687.5	-3.69	-29.24
B36937-1	gw	30/09/15 13:30	12700	24.4	0.11	2905.2	-4.85	-35.17
B36937-2	gw	30/09/15 13:30	40370	24.4	0.1	1318.8	-4.16	-32.50
Bore36853-1	gw	10/01/15 09:15	377	23.8	0.11	13236.1	-3.45	-25.24
Bore36853-2	gw	10/01/15 09:15	35089	23.9	1.37	178.8	-4.12	-31.88

Appendix E – Transferability

Transferability Models

As part of the transferability examination, four models were developed to describe the depth/persistence time relationship across three river valleys; the Moonie, Culgoa and Narran rivers. The following section describes the models in greater detail.

Model 1

$$\mu_i = \beta_1 \times \mathrm{MaxDepthCulgoa_i} + \beta_2 \times \mathrm{RiverCulgoa_i} + \beta_3 \times \mathrm{RiverMoonie_i} + \beta_4 \times \mathrm{RiverNarran_i} + \beta_5 \times \mathrm{MaxDepthMoonie_i} + \beta_6 \times \mathrm{MaxDepthNarran}_i$$

Where

β_1 = Gradient of Culgoa regression

β_2 = Culgoa regression intercept

β_3 = Moonie regression intercept

β_4 = Narran regression intercept

β_5 = Gradient of Moonie regression

β_6 = Gradient of Narran regression

Where MaxDepthRiverX is used, if the waterhole being predicted falls within river system X, substitute the value, if not, substitute 0. For example, if predicting persistence for a waterhole in the Culgoa with a depth of 2 metres, $\mathrm{MaxDepthCulgoa_i}$ = 2 and $\mathrm{MaxDepthNarran_i}$ = 0.

Where RiverX is used, if the waterhole being predicted falls within river system X, substitute 1, if not, substitute 0. For example, if predicting persistence of a waterhole in the Culgoa, $\mathrm{RiverCulgoa_i}$ = 1 and $\mathrm{RiverNarran_i}$ = 0.

Model 2

$$\mu_i = \beta_1 \times \mathrm{MaxDepthCulgoa_i} + \beta_2 \times \mathrm{MaxDepthMoonie_i} + \beta_3 \times \mathrm{MaxDepthNarran}_i$$

Where

β_1 = Gradient of Culgoa regression

β_2 = Gradient of Moonie regression

β_3 = Gradient of Narran regression

Where MaxDepthRiverX is used, if the waterhole being predicted falls within river system X, substitute the value, if not, substitute 0. For example, if predicting persistence for a waterhole in the Culgoa with a depth of 2 metres, $\mathrm{MaxDepthCulgoa_i}$ = 2 and $\mathrm{MaxDepthNarran_i}$ = 0. For this model, the intercepts for the three separate regressions are zero.

Model 3

$$\mu_i = \beta_1 \times \mathrm{MaxDepth}_i + \beta_2 \times \mathrm{RiverCulgoa}_i + \beta_3 \times \mathrm{RiverMoonie}_i + \beta_4 \times \mathrm{RiverNarran}_i$$

Where

β_1 = Gradient of Overall regression

β_2 = Culgoa regression intercept

β_3 = Moonie regression intercept

β_4 = Narran regression intercept

Where RiverX is used, if the waterhole being predicted falls within river system X, substitute 1, if not, substitute 0. For example, if predicting persistence of a waterhole in the Culgoa, $\mathrm{RiverCulgoa}_i$ = 1 and $\mathrm{RiverNarran}_i$ = 0.

Model 4

$$\mu_i = \beta_1 \times \mathrm{MaxDepth}_i$$

Where

β_1 = Gradient of Overall regression

For this model, the intercept is zero.

Statistical Analysis

Statistical analysis of the depth-persistence relationship across the Moonie, Culgoa and Narran rivers was conducted in the R statistical software environment version 3.2.2 (R Core Team 2015) using specific libraries MASS (Venables & Ripley 2002) and ggplot2 (Wickham 2013).

Appendix F – Scenario Evaluation

Cumulative Frequency Graphs

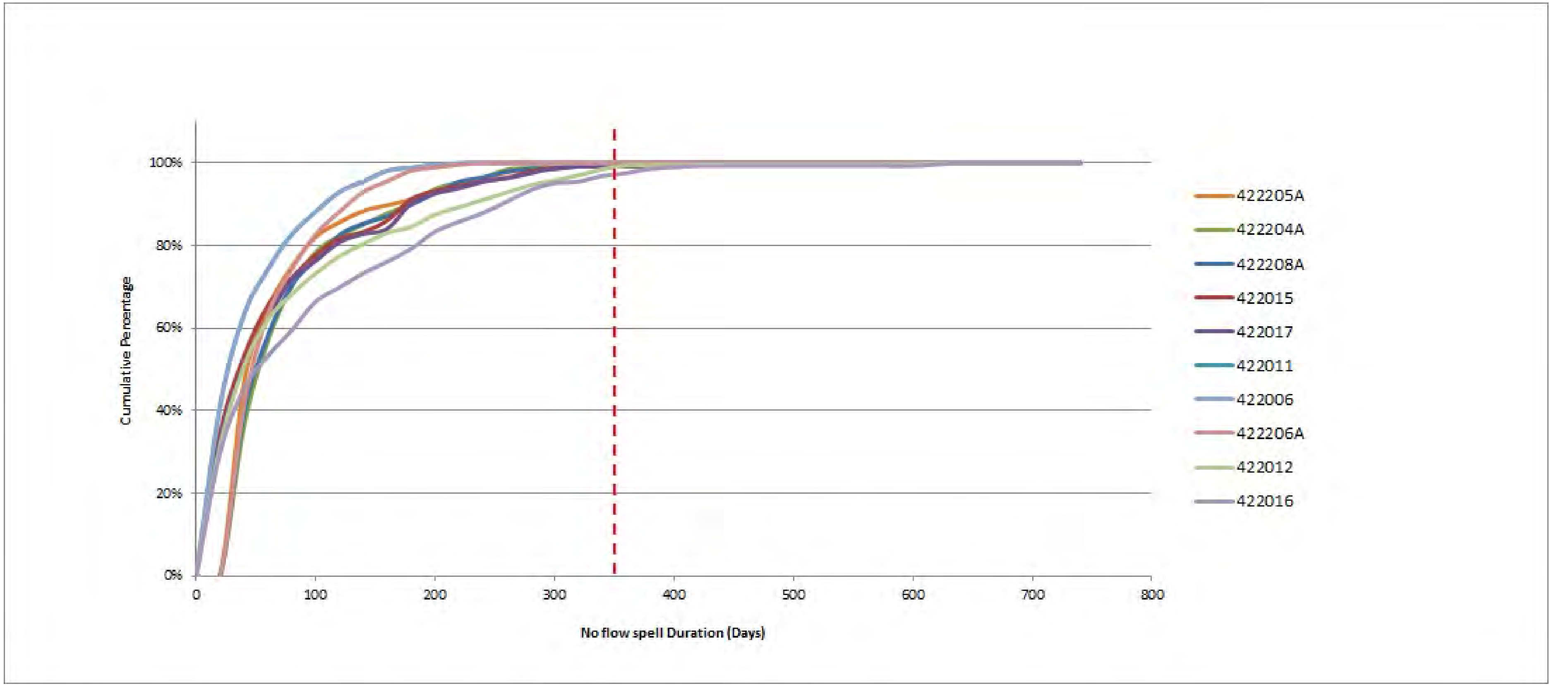

Figure F.1. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Without Development scenario in relation to stress Level 1 ToC

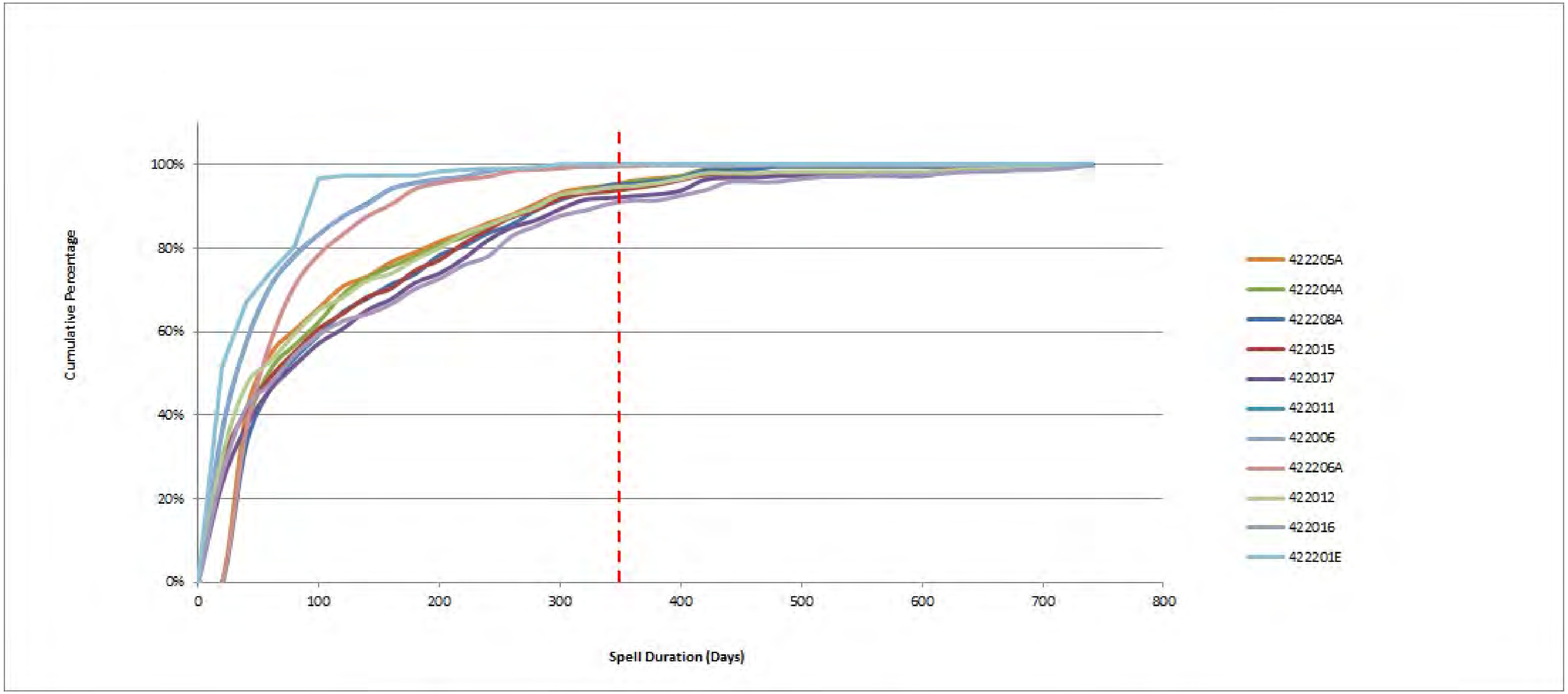

Figure F.2. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Baseline scenario in relation to stress Level 1 ToC

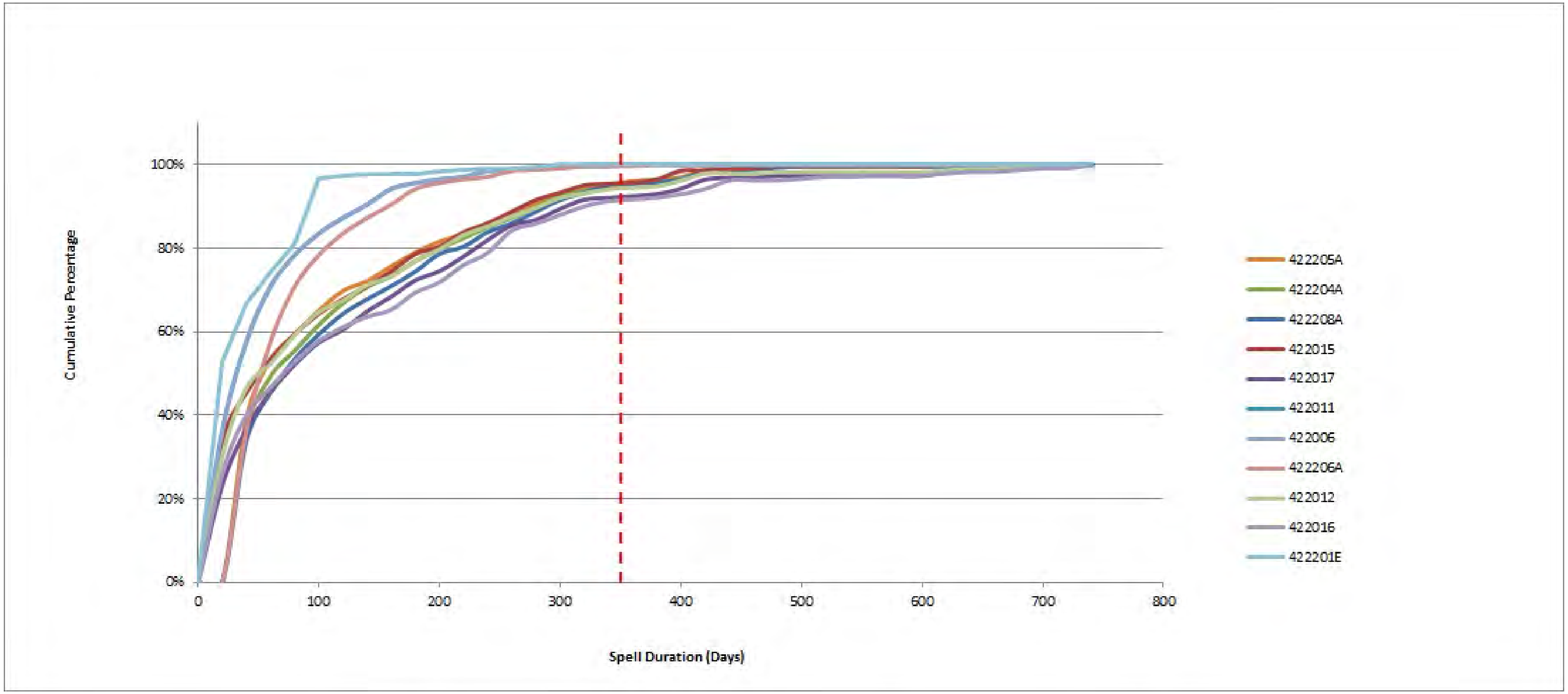

Figure F.3. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Northern Standard scenario in relation to stress Level 1 ToC

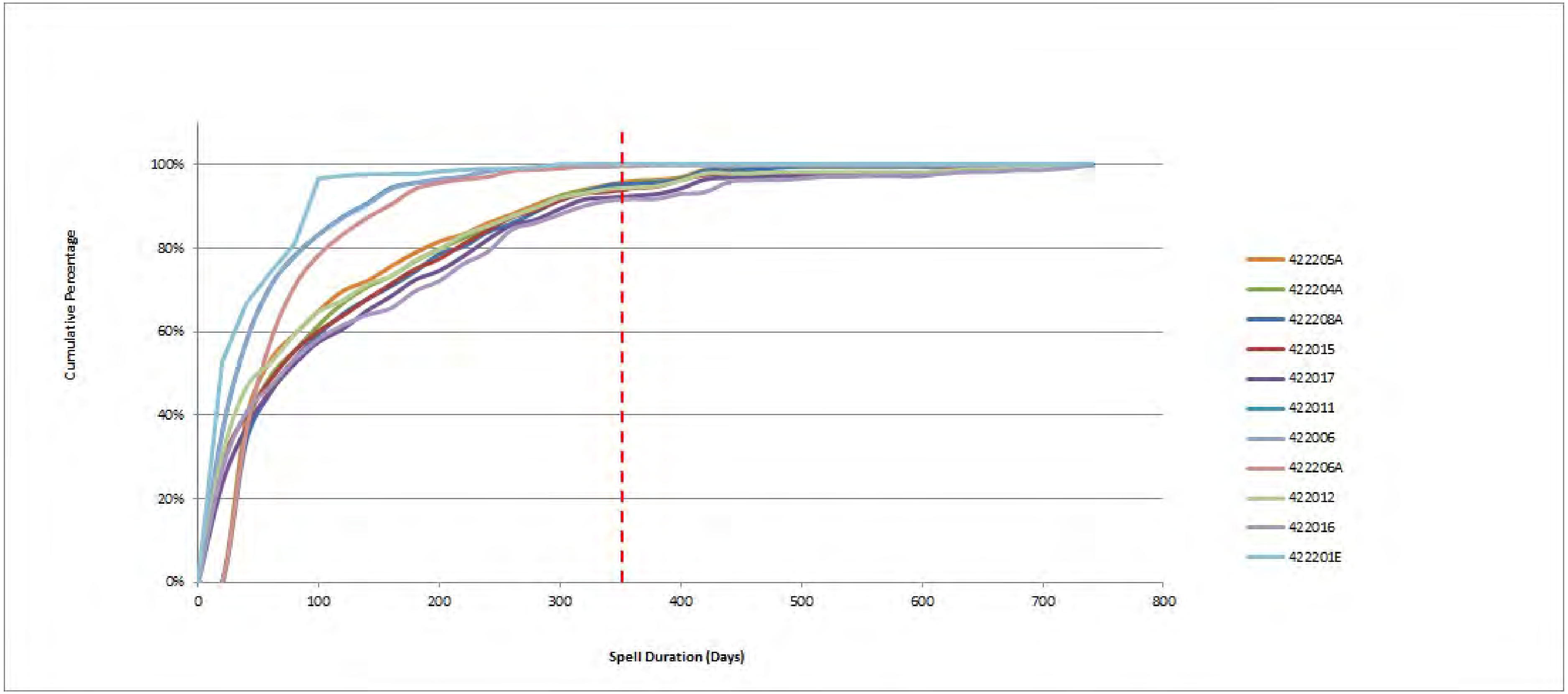

Figure F.4. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Northern Standard 100 scenario in relation to stress Level 1 ToC

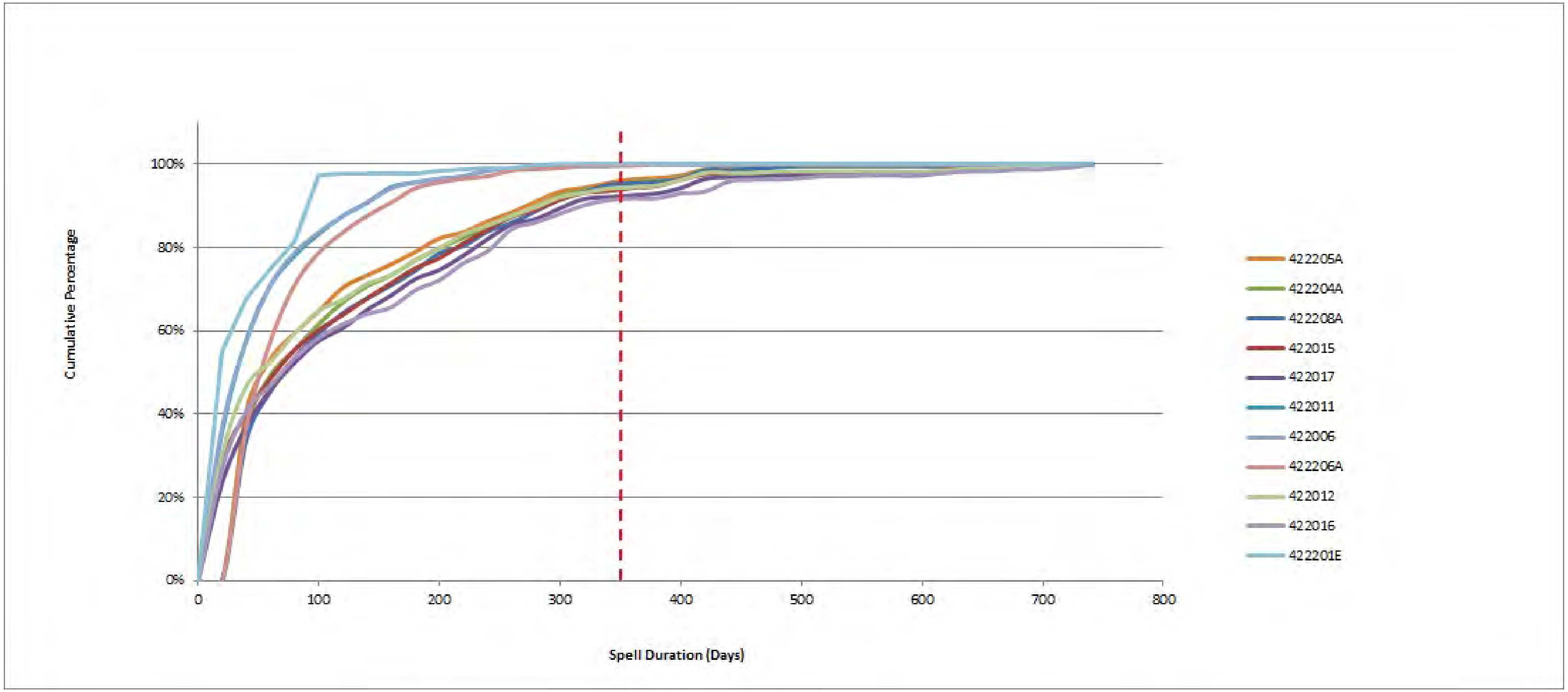

Figure F.5. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Beardmore scenario in relation to stress Level 1 ToC

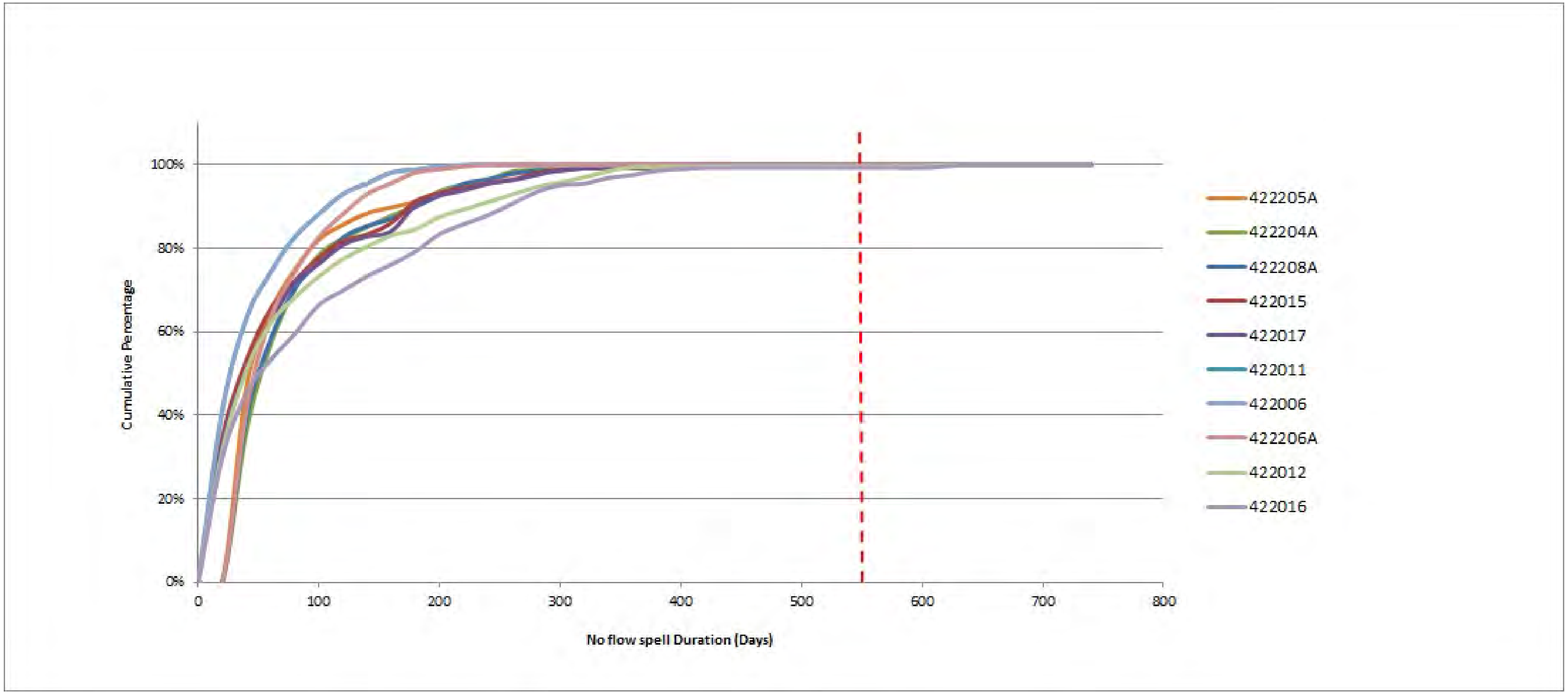

Figure F.6. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Without Development scenario in relation to stress Level 2 ToC

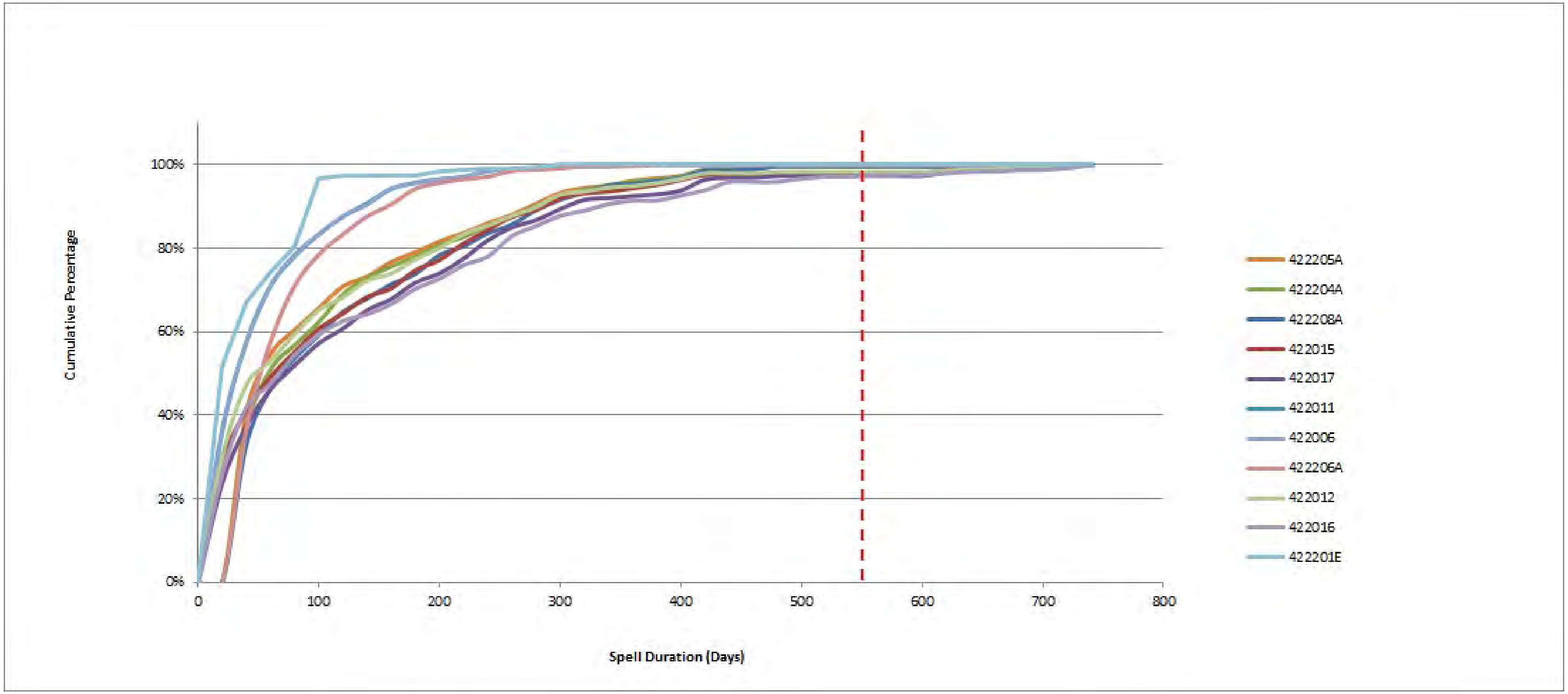

Figure F.7. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Baseline scenario in relation to stress Level 2 ToC

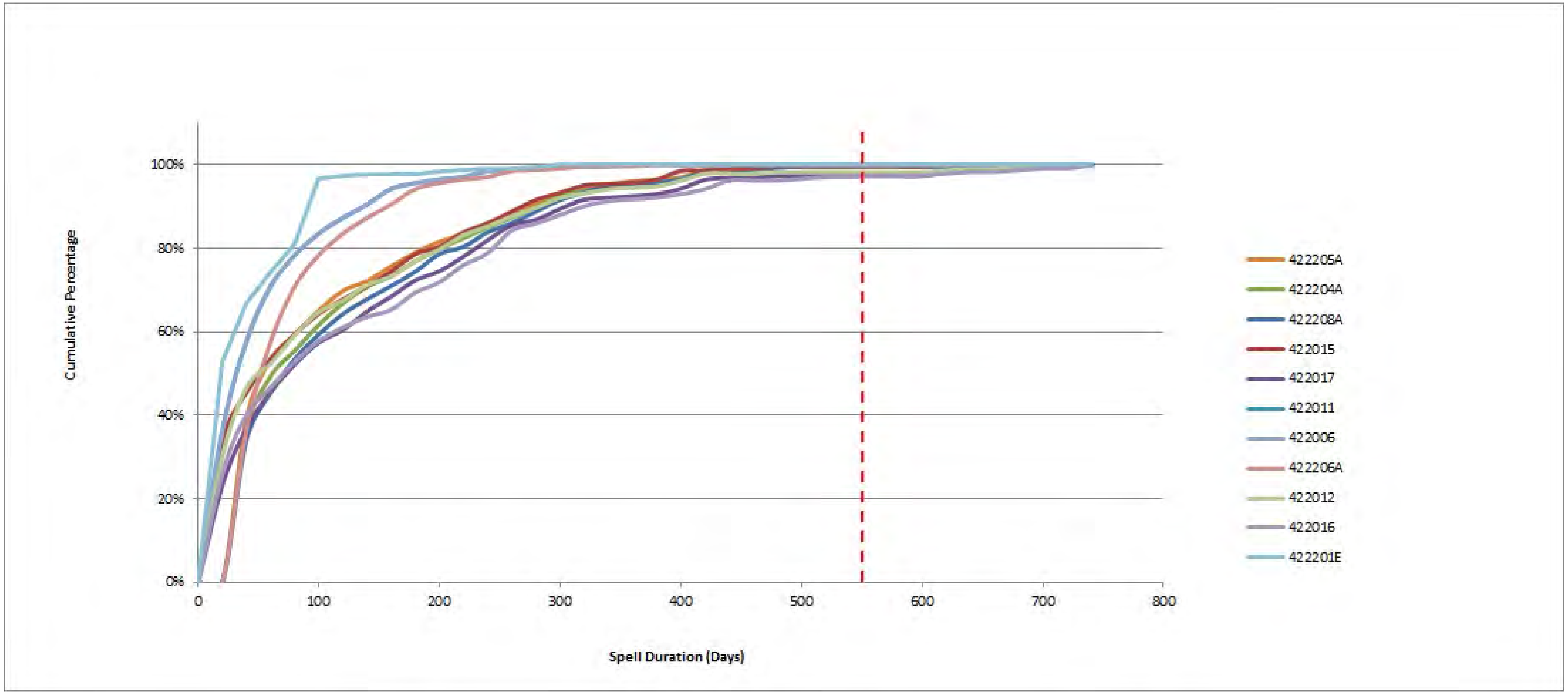

Figure F.8. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Northern Standard scenario in relation to stress Level 2 ToC

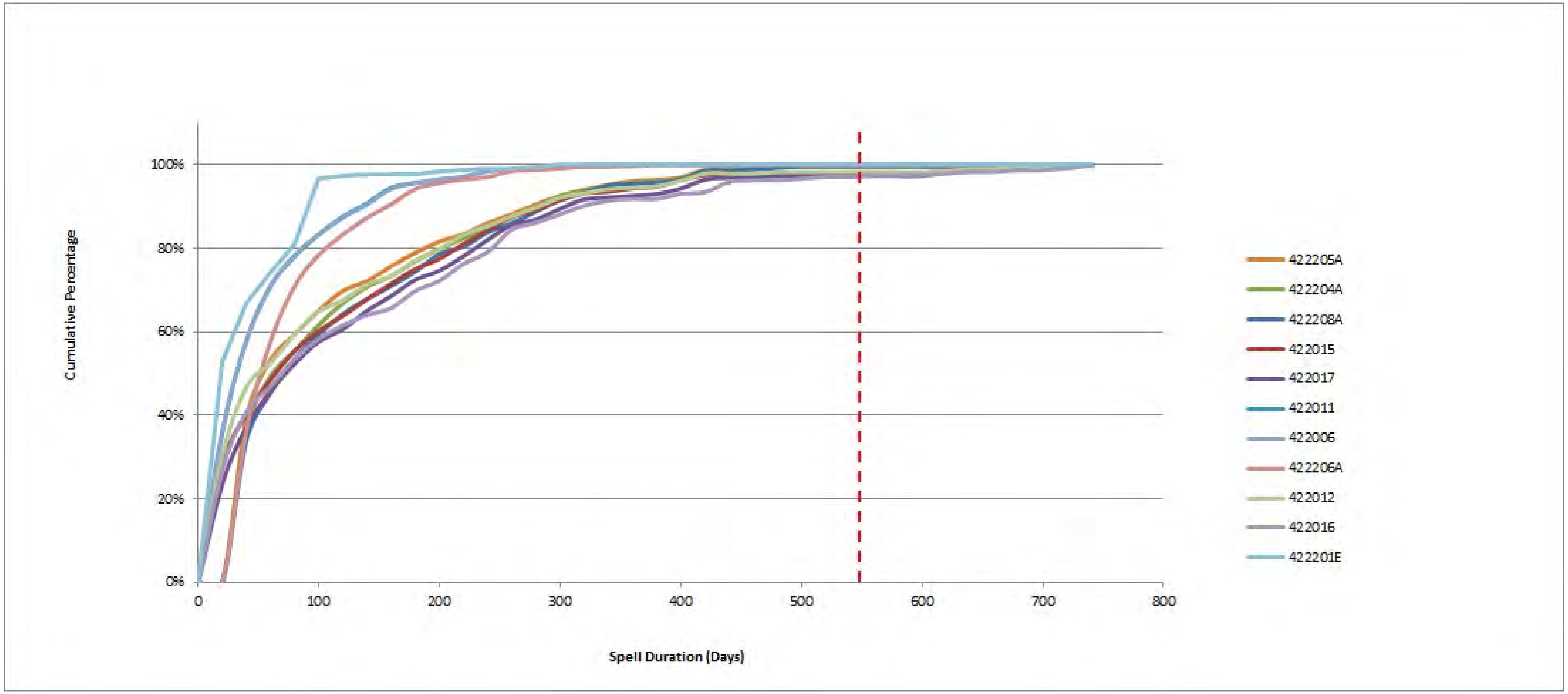

Figure F.9. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Northern Standard 100 scenario in relation to stress Level 2 ToC

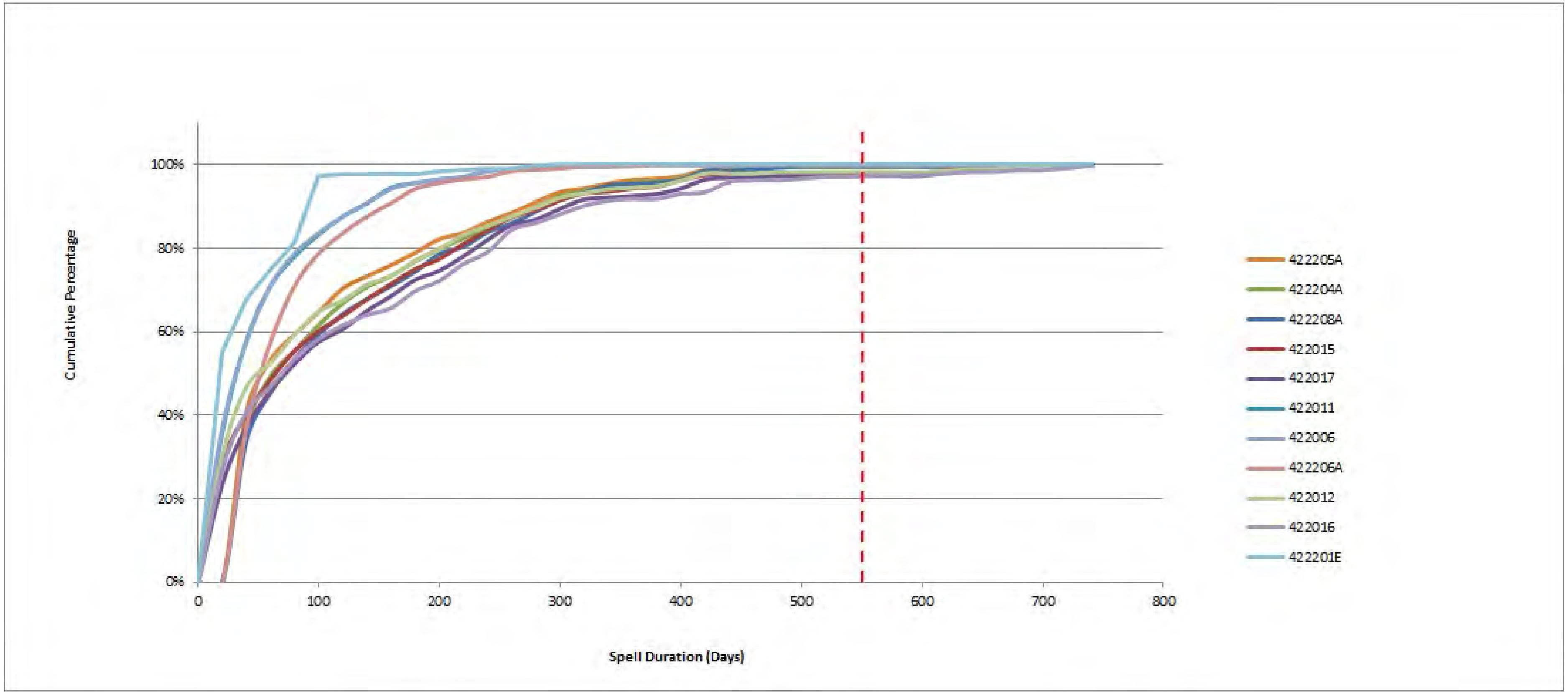

Figure F.10. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Beardmore scenario in relation to stress Level 2 ToC

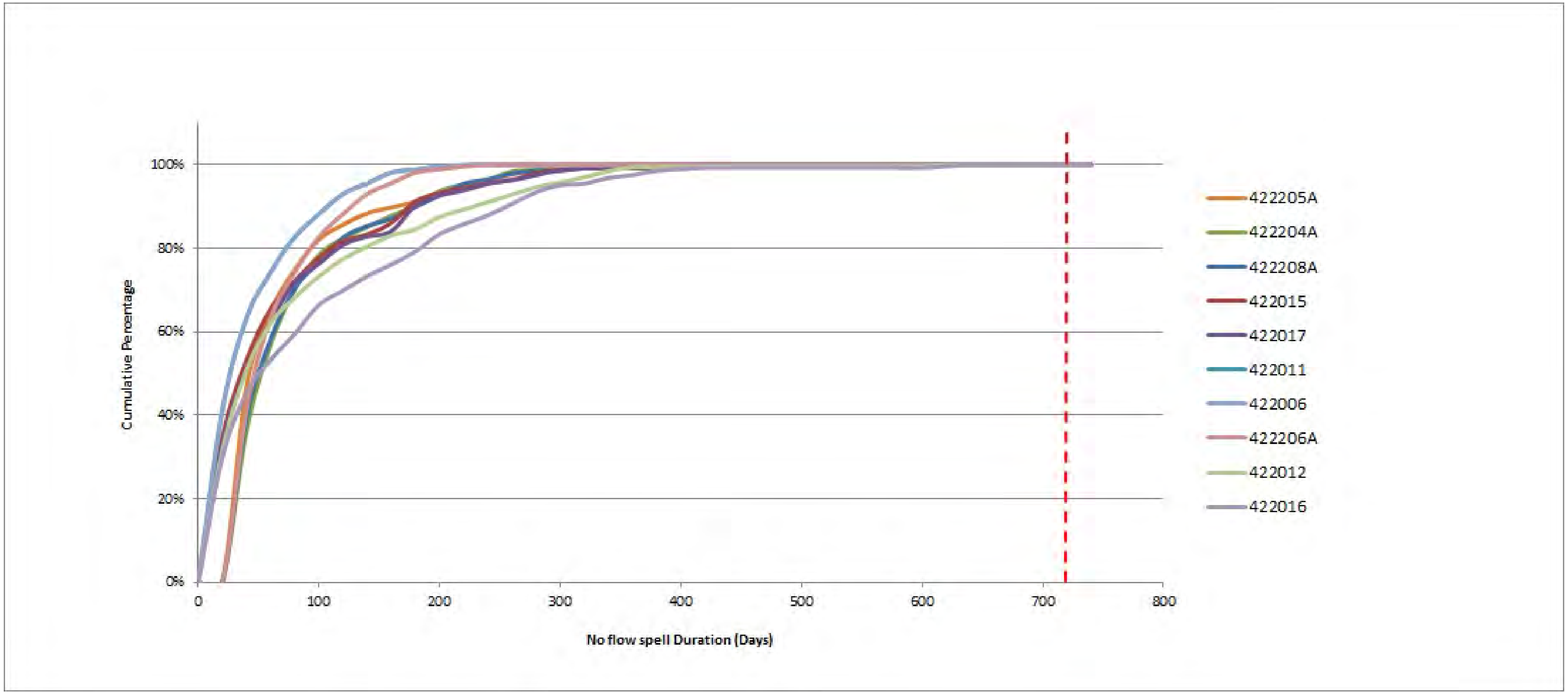

Figure F.11. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Without Development scenario in relation to stress Level 3 ToC

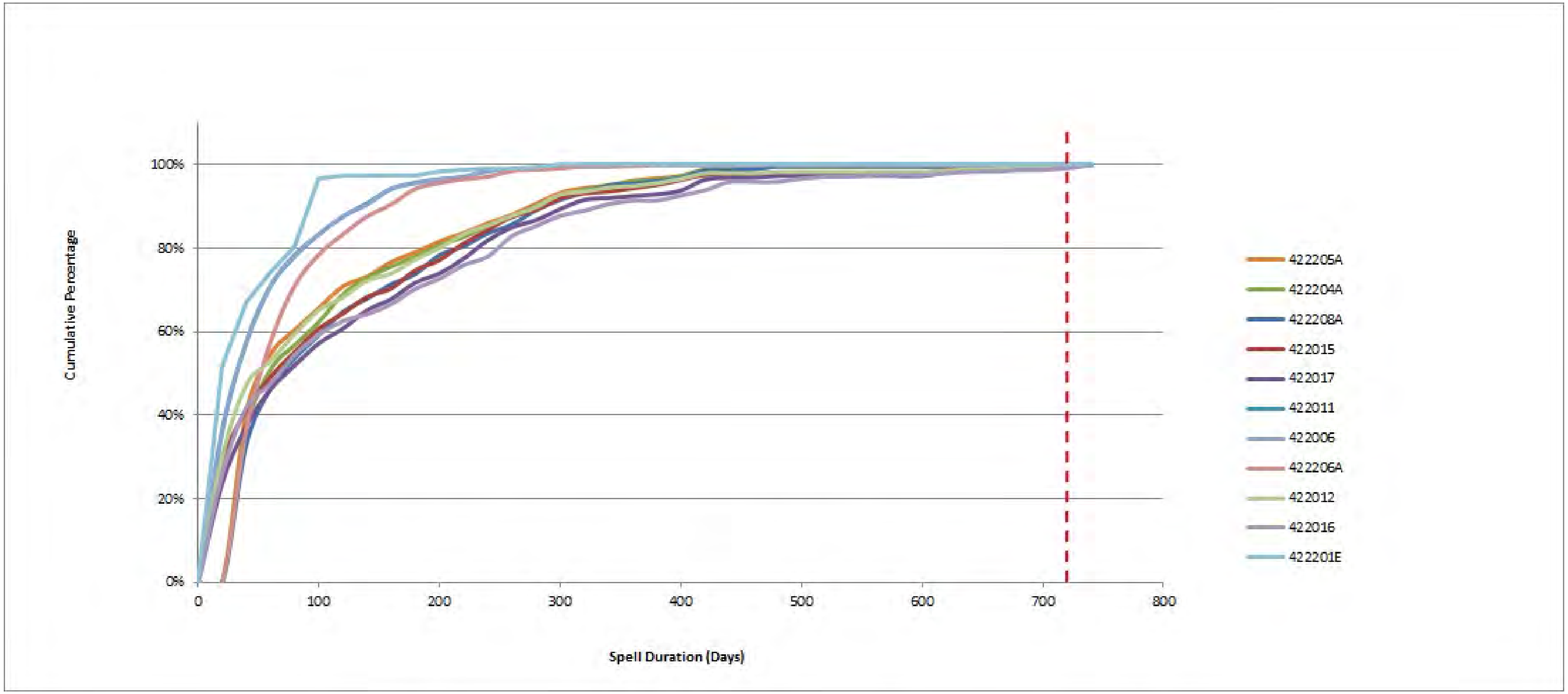

Figure F.12. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Baseline scenario in relation to stress Level 3 ToC

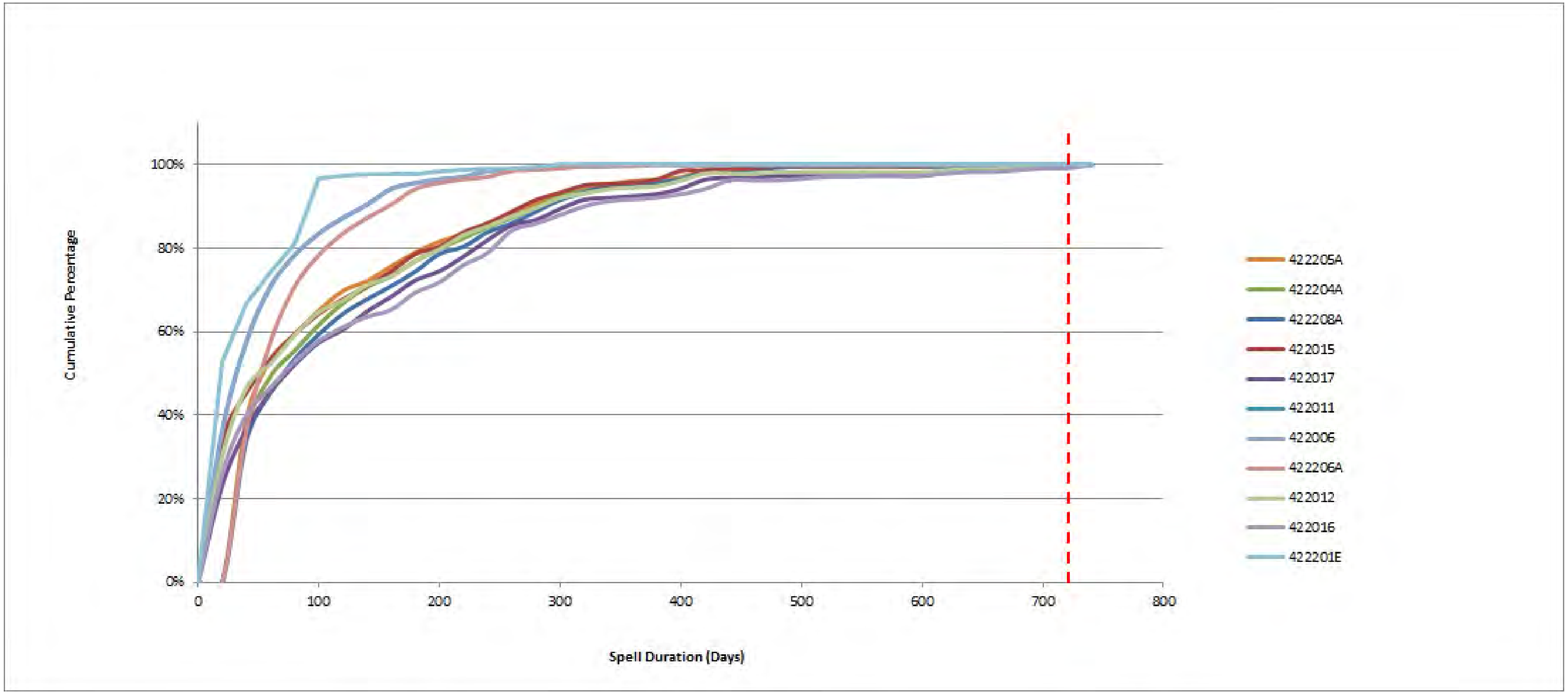

Figure F.13. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Northern Standard scenario in relation to stress Level 3 ToC

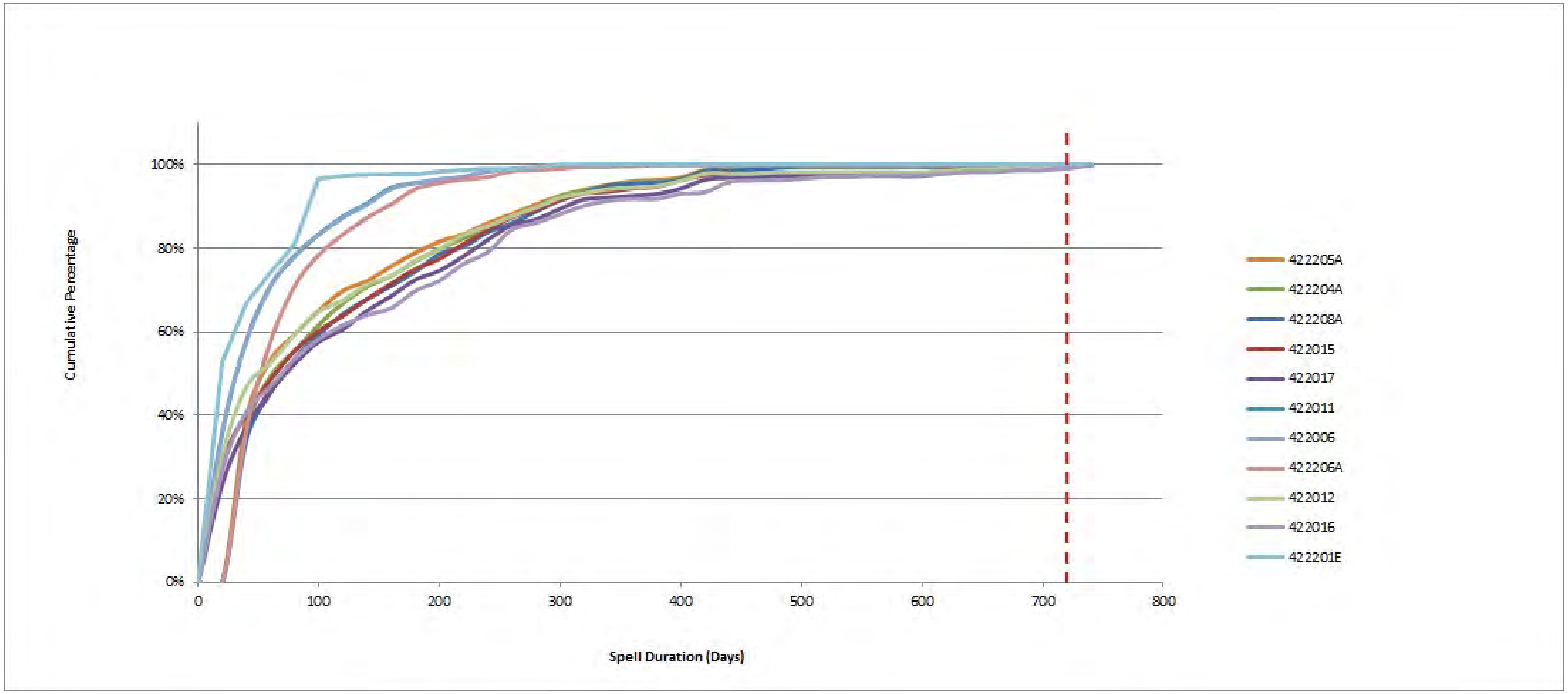

Figure F.14. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Northern Standard 100 scenario in relation to stress Level 3 ToC

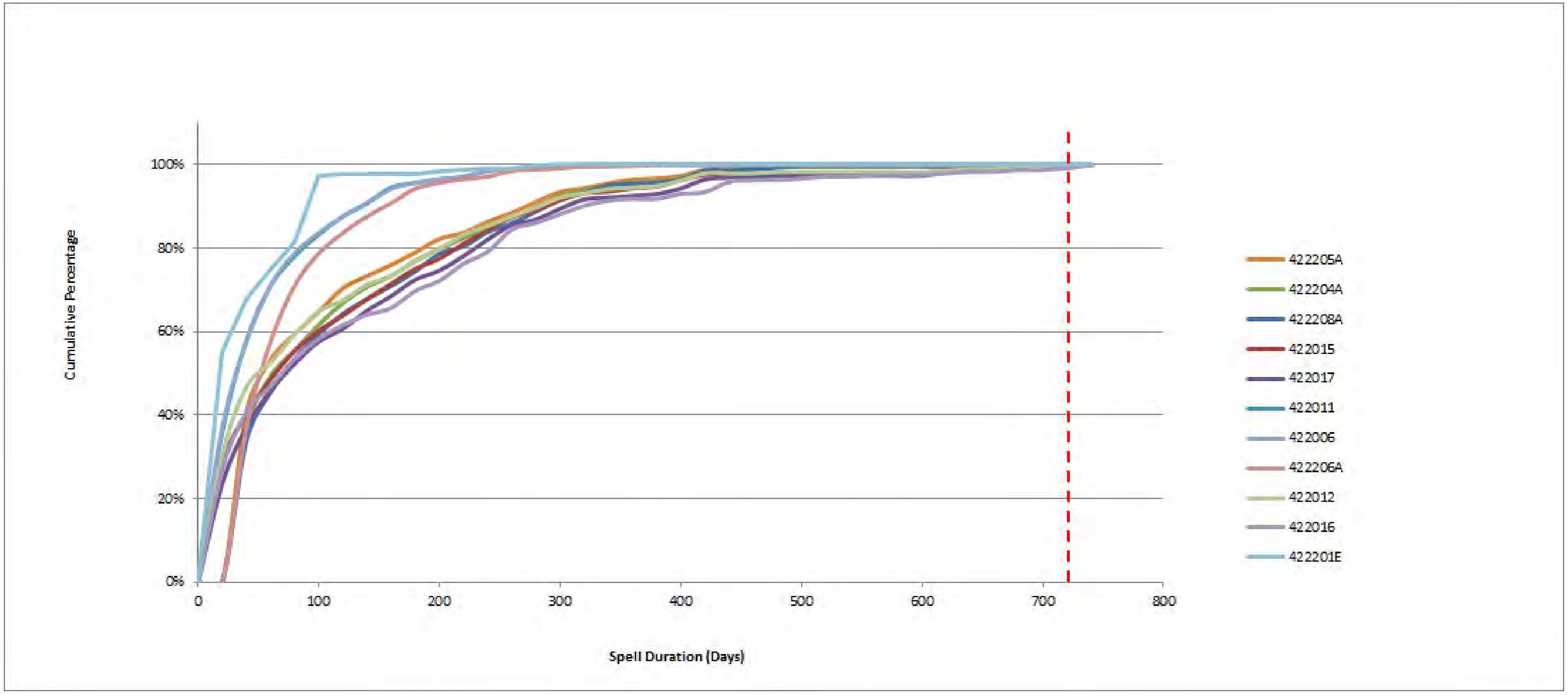

Figure F.15. Cumulative frequency of environment assessment reaches in the Narran and Culgoa rivers for Beardmore scenario in relation to stress Level 3 ToC

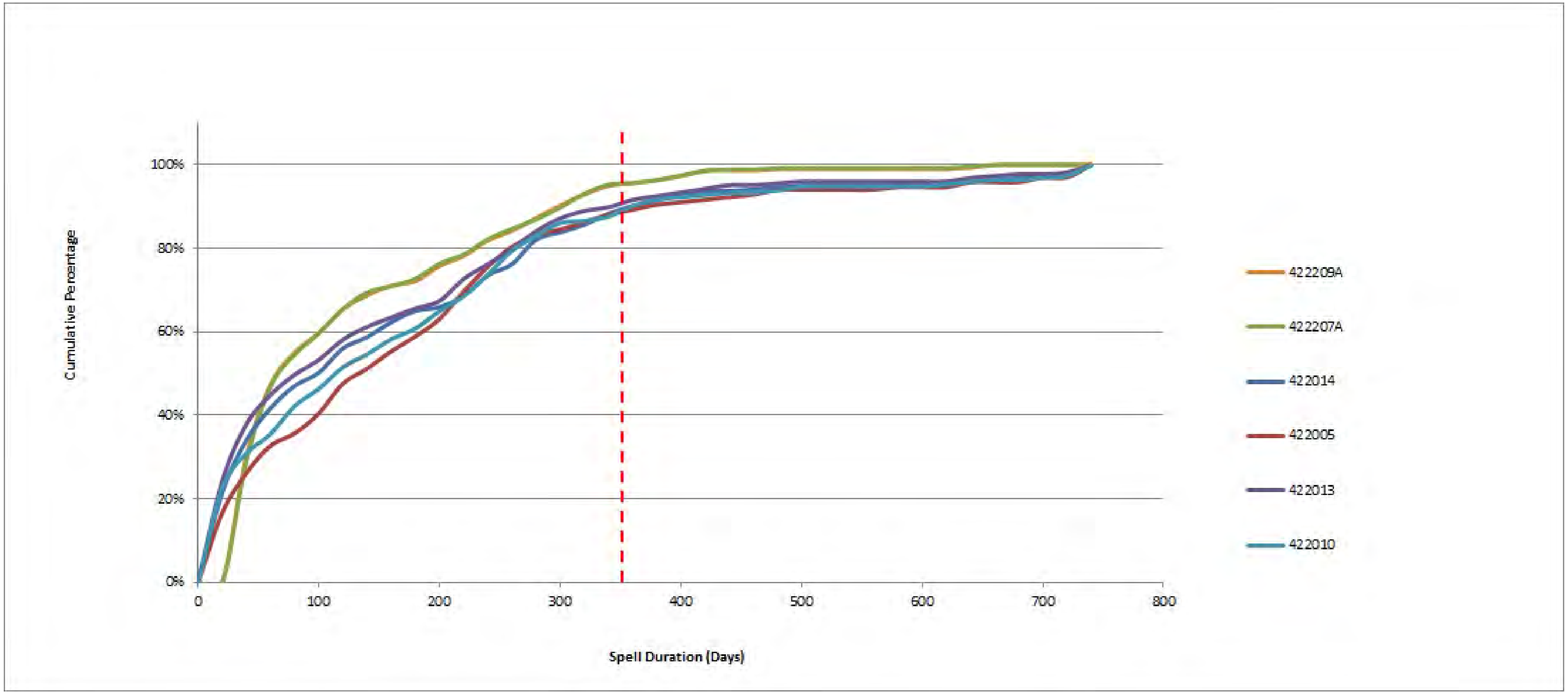

Figure F.16. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Without Development scenario in relation to stress Level 1 ToC

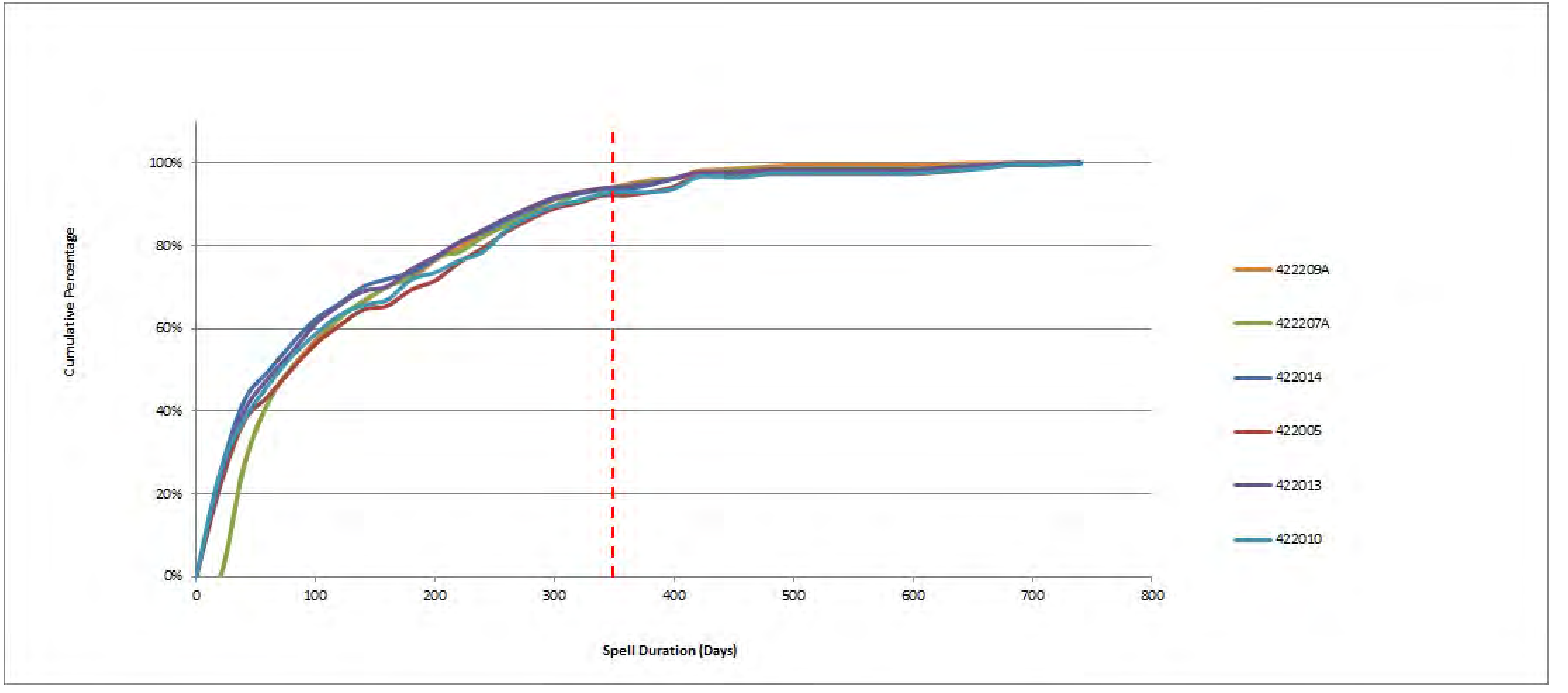

Figure F.17. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Baseline scenario in relation to stress Level 1 ToC

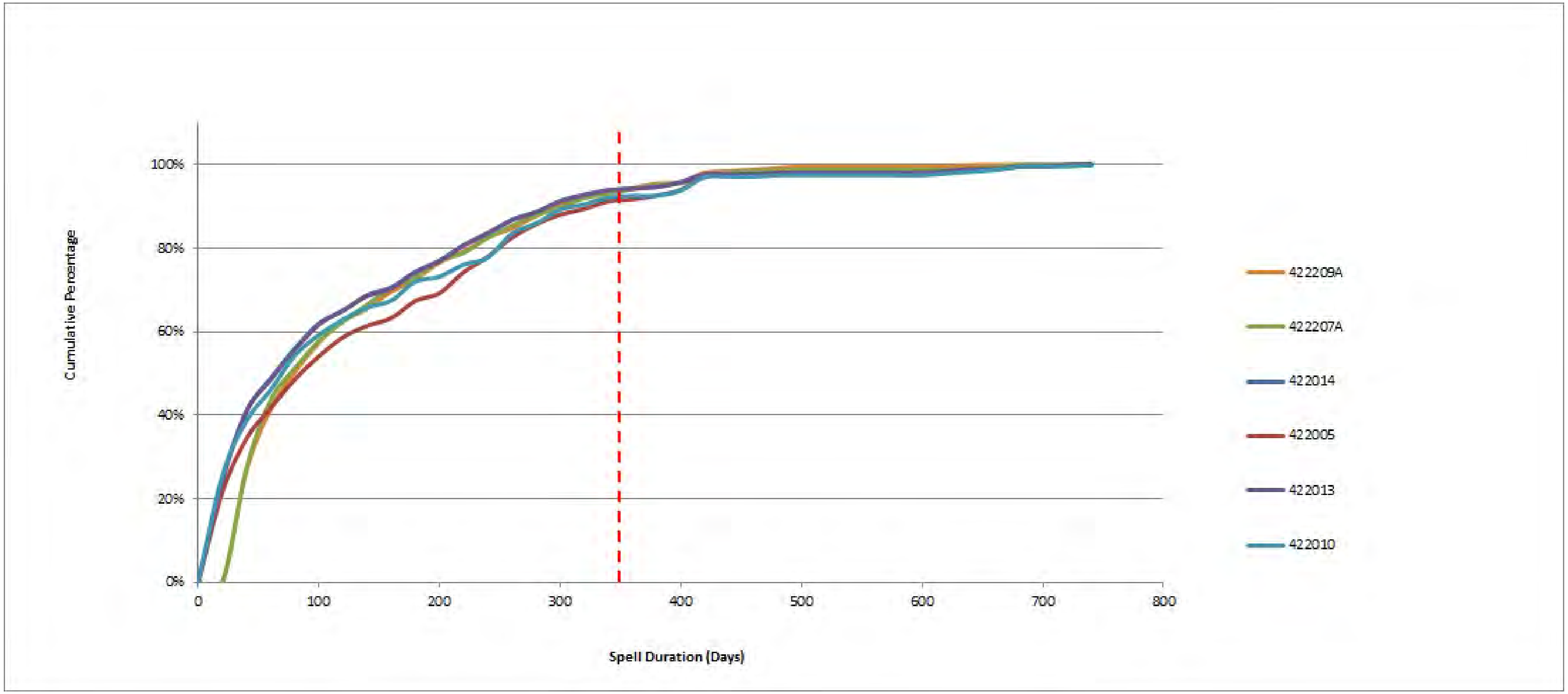

Figure F.18. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Northern Standard scenario in relation to stress Level 1 ToC

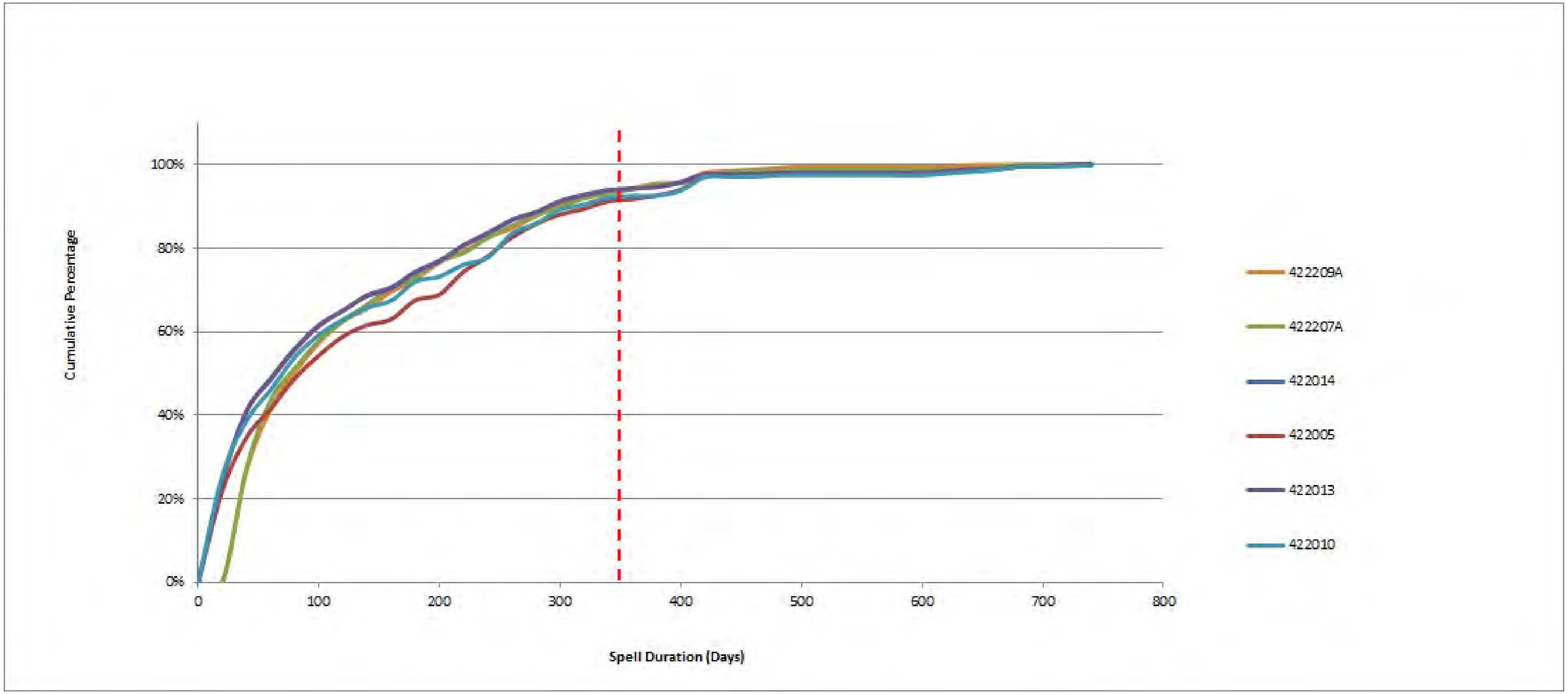

Figure F.19. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Northern Standard 100 scenario in relation to stress Level 1 ToC

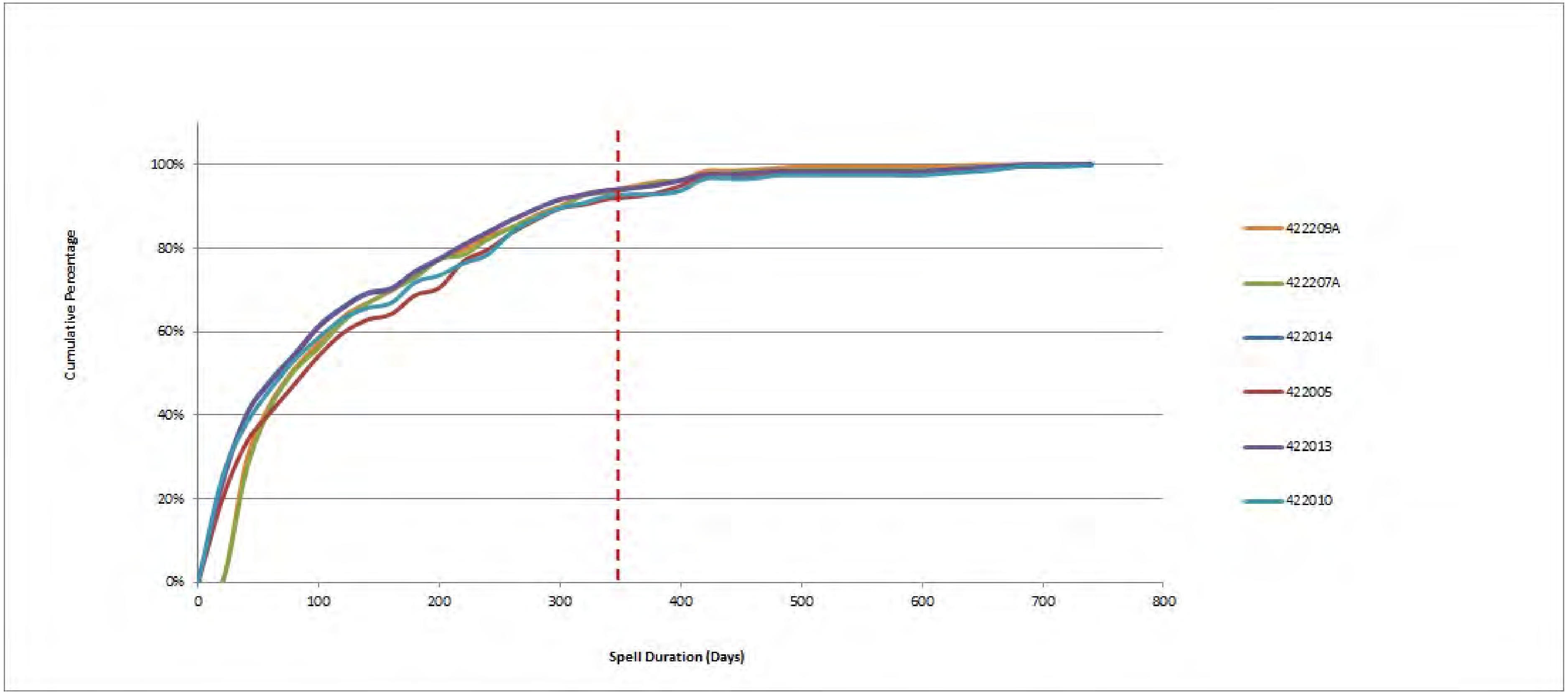

Figure F.20. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Beardmore scenario in relation to stress Level 1 ToC

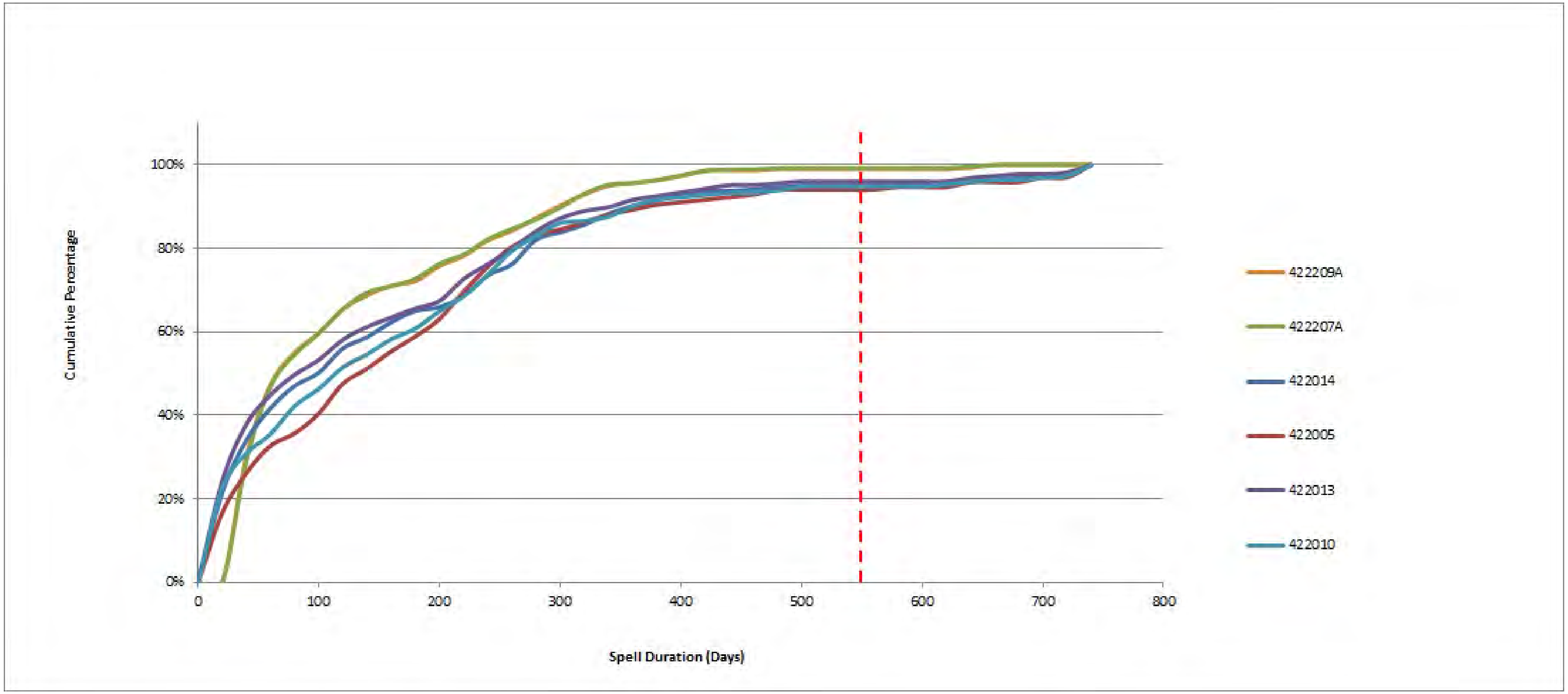

Figure F.21. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Without Development scenario in relation to stress Level 2 ToC

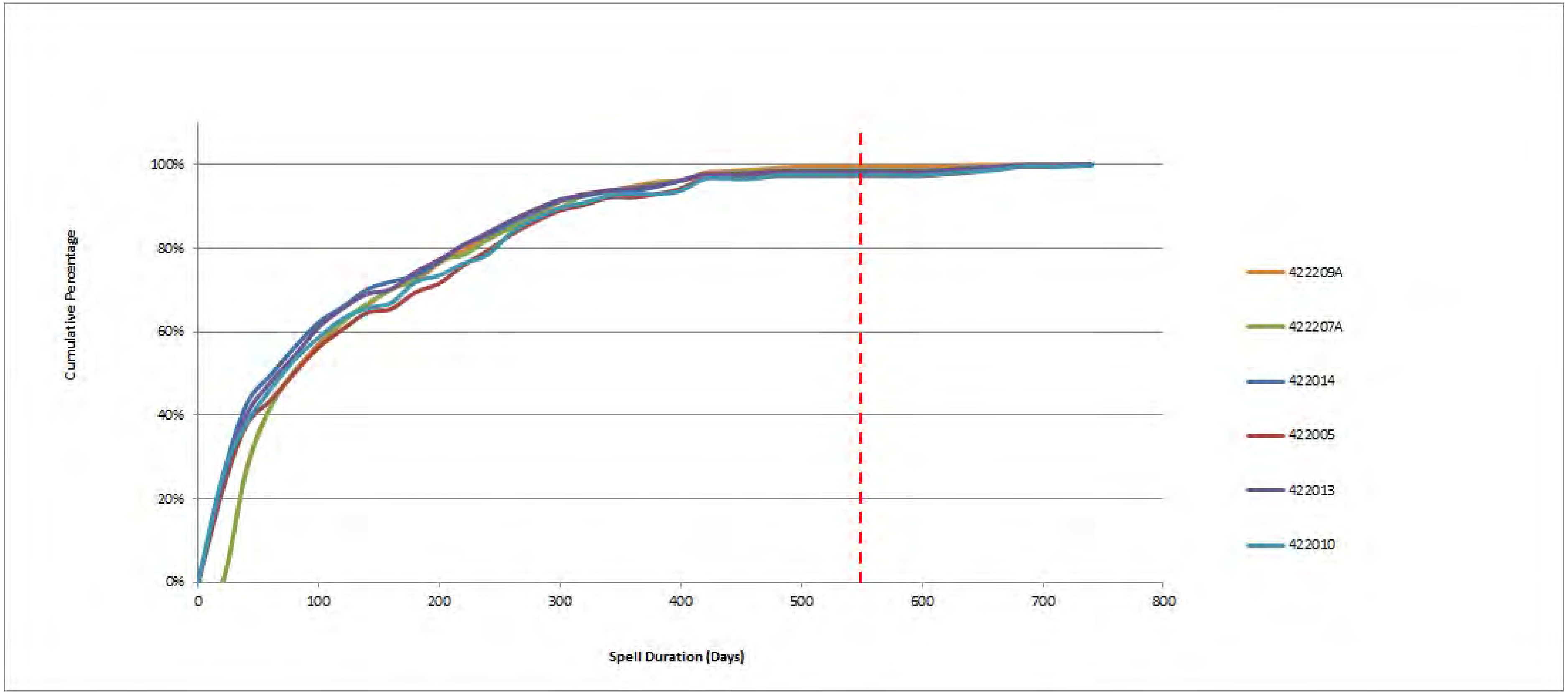

Figure F.22. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Baseline scenario in relation to stress Level 2 ToC

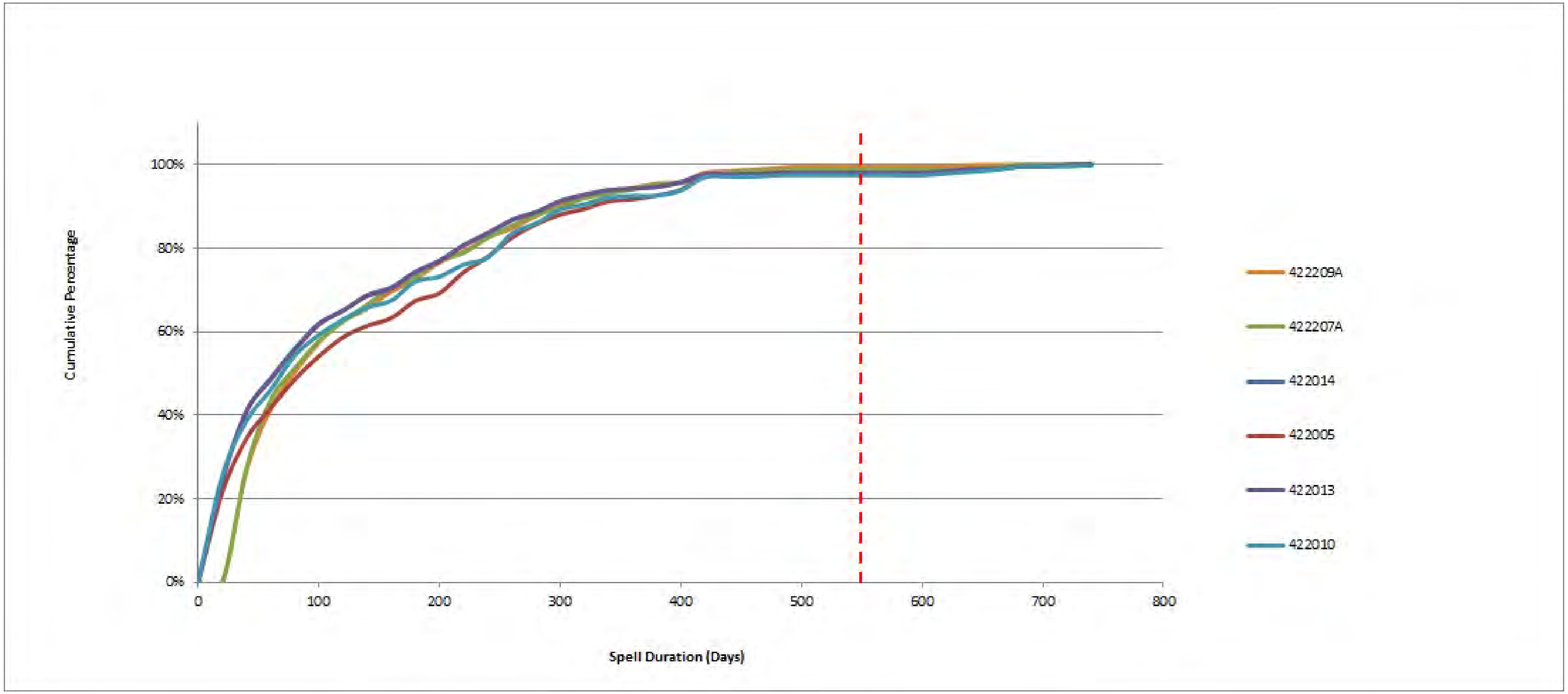

Figure F.23. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Northern Standard scenario in relation to stress Level 2 ToC

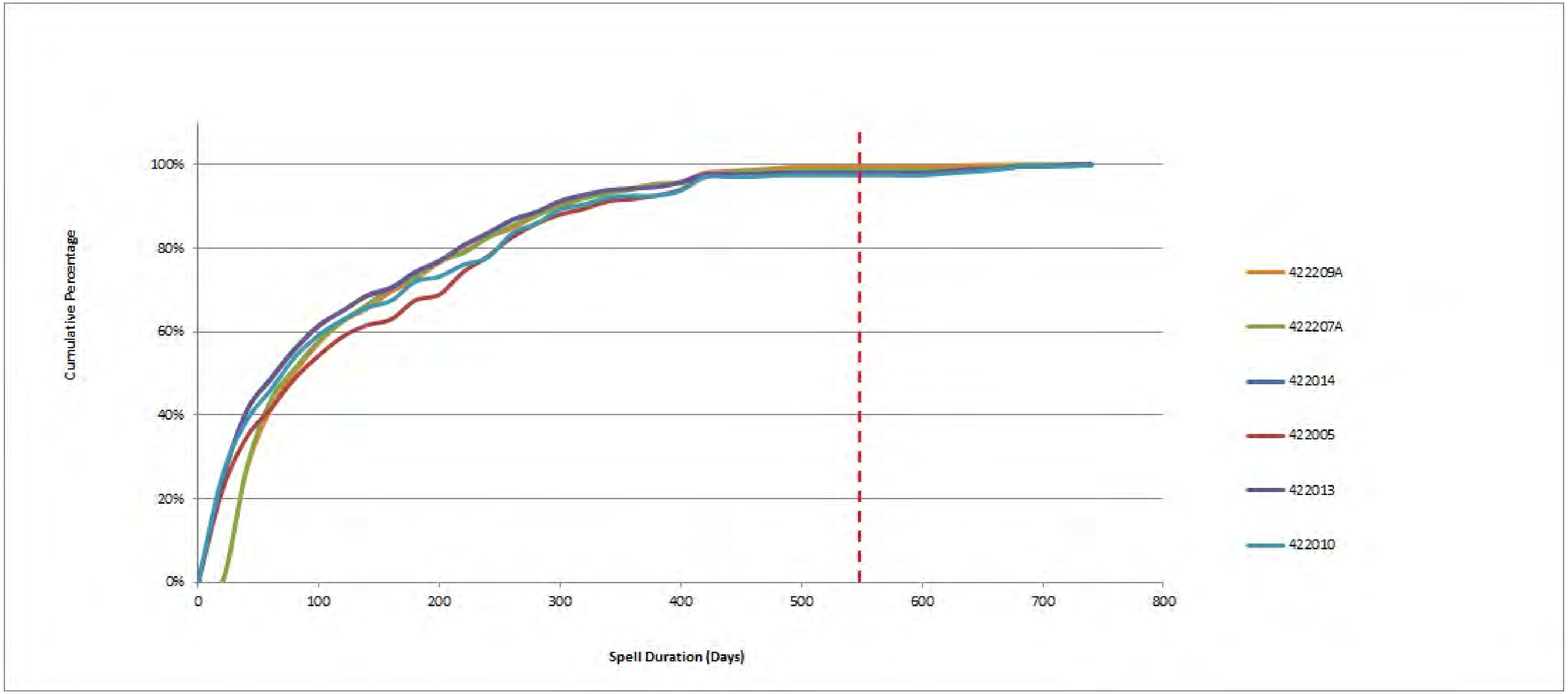

Figure F.24. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Northern Standard 100 scenario in relation to stress Level 2 ToC

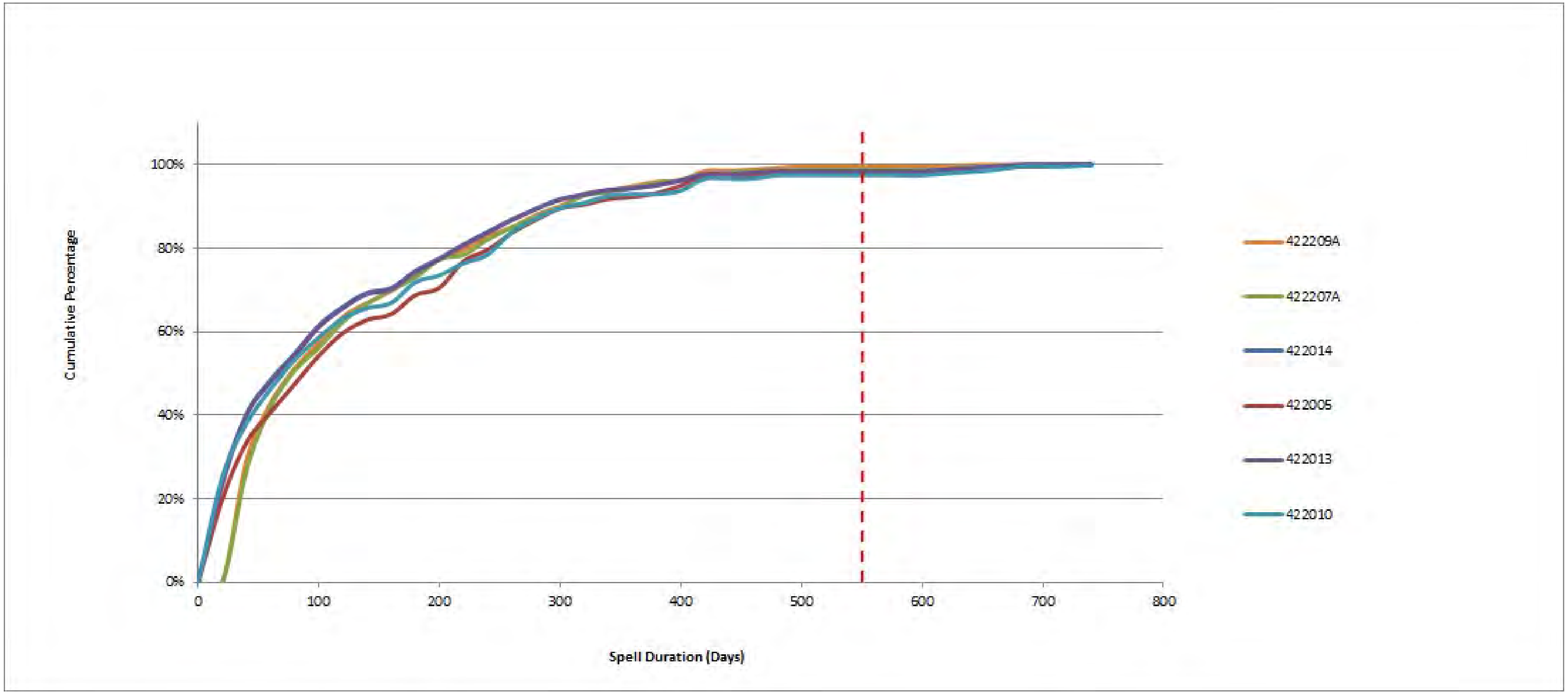

Figure F.25. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Beardmore scenario in relation to stress Level 2 ToC

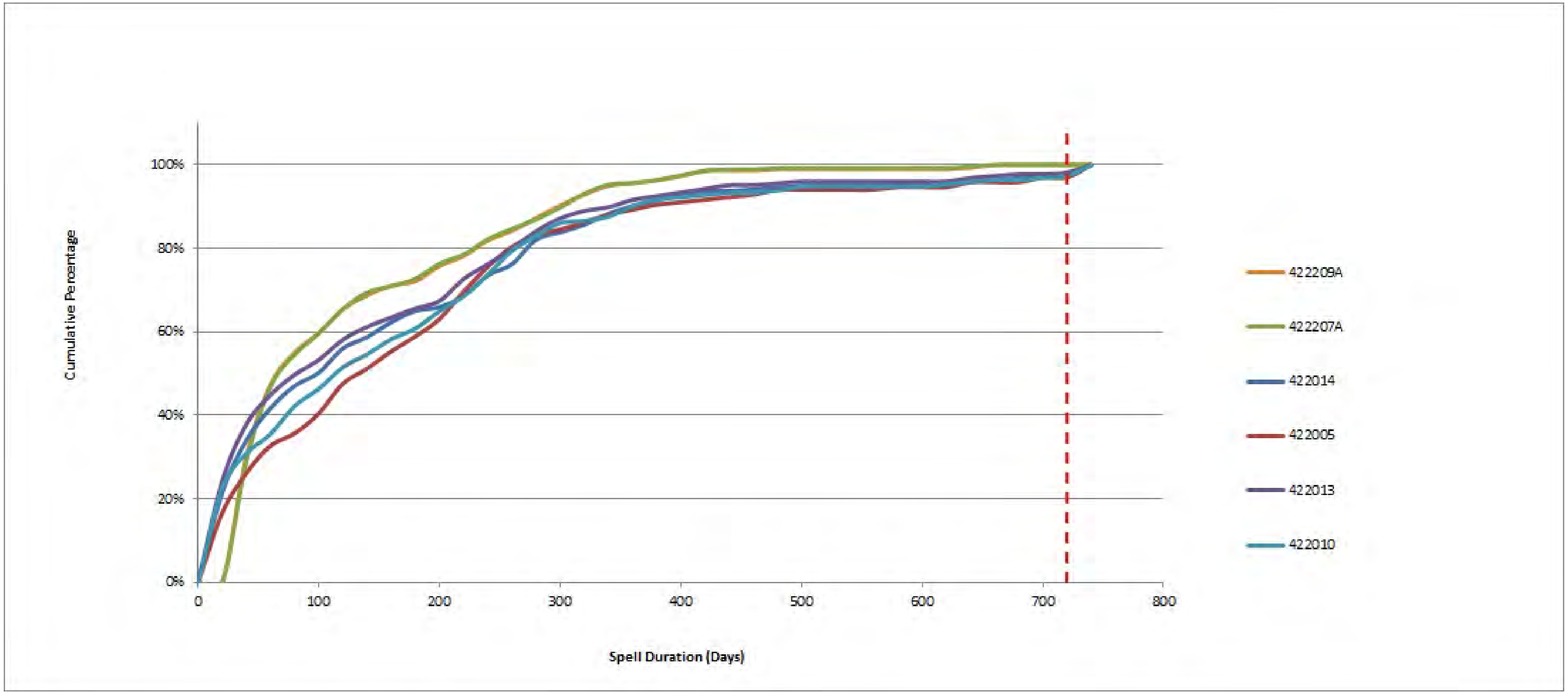

Figure F.26. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Without Development scenario in relation to stress Level 3 ToC

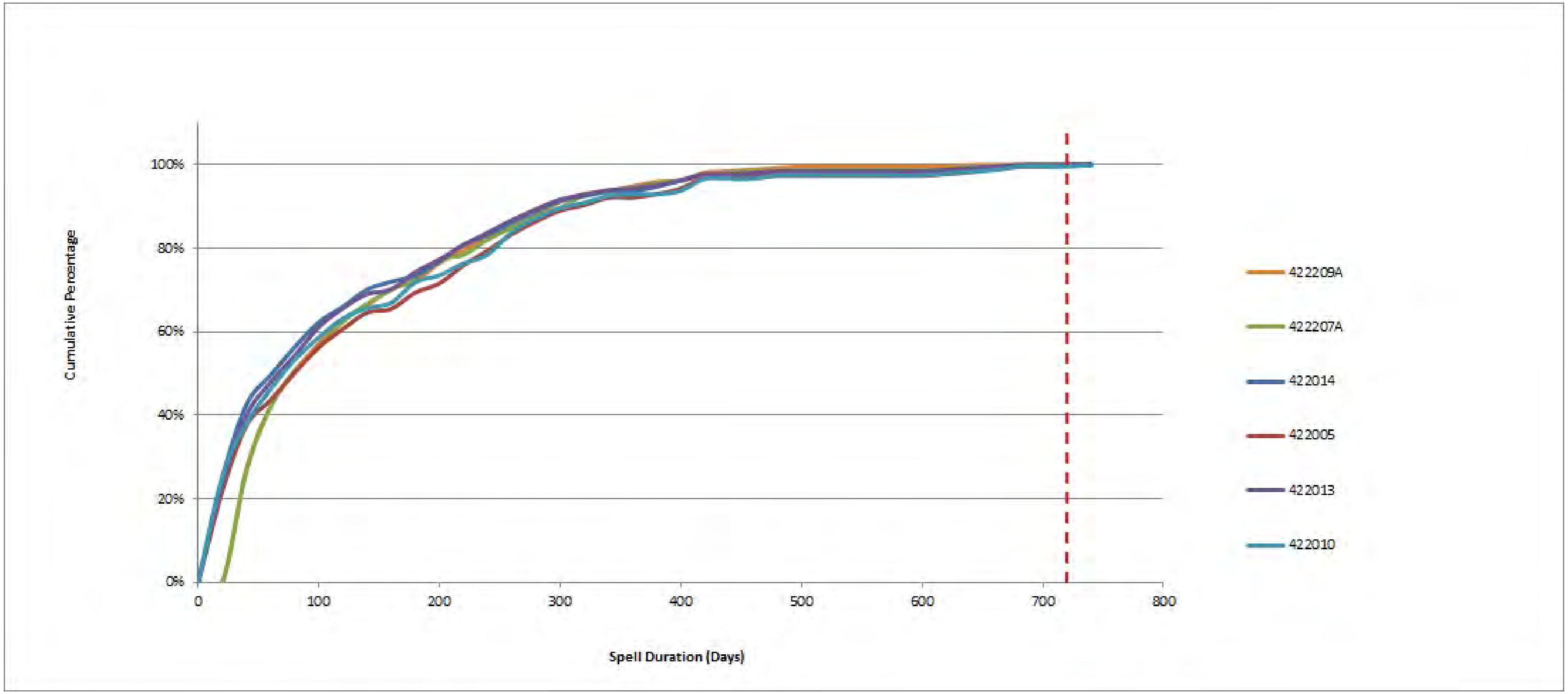

Figure F.27. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Baseline scenario in relation to stress Level 3 ToC

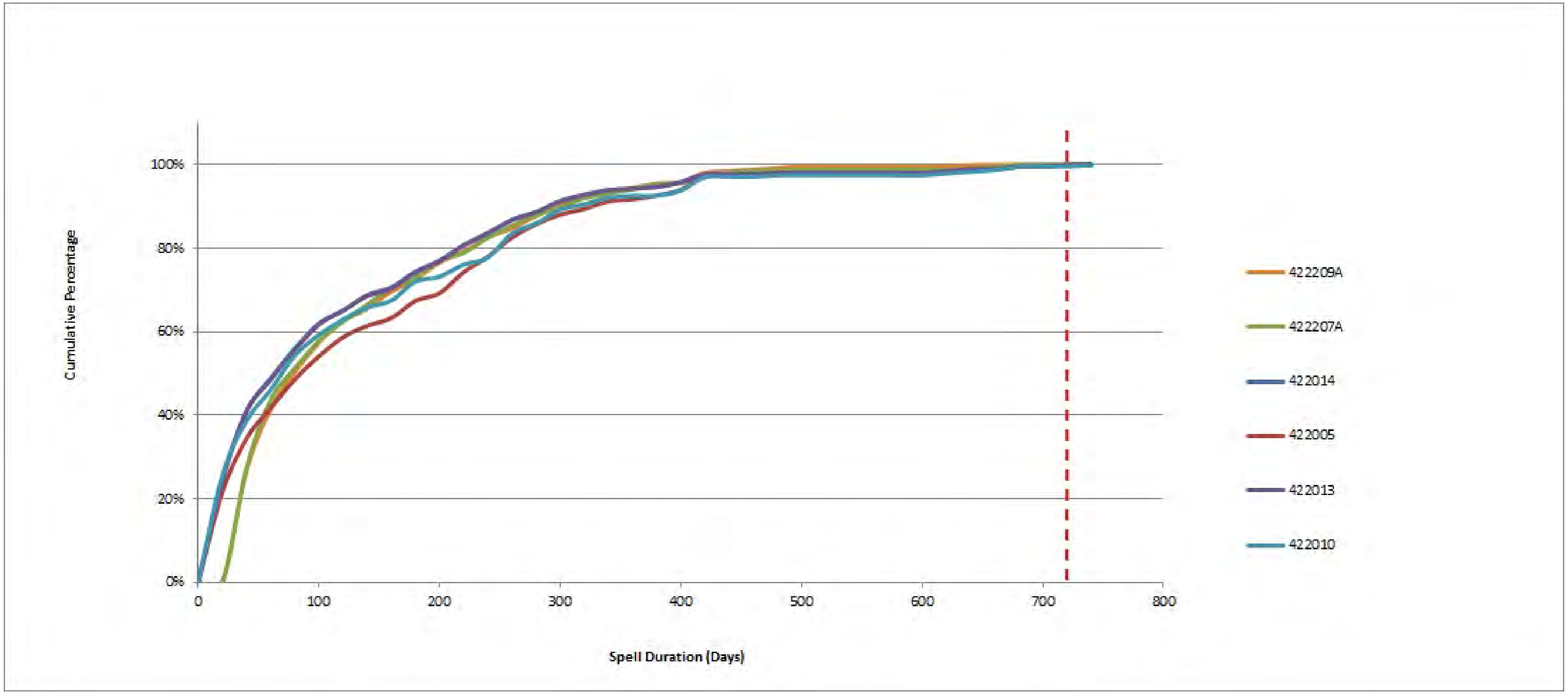

Figure F.28. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Northern Standard scenario in relation to stress Level 3 ToC

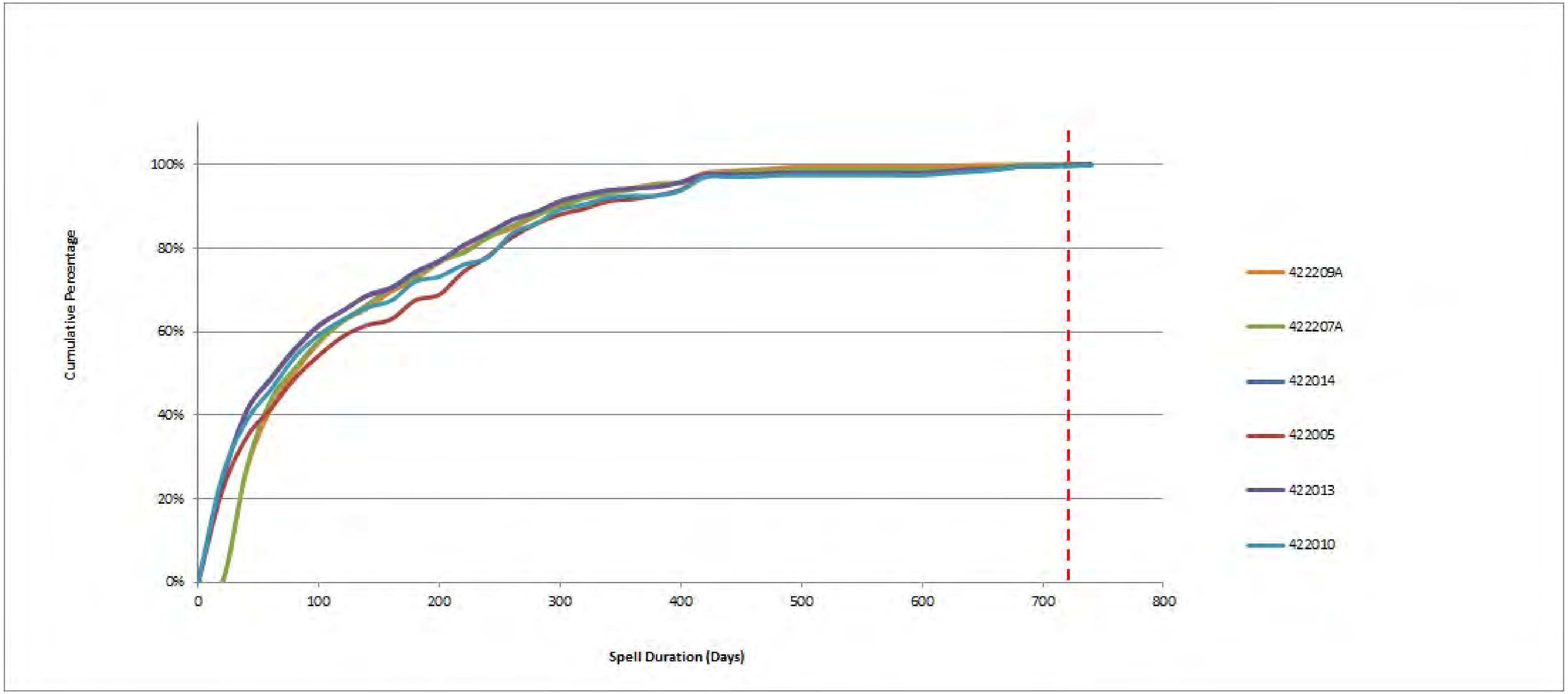

Figure F.29. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie Rivers for Northern Standard 100 scenario in relation to stress Level 3 ToC

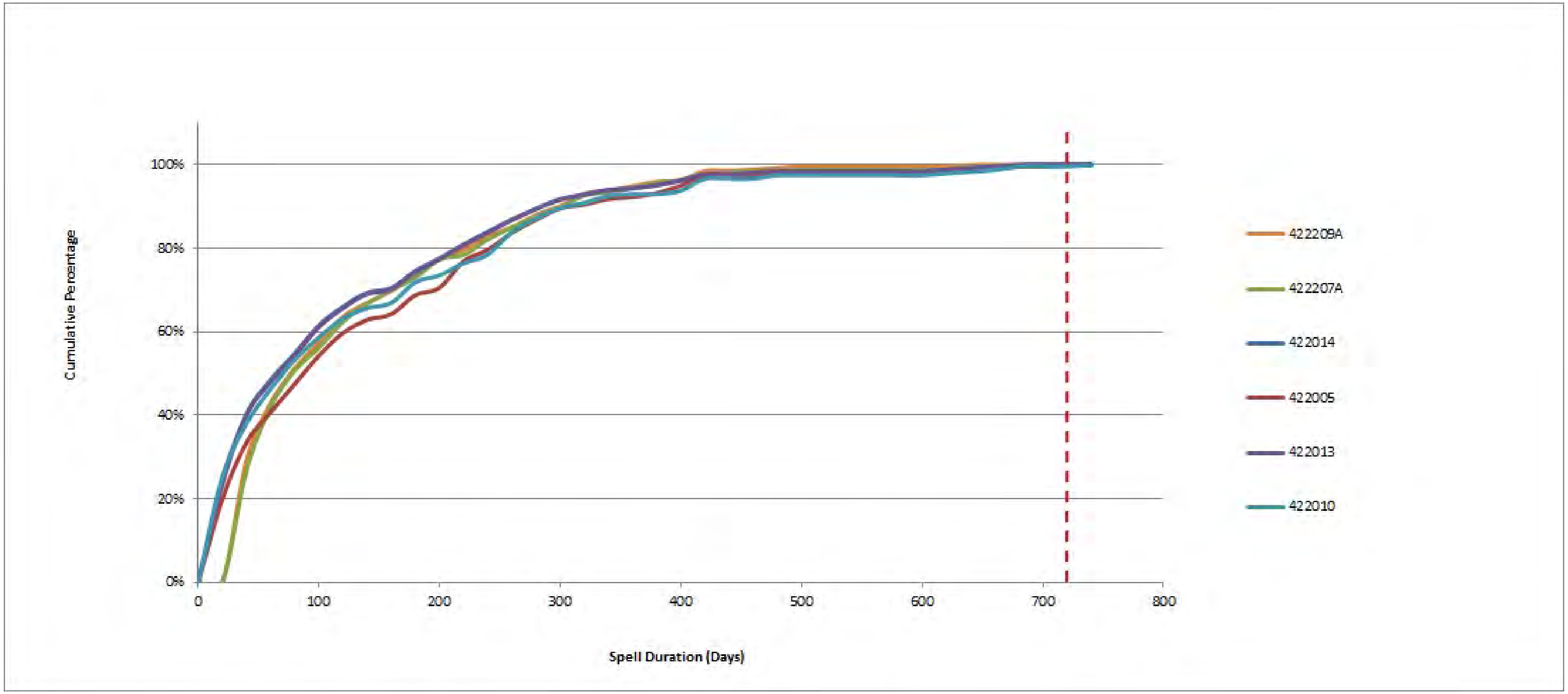

Figure F.30. Cumulative frequency of environment assessment reaches in the Bokhara and Birrie rivers for Beardmore scenario in relation to stress Level 3 ToC

Risk Assessment Profiles

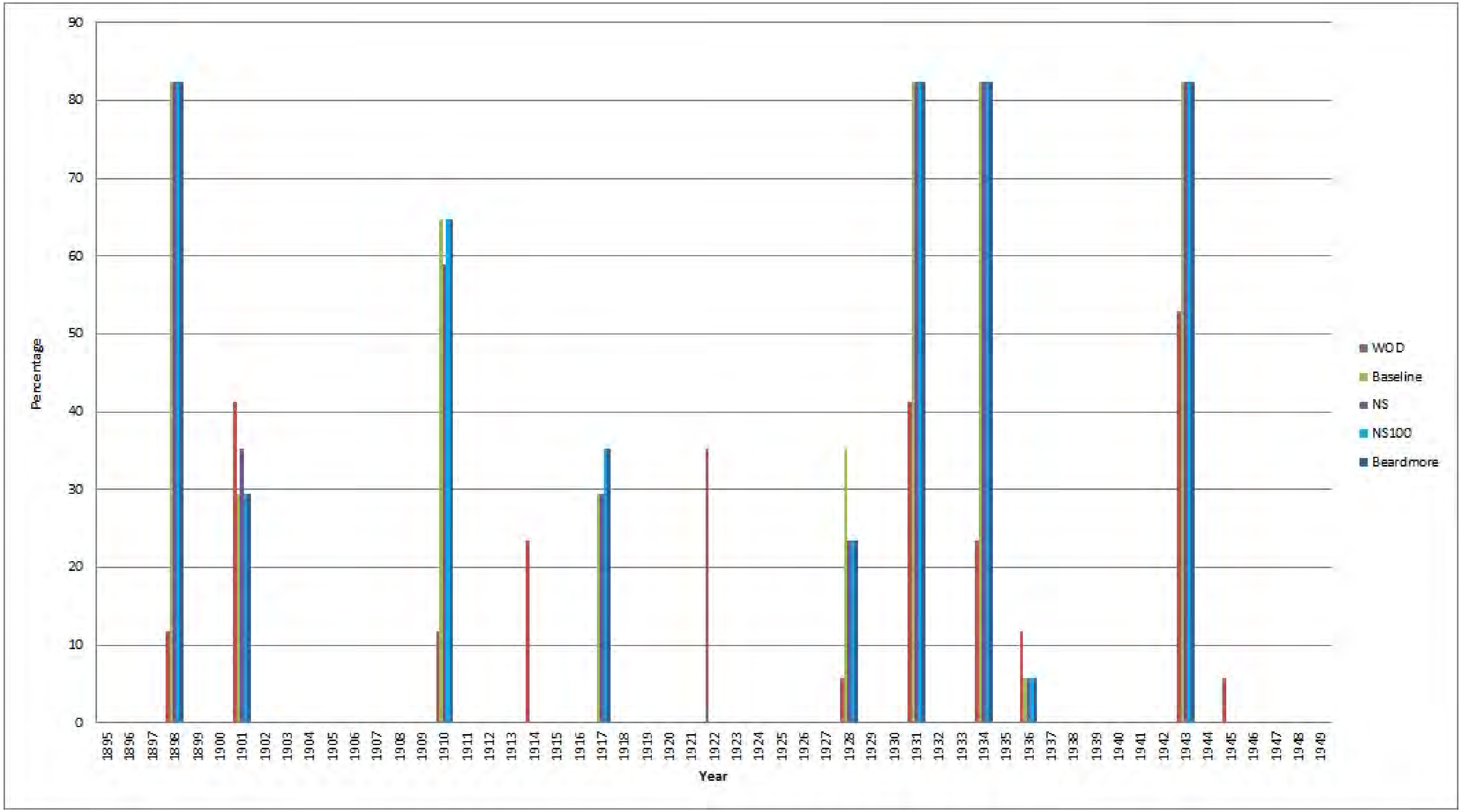

Figure F.31. Annual percentage of environment assessment reaches that exceeded stress Level 1 ToC from 1895 to 1949

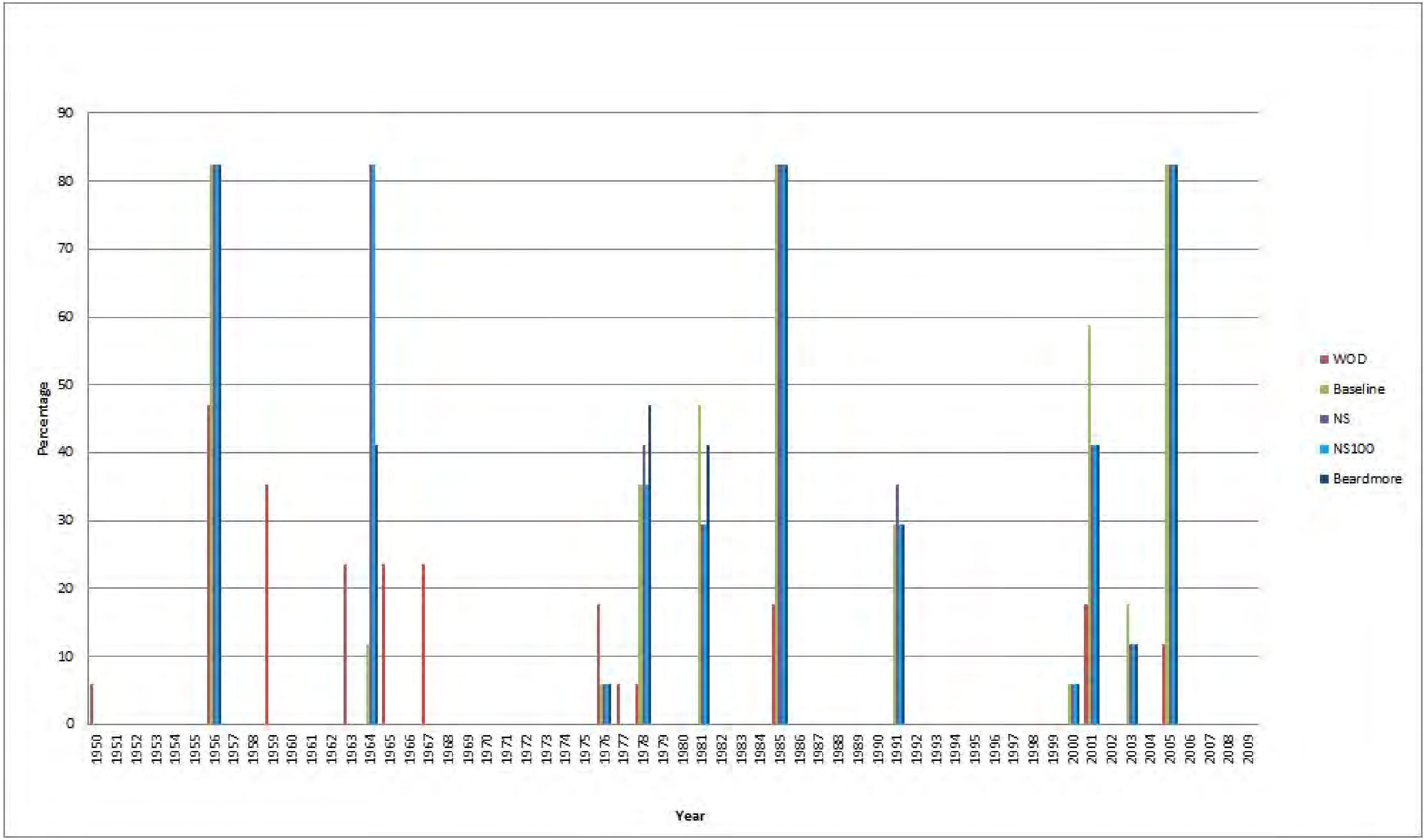

Figure F.32. Annual percentage of environment assessment reaches that exceeded stress Level 1 ToC from 1950 to 2009

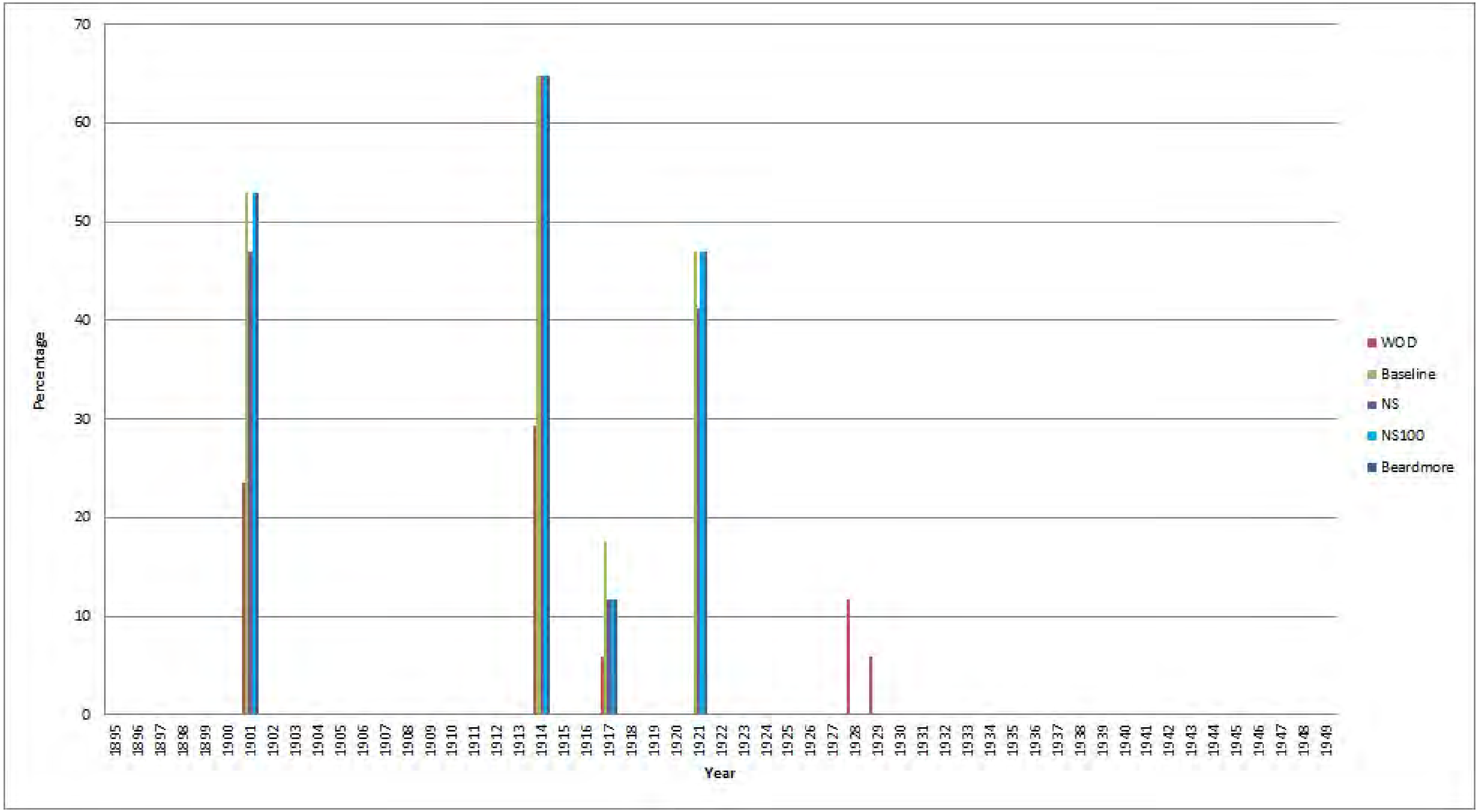

Figure F.33. Annual percentage of environment assessment reaches that exceeded stress Level 2 ToC from 1895 to 1949

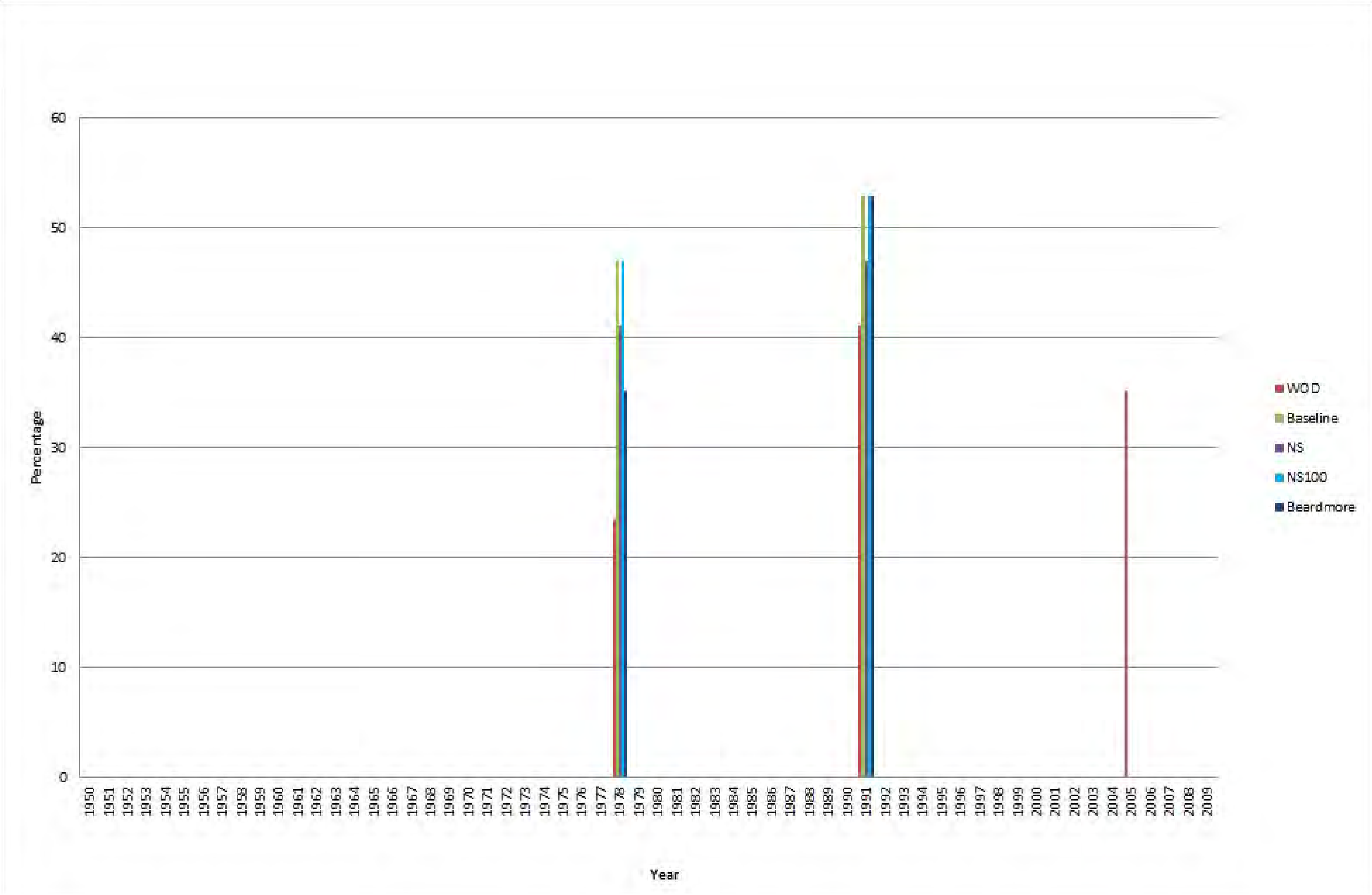

Figure F.34. Annual percentage of environment assessment reaches that exceeded stress Level 2 ToC from 1950 to 2009

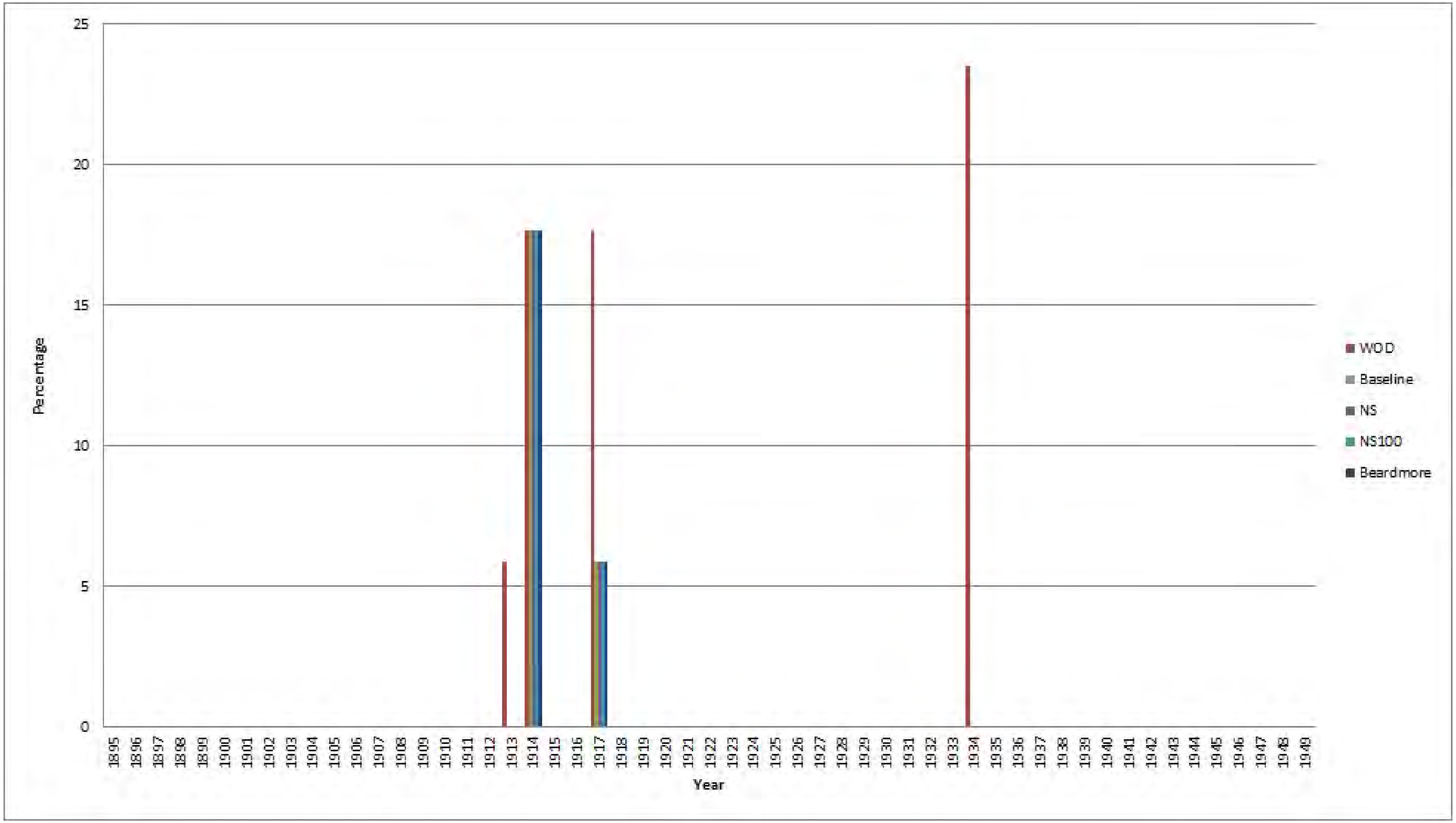

Figure F.35. Annual percentage of environment assessment reaches that exceeded stress Level 3 ToC from 1895 to 1949

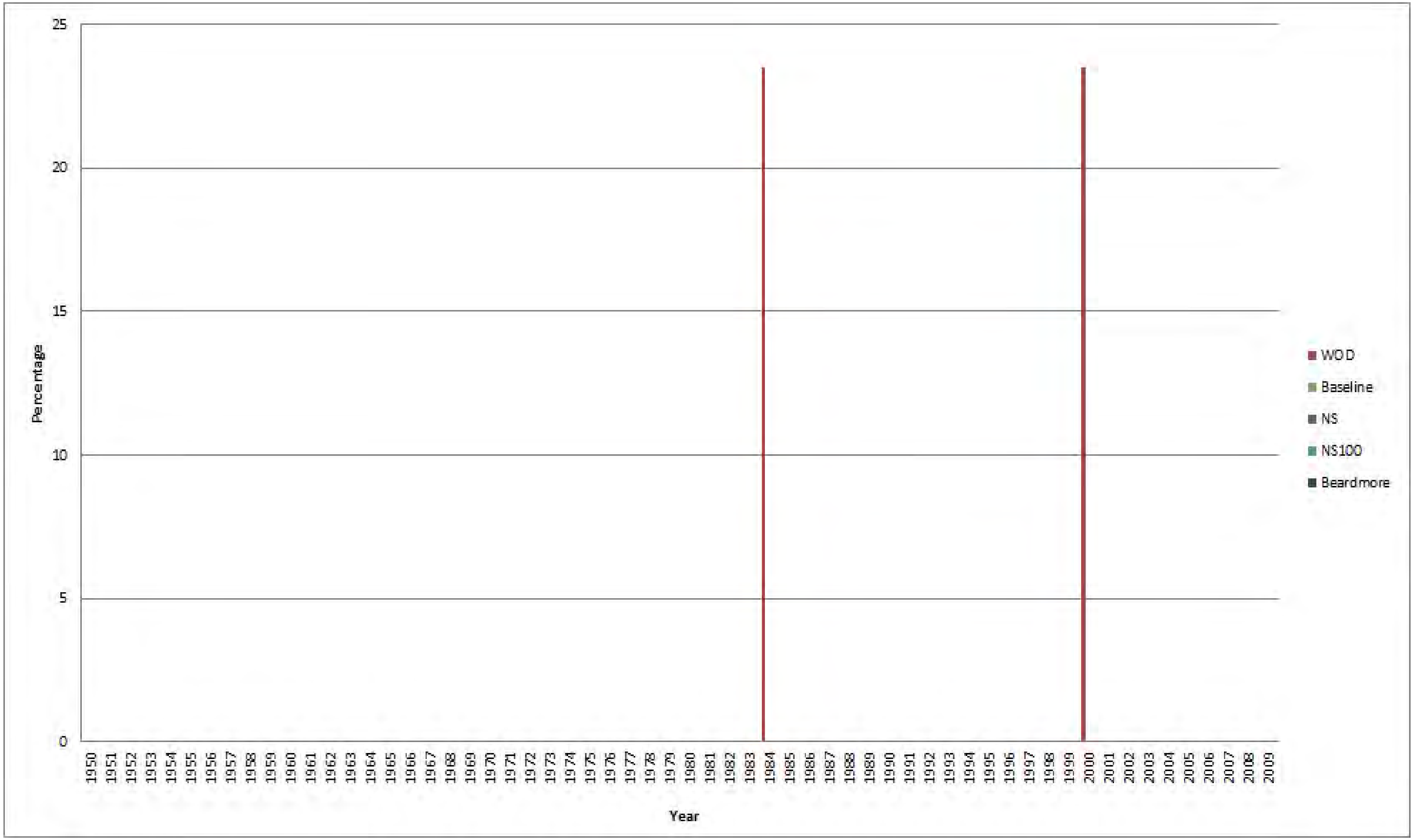

Figure F.36. Annual percentage of environment assessment reaches that exceeded stress Level 3 ToC from 1950 to 2009