Appendix I

Balranald Mineral Sands Project
Groundwater Assessment

Balranald Mineral Sands Project

ILUKA RESOURCES LIMITED

Balranald Mineral Sands Project Groundwater Assessment

rev 3

27 Mar 2015

Balranald Mineral Sands Project

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1	23-Feb-15	Addresses comments from Iluka and EMM on rev 0	DW	BB	DW
2	25-Mar-15	Addresses comments from Iluka and EMM on rev 1	DW	BB	DW
3	27-Mar-15	Minor text correction	DW	BB	DW

Contents

Acronyms

AHD: Australian Height Datum

ASS: acid sulfate soils

BOM: Bureau of Meteorology

CRT: constant rate test

DEM: digital elevation model

DEPI: Victoria Department of Environment and Primary Industry

DFS: Detailed Feasibility Study

EC: electrical conductivity

EIS: Environmental Impact Statement

EMM: EMGA Mitchell McLennan

GDE: groundwater dependent ecosystem

LPS: Loxton-Parilla Sands

LTT: long term trial

MDBA: Murray-Darling Basin Authority

NSW: New South Wales

OW: Office of Water

PFS: Pre-Feasibility Study

SKM: Sinclair Knight Merz

SRMS: scaled root mean squared

SRT: step rate test

STT: short term trial

TDS: total dissolved solids

TN: turkeys nest

VWP: vibrating wire piezometer

Executive Summary

A regional groundwater model (BAL2.0) has been developed and used to simulate groundwater management during operation of the Balranald Project. The model has been constructed using available hydrogeological data and calibrated using groundwater monitoring data recorded during a number of production and injection trials. The model, and its documentation in this report, has been found to be suitable for predicting impacts of mining in a review carried out by Hugh Middlemis of HydroGeoLogic.

Groundwater modelling has demonstrated that a groundwater management scheme can be effectively implemented for mining of the West Balranald and Nepean deposits. The scheme involves dewatering at both deposits, at rates of up to around 1,300 L/s at West Balranald (about 700 L/s on average) and around 190 L/s at Nepean (about 100 L/s on average). The model has been constructed in such a way that these are expected to be conservative estimates, with actual dewatering rates expected to be lower than the model estimates. Drawdown from dewatering at West Balranald is predicted to extend up to around 15 km from the deposit. Drawdown at Nepean is localised, extending a maximum of 2 km from the deposit.

Water produced by dewatering operations is injected into the Loxton-Parilla Sands via on-path injection wells at West Balranald and an off-path injection wellfield, located on and accessed from the proposed West Balranald-Nepean haul road. Peak injection is around 1,300 L/s. The off-path wellfield has been sized such that injection is spread over a large area. This is done to ensure that mounding of the water table in the overlying Shepparton Formation remains a minimum of 3 m below the ground surface to avoid waterlogging and salinisation of non-saline surface sediments. In addition, operating the wellfield such that pressures in the targeted injection aquifer, the Loxton-Parilla Sands, are maintained sub-artesian regionally will have associated infrastructure maintenance benefits during mining.

Predictive uncertainty analysis has explored the sensitivity of model predictions to variability or uncertainty in key hydrogeological parameters included in the model. It has demonstrated that the proposed dewatering and injection plan is capable of delivering acceptable engineering and environmental outcomes under most possible combinations of uncertain model parameters.

Modelling has demonstrated that operation of a water supply during the three years of pre-mining construction, at rates of up to 150 ML/yr, can be supported by the Olney Formation. Drawdown from the water supply wells is localised and not expected to have a significant impact on the regional groundwater system or adjacent third party groundwater users.

The model-predicted water balance suggests that dewatering and injection activities associated with the mine will primarily add and remove water from storage in the groundwater system. No significant impacts are predicted on leakage to or from the Murrumbidgee and Murray Rivers.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to document groundwater modelling carried out to inform a groundwater impact assessment of the Balranald Project in accordance with the scope of services set out in the contract between Jacobs and the Client. That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

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1. Introduction

Iluka Resources Limited (Iluka) is carrying out a Detailed Feasibility Study (DFS) for the Balranald Project (the Project). The Project comprises two mineral sands deposits, West Balranald and Nepean, located in the Murray-Darling Basin, near Balranald in southern New South Wales (NSW) (Figure 1.1).

The West Balranald deposit is approximately 20 km long, striking in a NW-SE direction. The southern end of the West Balranald deposit is approximately 10 km from Balranald and the Murrumbidgee River, which flows from the north-east towards its confluence with the Murray River, approximately 30 km further south-west of the deposit. The proximity of the West Balranald deposit to the Murrumbidgee and Murray Rivers necessitates impact assessment to consider these significant water bodies. The Lachlan River channel meets the Murrumbidgee River approximately 48 km north-east of Balranald, although it contributes flows only periodically. The southern end of the West Balranald deposit, its closest point to the Lachlan River, is located approximately 45 km from the confluence of the two rivers.

The Nepean deposit is located approximately 30 km north of the northern end of the West Balranald deposit. The deposit is smaller than West Balranald, striking in a similar direction and is around 10 km in length.

A study area was defined such that it encompasses both deposits, the Murrumbidgee and Murray Rivers to the south and sufficient distances north, east and west of the deposits to cover the area of potential groundwater impacts. The resulting study area measures 90 km east-west and 90 km north-south and has a total area of 8,100 km^2.

Mine plans for both deposits involve mining below the current water table. Iluka proposes dry-mining both deposits using a truck-and-shovel method and, therefore, operating a groundwater management scheme that will dewater the pits such that the water table will be located below the floor of the active pit during mining. At West Balranald, in particular, this will require lowering the water table significantly (approximately 65 m at the northern end of the West Balranald deposit).

Iluka proposes accessing groundwater from the brackish Olney Formation to meet pre-mining construction water needs. Iluka also proposes operation of a groundwater supply from the Loxton-Parilla Sands (LPS), during the last year of the West Balranald mine plan, when groundwater produced from dewatering activities is insufficient to meet plant make-up and dust suppression water requirements.

In order to develop a conceptual understanding of the hydrogeology of the area Iluka has carried out a range of groundwater monitoring and aquifer testing activities during the Pre-Feasibility Study (PFS) and subsequent DFS. Data and understanding from these studies have informed the development of a groundwater model, presented in this report, which is used to simulate the proposed groundwater-affecting activities associated with the Project. The model quantifies the necessary dewatering requirements and associated impacts on the regional groundwater system.

The Environmental Impact Statement (EIS) for the Project includes a water impact assessment, being carried out by EMGA Mitchell McLennan (EMM), and a groundwater dependent ecosystems (GDE) impact assessment, being carried out by CDM Smith. Both impact assessments will use outcomes of the groundwater modelling presented in this report. This report documents the groundwater modelling, and its basis, only. The associated impact assessments are carried out in the studies mentioned previously.

1.1 Model objectives

As part of the DFS, Iluka contracted Jacobs (previously SKM) to carry out groundwater modelling which would inform the design, and quantify impacts of a groundwater management scheme for the Project. The specific objectives of the groundwater modelling are to:

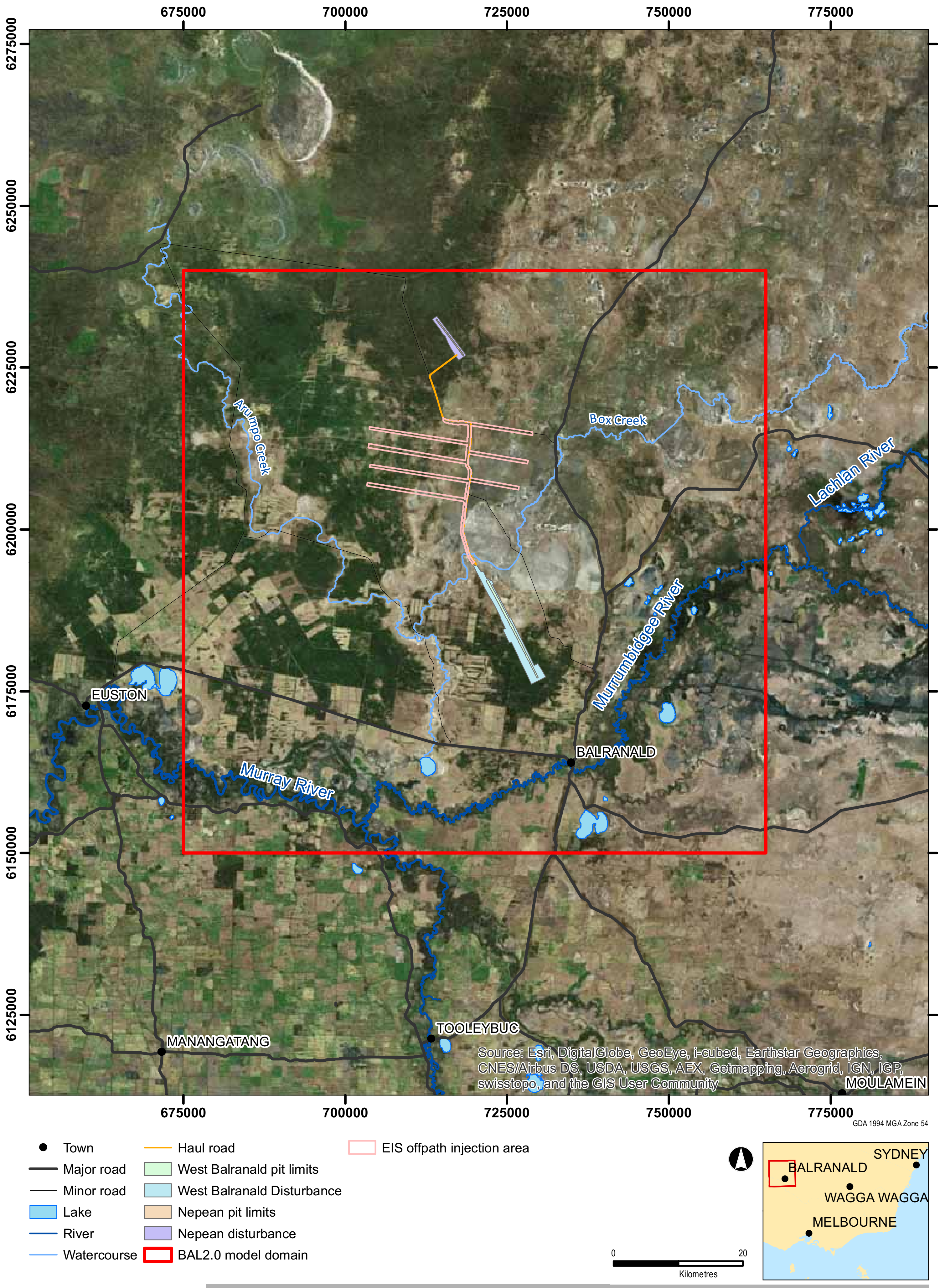
- Determine indicative dewatering rates necessary to undertake a dry mining operation at both West Balranald and Nepean;
- Optimise a dewatering strategy using operational constraints provided by Iluka;

- Determine the area required to operate an off-path injection wellfield such that groundwater produced from dewatering activities can be disposed of into the LPS;
- Optimise an injection strategy using operational constraints provided by Iluka; and
- Provide estimates of regional drawdown/mounding and water balance impacts resulting from operation of the proposed groundwater management scheme.

1.2 This report

This report documents the development of the regional BAL2.0 numerical groundwater model, used to simulate the groundwater-affecting activities associated with the Project. The conceptual model is presented along with summaries of key supporting data. The calibration process used to populate the model parameters is presented with associated calibration performance and sensitivity analyses. Predictive modelling is described and model estimates provided for dewatering rates at West Balranald and Nepean and for the size and layout of an off-path injection area required to dispose the excess produced water into the LPS. The model-predicted regional drawdown/mounding and water balance are documented and a predictive uncertainty analysis is presented, such that the effect of plausible variations in aquifer properties on model estimates can be understood.

The numerical groundwater model and this report documenting its development and predictions have been reviewed by Hugh Middlemis of HydroGeoLogic (see review in Appendix A). Hugh provided progressive review of the model at key stages of development; after construction and calibration and after predictive modelling. The outcome of the final review of the model and associated documentation in this report was that the model has been developed consistent with best practice and is suitable for predicting impacts of the proposed mining activities.



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Study area

Figure 1.1

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2. Conceptualisation

2.1 Data

Data available to inform the hydrogeological conceptualisation and groundwater modelling included the following:

- Iluka's Balranald groundwater database: well location, well construction information, screened hydrostratigraphic units, geological logs, regular groundwater depth monitoring, regular groundwater chemistry monitoring for wells installed and monitored by Iluka plus wells for which data are available from the NSW Office of Water (OW) groundwater database.
- Exploration logs: interpreted stratigraphy for over one thousand exploration holes drilled by Iluka in and around the study area. Exploration holes typically do not extend below the base of the LPS, as this is the unit hosting the mineralisation targeted by the exploration.
- Internal Iluka Exploration Department reports on stratigraphy and interpretation of Shepparton Formation characteristics;
- Public domain literature on the geology and hydrogeology of the study area.
- Reports to Iluka: these included hydrogeological conceptualisation by URS (2011 and 2012) and groundwater modelling by SKM (2013a and 2013c).
- Hydrogeological maps: 1:250 000 scale regional hydrogeological maps for the Balranald (Kellett, 1994) and Pooncarie (Kellett, 1991) areas.
- Climate data from the Bureau of Meteorology (BOM, 2014).
- River monitoring data for gauges on the Murray and Murrumbidgee Rivers were sourced from the Victorian Department of Environment and Primary Industries (DEPI, 2014) and the OW (2014).
- PFS pumping and injection trial data: production and injection rates and groundwater level monitoring from "short term trials" (STT) at two sites along the West Balranald strike (TN1 and TN5);
- DFS pumping and injection trial data: production and injection rates, groundwater level and chemistry monitoring from a "long term trial" (LTT) of approximately six weeks duration located along the West Balranald strike and two STTs ("Nanda" and "Upson Downs") located between the West Balranald and Nepean deposits.
- Drill cuttings: Jacobs team members attended a site visit during which chip trays containing drill cuttings from several drill holes were inspected and assessed. Iluka's structural and geological interpretation of the study area (Iluka, 2009) was made available. Members of Iluka's hydrogeology team, led by John Bean (Principal Hydrogeologist, Iluka), provided their interpretation and this was confirmed by Allison Currie (Principal Geologist, Iluka) and Ray Evans (Principal Hydrogeologist, Salient Solutions – contracted to Jacobs).

2.2 Topography

Topography within the study area displays relatively low relief, ranging from around 45 m AHD to a maximum of around 120 m AHD. 80 % of the study area has topography between 61 m AHD and 75 m AHD. Local topographic lows occur at the numerous ancient lakes across the study area, the larger of which can measure up to 10 km across. Typically the lakes have topography ranging between 5 m and 10 m below the nearby surrounding region. Several of these, including Tin Tin Lake, Pitarpunga Lake, Muckee Lake, Macommon Lake and Dundomallee Lake, are located close to the West Balranald deposit. A region of elevated topography exists to the north of the study area, near the Nepean deposit, where the southern end of the Iona Ridge, a basement feature, extends southward into the study area.

2.3 Climate

The study area is located in a semi-arid climate zone. Annual rainfall at Balranald (see Table 2.1) averages 325 mm with no significant seasonal variation. Pan evaporation at Mildura (see Table 2.2), approximately 140 km west of the Project, averages 2,192 mm/yr and does display some seasonality, with higher potential for evaporation in summer and less in winter. Average actual annual evapotranspiration in the study area is around 350 mm (BOM, 2014). Actual evaporation is substantially lower than pan evaporation because it is limited by available water, whereas pan evaporation represents evaporation that would occur from an unlimited water supply (such as a lake).

Table 2.1 : Average rainfall (mm) at BOM station 049002, Balranald RSL (1879-2014)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
22.6	25.3	22.6	23.3	31.3	29.4	26.5	29.6	29.2	30.9	28.0	25.5	324.5

Table 2.2 : Average evaporation (mm) at BOM station 076031, Mildura Airport (1965-2014)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
332	274	229	141	84	57	62	93	141	205	255	313	2192

2.4 Hydrostratigraphy

The term *hydrostratigraphy* is used in this report to describe the distribution of subsurface materials in an area in relation to the flow of water, within the context of stratigraphy – that is, it is a characterisation of the stratigraphy into units that can be used to build an aquifer framework. The hydrostratigraphy is not simply the geological nomenclature, but an interpretation of how the various geological units relate to and interact with each other in a groundwater sense. Therefore, some names used below are specifically hydrostratigraphic names and are informal, whereas geological names are used in their formal sense.

The hydrostratigraphy of the project area has previously been described by SKM (2013a). This previous understanding was based on a number of published reports and maps (Kellett, 1989, 1991, 1994; Brown and Stephenson, 1991; URS, 2012; Iluka, 2011a, 2011b). Further information has been incorporated into the previous assessment to develop a more detailed description of the various geological units that constrain the hydrogeology of the project area. Specifically, this information includes detailed geological models of the LPS developed by Iluka’s exploration division, detailed hydrogeological testing and characterisation of the LPS by Iluka’s hydrogeology division (Iluka, 2015), and more detailed stratigraphic information from various papers and reports that provide more detail regarding issues raised by Iluka’s geological model.

The overall stratigraphy of the region is based on (and consistent with) the basinal framework of Brown and Stephenson (1991). This basinal stratigraphy was developed and further refined for the area of interest for this report by Kellett (1989, 1991 and 1994) and MacPhail et al. (1993), particularly with regard to interpreting sediments of Late Miocene age. Iluka has undertaken extensive drilling in the region to assess the heavy mineral potential of the LPS, a broader Late Miocene to Pliocene package of sediments. This drilling and development of resultant detailed conceptual models was focussed at the deposit scale and as such provided a level of detail of the sediments studied that was not available to previous workers in the area. Kellett also developed a regional hydrostratigraphic model of the broader area around the project – the Ivanhoe Block and the western margins of the Riverine Plain.

Brown and Stephenson (1991) subdivide the sediments of the Murray Basin into three major correlated packages, an initial Palaeocene to Oligocene sequence, a Late Oligocene to Late Miocene sequence associated with a major marine transgression, and a final Late Miocene to Pleistocene sequence associated with another marine transgression. The LPS are part of the third package.

The major units of interest in developing a hydrostratigraphic conceptual model of the project area are the basement rocks, the Renmark Group (including the hydrostratigraphic units of the Lower, Middle and Upper Renmark Group aquifer as defined by Kellett (1989) and the Olney Formation described by Brown and Stephenson (1991)), the Geera Clay, the LPS and the Shepparton Formation. Note that the subdivision of the Renmark Group into aquifers as used by Kellett is a hydrostratigraphic grouping and has no formal stratigraphic meaning. The Renmark Group in the region consists entirely of the Olney Formation; however, the broader hydrostratigraphic nomenclature of Kellett's Renmark Group aquifers, as used to describe the Ivanhoe Block-Western Riverine Plain setting, is adopted here as it has more relevance to the local hydrogeological setting of the mineral deposits. The location of the study area and its hydrostratigraphy, in the context of the broader Murray Basin, is illustrated in Figure 2.1. The geological model of Brown and Stephenson (1991) is compared to the hydrostratigraphic model of Kellett (1989) in Figure 2.2.

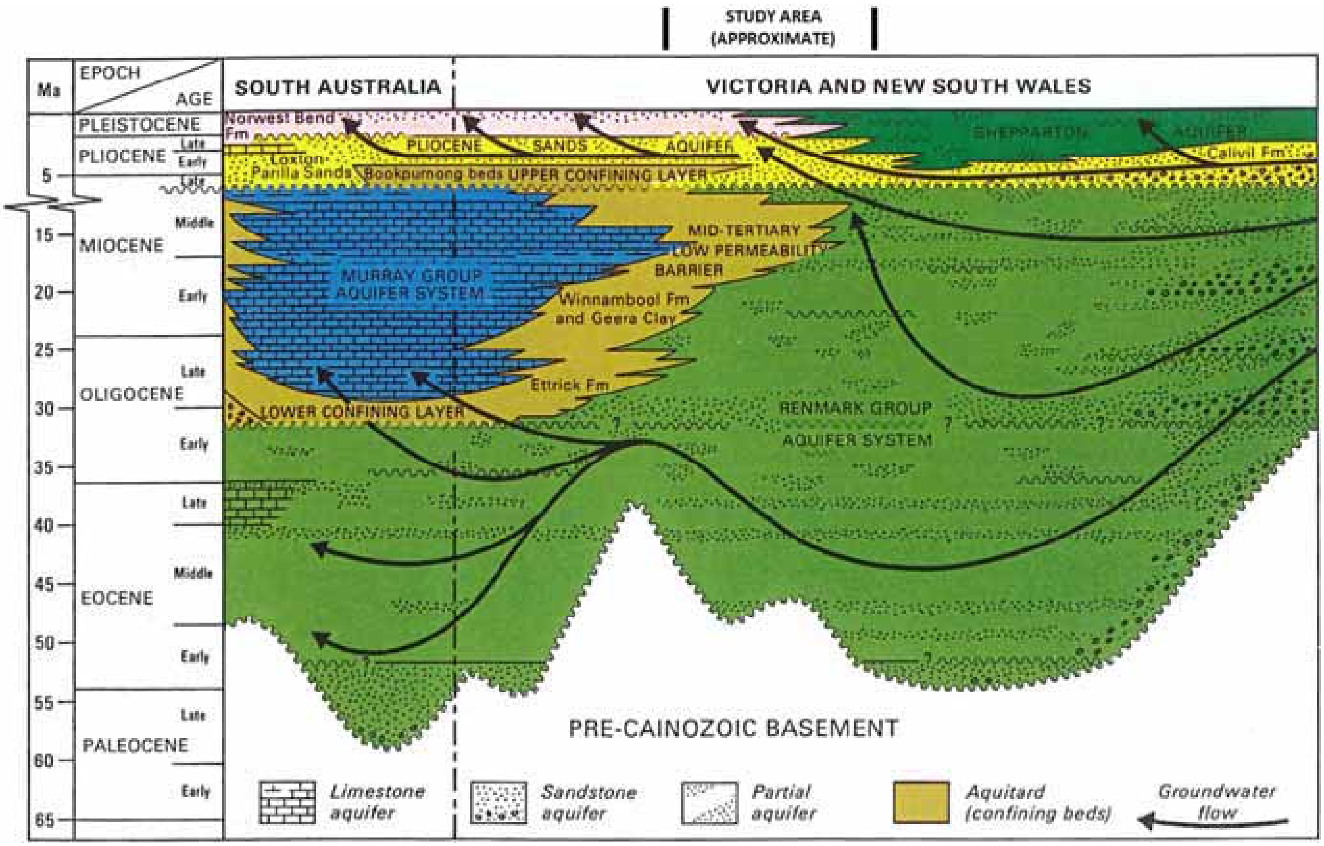


Figure 2.1 : Basinal-scale hydrostratigraphy of the Murray Basin, after Evans and Kellett (1989)

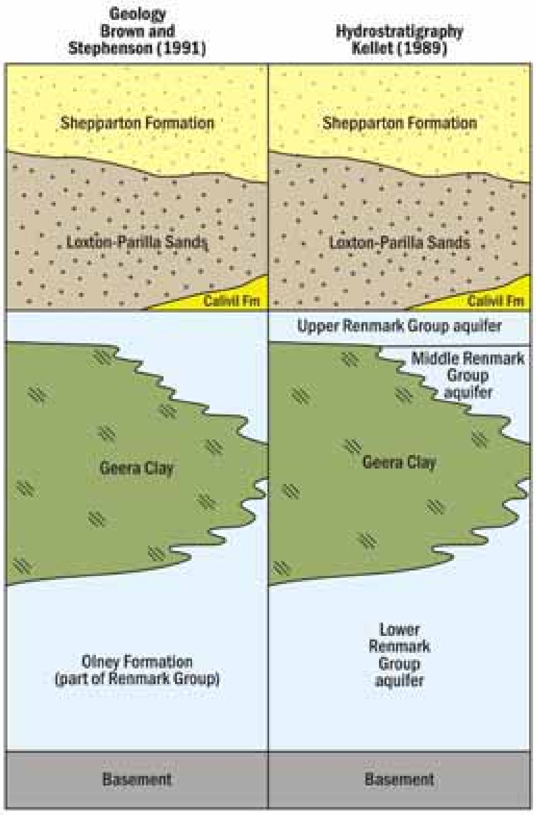


Figure 2.2 : Comparison of the geological (Brown and Stephenson, 1991) and hydrostratigraphic (Kellet, 1989) models of the study area.

The Lower Renmark Group aquifer overlies bedrock within the broader region that encompasses the project area. In the immediate vicinity of the project area the Lower Renmark Group aquifer is in turn overlain by the Geera Clay, a major low permeability layer. Further east and north-east of the project area, the Geera Clay grades laterally into the Middle Renmark Group aquifer. The Upper Renmark Group aquifer overlies the Middle Renmark Group aquifer and the Geera Clay.

The Pliocene Sands Aquifer as defined by Evans and Kellett (1989) overlies both the Upper Renmark Group aquifer and the Geera Clay. This regional aquifer consists of the Calivil Formation to the east and the LPS in the central and western parts of the Murray Basin. This section will not use the Pliocene Sands nomenclature further. The LPS hosts the mineralised zones targeted for mining at West Balranald and Nepean. In turn, the LPS is then overlain by the Shepparton Formation, with the Shepparton Formation absent in the north-west of the study area. The Coonambidgal Formation is a Pleistocene unit associated with late stage alluvial activity and is restricted to the vicinity of the Murray, Murrumbidgee and Wakool Rivers.

There are two main aquifer units in the immediate vicinity of the project area – the LPS and the Lower Renmark Group aquifers. There are other units, such as the Shepparton Formation, whose sediments are heterogeneous in nature and in some instances can act as aquifers in a local sense.

The hydrostratigraphic units present at the mine sites are described below primarily in accordance with SKM (2013a) with some changes.

2.4.1 Shepparton Formation

URS (2012) describe the fluvio-lacustrine Shepparton Formation as ranging from 20 to 40 m thick in the vicinity of the West Balranald deposit, decreasing to around 25 m at Nepean – the unit thickens to the east and does not exist on the Iona Ridge and to the west of the Iona Ridge. This is broadly consistent with information from the regional 1:250 000 hydrogeological map (Kellet, 1994) and the geological model of the deposit (Iluka, 2011b). URS (2012) describe the unit as being comprised of unconsolidated sandy clay and clayey sand with bands of fine grained sand. The horizontal stratification of bands of material with higher/lower clay and silt content is likely to result in a significant level of anisotropy, with higher hydraulic conductivity in the horizontal direction along bands of higher sand content.

The Shepparton Formation hosts the water table for the majority of the study area, but it is unsaturated at Nepean. AquaGeo (pers. comm.) reported the presence of a shallow perched water table at the West Balranald deposit, providing further evidence of significant horizontal to vertical anisotropy in permeability. URS (2012) identify the presence of a clay layer at most West Balranald drill sites, located at the base of the Shepparton Formation and separating it from the LPS. AquaGeo (pers. comm.) confirmed the presence of a significant clay layer and indicated it was expected to act as a barrier to flow between the Shepparton Formation and LPS and hence confines the LPS. However, Iluka (2013) undertook a study of the Shepparton Formation in the broader area of the deposits and concluded that clay rich layers exist throughout the Formation, but they were not universally continuous intervals.

This conflicting data suggests that locally the Shepparton Formation can be very fine grained and may constrain localised vertical flow at the small scale.

To the east the Shepparton Formation forms the water source of the Lower Murrumbidgee Groundwater Source – Shallow area.

2.4.2 Loxton-Parilla Sands

The marine LPS underlies the Shepparton Formation and hosts the mineralised zones at both West Balranald and Nepean. The LPS is saturated at West Balranald and partially saturated at Nepean. URS (2012) indicate that the LPS is between 40 m and 60 m thick at West Balranald and 25 m to 40 m thick at Nepean. URS (2012) describe the LPS as being composed of fine grained sand with some horizons of coarser grained sand with interspersed bands of clay and sandy clay. Clay layers are indicated to be less prevalent in the LPS than in the overlying Shepparton Formation. Iluka (2009) reports a geological model for the LPS that divides into repeating cycles of a facies stack that moves upwards from offshore to lower shore to surf zone to foreshore facies (Figure 2.3).

Detailed monitoring during pumping and injection trials (Iluka, 2015) indicates that the surf zone facies has the highest hydraulic conductivity and can be several metres thick. The offshore facies is the thickest unit, especially towards the west and is comprised of fine to very fine-grained sand layers. The other facies have hydraulic properties between these two extremities. The LPS surf zones are conceptualised as a highly transmissive aquifer; the offshore facies are conceptualised as a lower permeability layer.

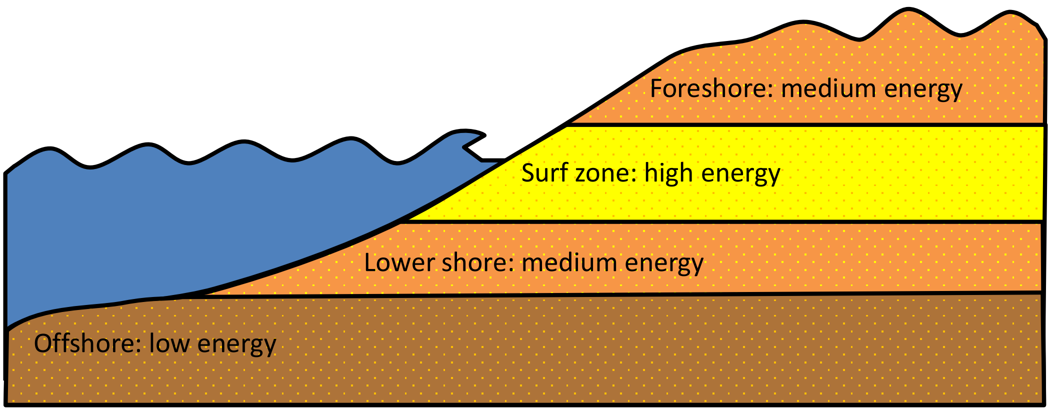


Figure 2.3 : Depositional environments of the LPS

2.4.3 Upper Renmark Group Aquifer

Regionally the Upper Renmark Group aquifer underlies the LPS. The Upper Renmark Group aquifer is seen to overlie the Middle Renmark Group aquifer; the latter unit was assigned as a finer grained facies of the Renmark Group equivalent to the Geera Clay. By definition, then, any Upper Renmark Group aquifer sediments must overlie the Geera Clay. However, the drilling undertaken by Iluka has not been able to identify the unit in the project area.

As a consequence Iluka commissioned Ray Evans to undertake a review of the available information and advise on the consistency or otherwise between Iluka's general geological model and that of Kellett from his various reports. This review (Evans; 2014) was aimed at providing a better understanding of the stratigraphy in the vicinity of the West Balranald strand. Evans agreed with Iluka's stratigraphic interpretation and the discussion below is based on Evans's report.

Kellett (1989) describes the Upper Renmark Group aquifer as comprising a 40 to 60 m thick sequence of mostly medium to fine sand with minor silt interbeds. The sand is micaceous and carbonaceous, but not as rich in lignitic material as deeper Renmark Group sediments. The colour varies between brownish grey to greenish grey. Kellett also identified a purplish coloured ferruginised zone at the top of the layer that he correlated with the Mologa Weathering Surface as identified by Macumber (1978, 1991). This Surface had been shown in the Loddon Valley to represent the hiatus in sedimentation between the Renmark Group and the Calivil Formation in the Late Miocene.

Kellett (1989) also used palynological data to further constrain the distribution of the Upper Renmark Group aquifer. It appears that the presence of the *C Bellus* palynological zone (previously named *T Bellus*), which is dated as late Lower Miocene to early Upper Miocene in the Murray Basin, was used to assign sediments to the Upper Renmark Group aquifer. Presumably this was viewed as consistent with the proposed age of the Mologa Surface as well as the age of the LPS sequence as deduced from fossil evidence elsewhere.

The distribution of the Upper Renmark Group aquifer layer is also shown on the Balranald Hydrogeological Map (1:250,000 scale) as extending across the West Balranald deposit and associated areas. It is not known how thick the unit was interpreted to be in the area from the available data. It is also noted that little direct drillhole control was available for the project area.

Given Kellett's conceptual stratigraphic model for the area, there is conjecture as to whether the unit identified by Iluka as the lower shore facies of LPS is in fact Kellett's Upper Renmark Group aquifer unit. This issue is further compounded by the lack of any evidence for the apparent Mologa Weathering Surface in Iluka's drillhole information for the West Balranald area (though Macumber comments that there is little ferruginisation associated with the Surface in the Loddon Plain sediment sequence). There is currently no palynological data available for the Iluka drillhole samples that could be used to assign the sediments to a particular age.

There is some evidence for the presence of the Mologa Weathering Surface at Nepean. Kellett (1989) reported the Surface as being identified by a large gamma ray spike on natural gamma geophysical logs. URS (2012) defined the Upper Renmark Group at depth below the ore. The natural gamma log for bore N11, presented in Figure 2.4, displays a large spike at a depth slightly greater than 40 m. This is associated with the mineral deposit. Several smaller spikes are evident below this major spike and the one at a depth of approximately 80 m may indicate the presence of the Mologa Weathering Surface. It is possible that the Mologa Weathering Surface is therefore present at Nepean and, therefore, that the sediments both below this depth and above the Geera Clay indeed represent the Upper Renmark Group aquifer and/or possibly the Middle Renmark Group aquifer.

Evans concluded that the genetic sequence stratigraphic model developed by Iluka's exploration team appears internally consistent and can be supported by sedimentological arguments based on environment of deposition. There is no need to introduce a further unit below the LPS2 package of sediments and the fine grained basal unit is consistent with the pervading model of the evolution of the Pliocene package of sediments in the Murray Basin. There are no identified breaks in deposition that can be recognised as the Mologa Weathering Surface (as used by Macumber and Kellett). The description of materials in the vicinity of the West Balranald deposit is consistent with descriptions of the Parilla Sand in Macumber (1991).

However, Kellett's evidence of both a weathering break consistent with a Late Miocene depositional hiatus, and palynological data assigning a thick sequence of sediment above the Geera Clay to the Late Miocene is compelling evidence that an Upper Renmark Group aquifer unit does exist in the broader region. Interestingly, Miranda et al. (2009) have placed a tentative maximum date on the LPS transgressive event at about 7.2 Ma (or

Late Miocene). This may overlap with the very end of the *T bellus* pollen assemblage zone, further confusing the issue.

From a materials viewpoint the age, and therefore stratigraphic assignment, of the sediments is of less concern as they are able to be sufficiently described for inclusion in any further analysis of groundwater flow that is required by Iluka as part of development of the deposit.

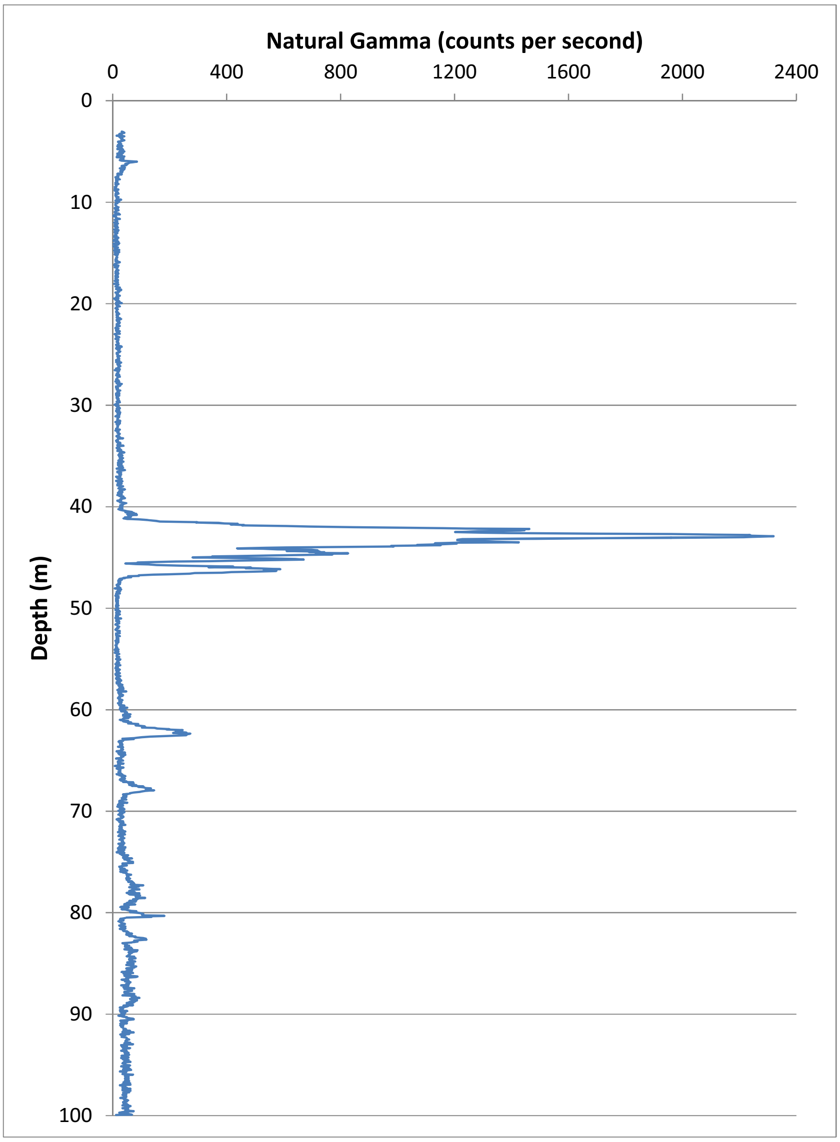


Figure 2.4 : Natural gamma log for bore N11, located at the Nepean deposit

2.4.4 Middle Renmark Group Aquifer

The marginal marine to fluvial Middle Renmark Group aquifer is a unit of low energy sediments, the finest-grained part of the Renmark Group (Kellett, 1989). It is described as being silty medium grained sand, laminated clay and silt and fine sand. URS (2012) indicates a thickness of around 100 m in the Balranald Trough to the east of the project area, thinning to around 50 m on ridges. The Middle Renmark Group aquifer interfingers laterally with the Geera Clay. The Middle Renmark Group aquifer has not been identified within the project area.

2.4.5 Geera Clay

The Geera Clay is a thick sequence of estuarine clays and muds laid down in the transgressive phase of the Oligo-Miocence high sea level stand. The Clay is usually black in colour with ubiquitous fossils. MacPhail et al. (1993) proposed a new but informal stratigraphic unit called the Geera Clay Equivalent, which represents the regressive phase of the Oligo-Miocene high sea stand. The assignment was based primarily on environment of deposition evidence as deduced from fossils. This regressive unit is a slightly coarser-grained (sandy clay) marginal marine unit that is suggested to lie sedimentologically between the Geera Clay (as a transgressive marginal marine unit) and the Olney Formation (Kellett's Upper Renmark Group aquifer layer). Within the context of the hydrostratigraphy of the project area, the occurrence of this unit is not important as it will have the same hydraulic properties as the Geera Clay.

The regional Balranald hydrogeological map (1:250,000 scale) illustrates the eastern boundary of the Geera Clay cutting through the southern end of the West Balranald deposit. Contrary to this, Brown and Stephenson (1991) provide isopachs for the Geera Clay that indicate it is present for the entire length of the West Balranald deposit with a thickness between 50 m and 100 m, and extends further east than indicated by the hydrogeological map (Kellet, 1991). Subsequent to the URS (2012) work, Iluka carried out drilling along the length of the West Balranald deposit and confirmed the presence of the Geera Clay along the strike of the proposed mine, including the area at the southern end where the hydrogeological map (Kellett, 1994) indicates that Geera Clay is not present (AquaGeo, pers. comm.). On that basis the isopachs presented by Brown and Stephenson (1991) combined with the recent drilling carried out by Iluka have been used as the conceptual basis for the distribution of the Geera Clay indicating its presence along the West Balranald deposit and extending some distance to the east.

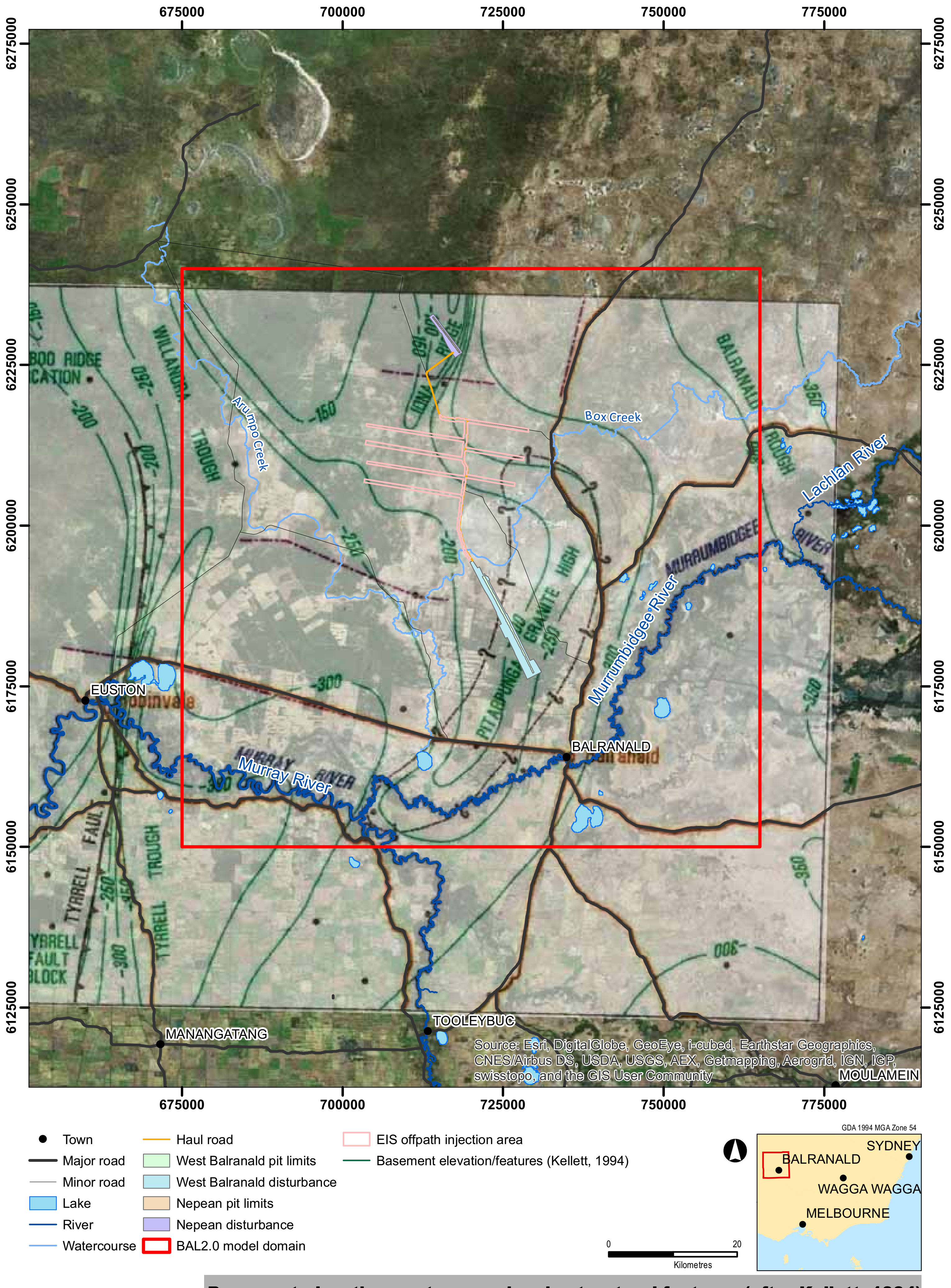
2.4.6 Lower Renmark Group Aquifer

The Lower Renmark Group aquifer overlies the basement and varies in thickness across the region. It is generally only 20 m to 30 m thick, but can exceed that locally, and may be absent across basement highs (Kellett, 1989). It is comprised of layers of sand and fine gravel interbedded with silty and sandy clay and minor lignite. Regional hydrostratigraphy presented by Kellett (1991 and 1994) shows the Lower Renmark Group aquifer to be absent in parts of the study area.

2.4.7 Basement

Basement consists of rocks associated with the Paleozoic Lachlan Fold Belt. The topography of the top of the basement rocks has significant impacts on the overlying sedimentary geology and associated groundwater flow in the study area as shown by Kellett (1991 and 1994). A basement high, the Iona Ridge, lies to the north of the study area (see Figure 2.5). The Tyrrell Fault Block approximately 10 km outside the south-west of the study area is a region of elevated basement material between the north-south trending Tyrrell and Wemen Faults. East of the Tyrrell Fault lies the Tyrrell Trough. From a low at the Tyrrell Fault, the basement rises eastward towards the West Balranald deposit and Pitarpunga Granite High, which aligns roughly with the Iona Ridge to the north. East of the Iona Ridge and Pitarpunga Granite High is the Balranald Trough.

URS (2012) suggests that the West Balranald and Nepean deposits are located in the Balranald Trough. However, comparison of the site locations with structural information provided by Kellett (1991 and 1994) indicates that the Nepean deposit is located on the southern end of the Iona Ridge and the West Balranald deposit is located on the eastern side of the Pitarpunga Granite High. Exploration drilling by Iluka has allowed a more detailed analysis of structure in the region of the project area. Structure contours on key horizons, generally within the LPS sequence, can be inferred to reflect basement structures in a general sense. These structures show a level of detail not evident in the contours compiled for the Balranald Hydrogeological Map, and highlight the Cainozoic tectonic evolution of the area.



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Basement elevation contours and main structural features (after Kellett, 1994)

Figure 2.5

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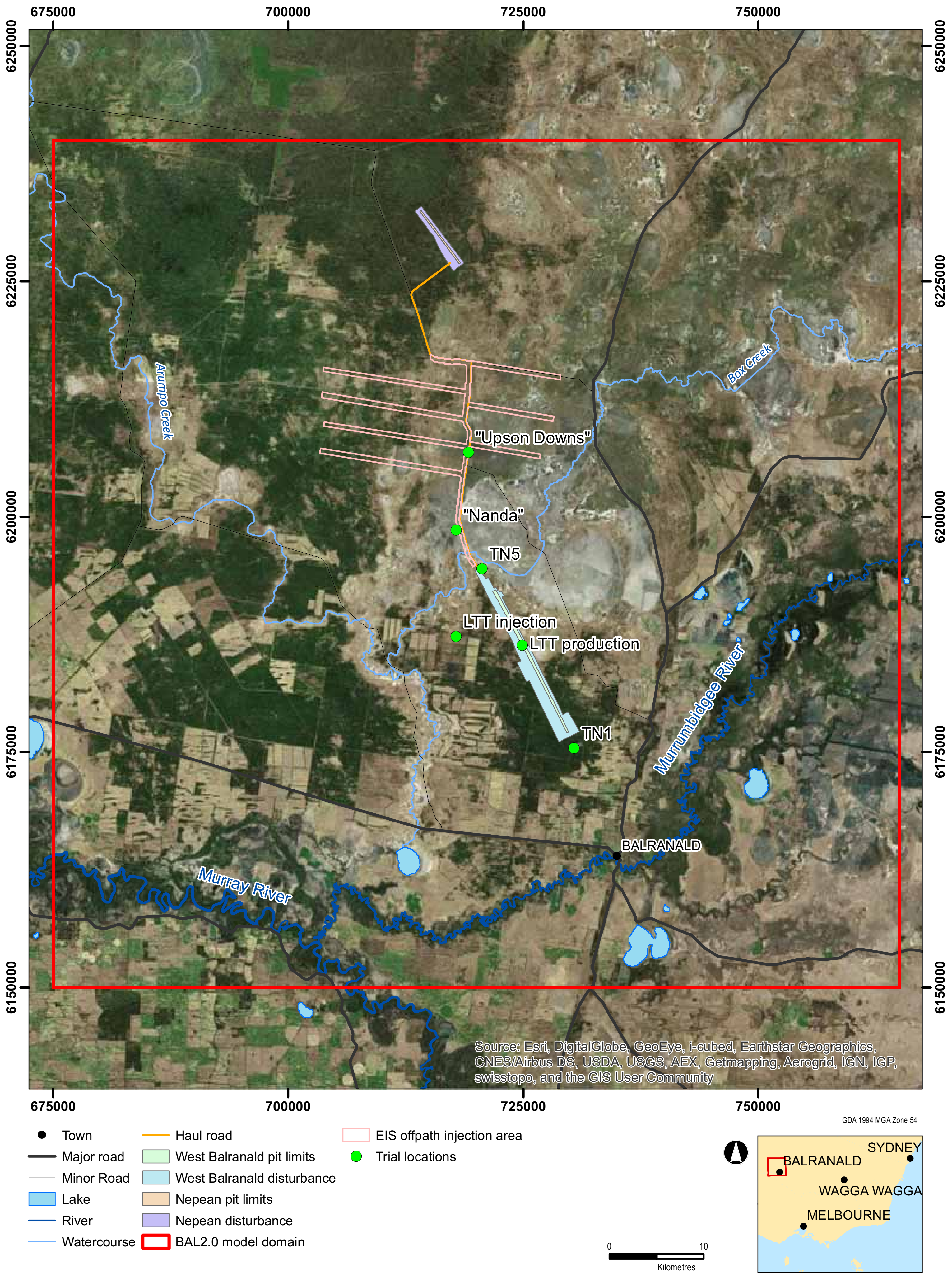
2.5 Aquifer properties

The understanding of the characteristics of the hydrostratigraphic units in the study area has been progressively developed and refined from initial regional-scale estimates available from literature, through a series of relatively small-scale step rate pumping and injection tests (SRTs) and constant rate pumping and injection tests (CRTs) during the PFS and, subsequently, two more short term pumping and injection trials (STTs) and a long term pumping and injection trial (LTT) as part of the DFS. The location of key trial sites is presented in Figure 2.6. Field activities are summarised in the following sections. The field activities with the most useful data are used in this study to calibrate modelled aquifer properties.



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Pumping and injection trial locations

Figure 2.6

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2.5.1 Prior to the Project

Prior to Iluka carrying out hydrogeological investigations to identify site-specific aquifer properties in the vicinity of the Project, existing literature provided estimates of hydraulic properties on a regional scale. Kellett (1989) provides descriptions of how hydraulic conductivity varies within aquifers across the study area (see Table 2.3).

Table 2.3 : Estimates of hydraulic properties presented by Kellett (1989)

Hydrostratigraphic Unit	K (m/d)
Shepparton Formation	1 – 2
LPS	4
Upper Renmark Group aquifer	1 - 2
Middle Renmark Group aquifer	0.5 – 1
Lower Renmark Group aquifer	1 – 5

Notes: K = hydraulic conductivity

2.5.2 2009 field activities

During the scoping study, URS (2009) undertook a literature review and data assessment to develop an initial conceptual hydrogeological model of the deposits and the surrounding area. As part of this assessment a limited drilling and pumping test program was undertaken. This included the installation of four production wells (SHPB03, LPSPB03, SHPB04 and LPSPB04) and two monitoring wells (SHOB03 and SHOB04) across two sites, “TN3” and “TN4”, at West Balranald. Pre-existing geotechnical monitoring wells, including WBGT03 and WBGT04, were also used during the program to assist with preliminary aquifer characterisation. Each production well was pumped for only 6 hours with rates ranging from 0.13 L/s to 6 L/s. Analysis of the tests provided the following:

- Transmissivity of the Shepparton Formation was estimated to range between 35 m^2/d and 151 m^2/d with corresponding hydraulic conductivities of 2.4 m/d and 10.4 m/d;
- Transmissivity of the LPS was estimated to range between 328 m^2/d and 1,305 m^2/d with corresponding hydraulic conductivities of 6.5 m/d and 25.8 m/d; and
- Storativity values of 0.09 and 0.08 were calculated for the Shepparton Formation and LPS respectively, suggesting unconfined to semi-confined conditions.

Groundwater chemistry showed salinities in the Shepparton Formation ranged between 37,700 mg/L and 48,100 mg/L and between 40,900 mg/L and 48,100 mg/L within the LPS. The groundwater major ions were dominated by sodium and chloride and were corrosive in nature. Heavy metal analysis showed that aluminium, iron and manganese were all below the adopted ANZECC 2000 ecosystem, guideline for fresh and marine waters.

A preliminary estimate of the expected mine dewatering rate, using various analytical techniques, was made. This predicted dewatering rates in the order of 25 ML/d to 40 ML/day (290 L/s to 463 L/s). URS (2009) suggested that, due to the data limitations and aquifer parameter uncertainty at the time, actual dewatering rates may be greater than those predicted at that stage and that further and more extensive field work, followed by numerical modelling was required.

2.5.3 2011 field activities

URS (2011) conceptualised the Cainozoic sediment-hosted aquifers at the West Balranald and Nepean deposits, which also involved conducting a hydrological census to capture existing hydrological and hydrogeological data within the proximity of the project site. The study concluded that there was relatively limited site specific hydrogeological information available and the planned upcoming 2011-2012 field program would greatly improve the conceptual understanding of the site. Further findings of the study were:

- the hydrogeological conceptual model developed showed the principal hydrogeological units, from shallowest to deepest, are:
  - Coonambidgal Formation (local aquifer)
  - Woorinen Formation (local aquifer)
  - Shepparton Formation (regional aquifer)
  - LPS (regional aquifer)
  - Renmark Group aquifers (comprising Upper, Middle and Lower regional aquifers)
  - Geera Clay (Aquitard between the Middle and Lower Renmark Group aquifers)
  - Basement (Aquitard/Aquiclude)
- Groundwater salinity is generally higher in the Shepparton and LPS aquifers compared to the Lower Renmark Group aquifers. Bore yields are generally higher in the Renmark Group aquifers;
- The hydraulic connectivity between the LPS and Renmark Group aquifers is a key data gap that needs to be assessed if the impact of mining is to be well understood. Contamination of the Renmark Group aquifers by injection of saline groundwater from the Shepparton Formation and LPS is also a potential issue; and
- Understanding the extent of the Geera Clay and its ability to impede vertical flow between the LPS and the Renmark Group aquifers was still a clear data gap.

Further investigations undertaken by URS (as described below) and by Iluka (including both desk top reviews of available data and field based studies) were aimed at eliminating the identified data gaps and at improving the conceptual understanding of the hydrogeology at the mine site.

Subsequent to the hydrological census and associated study, URS (2012) supervised a substantial drilling and pumping test program across four sites along the West Balranald deposit and three sites along the Nepean deposit. The following infrastructure was installed between May 2011 and February 2012:

- One production well (WB6), two injection wells (WB2 and WB5) and four monitoring wells (WB1, WB3, WB7 and WB8) at TN1, the southernmost site on the West Balranald deposit;
- One production well (WB25), two injection wells (WB18 and WB22) and two monitoring wells (WB20 and W21) at TN3, located approximately at the mid-point of the West Balranald deposit;
- One production well (WB28) at site TN4, located approximately 2.5 km north of TN3;
- One production well (WB41), one injection well (WB40) and four monitoring wells (WB38, WB39, WB42 and WB43) at the northern-most site (TN5) on the West Balranald deposit;
- One production well (N29), one injection well (N23) and four monitoring wells (N21, N22, WB27 and N28) at the southern-most Nepean site (NTN1);
- One production well (N10) and two monitoring wells (N11 and N12) at a central site on the Nepean deposit (NTN2); and
- One production well (N8) and one monitoring well (N7) at the northern-most Nepean site (NTN3).

Following well installation, Iluka assisted URS with SRT and CRT pumping tests at each site. The purpose of the tests was to determine the response of various aquifers to pumping and injection, allowing a) aquifer properties to be determined and b) a preliminary assessment of dewatering and injection feasibility. Aquifers at NTN2 and NTN3 were not sufficiently transmissive to allow these types of pumping tests to be carried out. This suggested the Nepean deposit may be relatively easy to dewater for the purpose of dry-mining operations in comparison to West Balranald.

The CRTs commenced in July 2011 and were completed by February 2012. Test durations ranged from 15 hours at TN1 to seven days at TN5. Flow rates ranged from 8 L/s at NTN1 to 35 L/s at West Balranald sites TN1 and TN4.

Analysis of the CRTs to determine aquifer parameters, was primarily undertaken using AqteSOLV Pro version 4.0 (HydroSOLVE, 2015), with supporting analysis undertaken using the Cooper-Jacob straight line method. Analysis was undertaken using several different methods available in the AqteSOLV program; with the ‘best fit’ achieved using the Hantush (1955) leaky confined aquifer method (URS, 2012). SKM (2013a) was asked to carry out a brief independent analysis of the CRT data to determine aquifer properties. The results of the CRT analyses undertaken during the PFS are presented in Table 2.4. The table illustrates differences between results obtained by URS (2012) and by SKM (2013a). These differences generally arise from different assumptions and interpretations included in the aquifer test analyses. They illustrate typical levels of uncertainty inherent in current methods used to analyse aquifer pumping test results.

Table 2.4 : Interpreted hydraulic properties from PFS CRTs

Hydrostratigraphic Unit Site	Property	URS (2012)	SKM (2013a)
LPS TN1*	K (m/d) S (-)	0.5 – 3.1 $2.4 \times 10^{-6} – 4 \times 10^{-4}$	7.3 2×10^{-4} - 6×10^{-4}
LPS TN3*	K (m/d) S (-)	0.7 – 2.3 $1.94 \times 10^{-5} – 3.2 \times 10^{-3}$	1.9 1×10^{-3}
LPS TN4*	K (m/d) S (-)	1.4 2.4×10^{-3}	2.7 8×10^{-4}
LPS TN5*	K (m/d) S (-)	1.6 – 2.2 2.3×10^{-7} – 5.4 – 10^{-5}	4 1.3×10^{-4}
LPS N Cluster 1#	K (m/d) S (-)	0.4 – 0.8 $4.8 \times 10^{-3} – 9 \times 10^{-3}$	- -

Notes: * = West Balranald, # = Nepean, S = Storativity

2.5.4 2014 field activities

Beginning in late 2013, Iluka (2015) installed further groundwater infrastructure at three sites. Wells were installed at “Nanda” and “Upson Downs”, located north of the West Balranald deposit, and LTT wells were installed near the midpoint of the West Balranald deposit (Figure 2.6). A total of four production, 16 injection and 24 monitoring wells were constructed across the three sites (Table 2.5).

Most monitoring wells and VWPs targeted LPS sub-units. Details of VWP installations are provided in Table 2.6.

Table 2.5 : Wells installed during the DFS (Iluka, 2015)

Well ID	Type	Site	Total depth (m)	Screened depth (m)
WBPW01	Production	LTT production	109	37 - 79
WBPW02	Production	LTT production	91	44 - 80
“Karra” Homestead	Production/monitoring	LTT production	239	218.8 - 230.8
WBMW02S	Monitoring	LTT production	98	43 - 47
WBMW02D	Monitoring	LTT production		84 - 86
WBMW03S	Monitoring	LTT production	82	32 - 35
WBMW03D	Monitoring	LTT production		66 - 70
WBMW04	Monitoring	LTT production	264	n/a
WBMW05S	Monitoring	LTT production	114	30 - 33
WBMW05D	Monitoring	LTT production		85 - 86

Well ID	Type	Site	Total depth (m)	Screened depth (m)
WBMW06S	Monitoring	LTT production	112	16 - 20
WBMW06D	Monitoring	LTT production		58 - 64
WBIW01A	Injection	LTT injection	105	57 - 98
WBIW02	Injection	LTT injection	117	53 - 108
WBIW03	Injection	LTT injection	115	50 - 103
WBIW04	Injection	LTT injection	113	47 - 107
WBIW05	Injection	LTT injection	114	60 - 108
WBIW06	Injection	LTT injection	113	55 -103
WBIW07A	Injection	LTT injection	112	58 - 110
WBIW08	Injection	LTT injection	119	52 - 104
WBIW09	Injection	LTT injection	110	59 - 105
WBIW10	Injection	LTT injection	108	55 - 107
WBIW11	Injection	LTT injection	126	60 - 102
WBIW12A	Injection	LTT injection	114	67 - 102
WBMW07S	Monitoring	LTT injection	89	17 - 20
WBMW07D	Monitoring	LTT injection		79 - 82
WBMW08D	Monitoring	LTT injection	102	95 - 101
WBMW09S	Monitoring	LTT injection	90	27 - 30
WBMW09D	Monitoring	LTT injection		69 - 78
WBMW10	Monitoring	LTT injection	295	277 - 283
WBMW11S	Monitoring	LTT injection	119	21 - 23
WBMW11D	Monitoring	LTT injection		85 - 103
WBMW12S	Monitoring	LTT injection	96	18 - 21
WBMW12D	Monitoring	LTT injection		69 - 75
WBMW13S	Monitoring	LTT injection	114	30 - 36
WBMW13D	Monitoring	LTT injection		76 - 79
WBPW04	Production	“Nanda”	108	39 - 105
WBIW15	Injection	“Nanda”	101	58 - 98
WBIW16	Injection	“Nanda”	114	71 - 105
WBMW17S	Monitoring	“Nanda”	119	42 - 45
WBMW17D	Monitoring	“Nanda”		91 - 94
WBMW18S	Monitoring	“Nanda”	120	16 - 20
WBMW18D	Monitoring	“Nanda”		76 - 94
WBMW19S	Monitoring	“Nanda”	119	39 - 42
WBMW19D	Monitoring	“Nanda”		72 - 75
WBPW03A	Production	“Upson Downs”	89	41 - 83
WBIW13	Injection	“Upson Downs”	107	46 - 104
WBIW14	Injection	“Upson Downs”	104	46 - 104
WBMW14S	Monitoring	“Upson Downs”	137	34 - 37
WBMW14D	Monitoring	“Upson Downs”		75 - 78

Well ID	Type	Site	Total depth (m)	Screened depth (m)
WBMW15S	Monitoring	“Upson Downs”	137	81 - 83
WBMW15D	Monitoring	“Upson Downs”		117 - 120
WBMW16S	Monitoring	“Upson Downs”	137	29 - 32
WBMW16D	Monitoring	“Upson Downs”		74 - 77

Table 2.6 : VWPs installed during the DFS (Iluka, 2015)

Site	VWP ID	Total well depth (m)	VWP depth (m)
LTT production	WBMW02 (P1)	98	25
LTT production	WBMW02 (P2)		65
LTT production	WBMW03 (P1)	82	25
LTT production	WBMW04 (P1)	264	253
LTT production	WBMW04 (P2)		240
LTT production	WBMW04 (P3)		180
LTT production	WBMW04 (P4)		125
LTT production	WBMW04 (P5)		110
LTT production	WBMW04 (P6)		85
LTT production	WBMW04 (P7)		60
LTT production	WBMW04 (P8)		54
LTT production	WBMW04 (P9)		45
LTT production	WBMW04 (P10)		38
LTT production	WBMW04 (P11)		33
LTT production	WBMW05 (P1)	114	39
LTT production	WBMW05 (P2)		69
LTT production	WBMW06 (P1)	112	31
LTT production	WBMW06 (P2)		45
LTT injection	WBMW07 (P1)	89	44
LTT injection	WBMW08 (P1)	102	31
LTT injection	WBMW08 (P2)		38
LTT injection	WBMW08 (P3)		79
LTT injection	WBMW09 (P1)	90	37
LTT injection	WBMW09 (P2)		15
LTT injection	WBMW10 (P1)	295	17
LTT injection	WBMW10 (P2)		23
LTT injection	WBMW10 (P3)		29
LTT injection	WBMW10 (P4)		37
LTT injection	WBMW10 (P5)		44
LTT injection	WBMW10 (P6)		73
LTT injection	WBMW10 (P7)		87
LTT injection	WBMW10 (P8)		104
LTT injection	WBMW10 (P9)		143

Site	VWP ID	Total well depth (m)	VWP depth (m)
LTT injection	WBMW10 (P10)		199
LTT injection	WBMW10 (P11)		241
LTT injection	WBMW11 (P1)	119	43
LTT injection	WBMW11 (P2)		71
LTT injection	WBMW12 (P1)	96	49
"Upson Downs"	WBMW15 (P1)	137	24
"Upson Downs"	WBMW15 (P2)		34
"Nanda"	WBMW17 (P1)	119	19
"Nanda"	WBMW17 (P2)		34

During the LTT, groundwater was pumped from up to two production wells installed mid-way along the West Balranald strand, to 12 injection wells located between 6 and 8.5 km to the west (refer Figure 2.7 and Figure 2.8). These wells were screened in the LPS, and constructed such that grout prevented preferential flow from and into the overlying Shepparton Formation via the annulus.

The LTT ran almost continuously for 47 days.

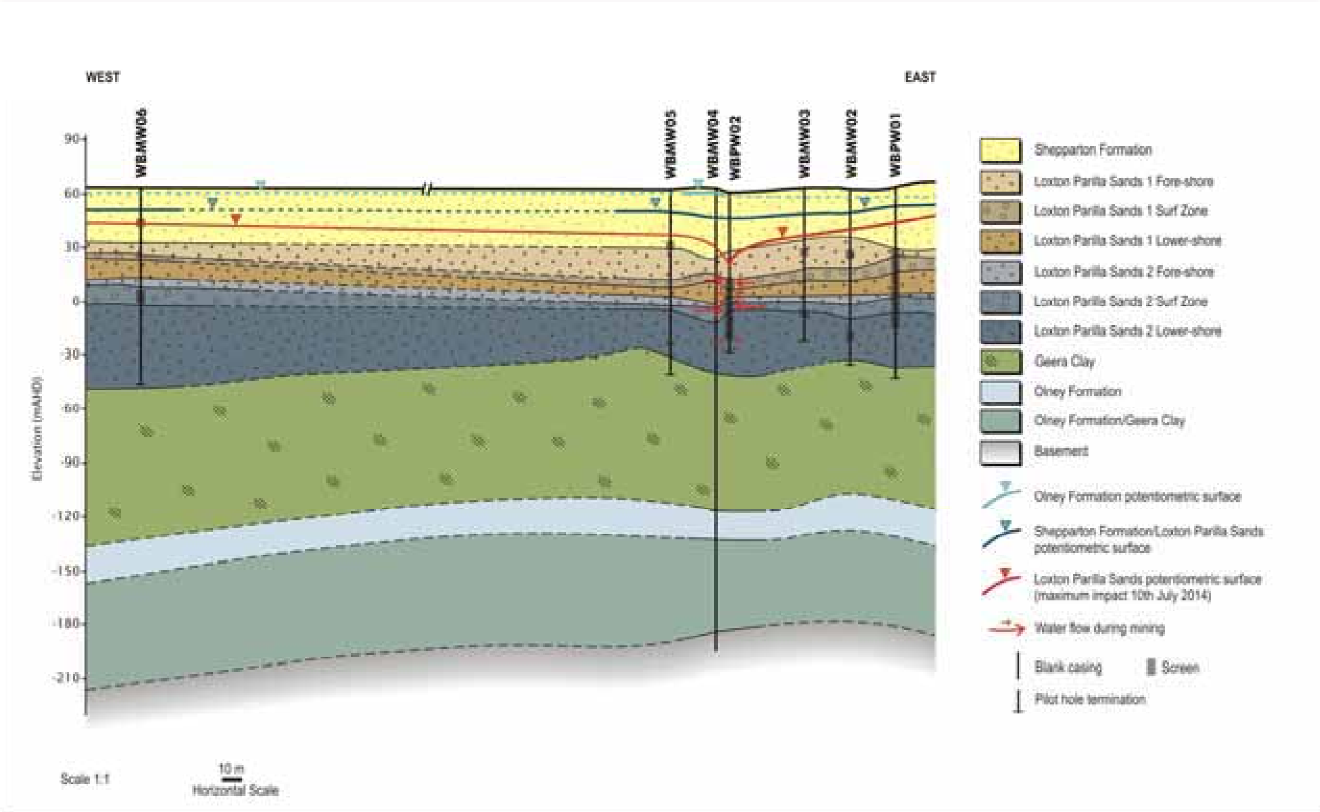


Figure 2.7 : Site hydrostratigraphy and maximum potentiometric impacts at the LTT production wellfield on 10 July 2014

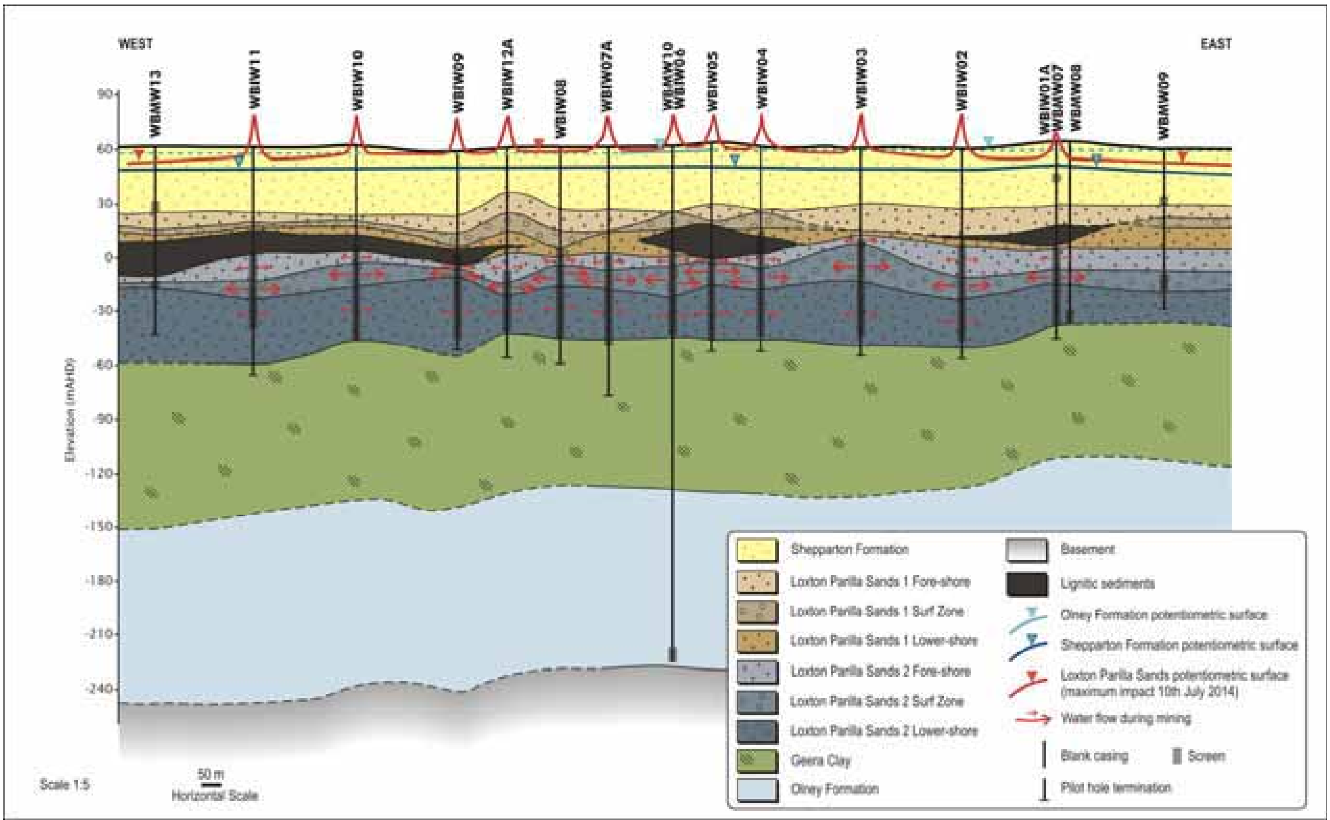


Figure 2.8 Site hydrostratigraphy and maximum potentiometric impacts at the LTT injection wellfield on 10 July 2014

During the STT at “Nanda” groundwater was transferred from production well WBIW15 to injection well WBPB04, a distance of approximately 1 km, at a constant rate of 15 L/s for 8.8 days. Both of these wells were screened in the LPS, and grouted from the LPS-Shepparton Formation interface to the site surface (Figure 2.9).

At "Upson Downs", groundwater was transferred from production well WBPW03A to injection wells WBIW13 and WBIW14 at rates up to 25 L/s. Each of these wells was screened in the LPS, such that preferential flow via the overlying borehole-casing annulus could not occur (Figure 2.10). The distance between the production and injection wells was approximately 1 km.

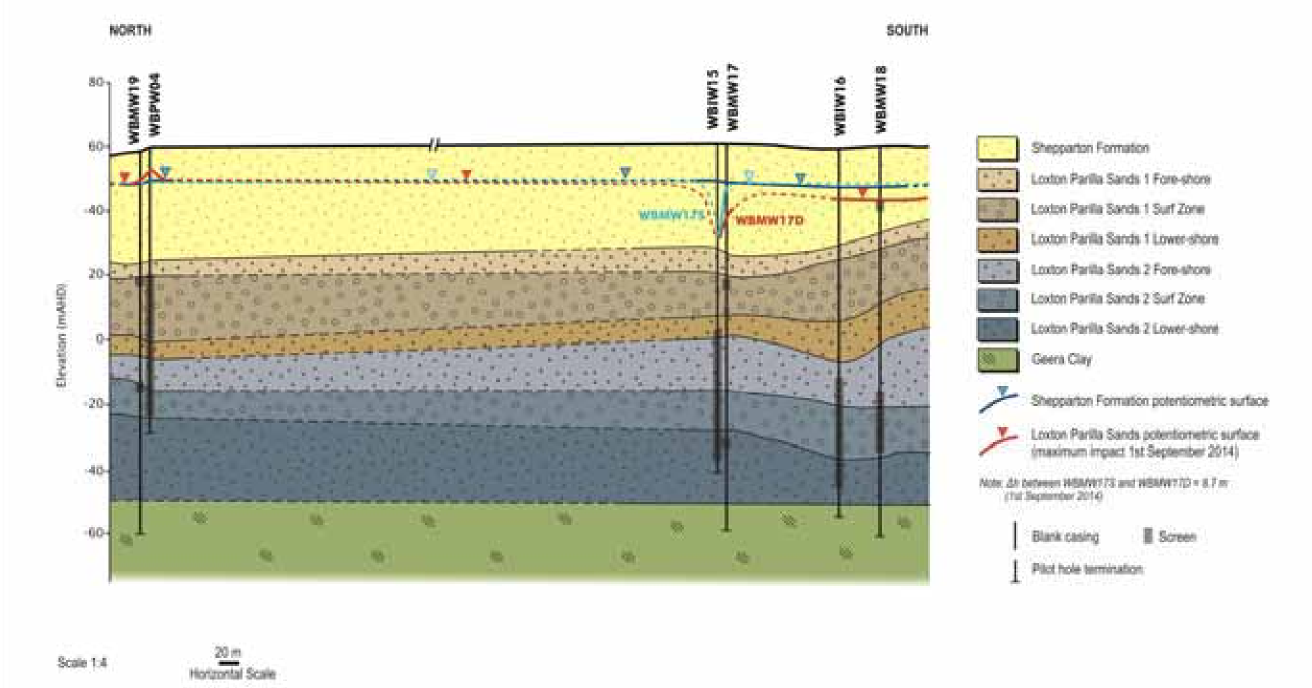


Figure 2.9 : “Nanda” hydrostratigraphy and maximum potentiometric impacts

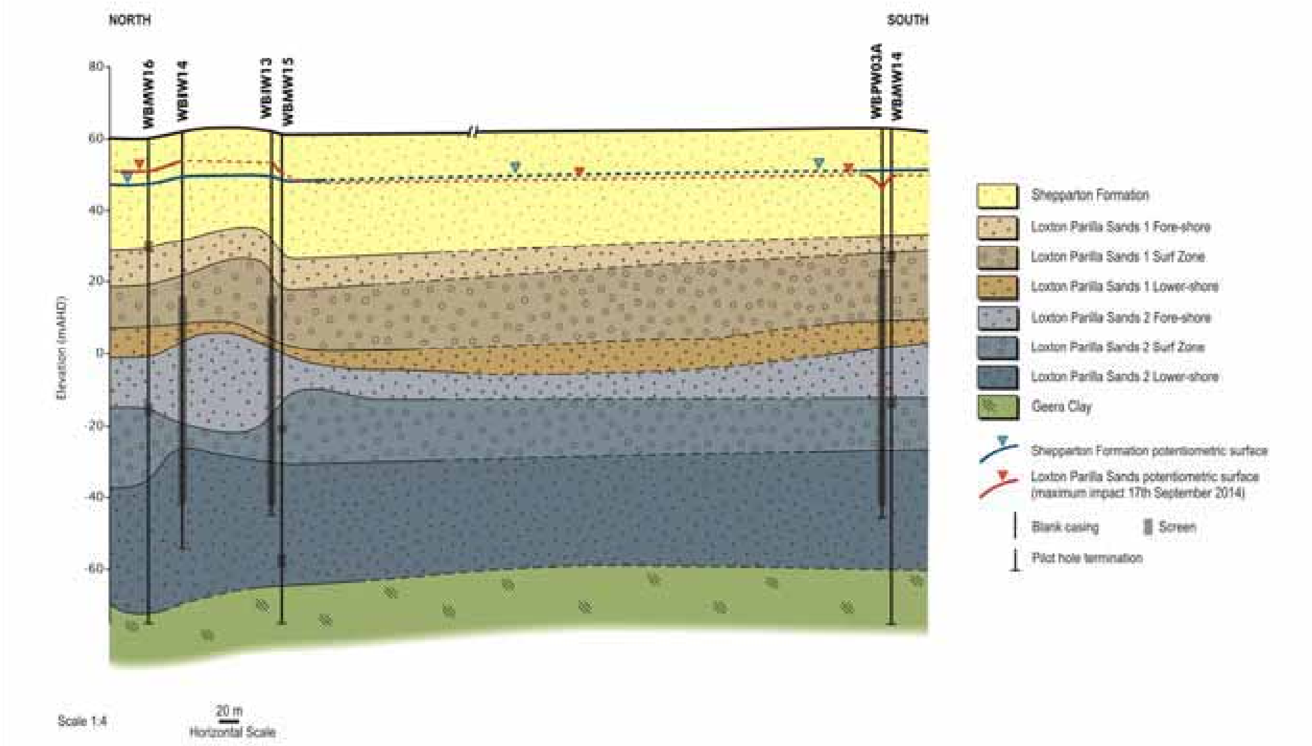


Figure 2.10 : “Upson Downs” hydrostratigraphy and maximum potentiometric impacts

Iluka (2015) employed a more detailed model of hydrostratigraphy than previous studies when interpreting the results of the LTT and STTs. The DFS test analyses take into account sub-units within the LPS such that hydraulic variability within the LPS can now be quantified. This is the first time the LPS has been analysed in such detail in the study area. The interpretation, summarised in Table 2.7, demonstrates a clear difference between the surf zones and the non-surf zone material within the LPS. Indeed, the latest interpretation supports the requirement to update the hydrogeological conceptualisation, which includes significant anisotropy within the LPS and preferential flow through the surf zones. This represents a significant change from the previous conceptualisation and modelling studies.

Table 2.7 : Interpreted hydraulic properties from the LTT and STTs carried out by Iluka (2015)

Hydrostratigraphic Unit	Well	K (m/d)	T (m^2/d)	Ss (1/m)	S (-)
LTT Site					
LPS (bulk)	WB28	3.3	196	6.9×10^{-6}	4.1×10^{-4}
LPS (bulk)	WB22	3.2	193	9.4×10^{-6}	5.6×10^{-4}
LPS (bulk)	WB25	3.2	193	1.0×10^{-5}	6.2×10^{-4}
LPS1 Surf Zone	WBMW06D	15.6 - 26	140 – 234	9.6×10^{-6} – 1.9×10^{-5}	8.7×10^{-5} – 1.7×10^{-4}
LPS1/LPS2 Surf Zones	WBMW04_P8	15.5 – 19.5	171 - 215	4.8×10^{-6} – 2.2×10^{-5}	5.3×10^{-5} – 2.4×10^{-4}
LPS2 Foreshore	WBMW03D	1.0 – 1.3	23 – 30	1.7×10^{-5} – 2.0×10^{-5}	4.0×10^{-4} – 4.8×10^{-4}
LPS2 Lower Shore	WBMW04_P6	2.9	73	9.4×10^{-6}	2.4×10^{-4}
LPS2 Lower Shore	WBMW05D	1.6	40	1.6×10^{-5}	4.0×10^{-4}
“Nanda” STT Site					
LPS (bulk)	WBIW15	3.4 – 4.8	136 - 190	-	-
LPS1 Surf Zone	WBMW17S	11.8 - 168	36 - 503	3.3×10^{-4}	1.0×10^{-3}
LPS1 Lower Shore	WBMW17D	2.2 – 3.4	7 – 10	8.7×10^{-5} – 2.2×10^{-3}	2.6×10^{-4} – 6.7×10^{-3}
“Upson Downs” STT Site					
LPS (bulk)	WBPW03a	12.5 – 17.9	824 - 1180	-	-
LPS1 Foreshore	WBMW14S	6.4	19	4.3×10^{-7}	1.3×10^{-6}

Note: T = transmissivity, Ss = specific storage

2.5.5 Aquifer characteristics

Available information from literature and testing carried out as part of the Project indicates the following general properties:

- Shepparton Formation: Literature indicates a regional horizontal conductivity on the order of 1 m/d to 2 m/d. The presence of interbedded fine materials and, in particular the presence of an ironstone/silcrete layer and a two to three metre thick clay layer towards the base of many of Iluka’s bore logs, suggest the vertical conductivity is likely to be very low. This is consistent with results of hydraulic testing carried out by Iluka (2015) in which the Shepparton Formation typically displays a poor hydraulic connection to the underlying LPS.
- LPS: Most estimates of bulk horizontal hydraulic conductivity indicate a range of generally between 2 m/d and 5 m/d. The surf zones consistently display a significantly higher hydraulic conductivity, typically on the order of 15 m/d to 25 m/d. The foreshore and lower shore sediments, consisting of finer material than the surf zones, typically have a hydraulic conductivity of 1 m/d to 3 m/d. The stratification both within and between the sub-units of the LPS is likely to cause significant horizontal to vertical anisotropy in hydraulic conductivity.
- Geera Clay: The nature of the Geera Clay aquitard makes aquifer testing directly from the unit impractical. However, hydraulic testing undertaken for the Project has indicated that the unit acts as a hydraulic barrier between the underlying Olney Formation and the overlying LPS. A range of hydraulic conductivity values

for clay is indicated by Domenico and Schwartz (1998) as between 8.6 x 10^{-7} m/d and 4.0 x 10^{-4} m/d. In addition, the hydraulic conductivity for the Geera Clay has previously been estimated by Lawrence (1975) to have a horizontal component of 4 x 10^{-4} m/d, and a vertical component of 2 x 10^{-5} m/d (Evans and Kellett, 1989).

- Olney Formation: Kellett (1989) indicates a hydraulic conductivity range for the Lower Renmark Group aquifer (Olney Formation) of 1 m/d to 5 m/d. The aquifer is known to be used as a source of brackish groundwater for stock water supply purposes in the study area and, hence, must have sufficient transmissivity to support functional well yields.

2.6 Groundwater flow

2.6.1 Rainfall recharge

Local climatic conditions provide little opportunity for rainfall derived recharge to the groundwater system. Further, the presence of stratified low permeability clays and silts in the Shepparton Formation have the potential to cause shallow recharge to be trapped in perched systems, potentially reducing recharge to the regional water table aquifer. URS (2012) reports a small downward gradient from the Shepparton Formation to the LPS and again to the Upper Renmark Group aquifer (now considered to be the LPS2 lower shore). A downward hydraulic gradient may indicate a system in which recharge to the groundwater system is greater than evapotranspiration from shallow groundwater. However, the same report concludes, based on the little transient data available, that seasonal variations are small (0.4 to 0.8 m in the shallow aquifers) and therefore it is likely that recharge from rainfall is minimal.

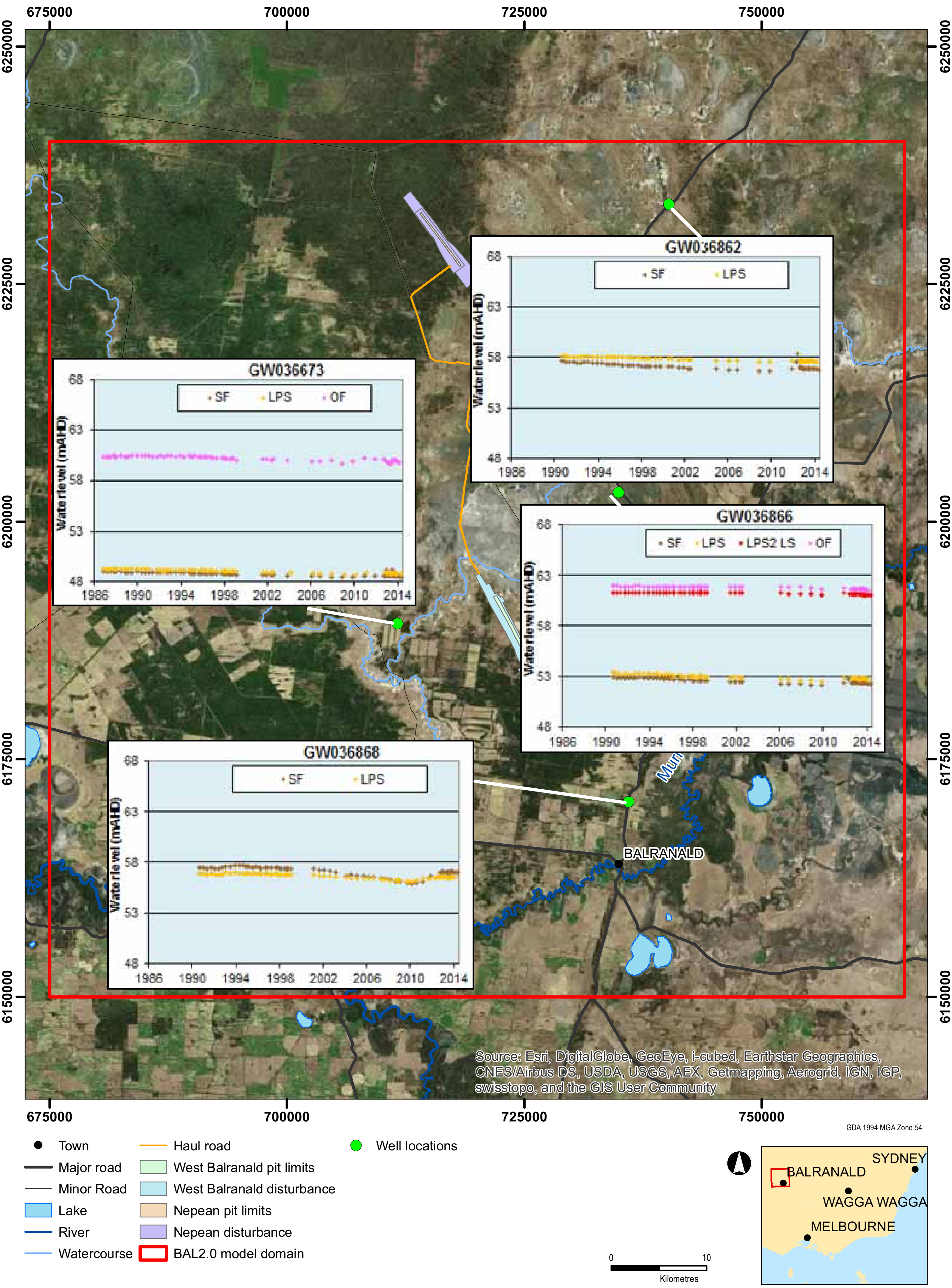
Clearing of Mallee vegetation in parts of the Murray-Darling Basin is thought to have caused an increase in rainfall recharge. Allison and Hughes (1983) used natural tracers to assess recharge at sites near Walpeup, Victoria (approximately 150 km south-west of Balranald). Their analysis of areas covered with native Mallee scrub and those that had been cleared and used for cropping suggested that, during the high rainfall period of their study, recharge under native vegetation was less than 0.1 mm/yr but was elevated to approximately 3 mm/yr in areas that had been cleared for cropping.

A subsequent study by Budd et al. (1990), also using natural tracers to estimate recharge, determined recharge under Mallee vegetation to be less than 0.1 mm/yr. The study determined recharge under cleared and cropped land to be 4 mm/yr and 10 mm/yr at a site in Balranald and 3 mm/yr and 10 mm/yr at a site in Euston. The study found the recharge under cleared sites to be affected by clay content in the near surface soils. Those with higher clay content experience lower recharge.

SKM (2013b) summarises recharge estimates used by Murray-Darling Basin Authority (MDBA) in 2012 for the Western Porous Rock Sustainable Diversion Limit resource unit. Recharge is estimated for four land use categories. Recharge under ‘native vegetation’ is estimated to be 0.1 mm/yr. Recharge under ‘cleared and grazed’ and ‘cleared and cropped’ land uses is estimated to be 7 mm/yr. A fourth land use type, ‘other’ is estimated to receive no recharge. SKM (2013b) notes that the origin of the adopted recharge rates is not evident in the documentation.

A selection of hydrographs from OW monitoring bores across the study area and spanning several decades is presented in Figure 2.11. There are no clear and consistent long-term trends in the hydrographs. The relatively stable long term groundwater levels suggest that the groundwater system is effectively in equilibrium with the driving climatic stresses through the period of monitoring. Accordingly it can be concluded that the system has either already adjusted to changed land use and associated changes in recharge in affected areas, or the change is hydrogeologically insignificant.

Comparison of heads in the Shepparton Formation and LPS (Figure 2.11) demonstrates a small upward gradient at sites away from the rivers. This would tend to suggest that, away from the rivers, groundwater is moving upward. If this is the case then rainfall recharge cannot be significant, otherwise a downward gradient would be observed, and it is likely evapotranspiration is intercepting seepage of rainfall before it reaches the water table.



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Regional hydrographs

Figure 2.11

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Water level time series\Rev2\WB water level time series.mxd

2.6.2 Surface water interaction

The Murrumbidgee River flows into the study area from the east, not far west of the point at which the Lachlan River flows, when sufficient water is delivered from upstream, into the Murrumbidgee (see Figure 2.12). The Murrumbidgee River flows south-west towards Balranald then onward in a predominantly westward direction to its confluence with the Murray River. From this union, the Murray River flows westward and out of the study area.

Whilst weirs are present in the study area, their heights are small and therefore the impacts of man-made structures on river stage are relatively minor. Average water levels at river gauges on the Murrumbidgee and Murray Rivers are indicated in Figure 2.12. These demonstrate a drop of approximately 10 m from where the Murrumbidgee enters the study area in the east (~66 m AHD) to Balranald (~56 m AHD) in the centre of study area, then a further drop of approximately 9 m to where the Murray exits the western edge of the study area near Robinvale (47.7 m AHD). In total this represents a difference in river stage of less than 19 m over the 90 km from east to west across the study area. Meanders along the flow path and a southward component to the overall flow direction in the study area make the actual river flow path much longer than 90 km within this area.

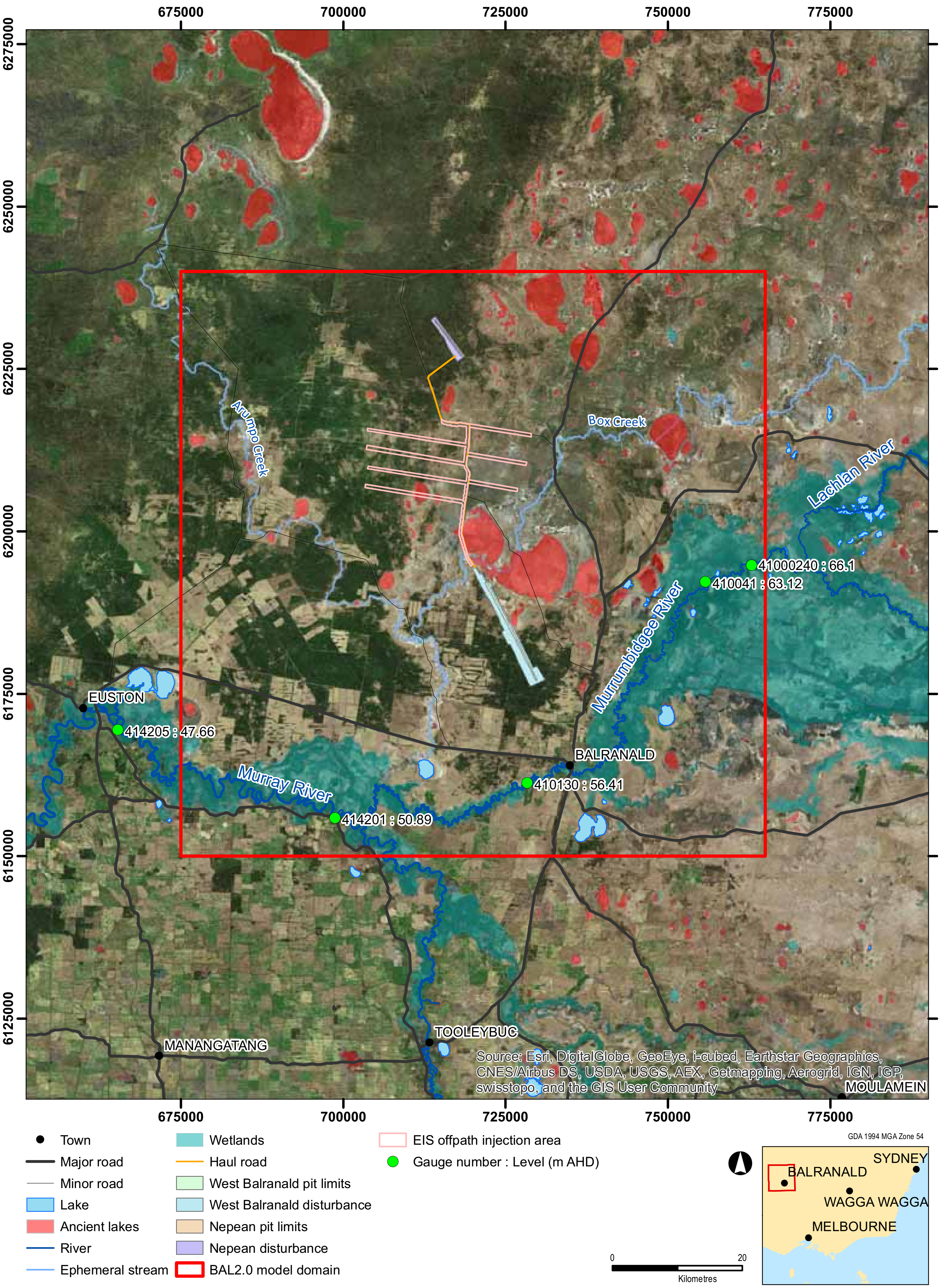
Monitoring wells in the Shepparton Formation suggest the river stage in the Murrumbidgee and Murray Rivers is higher than the regional water table and, hence, there is potential for the rivers to be primarily losing in the study area. The distribution of hydraulic heads in the Shepparton Formation and LPS are consistent with a losing river system, with elevated groundwater levels in the vicinity of the Murrumbidgee and Murray Rivers. Groundwater monitoring at GW036868, located near the Murrumbidgee River, demonstrates a downward gradient from the Shepparton Formation to the LPS (Figure 2.11). However, given that across the majority of the study area the gradient is reversed, this suggests that, near the Murrumbidgee River, the water table in the Shepparton Formation is likely elevated by seepage from the river. The conceptualisation of a river that is primarily losing is supported by the salinity distribution presented by Kellett (1994), in which a region of lower groundwater salinity surrounds the river channel. The potentiometric surface of the Olney Formation[1] does not display evidence of the impacts of surface water interaction seen in the shallower units. Figure 2.13 illustrates the conceptual hydrogeology from the Murrumbidgee River northward to the southern end of the West Balranald deposit.

A series of lagoons and wetlands are located along corridors flanking the Murrumbidgee and Murray Rivers (Figure 2.12). It is possible that some discharge of groundwater occurs into these features. Overbank flow may also feed water bodies near the rivers.

A number of ancient lakes are evident in the topography of the study area, mostly north of the Murrumbidgee River (Figure 2.12). The larger of these measure up to approximately 10 km across. Typically the ancient lakes have topography ranging between 5 m and 10 m below the nearby surrounding region. Several of these, including Tin Tin Lake, Pitarpunga Lake, Muckee Lake, Macommon Lake and Dundomallee Lake, are located close to the West Balranald deposit. The low topography at these sites, combined with apparent surface salinisation at several sites, suggest that many of the ancient lakes are likely to be localised groundwater discharge features experiencing evaporative losses from the water table, or areas of relatively low permeability where the salinity of water that ponds increases in response to evaporation.

Two ephemeral watercourses traverse the study area. Box Creek enters from the east, north of the Murrumbidgee River. Its path heads south-west, crossing the proposed haul road just north of the West Balranald deposit. It continues south-west until it meets Arumpo Creek, which traverses south-south-east from the north-west corner of the study area. From its convergence with Arumpo Creek, Box Creek continues almost due south to Dry Lake and then Waldaira Lake before terminating at the Murrumbidgee River.

[1] The term Olney Formation is used here to delineate the Renmark Group sediments present in the area. It is also used in preference to the Renmark Group aquifer subdivision of Kellett (1989). As a term it does not differentiate between the Upper, Middle and Lower Renmark Group aquifer units.



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Surface water features

Figure 2.12

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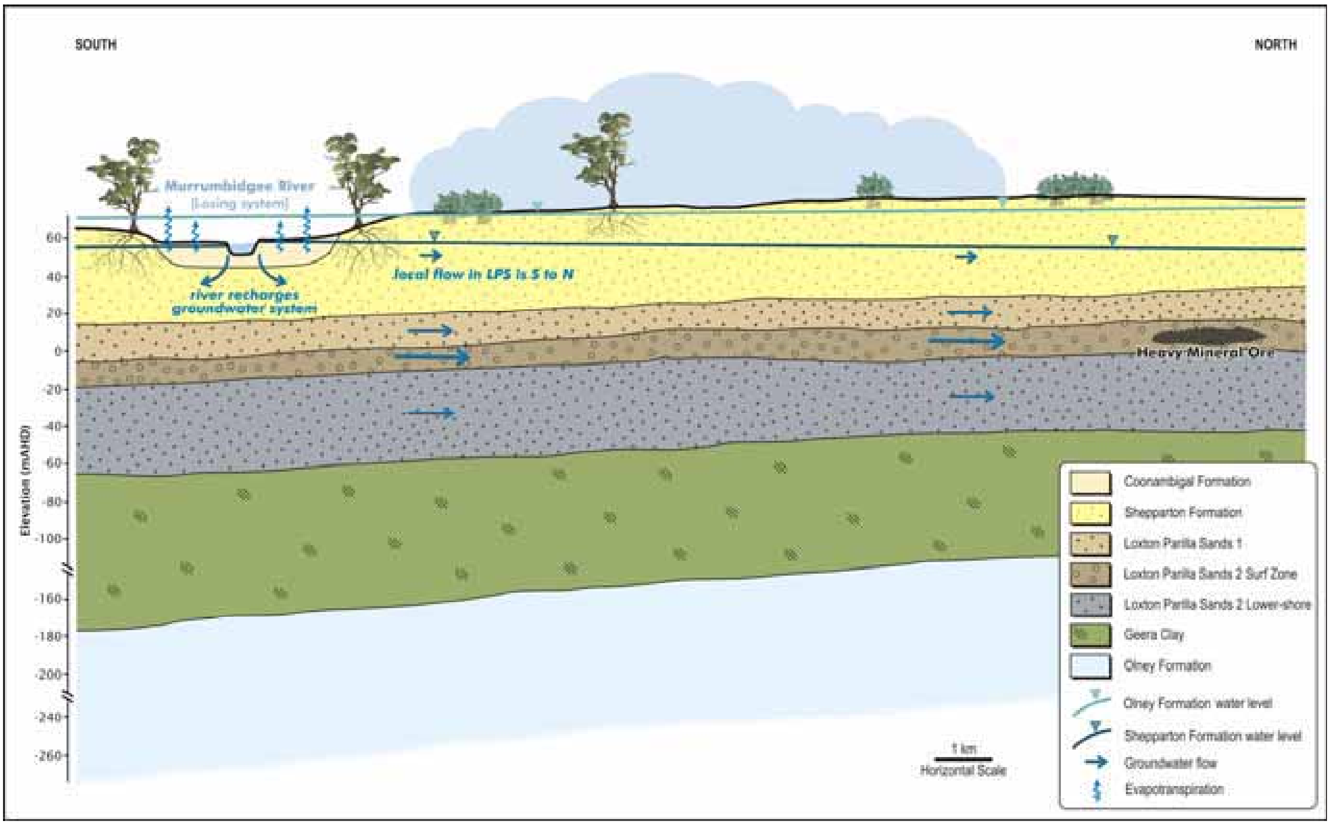


Figure 2.13 : Conceptual hydrogeology from the Murrumbidgee River to the southern end of the West Balranald deposit

2.6.3 Groundwater use

Available data suggest groundwater in the Shepparton Formation and LPS is too saline to be targeted as a source of domestic or stock water within several kilometres of the deposits. In fact the OW groundwater database has no registered wells in the LPS in the study area. Brackish groundwater in the Olney Formation is of much lower salinity and is accessed by a number of pastoral wells for stock water supply. Iluka has identified artesian conditions in two Olney Formation wells located near the West Balranald deposit.

There is currently no known licensed injection of water into the groundwater system within the study area.

2.6.4 Regional throughflow

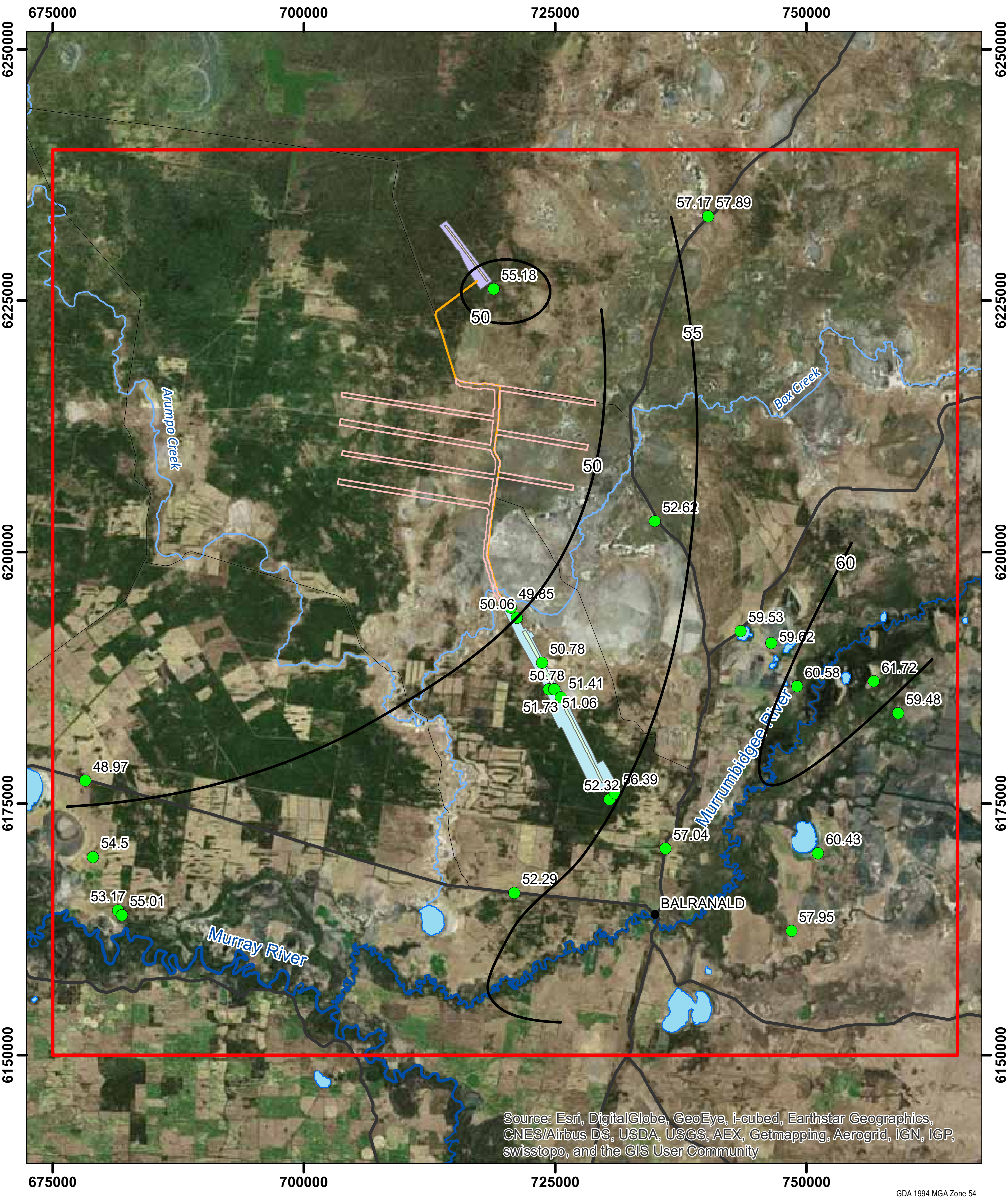
Kellett (1991 and 1994) presented potentiometric surfaces and flow lines for the major aquifers on a regional scale. Broadly, groundwater flows from east to west across the study area. Contouring of regional hydraulic head data currently available (as illustrated in Figure 2.14 to Figure 2.16) produces flow nets similar to those presented by Kellett (1991 and 1994).

Figure 2.14 to Figure 2.16 present conceptual present day, pre-development, potentiometric surfaces for the Shepparton Formation, LPS and Olney Formation. In all three units groundwater exits the study area to the west with a component of flow curving northward towards the north-western corner of the study area. In the shallow aquifers, a component of this northward flow may be attributed to leakage from the Murrumbidgee and Murray Rivers. However, given this flow is evident in the much deeper Olney Formation, it appears that basement structural features are probably the primary cause. The apparently thick and highly permeable LPS surf zones that exist north of the West Balranald deposit may also influence groundwater movement regionally (Iluka, 2015). The north-south aligned Tyrell Fault is located approximately 10 km west of the study area. To the west of the fault the basement rock is displaced upward by up to 200 m. The overlying sedimentary units thin across the fault and, hence, the regional westward flow evident east of the fault cannot continue across the plane of the fault in the same manner. Whilst some groundwater flows up over the fault, some heads further north, to where the basement displacement over the fault is less pronounced. Similar effects can be seen near the elevated basement of the Iona Ridge where aquifers become discontinuous and horizontal groundwater movement is constrained.

In the Shepparton Formation and, to a lesser extent, the LPS, the Murrumbidgee and Murray Rivers appear to cause local elevation in groundwater levels. This suggests groundwater is being recharged by leakage from the rivers and is consistent with the current understanding that these rivers are predominantly losing within the study area. Groundwater in the Olney Formation appears not to be affected by surface water interaction.

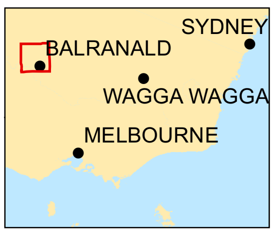
It should be noted that groundwater density differences associated with variable groundwater salinity may play a role in groundwater flow. Hydrochemistry is discussed in more detail later, but a broad-scale quantification of groundwater salinity is provided here to highlight the potential for it to impact groundwater flow. Groundwater salinity in the Shepparton Formation and LPS is typically in the range of 20,000 mg/L to 30,000 mg/L, similar to sea water, with some areas recording salinity up to around 50,000 mg/L. Groundwater in the Geera Clay is hypersaline and approaches five to ten times that of seawater. Groundwater in the Olney Formation has much lower salinity than in the shallow aquifers and typically a salinity of 3,000 mg/L to 5,000 mg/L may be encountered. These broad-scale indicative salinity values suggest that heads derived from depth to water measurements in the Shepparton Formation and LPS may, in fact, represent much higher equivalent fresh water heads.

Whilst the magnitude of density corrections may be higher in the Geera Clay, the very low hydraulic conductivity of this unit means that groundwater flow would be restricted to minor volumes that are insignificant when compared to flows in the aquifer units. Whilst density corrections can be carried out to correct horizontal or vertical flow directions and magnitudes, there is no way to correct variable-density head measurements in multiple aquifers in three dimensions as would be required for calibration of three-dimensional numerical groundwater models. Hence, this study deals with raw, uncorrected heads. Due to the relative homogeneity in groundwater salinity within hydrostratigraphic units, it is likely that density does not have a significant impact on horizontal groundwater flows.



Town
Major road
Minor Road
Lake
River
Watercourse
Haul road
West Balranald pit limits
West Balranald disturbance
Nepean pit limits
Nepean disturbance
BAL2.0 model domain
EIS offpath injection area
Potentiometric surface (mAHD)
Measured head (mAHD)

0 10 Kilometres



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Conceptual pre-development potentiometric surface in Shepparton Formation

Figure 2.14

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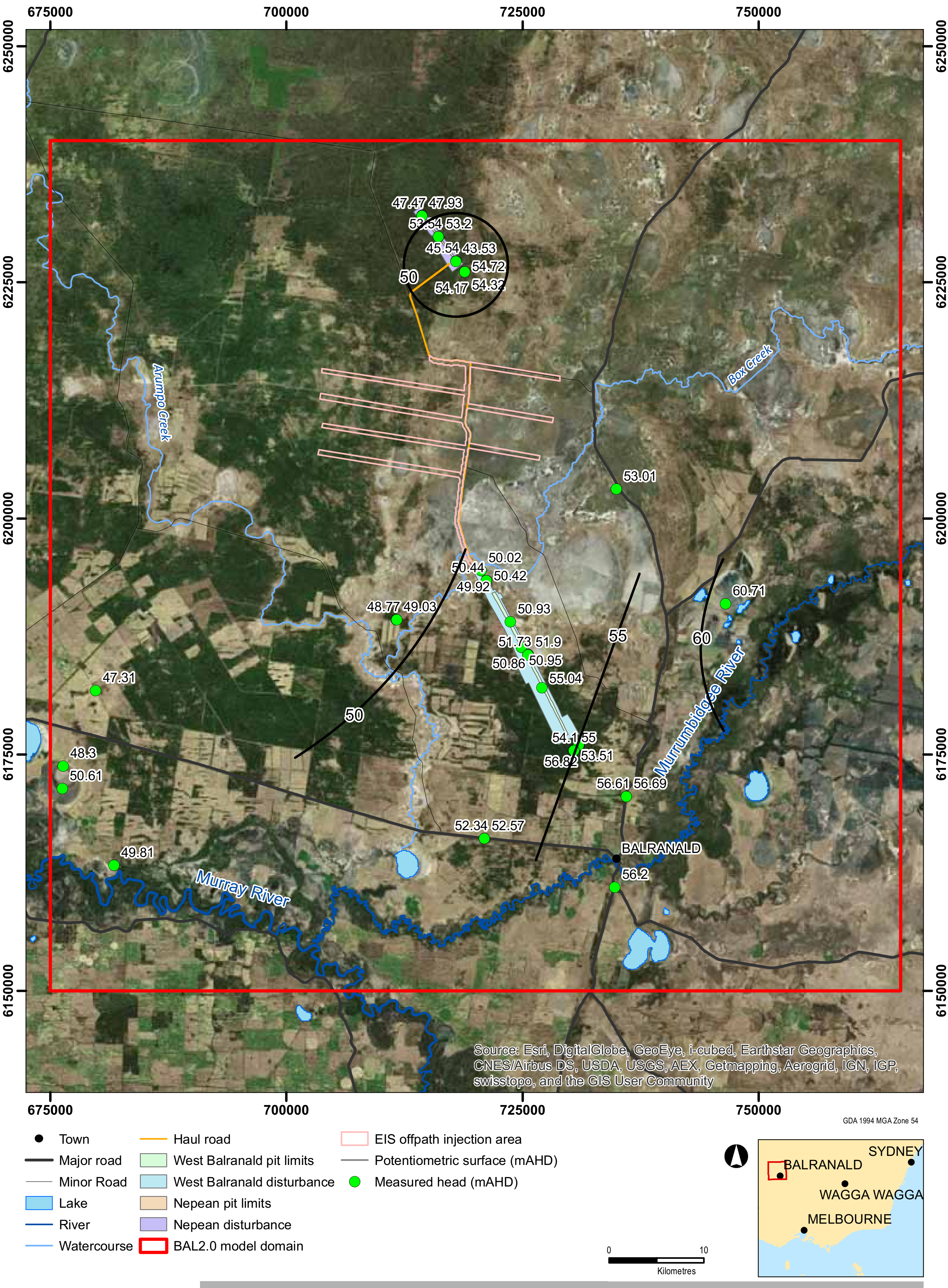

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Conceptual pre-development potentiometric surface in LPS

Figure 2.15

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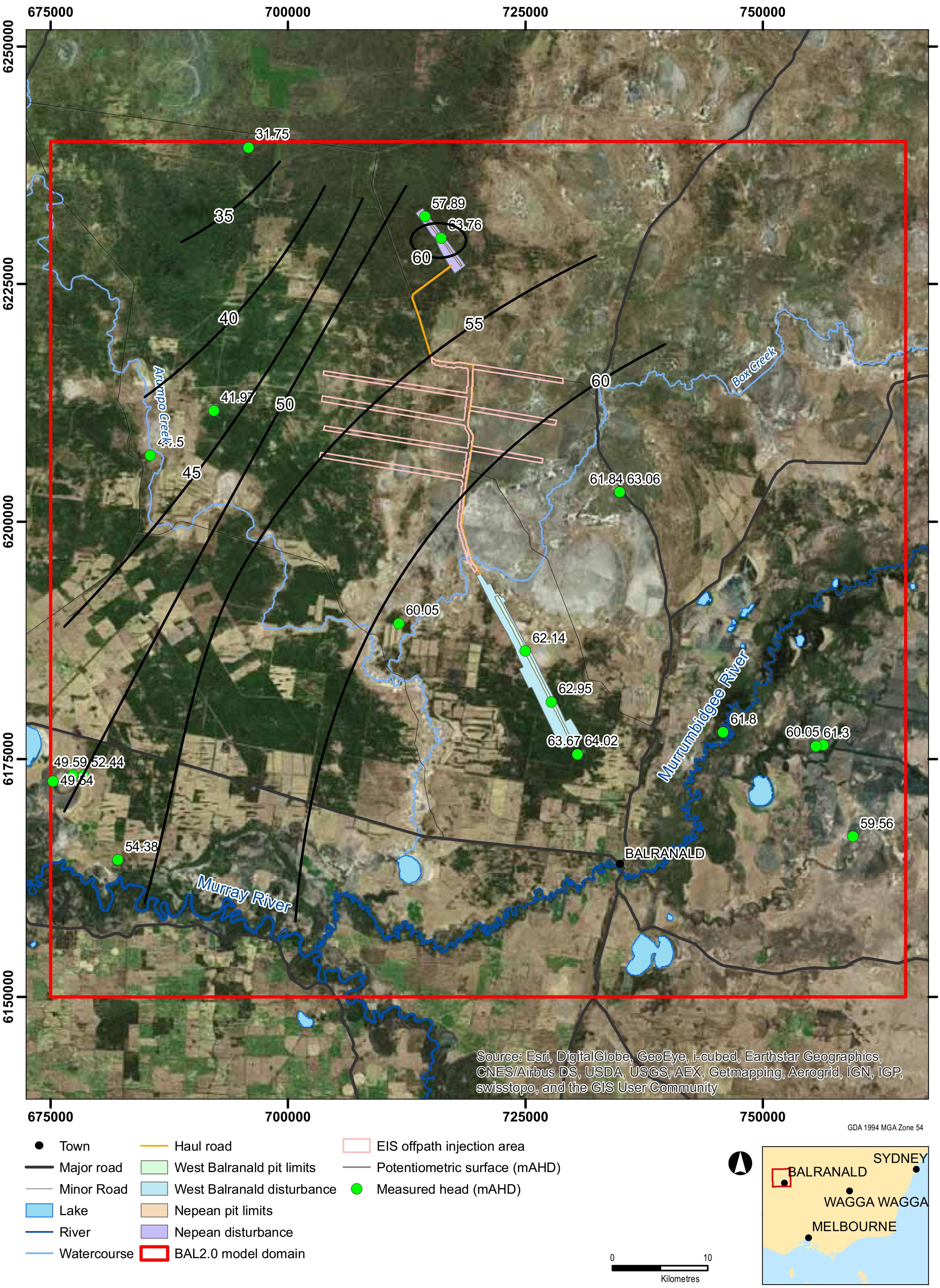

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Conceptual pre-development potentiometric surface in Olney Formation

Figure 2.16

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2.6.5 Vertical flow

URS (2012) reports a small downward gradient from the Shepparton Formation to the LPS, but hydrographs at three of the four nested sites presented in Figure 2.11 display heads slightly higher in the LPS than in the Shepparton Formation for the majority of the thirty year monitoring period. It seems likely that in areas away from the Murrumbidgee and Murray Rivers and, in particular, near ancient lakes that are thought to act predominantly as groundwater discharge features, there is an upward hydraulic gradient from the LPS to the Shepparton Formation. Along a corridor flanking the Murray and Murrumbidgee Rivers a downward gradient occurs as a result of river leakage that recharges the groundwater system and elevates the potentiometric surface in the Shepparton Formation (more so than in the LPS). Regardless of the direction of the hydraulic gradient, heads in the Shepparton Formation and LPS show very little difference at nested sites across the study area (see Figure 2.11). Although heads in the Shepparton Formation and LPS are very similar, results of pumping and injection trials indicate that the two units are poorly connected (Iluka, 2015) and that significant head differences may be created when water is extracted from or injected into one or other of these units.

Hydraulic heads in the Olney Formation are considerably higher than those in the Shepparton Formation and LPS. Two of the nested sites presented in Figure 2.11 monitor the Olney Formation. At these locations heads are approximately 10 m (GW036866) and 12 m (GW036673) above those in the Shepparton Formation and LPS. Kellett (1991 and 1994) indicate artesian conditions in the east of the study area and URS (2012) reports a measured head at West Balranald (WB3 P1) 3.1 m above the ground surface. Iluka have identified two artesian Olney Formation pastoral wells (HD1 and T02) in the vicinity of the West Balranald deposit.

Hydraulic head monitoring data suggest an upward hydraulic gradient from the Olney Formation to the Shepparton Formation and LPS with the Geera Clay preventing the artesian pressures in the Olney Formation from equilibrating with the shallower units. However, the aforementioned salinity distributions may impact this relationship to a degree. Given the groundwater in the Olney Formation is brackish, equivalent fresh water heads would differ little from their uncorrected values. The high salinity present in the Shepparton Formation and LPS would result in elevated equivalent fresh water heads in these units relative to their uncorrected values. This would reduce the apparent upward gradient and, perhaps, in areas where the uncorrected head gradient is smallest, even nullify or reverse it.

2.7 Hydrogeochemistry

Hydrogeochemistry has been applied to help constrain relationships between groundwaters in different formations and ascribe relevant processes to groundwater evolution. The geochemistry of the West Balranald and Nepean deposits and surrounding region is described in detail by Jacobs (2014). The following paragraphs provide a summary of key elements of the groundwater geochemistry as it relates to the development of the hydrogeological conceptualisation that forms the basis of the numerical groundwater flow model. Chemical data for local rainfall and surface water is also included for reference purposes.

2.7.1 Hydrochemistry datasets

To develop a conceptual understanding regarding the geochemical characteristics of groundwater found at the Project site, groundwater chemistry data was collected from the following sources:

- Results of a hydrocensus conducted by URS (2011);
- Hydrogeological information collected during Iluka’s feasibility studies (URS, 2012 and Iluka, 2015);
- New environmental tracer methods for quantifying solute sources in semi-arid alluvial aquifers (Horner, 2012); and
- Balranald Project soil-water-plant investigations (SKM, 2013d).

A total of 227 groundwater bores were identified in a 10,000 km^2 region around the Project that corresponds to the region modelled by SKM (2013a). 1,157 separate samples were analysed for at least salinity; 1,010 include pH; 869 have an electrical conductivity determination and 378 have major cation analyses. Unfortunately, only 192 have full anion analyses; metals are analysed variably in about 175 samples and only 69 have nutrient/organic values. Further, only 191 bores of the 227 identified bores contained aquifer/formation information that allowed distinction of which geological formation the bores screened. Basic quality assurance checks revealed that the geochemical data attributed to these bores varied significantly in quality and quantity, though time series from 153 bores helps constrain analyte variability.

Due to the inclusion of government-owned monitoring wells, many of which were drilled during hydrogeological studies in the 1980s, the dataset's date range is significantly broad. As the majority of data have been collected from 2011 to present, corresponding with the commencement of Iluka's investigative groundwater studies, the hydrogeochemical characterisation has been subsequently constrained to this date range.

Figure 2.17 presents the locations of the bores with accurate source formation information and Table 2.8 presents the number of installations within the geological formations. A subjective assessment is made of the quality and quantity of geochemical data available for each geological formation. Labelling in Figure 2.17 refers to current database assignments. Using the convention of this report, the Upper Renmark is equivalent to LPS2; Lower Renmark is equivalent to the Olney Formation; screen information referred to as "Renmark" relates specifically to government-owned wells and either have unknown screen intervals or are regional bores with questioned stratigraphy.

Table 2.8 : Groundwater bore installations within the study area

Geological formation	Number of locations *	Geochemical data quality / quantity
Shepparton Formation	51	Good
LPS1	56	Good
LPS2	53	Good
Geera Clay	6	Only salinity (EC) data
Renmark Formation	11	Limited information
Olney Formation	14	Okay
Total	191	

*Locations include discrete depths at nested bore sites

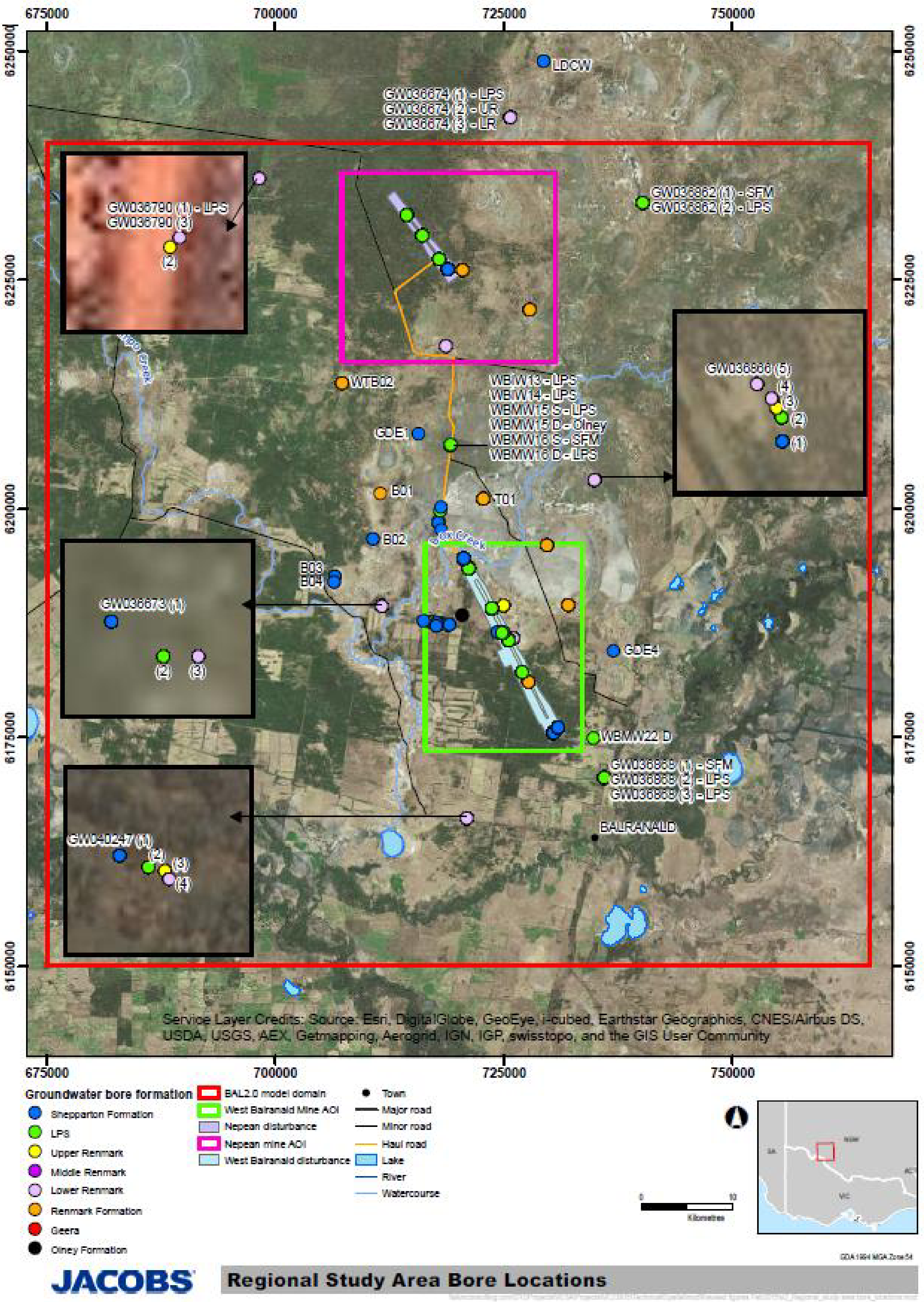


Figure 2.17 : Regional study area bore locations

2.7.2 Water types

Groundwater in the region present as sodium-chloride types with a few shallow bores consisting of mixed water types. This is illustrated in the tight cluster of data on a Piper plot (Figure 2.18) and the isolated samples from the Shepparton Formation. Within the cluster, however, the deeper (Olney Formation) samples are consistently low in sulphate and have elevated relative bicarbonate compared to other groundwaters and the LPS samples plot on tight trends between transition samples which may represent mixing trends. The observed shift to increasing calcium plus magnesium may represent increasing interaction with aquifer sediments. The shallow Shepparton Formation groundwaters also tend to have elevated sulphate compared to other groundwaters.

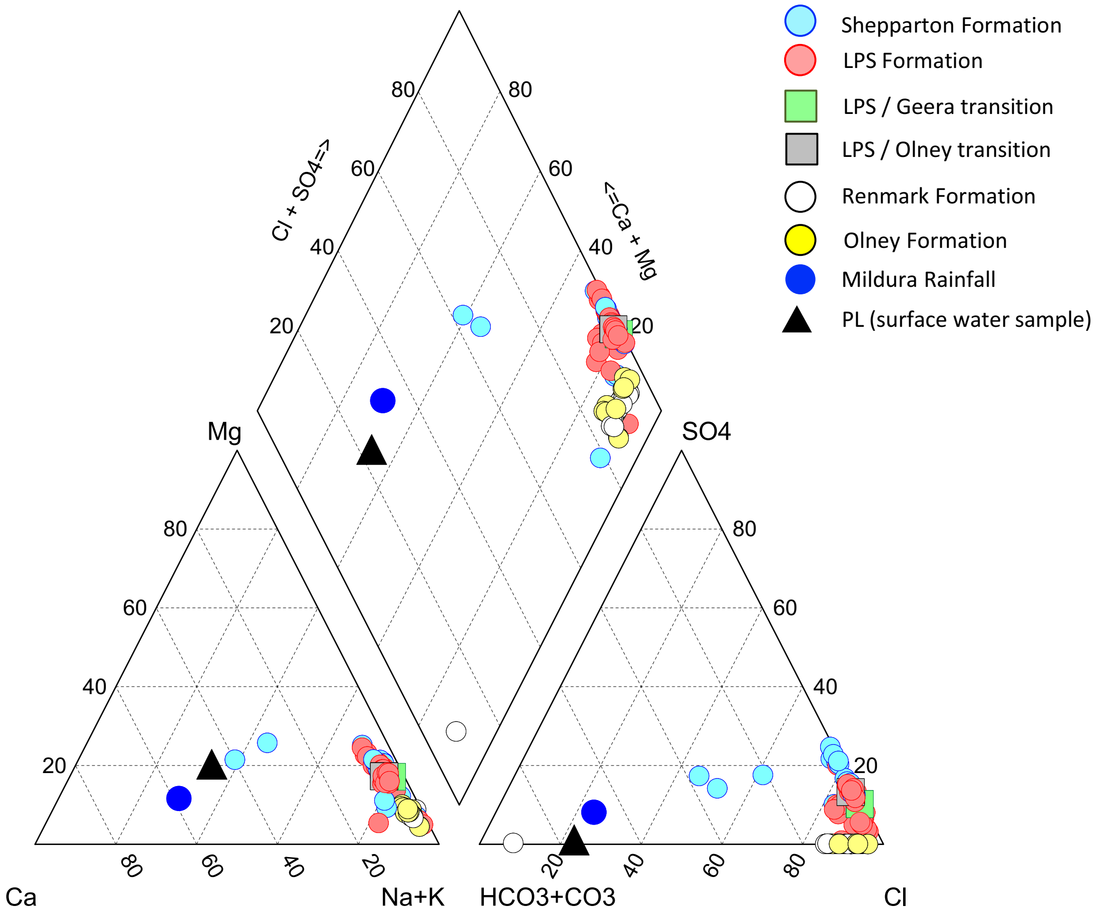


Figure 2.18 : Piper diagram for all groundwaters analysed in this study

Median weighted rainfall is plotted for comparison. The actual monthly variability in this input water source is illustrated in Figure 2.19, and suggests only a couple of shallow Shepparton Formation samples may have an indirect local rainfall source (see section 2.7.3). Almost all groundwater samples have been significantly altered from the original rainfall source and local rainfall is generally not seen as a direct input to local groundwaters, in accord with the very low recharge rates expected in the area.

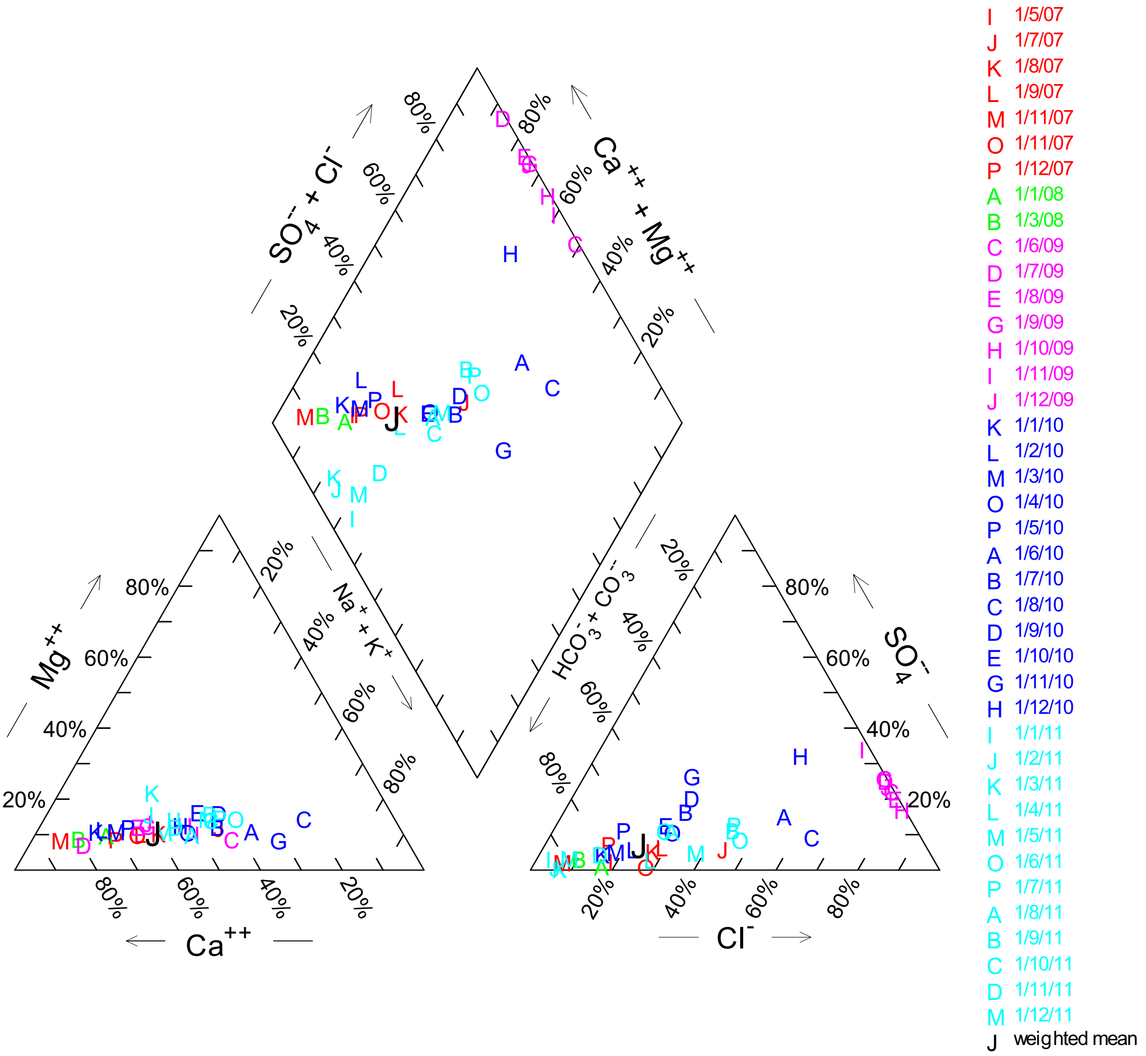


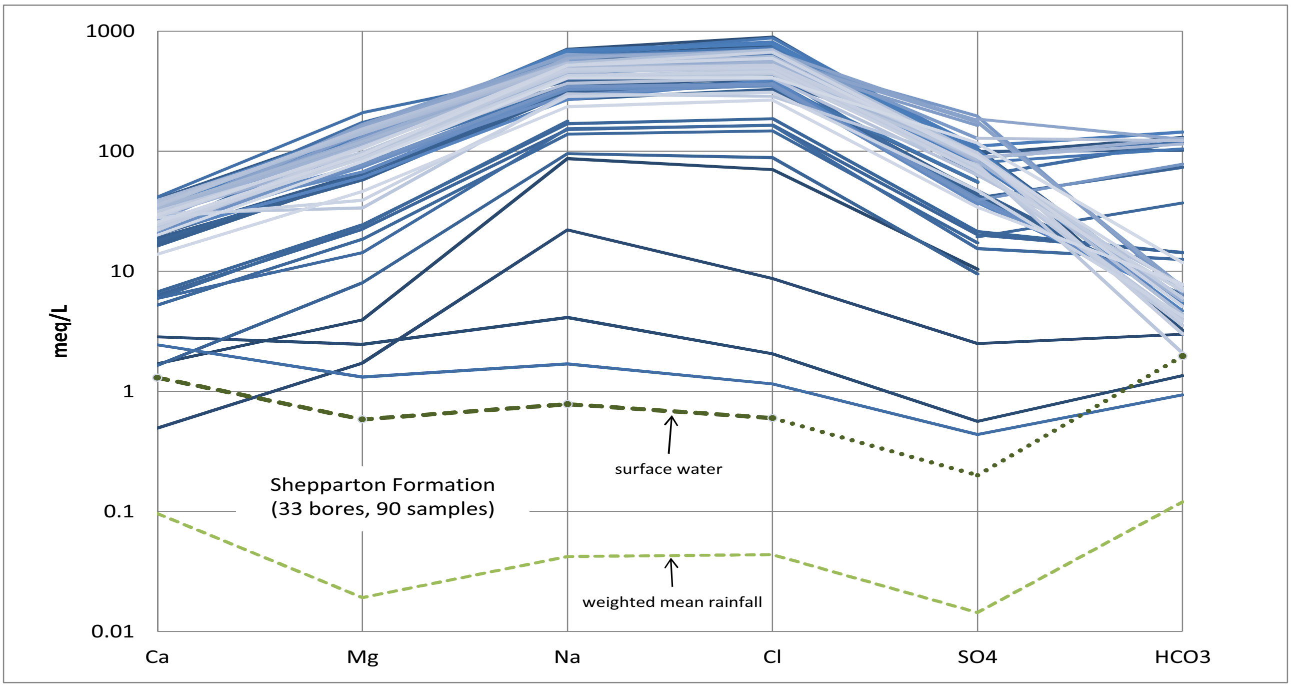
Figure 2.19 : Piper plot for rainfall chemistry at Mildura between 2007 and 2011

2.7.3 Formation characteristics

The distinction between different formation groundwaters is illustrated in a series of Schoeller plots (Figure 2.20 and Figure 2.21) which can be used to highlight formational similarities, differences and inter-dependencies.

The Shepparton Formation presents a regional groundwater composition dominated by high concentrations of sodium chloride. While other major ions (Ca, Mg, SO_4 and HCO_3) are less dominant, concentrations are generally high. Geochemical compositions range over two orders of magnitude, though lower concentrations generally correspond with wells located relatively close to the Murrumbidgee River and show an evaporated signature correlation to local surface waters, and therefore may represent diffusion of river water into this aquifer.

Samples sourced from the LPS present a regional groundwater quality signature similar to the Shepparton Formation, however some locations indicate are relatively lower ion concentration. Based on the presented datasets, spatial variability does not allow distinction between the LPS1 and LPS2, however the variability in LPS chemistry is inferred as a hydraulic relationship between the two sub-units and the overlying Shepparton Formation. The groundwater quality signature is again dominated by sodium and chloride, with high concentrations of Ca, Mg and HCO3 but with a group of distinctly lower sulphate, magnesium and calcium concentrations relative to the overlying Shepparton Formation.



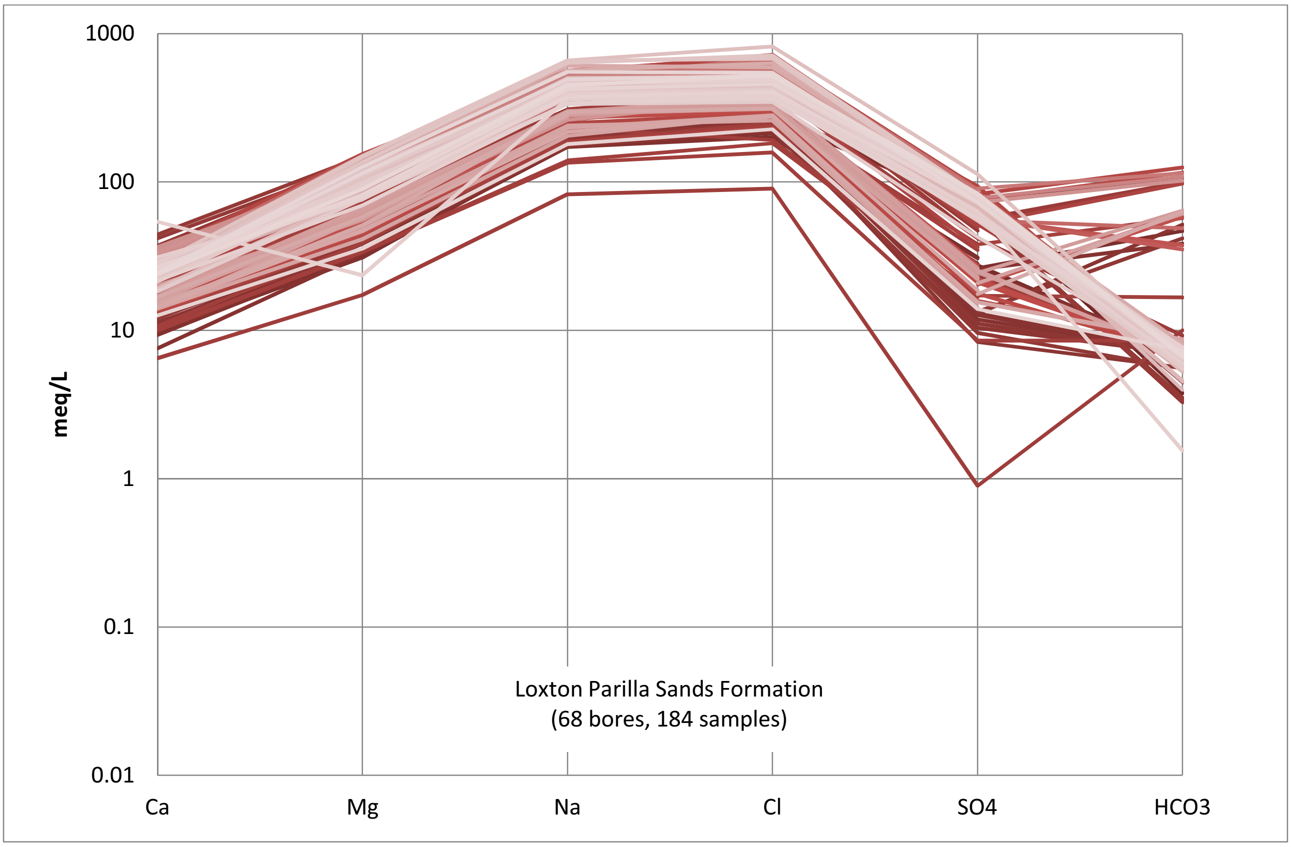


Figure 2.20 : Schoeller plots for groundwaters sourced from the Shepparton Formation and LPS

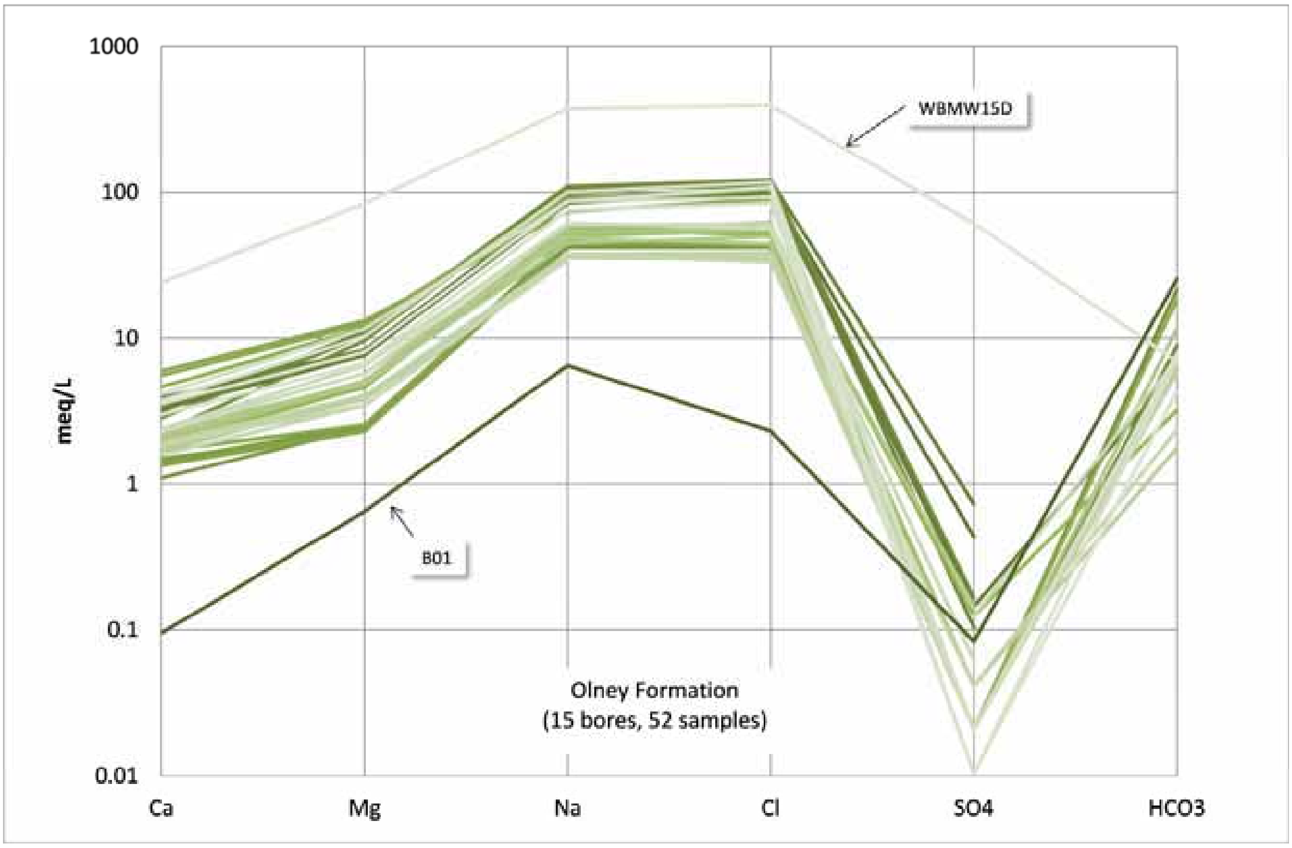


Figure 2.21 : Schoeller plots for groundwaters sourced from the Olney Formation

The Olney Formation groundwaters have the lowest salinities and their signature presents as a subdued sodium chloride-dominated groundwater composition in comparison to the overlying formations. SO_4 concentrations are particularly (and characteristically) low compared to the shallower aquifers.

There are currently no chemical analyses from the Geera Clay within the study area. Pore water samples collected from cores extracted from Geera Clay in wells drilled near Piangle in northern Victoria yielded TDS concentrations of about 200,000 mg/L (R Evans, pers. comm.) and electrical conductivity determinations in two bores in the area gave salinities of about 37,000 µS/cm.

2.7.4 Salinity considerations

Salinity relationships (Figure 2.22) show that different formations exhibit differing Electrical Conductivity (EC) readings reflecting their differing chemistries. Thus, the sodium chloride dominated LPS shows the closest agreement to the normal conversion factor of: Total Dissolved Solids (TDS) = 0.66EC. The low conversion factor for the Olney Formation samples likely results from the elevated relative bicarbonate levels for these samples which suppresses the conductivity signal, while samples with elevated sulphate result in a higher multiplier (0.7) as sulphate enhances the conductivity.

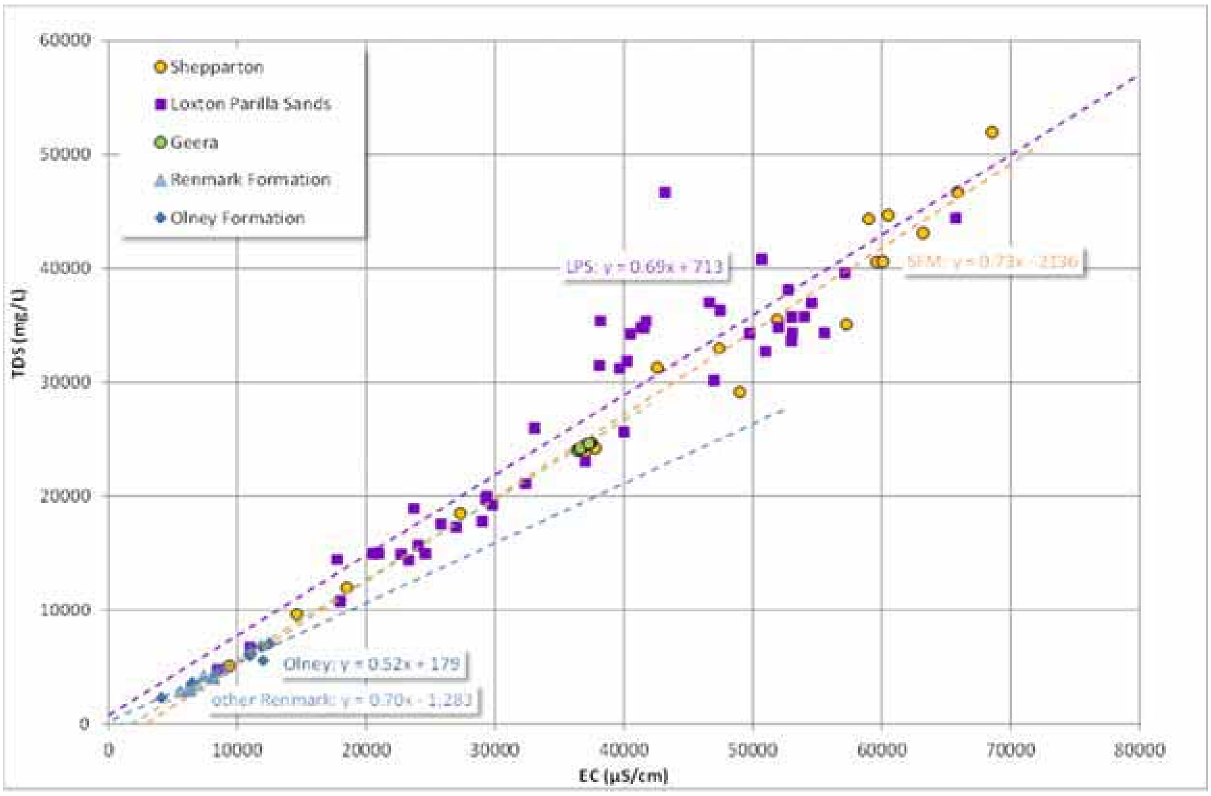


Figure 2.22 : TDS relationships for all analysed groundwater samples (*Geera samples plotted using the relationship: TDS=ECx0.66)*

Salinity relationships are instructive in assessing vertical connectivity. Two bores (GW36866 and GW40427, see Figure 2.25 for locations) include nested screens and a separation between the LPS1 and underlying units can be observed (Figure 2.23).

LPS2, however, is variably connected to over and under-lying units and this is reflected in salinity/sulphate relationships and is evident in Schoeller plot signatures (Figure 2.26). The Olney Formation, however, is confirmed to be separate from all overlying formations in the region.

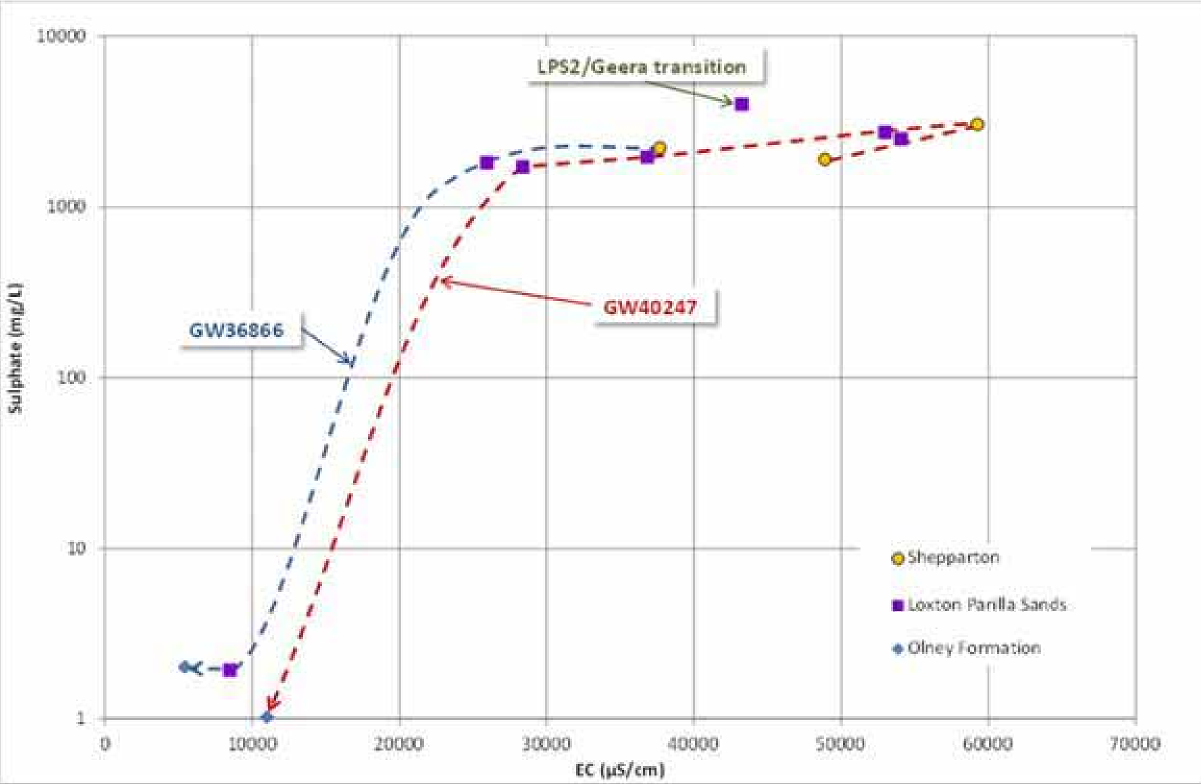


Figure 2.23 : Salinity and sulphate change with depth for bores GW36866 and GW40247

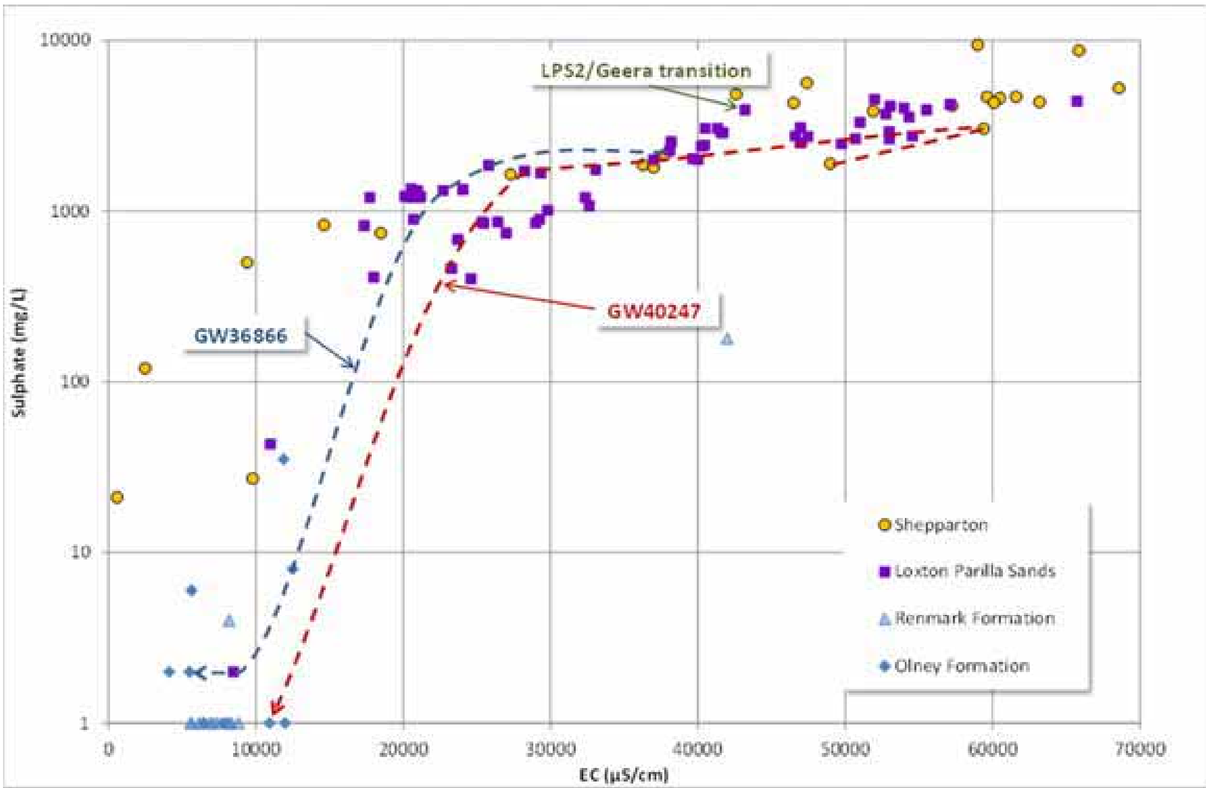


Figure 2.24 : Salinity and sulphate relationships for all bores

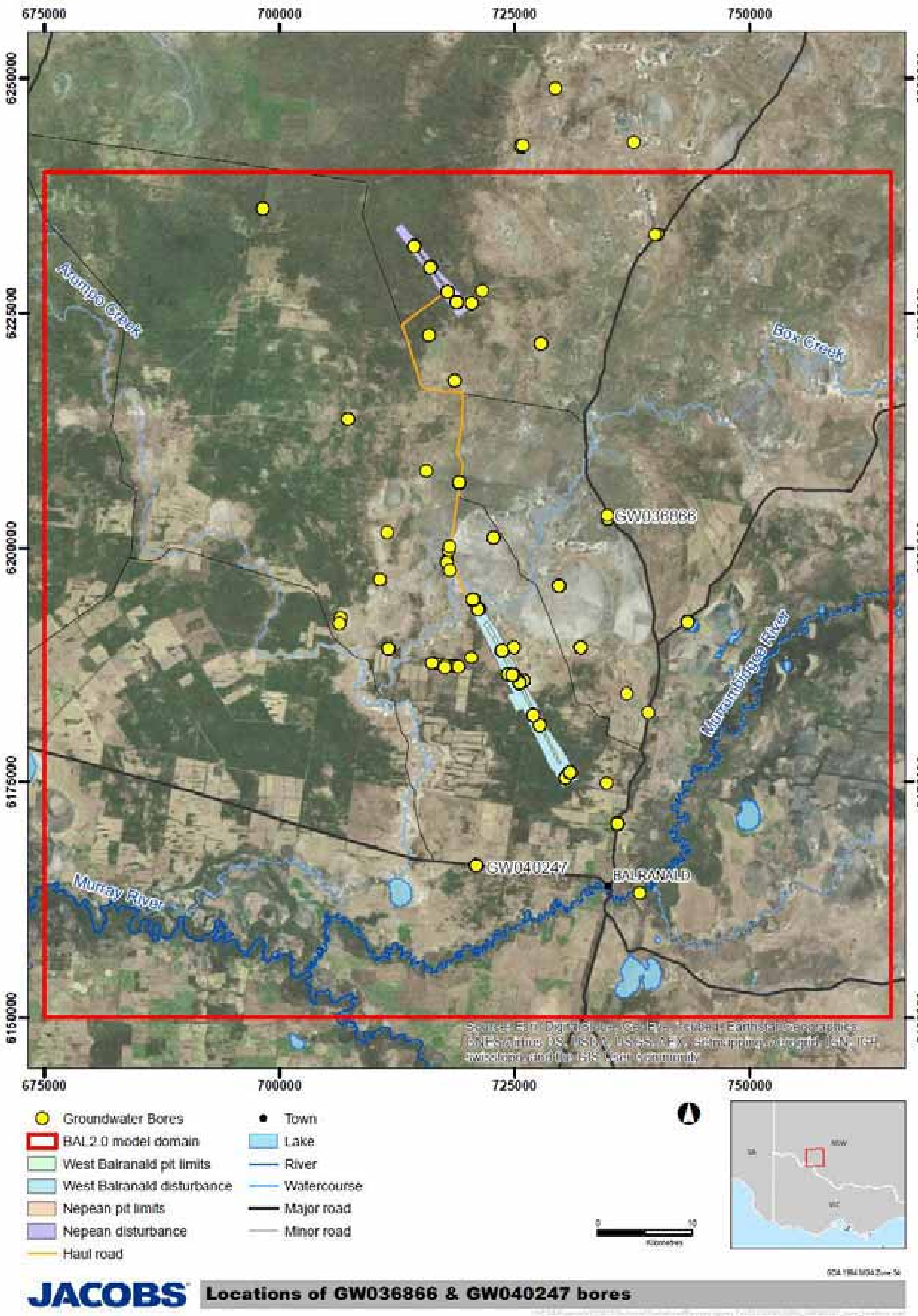


Figure 2.25 : Locations of nested bores: GW036866 and GW040247

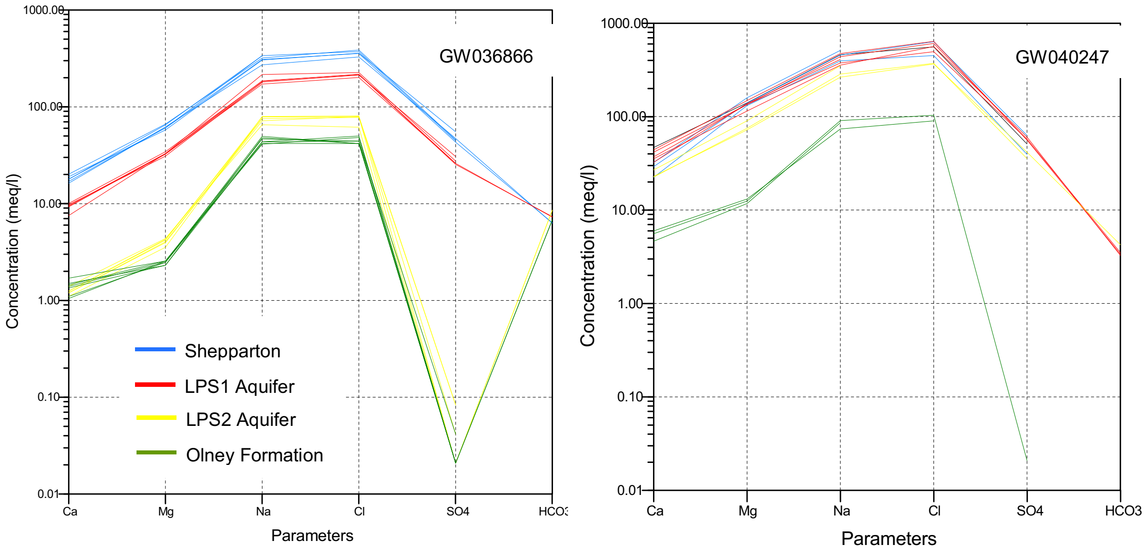


Figure 2.26 : Schoeller plots for groundwater bores GW036866 and GW040247

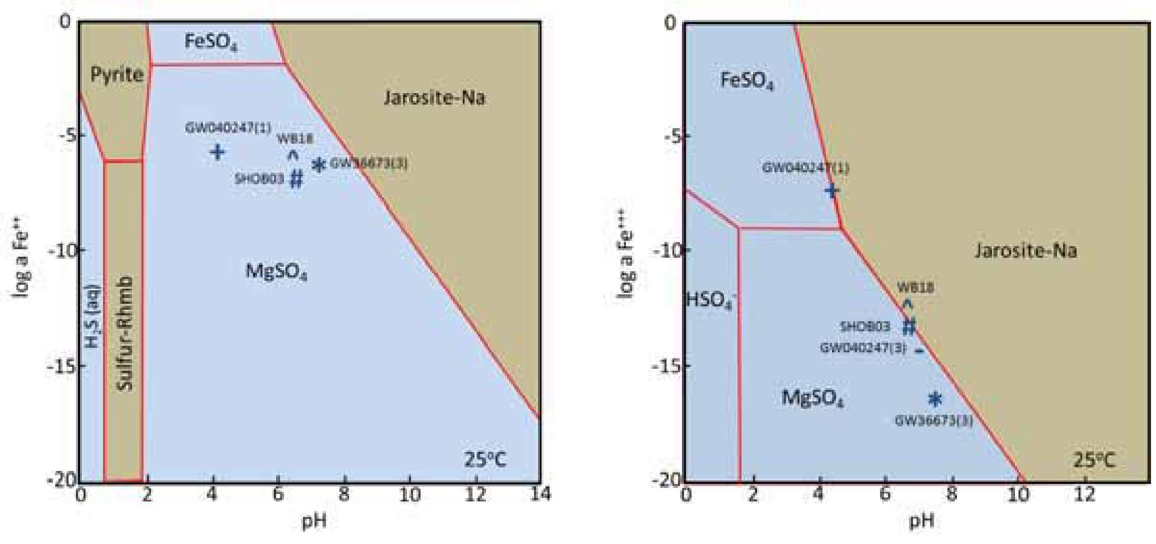
2.7.5 Injection well clogging

Elsewhere in the Murray Basin, pumping tests of wells in the LPS have exhibited rapid clogging, even where metal concentrations were initially low (Shand et al., 2006). In particular, aluminium hydroxide gels were seen to form and were thought to arise from local concentration of aluminium and precipitation due to a combination of cavitation and varying pump loads leading to stagnation of water in the injection vicinity (Shand et al., 2006). Thus, while the inherent local levels of aluminium and iron in the vicinity of West Balranald and Nepean are low, there is a potential for clogging to occur if prolonged periods of non-injection, or reverse pumping occur. The presence of organic carbon will facilitate this process and finite amounts (up to 350 ppm) have been observed in all formations, though the data set is currently small (only 18 holes currently have dissolved organic carbon data).

Varying oxidation potential (through exposure to air, for example) can lead to precipitation and dissolution of hydroxide minerals. To explore the viability of injection into the different formations, indicative sample chemistries (Table 2.9) are plotted on modified Pourbaix diagrams for reduced and oxidised conditions (Figure 2.27). As redox potential has not been measured for most samples, the traditional Pourbaix (Eh-pH) diagram is modified using the iron concentration in typical samples and assuming electron activities (pe) for reduced (pe= 2) and oxidised (pe=6) conditions. Under reduced conditions (plotted against $Fe2^{+}$) all groundwaters remain within aqueous fields. For oxidised conditions (against $Fe3^{+}$), Shepparton Formation groundwater may shift to mineralised fields, suggesting clogging would occur. As all injection is planned to target the LPS, this indicative exercise suggests clogging will not be a problem, or will be readily managed. It should be noted that the representative samples are those that contain appreciable iron. The majority of analysed groundwaters contain minimal iron (or sulphate) and are likely to be less likely to contain reactive constituents.

Table 2.9 : Indicative chemistry for samples referenced in Figure 2.27

Site	Unit	pH	HCO_3 (meq/L)	Cl (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	Fe (mg/L)
GW040247(1)	Shepparton	4.0	3.3	15,600	2900	630	90	1900	11,500	7
GW040247(3)	LPS2	7.1	4.2	13,000	1800	450	60	900	7,000	1
SHOB03	Shepparton	6.7	5.6	19,000	3800	550	50	1500	10,000	1
GW36673(3)	Olney	7.4	6.0	3700	10	75	40	100	2000	0.4
WB18	unknown	6.8	5.7	21,000	3600	550	50	1400	10,500	7



Blue field denotes aqueous species; yellow fields are minerals.

Figure 2.27 : Equilibrium fields for selected low carbonate (3 meq/L) groundwaters under reduced (ambient – left figure) and oxidised (exposed – right figure) conditions. Oxidation may thus lead to precipitation of hydroxide minerals in the shallow Shepparton Formation, but is unlikely in deeper formations

2.7.6 Summary and conceptual model

The available chemistry data confirm the importance of the Geera Clay in isolating the underlying Olney Formation from the shallower LPS and Shepparton Formation aquifers. Geochemical evidence of hydraulic separation between the Shepparton Formation and LPS aquifers is apparent in some locations but not in others, with water in the two units generally having similar hydrogeochemical signatures.

Figure 2.28 presents the refined geochemical conceptual model based on the current understanding of the available water quality data. The level of connectivity between the aquifers is considered to be controlled by the extent of clay lenses within the Shepparton Formation and the LPS and the presence of the Geera Clay. In locations where clay lenses are absent, thin or sufficiently discontinuous to allow connection between the LPS and the overlying Shepparton Formation, groundwater within the LPS is more saline, presenting geochemical composition signatures similar to that of the overlying Shepparton Formation. In areas when the clay restricts connectivity between the Shepparton and the underlying LPS geochemical signatures are more defined by formation.

The higher salinity zones of the Shepparton Formation are thought to arise through evaporative concentration of salts in recharge zones which are mobilised during recharge events. The processes of cyclical precipitation and evaporation are considered to be the primary source of salinisation of the regions aquifers, and this is a common process across the Murray Basin (Horner, 2012).

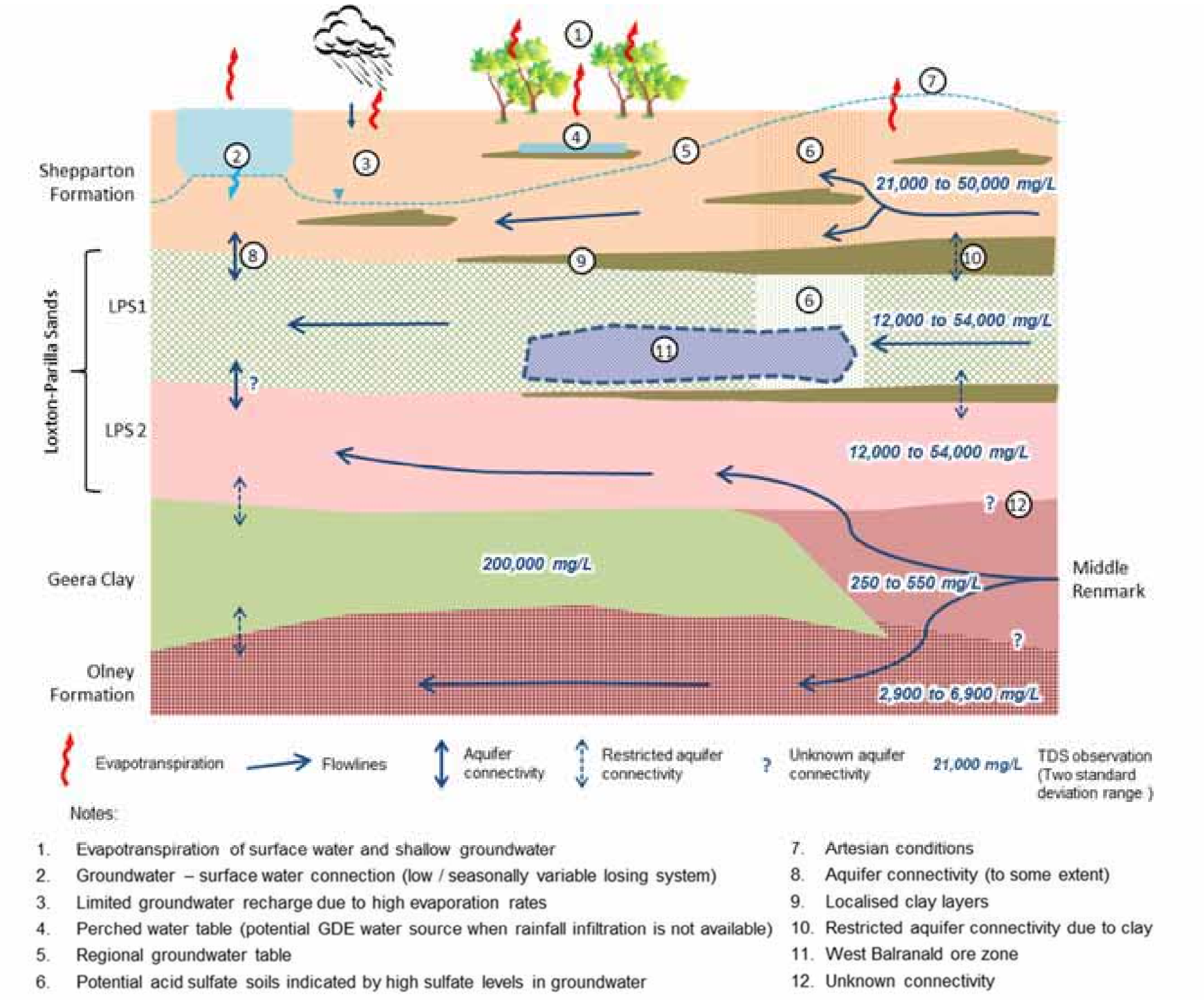


Figure 2.28 : Hydrogeochemically-constrained conceptual hydrogeological model

2.8 Future conditions

The Australian Groundwater Modelling Guidelines (Barnett et al., 2012) state that conceptualisation of the hydrogeological system should not only cover past and current states, but the anticipated future states of interest to the study. Anticipated changes to the hydrogeological system are outlined below.

2.8.1 Hydrostratigraphy and aquifer properties

On a regional scale the current hydrostratigraphy and associated aquifer properties are not expected to change. However, along the West Balranald and Nepean mine paths the Shepparton Formation and the LPS will be excavated to the base of the ore body and backfilled following mining. Backfilling will return mixed overburden sediments to the mining voids. The hydrogeological properties of the back filled material are likely to reflect its mixed origins.

The porosity and associated specific yield of backfill material is expected to be elevated from current levels. Backfill will be compacted to some degree, but not with the specific aim of replicating pre-mining porosity and specific yield properties.

Along the mine paths, where the degree of stratification is reduced by the mining and backfilling process, it is expected that post-mining hydraulic conductivity will differ from current conditions. Generally, it is expected that, due to the reduction in stratification, vertical hydraulic conductivity will increase. Under such conditions localised perched low salinity water tables are less likely to occur with recharge more readily percolating down to the regional water table.

Iluka plan to isolate the top 5 m of non-saline overburden and replace it during the rehabilitation process. Given this material is currently, and will be replaced, above the water table it is not expected to significantly alter the hydrogeological system.

In the event that the earthworks dissect major water courses there will be a potential for increased groundwater recharge through the rehabilitated ground surface. This impact can be mitigated by appropriate compaction of sediments within the water course.

2.8.2 Groundwater flow

There is an expectation that significant dewatering of the LPS will be required to enable dry mining, particularly at West Balranald. Iluka plans to inject this water both along the mine path and in an off-path injection wellfield.

Dewatering is expected to create local low points in the potentiometric surfaces of the Shepparton Formation and LPS. The drawdown associated with dewatering is expected to be sufficient to cause regional groundwater flow towards the West Balranald and Nepean sites. Dewatering is expected to have little, if any, impact in the Olney Formation due to the presence of the Geera Clay aquitard between it and the dewatering operations in the shallow aquifers. Figure 2.29 presents a conceptualisation of the region from the Murrumbidgee to the southern end of the West Balranald deposit during mining. An equivalent pre-mining conceptualisation is presented in Figure 2.13.

Injection of groundwater from dewatering operations into the LPS is expected to create a large area of elevated hydraulic head around the footprint of the off-path injection wellfield. Given that the off-path wellfield is expected to operate for several years, it is likely that some mounding of groundwater will occur in the overlying Shepparton Formation but, due to the presence and thickness of the Geera Clay aquitard, little or no impact is expected in the Olney Formation.

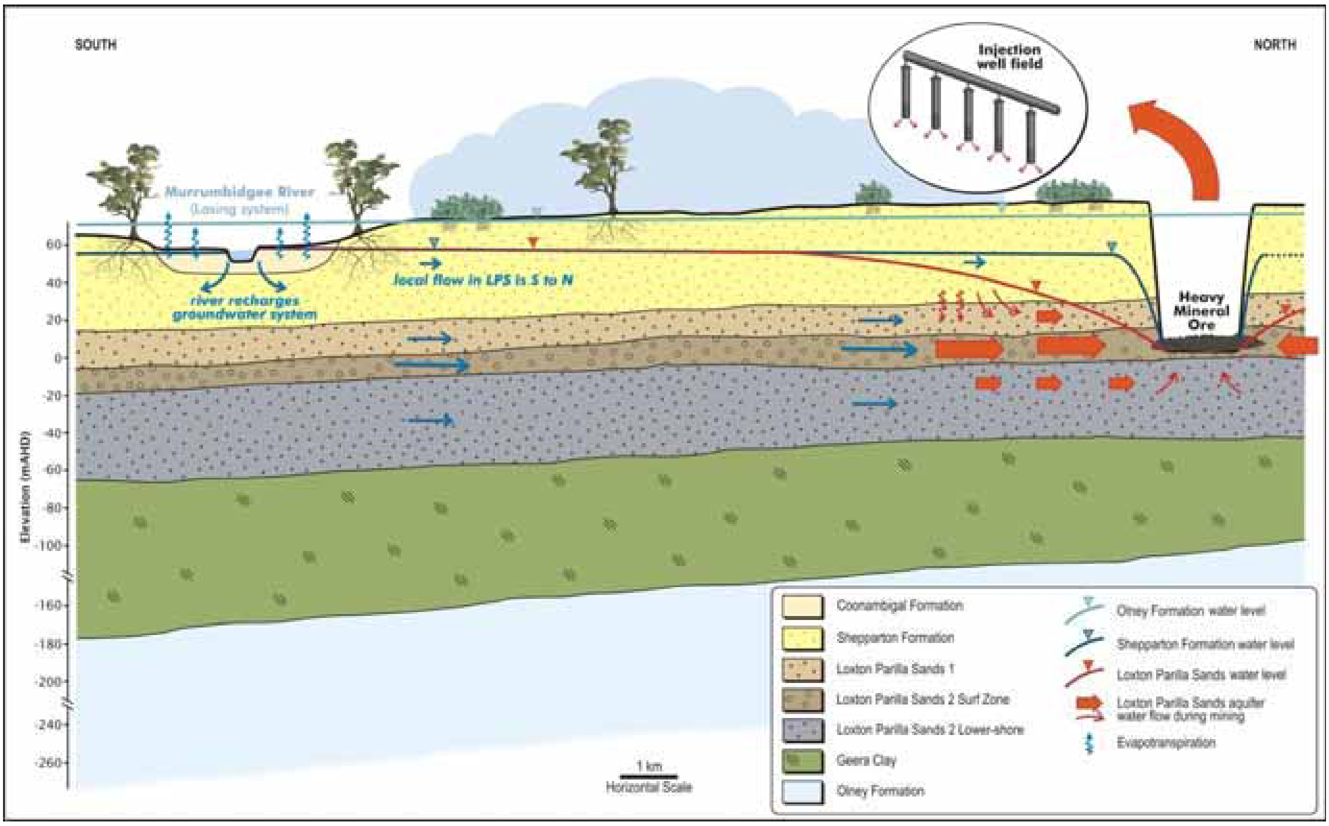


Figure 2.29 : Conceptual hydrogeology from the Murrumbidgee River to the southern end of the West Balranald deposit, during mining

2.8.3 Hydrogeochemistry

Dewatering and injection of groundwater at the West Balranald and Nepean deposits have the potential to affect groundwater quality. The geochemistry of groundwater at the site has been investigated by Earth Systems (2015). This work includes a detailed assessment of the potential water quality related problems and issues that may arise from the planned mining and groundwater management activities.

Injection of groundwater can cause clogging of wells via precipitation of gels. Borehole clogging is a common issue with injection operations due to aeration and mixing of water types. However, a preliminary analysis of groundwater chemistry suggests that, provided injection wells are screened in the LPS only, clogging will not be a problem, or will be readily managed.

The Olney Formation appears to be largely disconnected from the shallower formations. This is attributed to the presence of the Geera Clay, the presence of which has been confirmed along the entire West Balranald deposit and along the proposed haul road towards Nepean.

3. Model Design

3.1 Confidence level classification

The Confidence Level Classification is a cornerstone of the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). It is used to indicate the reliability of model predictions and is based on a number of criteria related to the available data with which the model is conceptualised and calibrated, the manner and accuracy of calibration and the manner in which the predictions are formulated. The Guidelines provide advice as to the model confidence level class that are suitable (there are three classes of model defined) for different types of modelling investigation and different types of hydrogeological settings. For the Environmental Impact Assessment of the Balranald Project a Class 2 Classification is considered appropriate. Accordingly the model aims to achieve this confidence level. A Class 2 model has a sound conceptual hydrogeological model based on a good compilation of data to describe the hydrostratigraphy, recharge and discharge features and groundwater flow directions. It is typically well calibrated but with stresses smaller in magnitude and/or duration than those the model will be used to simulate in predictions. It will often be calibrated only to measured hydraulic head data and not to measured groundwater flows and/or chemistry.

Calibration data are available in the form of regional and local hydraulic heads as well as local head and drawdown data during small and medium scale (compared to the stresses in predictions) aquifer pumping and injection tests. The dewatering rates necessary for a dry pit are expected to be sensitive to the specific yield (Sy) of the LPS. Current data available for calibration do not provide insight into this key hydraulic property and, hence, a value has been adopted based on other Iluka models developed in similar environments in northern Victoria.

Flow data are not available to quantify regional groundwater fluxes including surface water-groundwater interaction. There is not a great deal of knowledge regarding the interaction between the Murrumbidgee and Murray Rivers and the groundwater system in the study area, except for the understanding that the river is generally losing in the vicinity of Balranald. This limits the model’s ability to represent spatially detailed surface-groundwater interaction, although it is expected that the model provides a good regional-scale representation of the overall interaction between the rivers and the groundwater system.

Whilst BOM (2014) provides monitoring data for rainfall and evaporation, the spatial distribution of these across varying landuse types, and the components of these that impact groundwater, are not measured directly. Some studies (Allison and Hughes, 1983; Budd et al., 1990; SKM 2013b) do provide estimates of groundwater recharge but, because these are point-based estimates, they provide a guide rather than a quantity that can be used as a rigid input to a regional numerical groundwater flow model. However, recharge and groundwater evapotranspiration fluxes within the mining area are expected to be relatively small in comparison to the dewatering and reinjection requirements of the Project and, hence, the inability to accurately quantify these processes is not deemed to be a significant weakness in the model.

Key features of the available data, calibration approach and the predictions that limit the modelling from attaining a higher (Class 3) confidence level classification include:

- Length of predictions (years) is significantly longer than the length of calibration (weeks);
- Level of stresses in predictions (hundreds of L/s) is significantly higher than those in calibration (tens of L/s);
- Regional extent of some key stratigraphic units are not well understood (e.g. thickness and eastern extent of the Geera Clay, extent of thick region of surf zone targeted by the off-path injection wellfield;
- Hydraulic properties of reformed backfill material are not well understood; and
- Calibration is to heads/drawdown only. No measurements of groundwater flow are available (particularly of relevance to surface water-groundwater interaction) although pumping and injection flows are represented explicitly in the model.

An additional point to note is that the calibration approach involves taking ‘cookie cut’ sections from the regional model in localised areas around the transient pumping and injection tests, refining the model grid and then calibrating to measured drawdown responses (see Table 3.1). The reason for doing so is to avoid running simulations using the entire regional model domain with a refined grid, which would require unnecessarily long computation times and create unnecessarily large model files. Therefore, in the strictest sense, the regional model has not been calibrated to transient data but, rather, informed by transient calibration of sub-models. The regional model is explicitly calibrated only in steady state to regional groundwater head data.

Table 3.1 : Numerical groundwater models developed for this study

Model name	N-S extent (m)	E-W extent (m)	purpose
BAL2.0*	90,000	90,000	Steady state calibration Predictive scenario modelling
LTT1.0	8,000	18,000	Local-scale transient calibration to the Long Term Trial
Nanda1.0	3,000	3,000	Local-scale transient calibration to the “Nanda” STT
UD1.0	3,000	3,000	Local-scale transient calibration to the “Upson Downs” STT
TN1_1.0	1,000	1,000	Local-scale transient calibration to the TN1 pumping test
TN5_1.0	1,000	1,000	Local-scale transient calibration to the TN5 pumping test

A review of the model and its associated documentation in this report was carried out by Hugh Middlemis of HydroGeoLogic. A copy of the review is presented in Appendix A. The review found that the model was developed consistent with best practice, was best described as a Class 2 model (its targeted Class) and was therefore suitable for predicting the impacts associated with the mining activities proposed in the Project.

3.2 Software

The model is built in the Groundwater Vistas 6 (ESI, 2014) graphical user interface and run using the MODFLOW-SURFACT 4 (HGL, 2014) numerical modelling code. MODFLOW-SURFACT is used to allow access to a number of its features and packages that are not available in the suite of standard MODFLOW codes. When used in combination with Groundwater Vistas, it provides a modelling platform on which models can be efficiently and easily built, run and their outputs processed. Specific features that are not available in standard MODFLOW and that are used in this study are listed below.

- Stable handling of rewetting of dry cells: In standard MODFLOW, rewetting of dry cells is often numerically unstable. MODFLOW-SURFACT’s Block-Centred Flow (BCF4) package incorporates an option to represent unsaturated model cells with a ‘pseudo soil’ technique. When a simulation requires model cells to resaturate, such as when dewatering ceases locally, the pseudo soil approach usually results in a more stable numerical outcome than would be achieved using the standard MODFLOW rewetting algorithm.
- Adaptive time-stepping: MODFLOW-SURFACT’s Adaptive Time-Stepping and Output Control (ATO4) Package enables a simulation to adaptively increase the length of timesteps when the groundwater system is relatively stable, and refine timesteps as necessary to obtain numerical convergence at times when larger changes in groundwater stresses and heads are occurring. The standard MODFLOW Output Control (OC) package requires prior definition of timesteps and cannot subsequently refine a timestep should it fail to produce a converged numerical solution. The ATO4 package therefore enables faster and more efficient computing.
- Ability to vary material properties over time: MODFLOW-SURFACT’s Time-Varying Material Property (TMP1) Package allows simulation of changing material properties over time, as occurs when a pit is excavated and backfilled, within the one model run. Standard MODFLOW cannot simulate time-varying material properties.
- Dynamic distribution of pumping across multiple model layers: MODFLOW-SURFACT’s Fracture-Well (FWL4) Package distributes the pumping from/into a well screened over multiple model layers, based on the respective transmissivity of the individual layers at that time. This is particularly important for wells in which model layers will go dry, such as dewatering wells. It is also important for wells in which hydraulic conductivity varies significantly between screened layers, as occurs between the surf zone and non-surf zone sub-units in the LPS.

All model runs use the MODFLOW-SURFACT PCG4 solver. Different conversion criteria are employed depending on the magnitude of stresses simulated in individual model runs. The steady state model, solving only for equilibrium conditions, is able to employ a more rigid head closure (HCLOSE) convergence criterion than the other model runs, particularly the predictive scenario. All calibration models (steady state and transient) are able to employ much more stringent relative closure criteria (RCLOSE) than the predictive scenario. Convergence criteria employed in the model runs are summarised in Table 3.2. All model runs generate a cumulative water balance error less than 1 % (all but the predictive scenario are less than 0.1 %) with errors usually less than 1 % for individual timesteps.

Table 3.2 : Convergence criteria

Model	HCLOSE (m)	RCLOSE (m)
BAL2.0_cal1	0.001	0.1
LTT1.0_tcal1	0.01	0.01
Nanda1.0_tcal1	0.01	0.001
UD1.0_tcal1	0.09	0.001
TN1_1.0_tcal1	0.01	0.01
TN5_1.0_tcal1	0.001	0.01
BAL2.0_TS2_opt29	0.25	0.25

3.3 Model domain and spatial discretisation

Given an expected high computational burden to run the models, the domain is defined to be as small as it can be such that the location of the model boundaries does not affect the predicted operational outcomes or regional groundwater impacts. It is necessary that the domain include the West Balranald and Nepean deposits, the Murrumbidgee and Murray Rivers and associated wetlands. In addition to these key features the extent of groundwater impacts predicted by modelling at the PFS stage of the Project (SKM, 2013a) was used to define a model domain measuring 90 km east-west and 90 km north-south. The model domain is smaller than the 120 km x 120 km BAL1.2 regional model domain used in the PFS. In line with predicted PFS groundwater impacts, the model domain extends 10 km less to the east and west and 20 km less to the north. The model extent is such that impact to adjacent water sources (both groundwater and surface water) can be assessed,

The model is discretised vertically into nine model layers (Table 3.3 and Figure 3.1). These are defined to align with the key hydrostratigraphic layers. All stratigraphic layers identified in the study are modelled as explicit model layers with the exception of:

- The LPS1 lower shore and LPS2 foreshore, which are lumped together into a single model layer due to their adjacent stratigraphic position and similar hydraulic properties; and
- The basement, the top of which is set as the base of the model. The basement is not included in the model due to its relatively impermeable nature and lack of hydraulic interaction with the overlying groundwater system.

The Shepparton Formation was initially represented using a single layer but, during the calibration process, it became apparent that shallow wells behaved in an unconfined manner (small drawdown response to pumping to/from the underlying LPS) whilst deeper wells behaved in a confined manner (larger drawdown response). The highly stratified nature of the Shepparton Formation, including layers of clay, silt and relatively impermeable material is assumed to be the reason for the vertical differentiation of responses. To simulate these differing responses the Shepparton Formation was split in two model layers. A number of approaches to splitting the Shepparton Formation were trialled. The most effective and adopted approach was to split the total Shepparton Formation thickness using a 2:1 ratio of ‘shallow’ to ‘deep’ thickness. Because the uppermost part of the Shepparton Formation lies above the water table, the saturated part of Shepparton Formation is approximately split in half over much of the model domain. The deeper of the two Shepparton formation model layers includes the basal aquitard that acts as a confining layer between the Shepparton Formation and the underlying LPS.

Table 3.3 : Model layers

Model layer	Hydrostratigraphic unit/s
1	Shepparton Formation (shallow)
2	Shepparton Formation (deep)
3	LPS1 foreshore
4	LPS1 surf zone
5	LPS1 lower shore / LPS2 foreshore
6	LPS2 surf zone
7	LPS2 lower shore
8	Geera Clay
9	Olney Formation

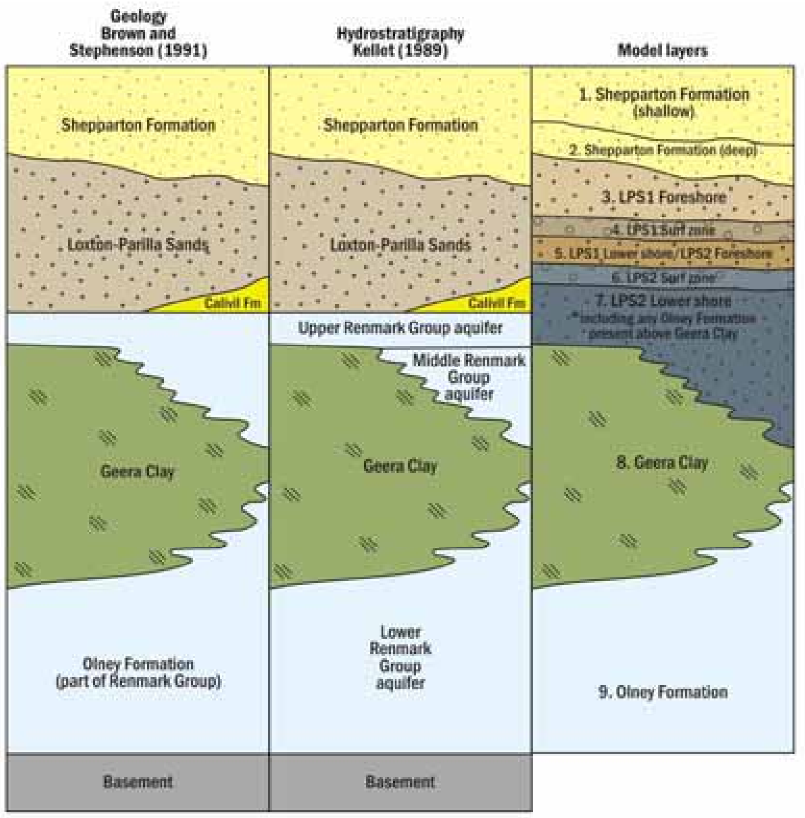


Figure 3.1 : Relationship between geology, hydrostratigraphy and model layers

Surfaces defining the top and bottom of model layers were obtained from a combination of data sources. The data sources used to define each of the model layer surfaces is summarised in Table 3.4. Figures illustrating the types and locations of available data used to inform the creation of model layer elevations are provided in Appendix B. The resulting model layer surfaces and thicknesses are presented in Appendix C.

Table 3.4 : Model surface data sources

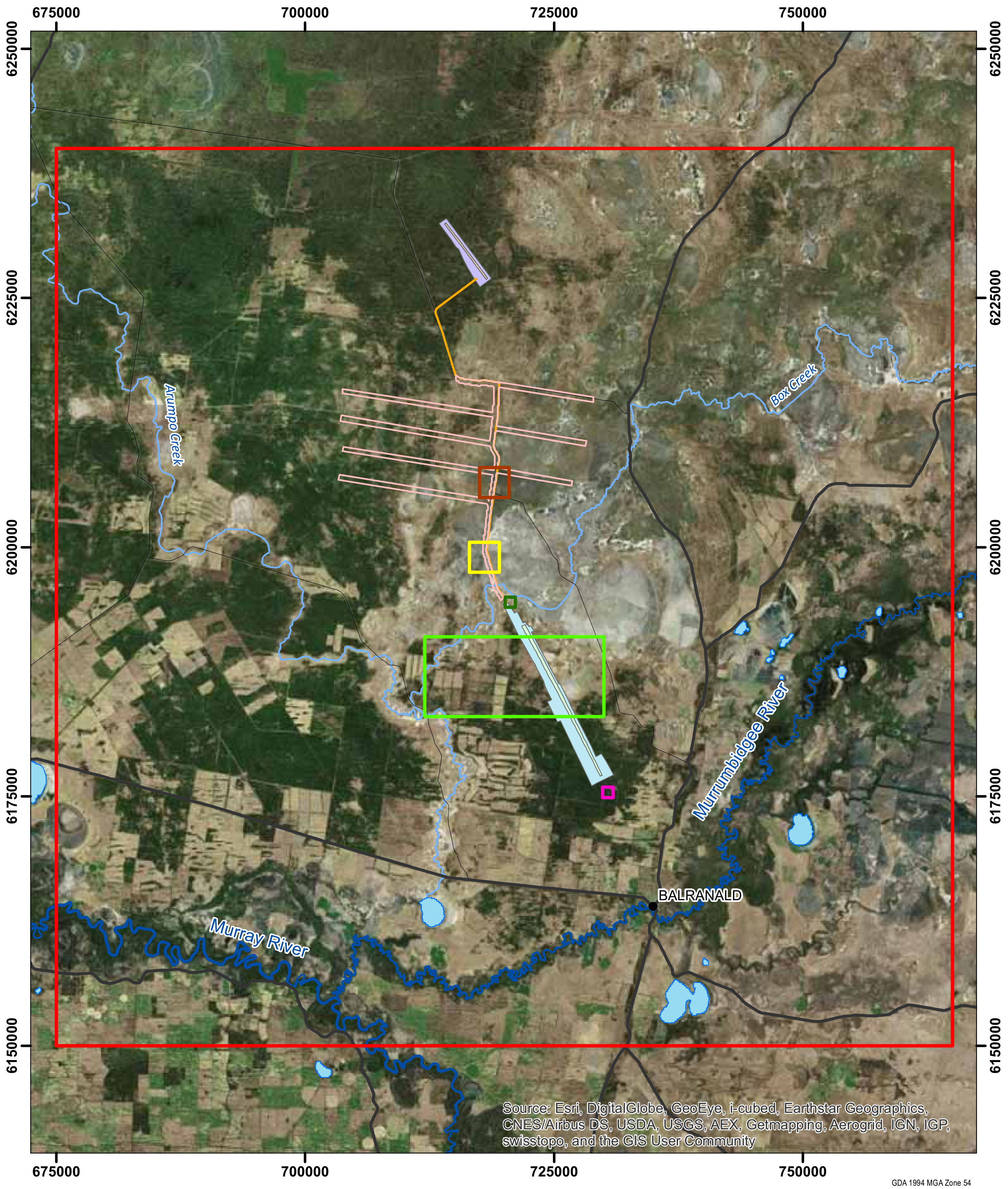
Surface	Data
Topography / top of Shepparton Formation	Shuttle Radar Topography Mission (SRTM) digital elevation model
Base of Shepparton Formation / top of LPS1 foreshore	Bore logs, topography assigned where hydrogeological maps indicate Shepparton Formation not present unless bore logs indicate its presence
Base of LPS1 foreshore / top of LPS1 surf zone	Bore logs
Base of LPS1 surf zone / top of LPS1 lower shore	Bore logs
Base of LPS2 foreshore / top of LPS2 surf zone	Bore logs
Base of LPS2 surf zone / top of LPS2 lower shore	Bore logs
Base of LPS2 lower shore / top of Geera Clay	Bore logs
Base of Geera Clay / top of Olney Formation	Bore logs, Geera Clay isopachs presented by Brown and Stephenson (1991)
Base of Olney Formation / top of basement	Bore logs, basement elevation contours from regional hydrogeological maps (Kellett, 1994 and 1991)

Local-scale models of each of the transient pumping and injection trial sites are used to calibrate aquifer parameters. The local-scale models use the same model layer structure and associated layer elevation surfaces as the regional BAL2.0 model, but for smaller sections of the study area. The BAL2.0 model employs a uniform 500 m x 500 m cell size for steady state calibration. However, for scenario modelling the grid is refined to 100 m x 100 m around the mine pits and the off-path injection wellfield. The local-scale models used to calibrate aquifer parameters employ a 100 m x 100 m regional cell size, progressively refined down to 0.25 m x 0.25 m at locations of all production, injection and multi-layer observation wells. A summary of the various model domains and associated model grids is presented in Table 3.5 and the location of the regional and local model domains is presented in Figure 3.2.

Table 3.5 : Local-scale transient calibration model domains and discretisation

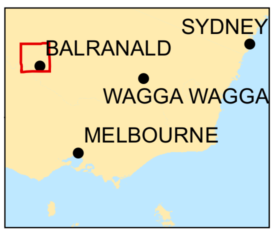
Model	N-S extent (m)	E-W extent (m)	Rows	Columns	Total cells
BAL2.0*	90,000	90,000	180	180	291,600
BAL2.0#	90,000	90,000	508	400	1,828,800
LTT1.0	8,000	18,000	208	327	612,144
Nanda1.0	3,000	3,000	197	197	349,281
UD1.0	3,000	3,000	174	176	275,616
TN1_1.0	1,000	1,000	123	121	133,947
TN5_1.0	1,000	1,000	111	111	110,889

* Steady state calibration carried out with uniform 500 m x 500 m cells. # Transient predictions run with grid refined around dewatering and injection areas, down to 100 m x 100 m, and with more distant parts of the model remaining at 500 m x 500 m cell spacing.



Town
Major road
Minor Road
Lake
River
Watercourse
Haul road
West Balranald pit limits
West Balranald disturbance
Nepean pit limits
Nepean disturbance
EIS offpath injection area
BAL2.0 model domain
LTT 1.0 model domain
NANDA 1.0 model domain
TN1 1.0 model domain
TN5 1.0 model domain
UD 1.0 model domain

0 10
Kilometres



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Model domains

Figure 3.2

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3.4 Temporal discretisation

The steady state calibration model, used to generate appropriate starting heads for transient scenario modelling, employs a single steady state stress period.

The local-scale models, used for transient calibration, employ stress periods and timesteps appropriate to the timing and magnitude of the production and injection carried out at each location. Further details are provided in the subsequent chapter on calibration. The MODFLOW-SURFACT ATO package is not employed in the transient calibration models.

Models of mining scenarios, using the regional BAL2.0 model, use stress periods and timesteps appropriate to the timing and magnitude of the production and injection carried out at various times during the scenarios. The MODFLOW-SURFACT ATO package is not employed for impact assessment modelling. However, it is anticipated that it will be required for subsequent modelling to optimise groundwater management at a more detailed level than required for impact assessment.

3.5 Boundary conditions

Boundary conditions employed in the models are summarised in Table 3.6 and those assigned to the BAL2.0 regional model are illustrated in Figure 3.3 to Figure 3.5. In the BAL2.0 model general head boundary (GHB) conditions are assigned along the edges of model layers with the exception of the Geera Clay, for which no flow is assumed. The heads assigned to the GHBs in the Shepparton Formation layers (1 and 2) and the LPS layers (3 to 7) are uniform from layer to layer, consistent with observations from nested piezometers that show very similar heads in these units under natural conditions. Heads assigned to GHBs in the Olney Formation are generally several metres higher than those in the units overlying the Geera Clay. Conductance values assigned to the GHBs are based on the layers' horizontal hydraulic conductivity and average thickness and assume a distance of 5 km to a location outside the model domain where no head changes would be experienced as a result of stresses simulated within the model domain. GHB Conductance values are summarised in Table 3.7.

Constant head (CH) boundaries are assigned around the edges of each of the local-scale transient calibration models. Within each model layer specified boundary heads and initial heads do not vary. Because the local-scale calibration models cover relatively small areas, within which measured heads do not vary greatly, the approach of adopting a uniform initial potentiometric surface closely approximates reality. Further, because these models are calibrated to drawdown, that is changes in head rather than absolute heads, the absolute values are not of great significance (so long as the adopted values do not greatly affect saturated aquifer thickness and hence transmissivity).

Table 3.6 : Boundary conditions

Model	Model edge	Murray and Murrumbidgee Rivers
BAL2.0	GHB*: Shepparton Formation and LPS: head interpolated between 30 m AHD and 62 m AHD Geera Clay: No flow Olney Formation: head interpolated between 32 m AHD and 63 m AHD	River in model layer 1: stage interpolated between 48.25 m AHD and 66.75 m AHD
LTT1.0	CH#: 52 m AHD	n/a
Nanda1.0	CH#: 52 m AHD	n/a
UD1.0	CH#: 50 m AHD	n/a
TN1_1.0	CH#: 52.5 m AHD	n/a
TN5_1.0	CH#: 48 m AHD	n/a

* General Head Boundary condition, # Constant Head boundary condition

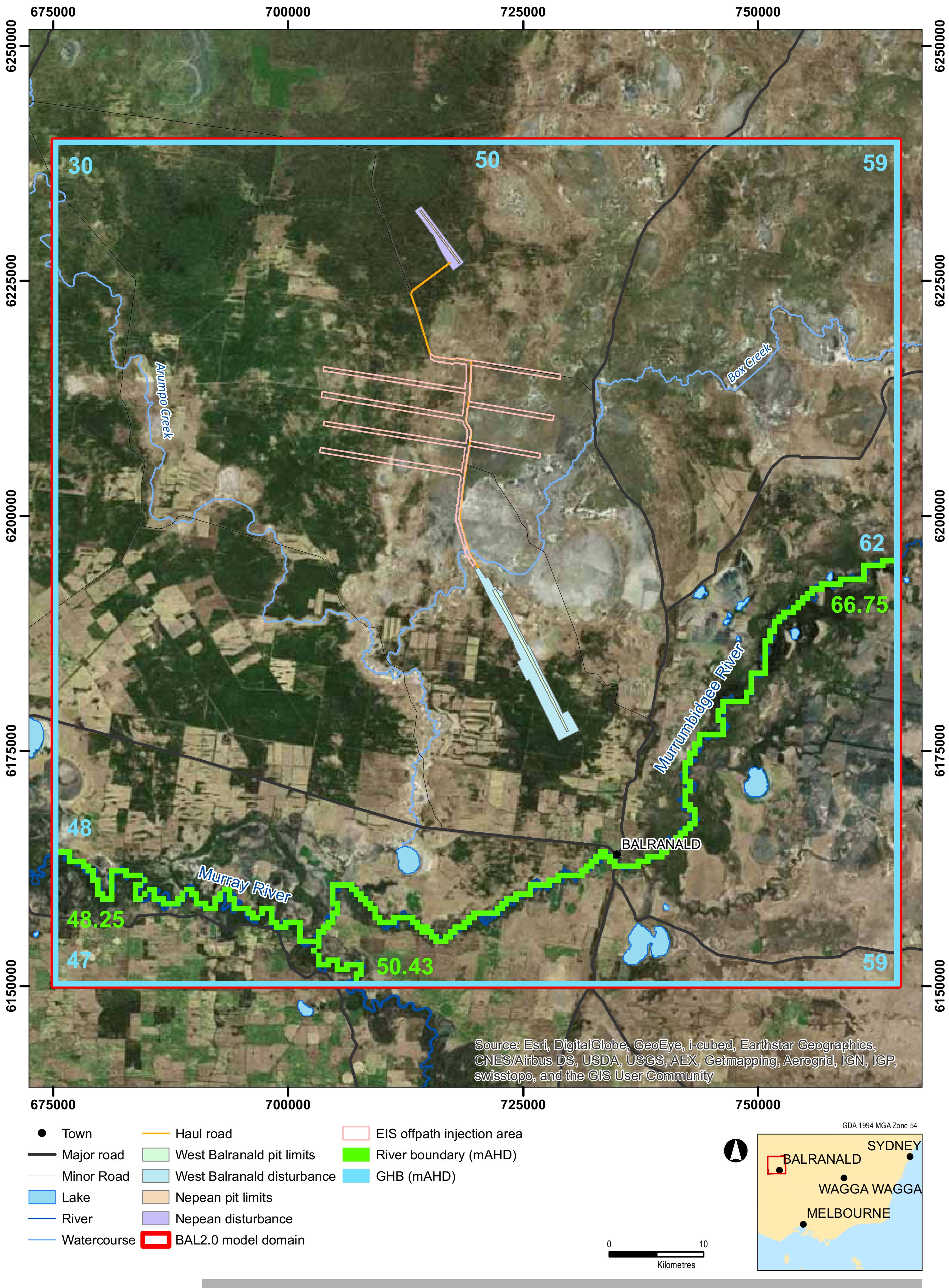
Table 3.7 : GHB Conductances assigned in the BAL2.0 model

Model layer	Hydrostratigraphic unit/s	North conductance (m^2/d)	South conductance (m^2/d)	West conductance (m^2/d)	East conductance (m^2/d)
1	Shepparton Formation (shallow)	2.7	2.2	0.9	4.5
2	Shepparton Formation (deep)	1.3	1.1	0.4	2.3
3	LPS1 foreshore	1.6	1.4	2.9	1.2
4	LPS1 surf zone	6.9	5.2	6.5	11.2
5	LPS1 lower shore / LPS2 foreshore	13.5	11.8	5.7	8.6
6	LPS2 surf zone	15.1	5.7	6.3	18.5
7	LPS2 lower shore	0.2	0.7	0.6	0.2
9	Olney Formation	59.9	51.2	42.8	86

Rainfall recharge is modelled using the MODFLOW recharge (RCH) package and is assigned uniformly across the model domain at a constant rate of 0.0365 mm/yr. This rate is more consistent with estimates of recharge under Mallee vegetation (estimated to be less than 0.1 mm/yr by Allison and Hughes, 1983 and Budd et al., 1990) than for cleared and cropped land (estimated to be 3 mm/yr by Allison and Hughes, 1983 and between 3 mm/yr and 10 mm/yr by Budd et al., 1990). The calibration process indicated that diffuse recharge must be relatively low because adoption of higher recharge rates resulted in poorer calibration to “steady state” regional hydraulic head observations.

Evapotranspiration from groundwater is modelled using the MODFLOW evapotranspiration (EVT) package. A maximum evapotranspiration rate of 2,000 mm/yr (measured pan evaporation at Mildura Airport is 2,192 mm/yr), applicable where/when the water table is at or above the ground surface, is applied uniformly across the model domain. Modelled evapotranspiration decreases linearly with increasing depth to the water table up to an ‘extinction depth’, set 3 m below ground surface. Below the 3 m extinction depth modelled evapotranspiration from groundwater is zero.

A river boundary condition is used to represent the Murrumbidgee and Murray Rivers. River stage is assigned using linear interpolation between gauges (see Figure 2.12) and river bottom elevation is set 4 m below river stage. A river bed conductance of 50 m^2/d is assigned to all river cells, based on the following assumed parameter values: river width = 100 m, river length (in a 500 m model cell) = 500 m, thickness of river bed sediment = 1 m and hydraulic conductivity of river bed sediment = 0.001 m/d.



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BAL2.0 Boundary conditions: Shepparton Formation (shallow)

Figure 3.3

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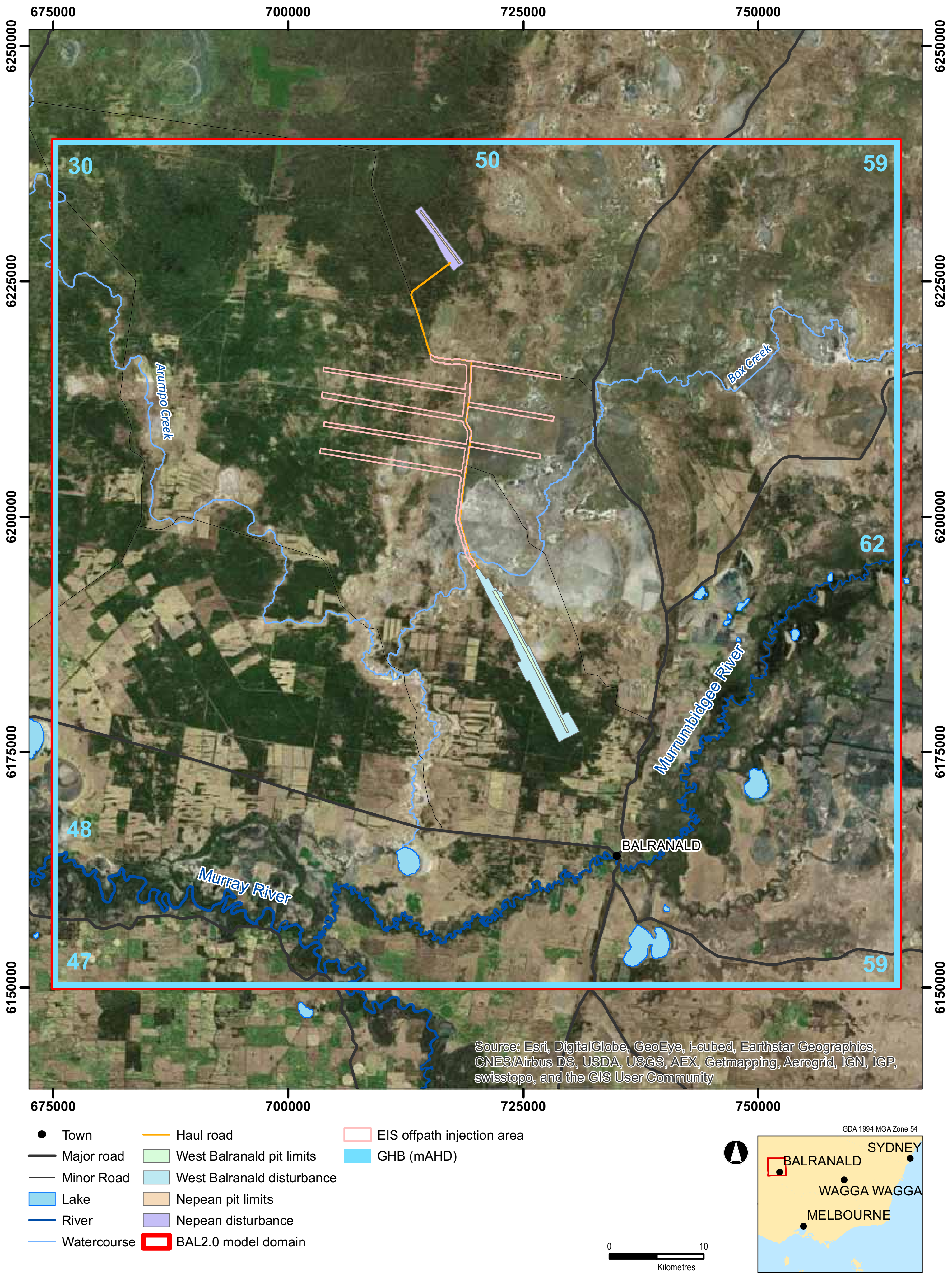

BAL2.0 Boundary conditions: Shepparton Formation (deep) and LPS

Figure 3.4

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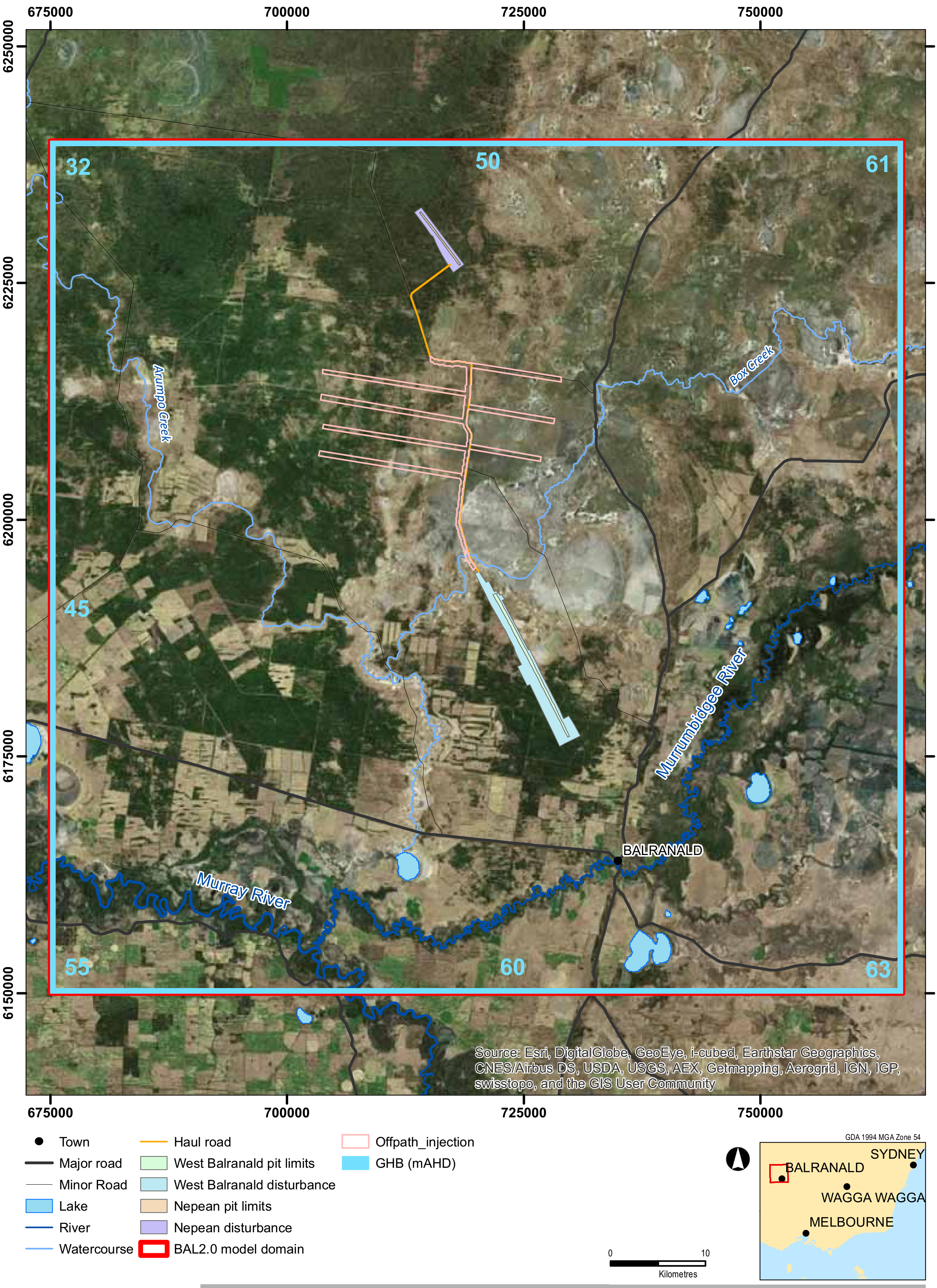

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BAL2.0 Boundary conditions: Olney Formation

Figure 3.5

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3.6 Initial conditions

Initial conditions for all transient prediction model runs are derived from running the model in steady state. This is consistent with the hydrogeological conceptualisation that the system is largely in equilibrium with present day recharge and discharge associated with climate, regional groundwater inflow/outflow, surface water interaction and groundwater pumping. The steady state head distributions are presented in the calibration chapter.

Initial conditions for the local-scale transient calibration models are assumed uniform within layers of each of the models, and are set equal to the constant head boundary conditions assigned around the model edges. This is appropriate given the local scale of the models.

3.7 Production and injection wells

Production and injection wells are not modelled in the steady state regional calibration. However, robust simulation of fluxes to/from pumped wells is vital to the transient calibration models. All wells are simulated using the MODFLOW-SURFACT Fracture-Well package. Where wells are screened over more than one hydrostratigraphic unit, spanning multiple model layers, they are represented in the model in that way. Details on simulated production and injection wells are provided in subsequent chapters on calibration and scenario modelling.

3.8 Mine dewatering and mining operations

For the purpose of impact assessment, mine dewatering is simulated using the MODFLOW drain (DRN) package. This ensures the water table is lowered to below the pit floor in the active section of the pit throughout the duration of mining and backfilling. Further details on simulated mine dewatering are presented in a subsequent chapter on scenario modelling.

The process of excavating the mine pits and then backfilling them will influence the hydraulic properties of the aquifer material in the area of the pit. This is not simulated for impact assessment modelling as the regional impacts are not expected to be sensitive to aquifer properties of the in-pit sediments.

4. Calibration

4.1 Methodology

The approach adopted to calibrate the regional model involved using a combination of local-scale ‘sub-models’ to calibrate aquifer parameters locally to transient production and injection tests and then extrapolating the calibrated parameter values regionally across the full BAL2.0 model domain. The reason for using local-scale models is that they enable much finer spatial discretisation around their respective features of interest (production, injection and monitoring wells) than could possibly have been achieved if the tests were simulated using the regional BAL2.0 model (due to computational demands). The domains of the local-scale models were made sufficiently large that the results are effectively the same as if the BAL2.0 model domain had been used, but results were obtained much more rapidly and produced output files of manageable size. The locations of local-scale models within the BAL2.0 model domain are presented in Figure 3.2.

Calibration of the local-scale models was carried out such that, as much as possible, parameter values are consistent between models. Where necessary, aquifer properties were allowed to differ between sites and, at “Nanda”, within a local-scale model. This approach minimises the level of heterogeneity in the BAL2.0 regional model, whilst maintaining acceptable transient calibration at each of the local-scale model test locations.

The calibration approach employed a combination of automated parameter estimation with PEST (Doherty, 2005) and manual ‘trail-and-error’ calibration.

The regional BAL2.0 model is calibrated in steady state to ‘raw’ measured heads assumed to represent long-term equilibrium conditions. That is, measured depth to water data were used to determine the elevations of the potentiometric surface in the monitoring wells and these data have not been modified to account for groundwater density variations (primarily caused by variations in salinity).

The local-scale models are calibrated to transient drawdown data obtained during five production and injection tests. As for steady state measured groundwater heads, the drawdown data are not modified to account for variations in groundwater density.

4.2 Local-scale transient calibration

The following sections outline the field trials carried out at each of the sites and how they are represented in the respective local-scale models used to calibrate aquifer parameters in transient mode. The transient calibration process aimed to provide the best possible match to measured drawdown responses during the pumping and injection trials, whilst maintaining aquifer parameter values within ranges consistent with the conceptual hydrogeological model.

Because the pumping and injection trials carried out to date have not caused desaturation of the LPS at monitoring wells (this has occurred at some production wells), the available data cannot be used to constrain or estimate the specific yield of this unit. Hence, previous studies were used to inform the selection of an appropriate specific yield value. Previous groundwater modelling studies (SKM, 2011 and 2013c) undertaken by Jacobs for Iluka’s WRP and Kulwin Mines in northern Victoria, included values of 0.1 and 0.2 respectively for specific yield of the LPS. These mine sites are located near the town of Ouyen in northern Victoria, approximately 120 km west of Balranald. The models developed by SKM were initially calibrated by matching modelled drawdown to observations obtained during pumping tests at a number of locations along the deposits. Models were further validated and refined by matching observations from the excavation and dewatering of a test pit (at Kulwin) and from validation during mining operations (after 24 months of mining at Kulwin and after 12 months of mining at WRP). Subsequent comparisons between model predictions and observed heads and pumping rates show excellent agreement and suggest that the models provide reliable simulation of the dewatering and disposal processes undertaken at these sites. The models of the Kulwin and WRP mines are probably best described as Class 3 models, the most reliable class of model described in the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). The average of the specific yield at these two sites, 0.15, is used for the Balranald site. Whilst this value is derived from the LPS at WRP and Kulwin (the

Shepparton Formation is not present at the Kulwin and WRP mines), it is applied to all hydrostratigraphic units in the present study.

4.2.1 Long Term Trial

The LTT carried out by Iluka (2015) consisted of production from two wells located on the West Balranald mine strike, each screened over all LPS1 sub-units plus the LPS2 foreshore and surf zone sub-units, and injection into twelve injection wells located along a 2.5 km transect beginning approximately 6 km from the production wells and extending to approximately 8.5 km from the production wells. All injection wells were screened over the entire LPS sequence. The LTT1.0 model domain and location of production, injection and monitoring wells are presented in Figure 4.1.

Measured production and injection rates are modelled using average rates over stress periods of varying length for which all injection and extraction can be reasonably approximated by single values. Measured and modelled production and injection rates are presented in Figure 4.2 and Figure 4.3.

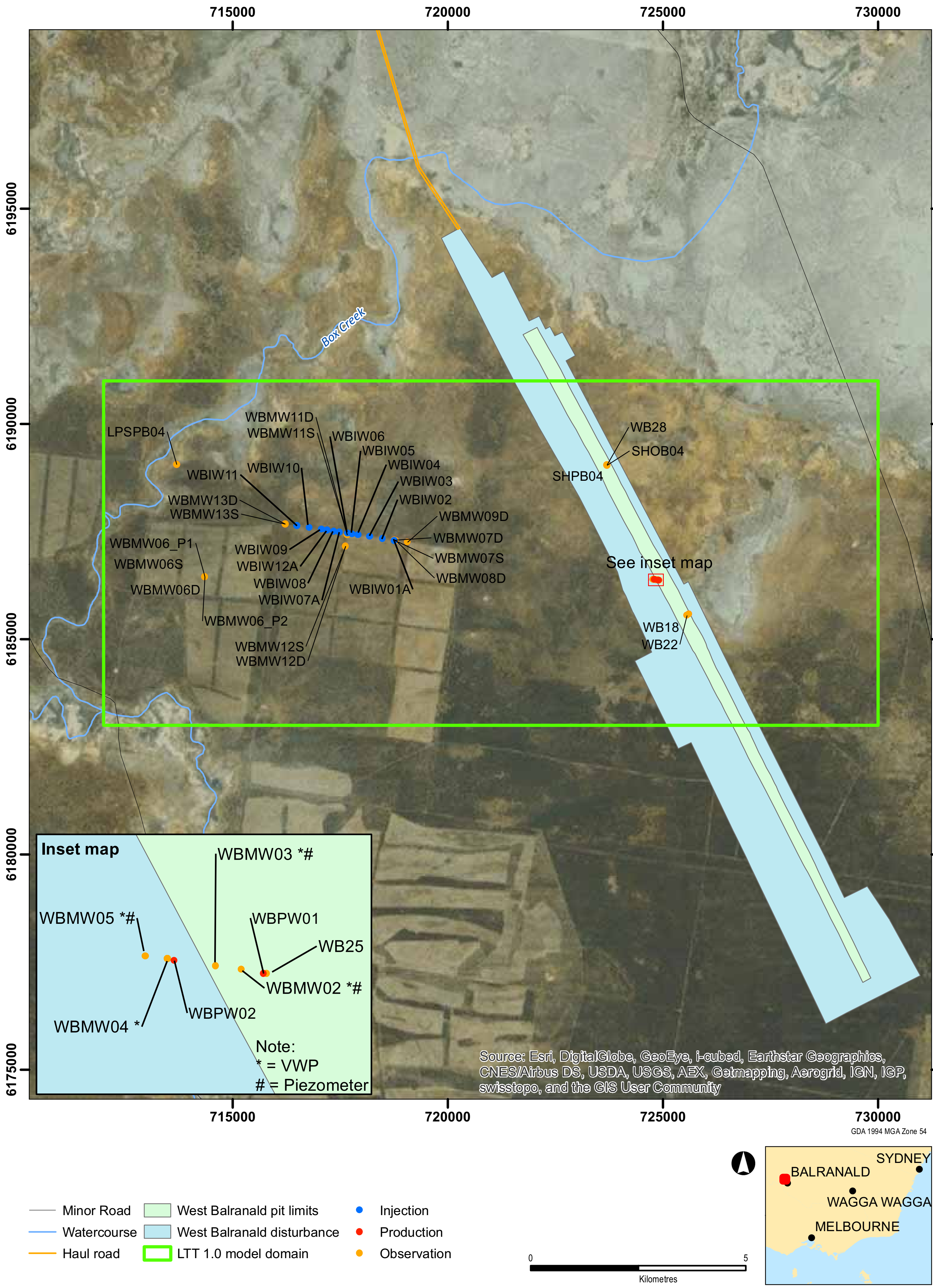
Due to the large number of data points produced by the data loggers installed at all but two monitoring locations, calibration was carried out to data collected manually and, for VWPs, to data averaged over hourly intervals (noting that recording intervals were as small as one minute in some cases).

4.2.1.1 Calibrated aquifer parameters

The calibrated aquifer parameter values obtained through calibration to transient drawdown data obtained during the LTT are presented in Table 4.1. Consistent with the conceptual model of a system of interbedded layers of finer and coarser material, a high degree of horizontal to vertical anisotropy is apparent in hydraulic conductivity of the LPS sub-units.

Table 4.1 : LTT calibrated aquifer parameters

Layer / hydrostratigraphic unit/s	Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)
1 & 2 Shepparton Formation	1	0.001	0.15	3×10^{-5}
3 LPS1 foreshore	0.9	0.001	0.15	3×10^{-5}
4 LPS1 surf zone	16	0.1	0.15	3×10^{-5}
5 LPS1 lower shore / LPS2 foreshore	0.9	0.001	0.15	3×10^{-5}
6 LPS2 surf zone	16	0.1	0.15	3×10^{-5}
7 LPS2 lower shore	0.9	0.001	0.15	3×10^{-5}
8 Geera Clay	0.0001	0.00001	0.15	3×10^{-5}
9 Olney Formation	3	0.3	0.15	3×10^{-5}



LTT1.0 groundwater wells

Figure 4.1

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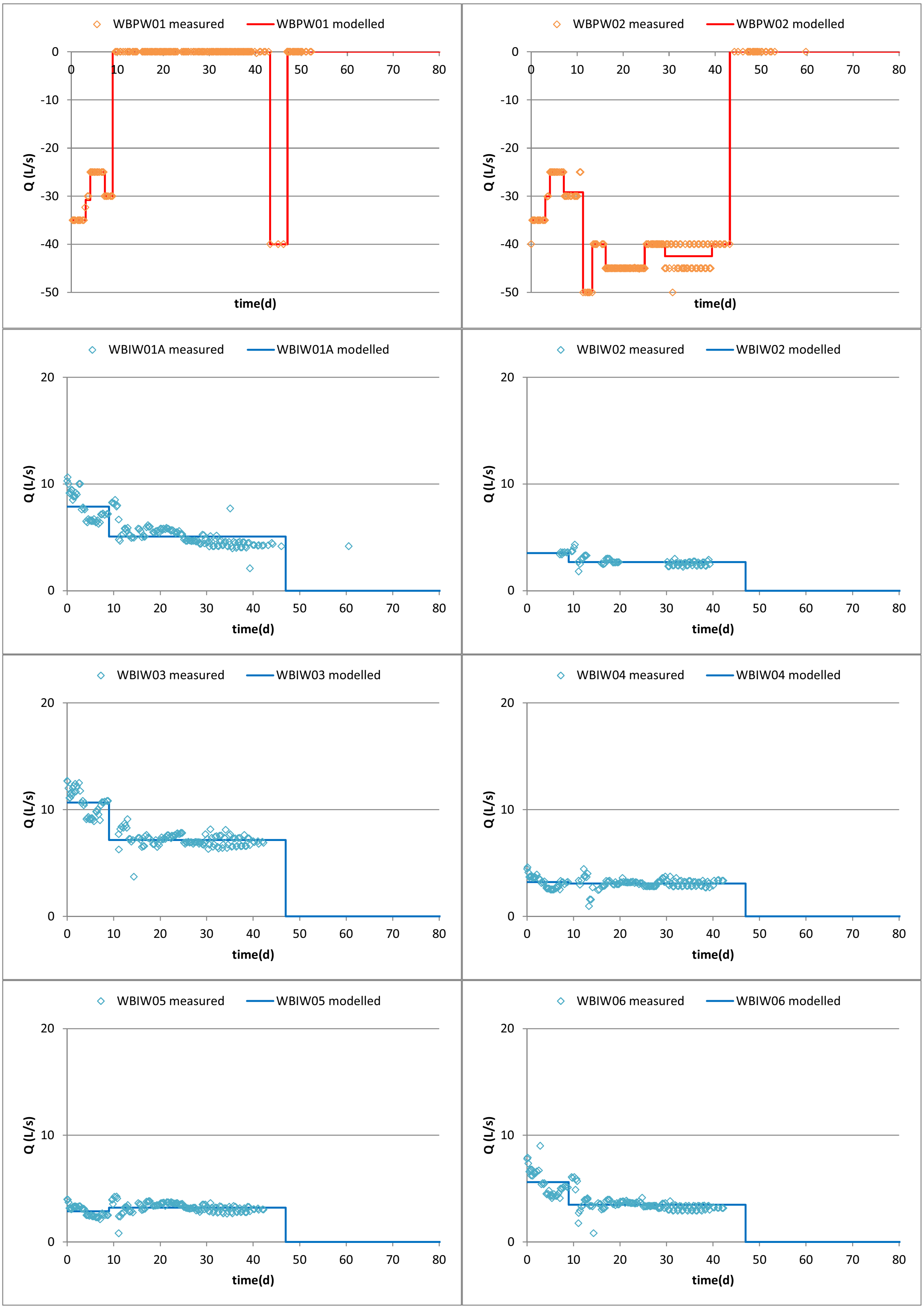


Figure 4.2 : LTT measured and modelled production and injection

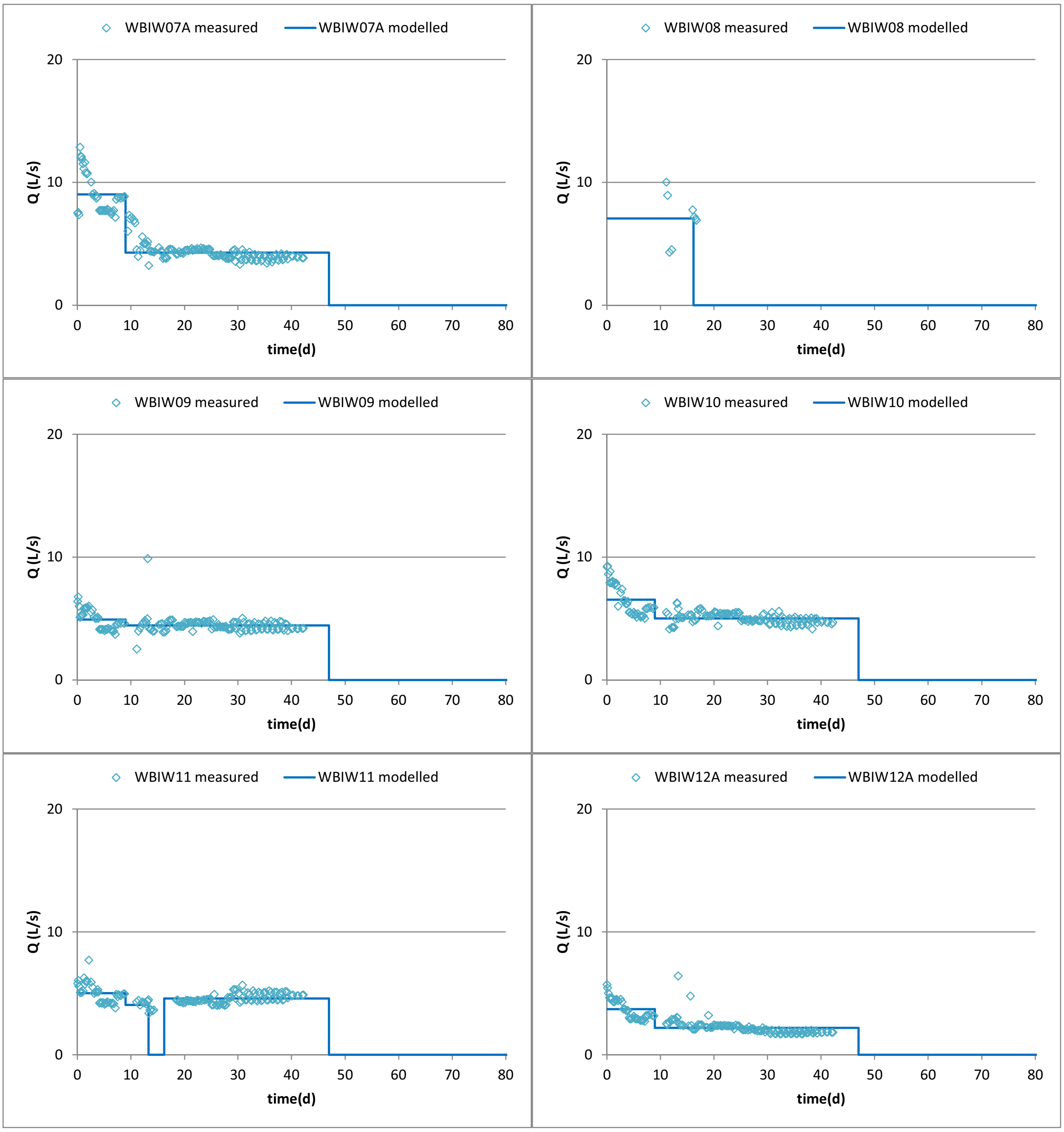


Figure 4.3 : LTT measured and modelled injection

4.2.1.2 Performance

A scatter plot of modelled versus measured drawdown for all monitoring locations and times is presented in Figure 4.4. There is a moderate level of scatter around what would be a 'perfect fit'. Several individual wells can be seen to contribute significantly to the scatter. The Scaled Root Mean Square (SRMS) error associated with this plot is 8.4 %.

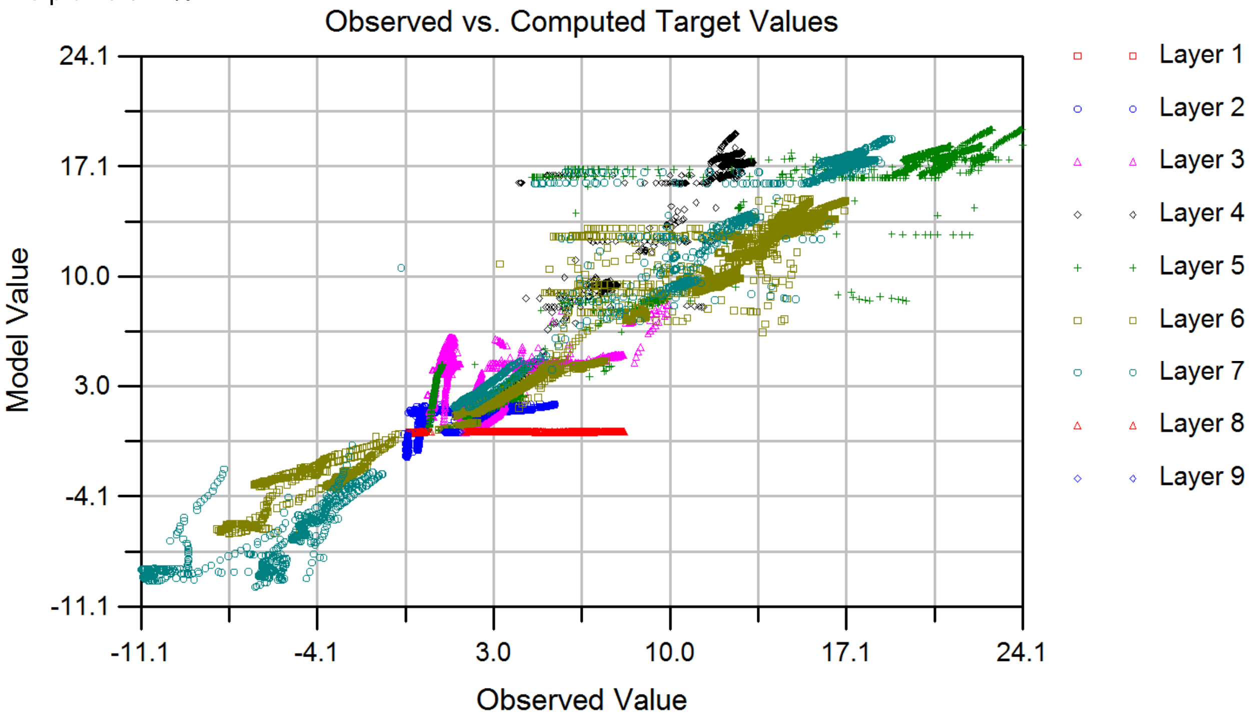


Figure 4.4 : LTT modelled versus measured drawdown scatter plot

Measured and modelled drawdown as a function of depth at WBMW04 (located 7.4 m from WBPW02) is presented in Figure 4.5. Interpreted stratigraphy taken from the well log is indicated at the left of the plot. Measured drawdown displays a clear spike at WBMW04 P8, located in the LPS1 lower shore sediments. These sediments are located between the LPS1 and LPS2 surf zones which are likely to be highly transmissive. All LPS VWPs display high drawdown whilst little to no drawdown is observed in the Shepparton Formation, Olney Formation and Basement. Surprisingly, significant drawdown is apparently measured in the Geera Clay. It may be that these two VWPs are actually installed in the LPS-Geera Clay transition zone. Alternatively, Iluka (2015) suggests that the apparent drawdown observed at VWPs adjacent the Geera Clay and Olney Formation units may be drawdown that has been transferred through the well annular grout, rather than through the hydrostratigraphic units.

The model replicates the measured high drawdown in the LPS but does not replicate the variation between LPS sub-units. It over-predicts drawdown in the Shepparton Formation and generates essentially no drawdown in the Geera Clay and Olney Formation.

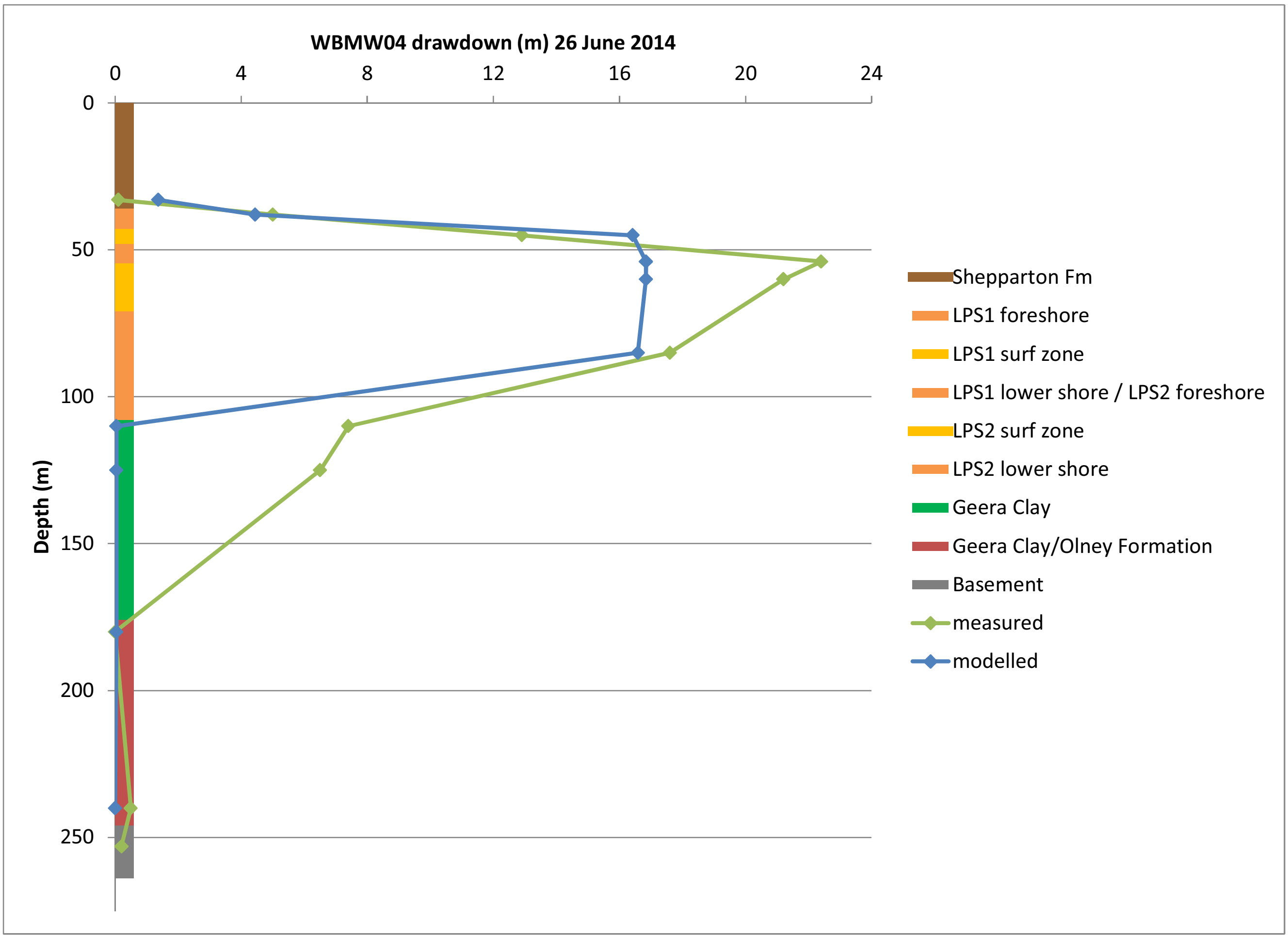


Figure 4.5 : Measured and modelled drawdown in WBMW04 nested VWPs

Hydrographs of measured and modelled drawdown for all monitoring sites are presented in Figure 4.6 to Figure 4.11. Overall a good match to temporal trends is produced for monitoring sites at both the production and injection areas as well as more regionally.

Maps of modelled drawdown in the Shepparton Formation and LPS are presented in Appendix D.

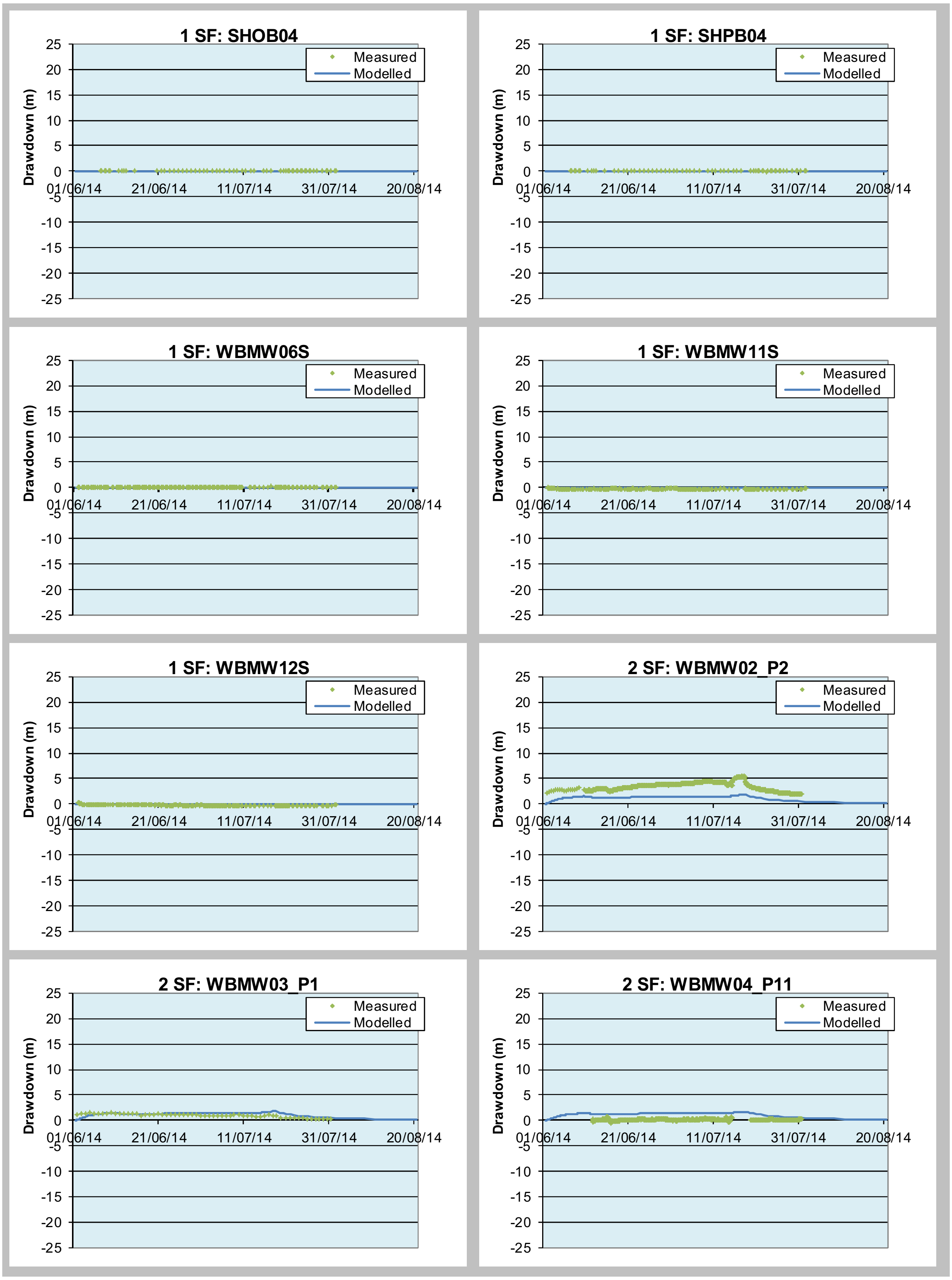


Figure 4.6 : LTT measured and modelled hydrographs

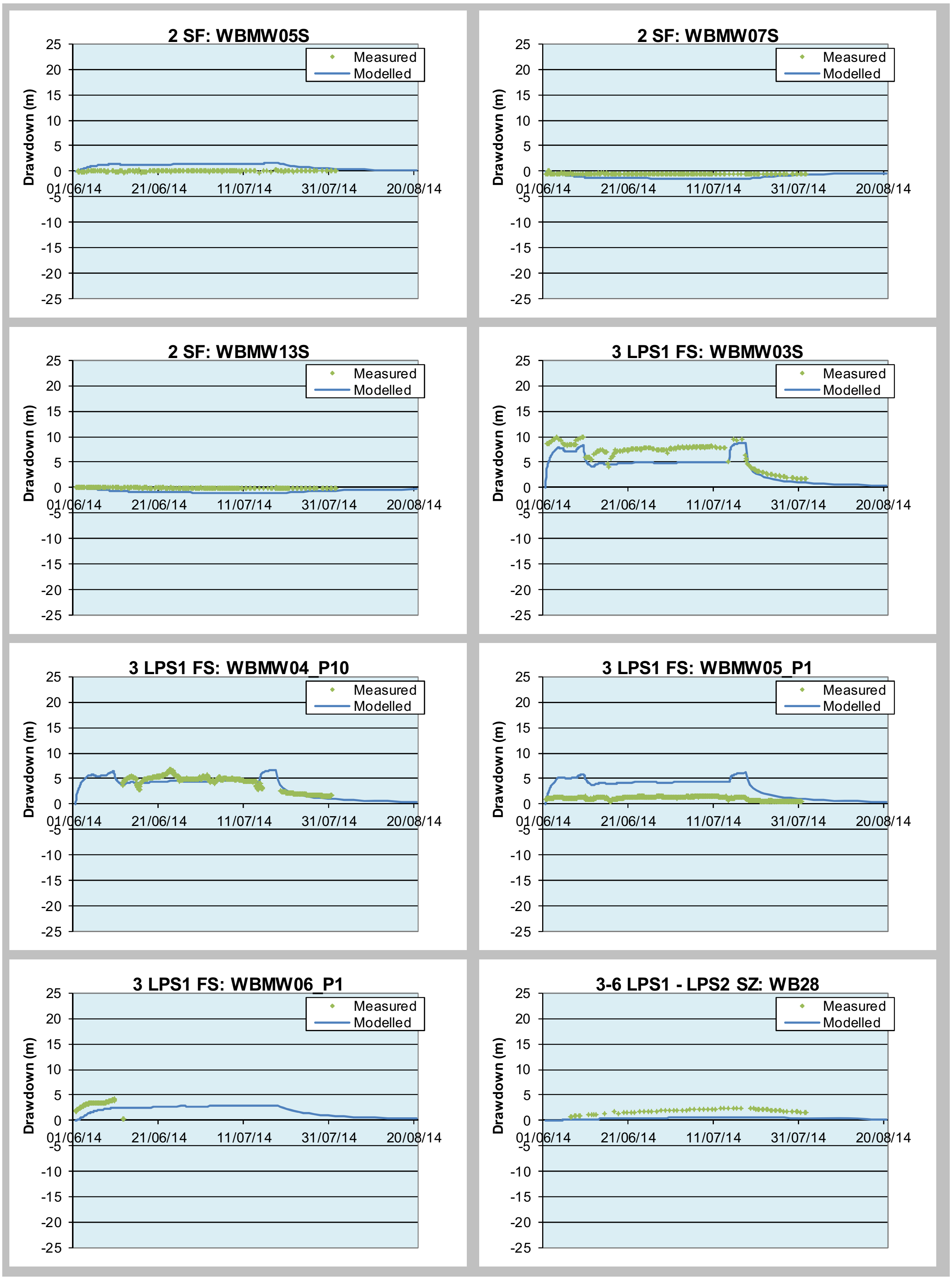


Figure 4.7 : LTT measured and modelled hydrographs

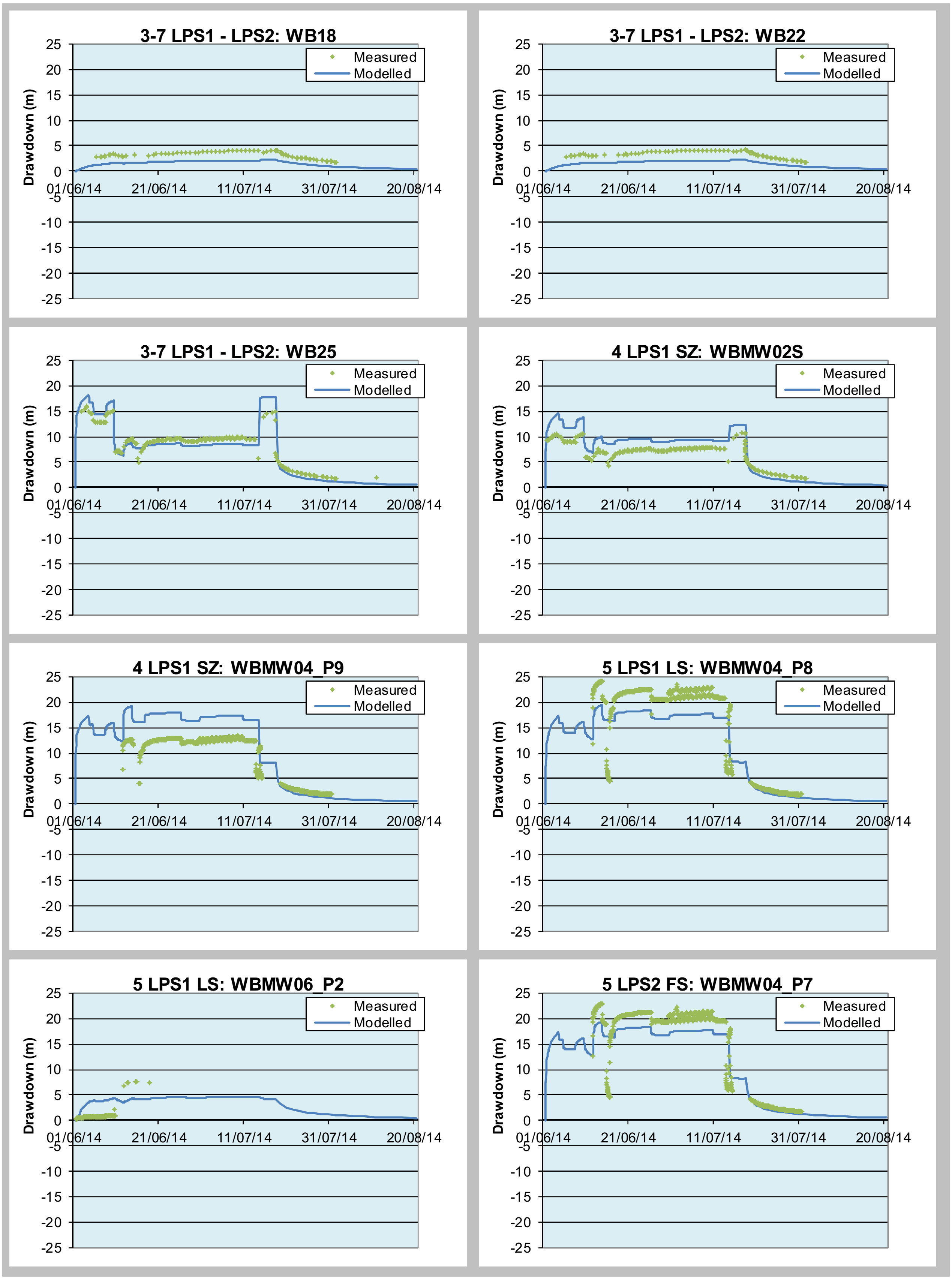


Figure 4.8 : LTT measured and modelled hydrographs

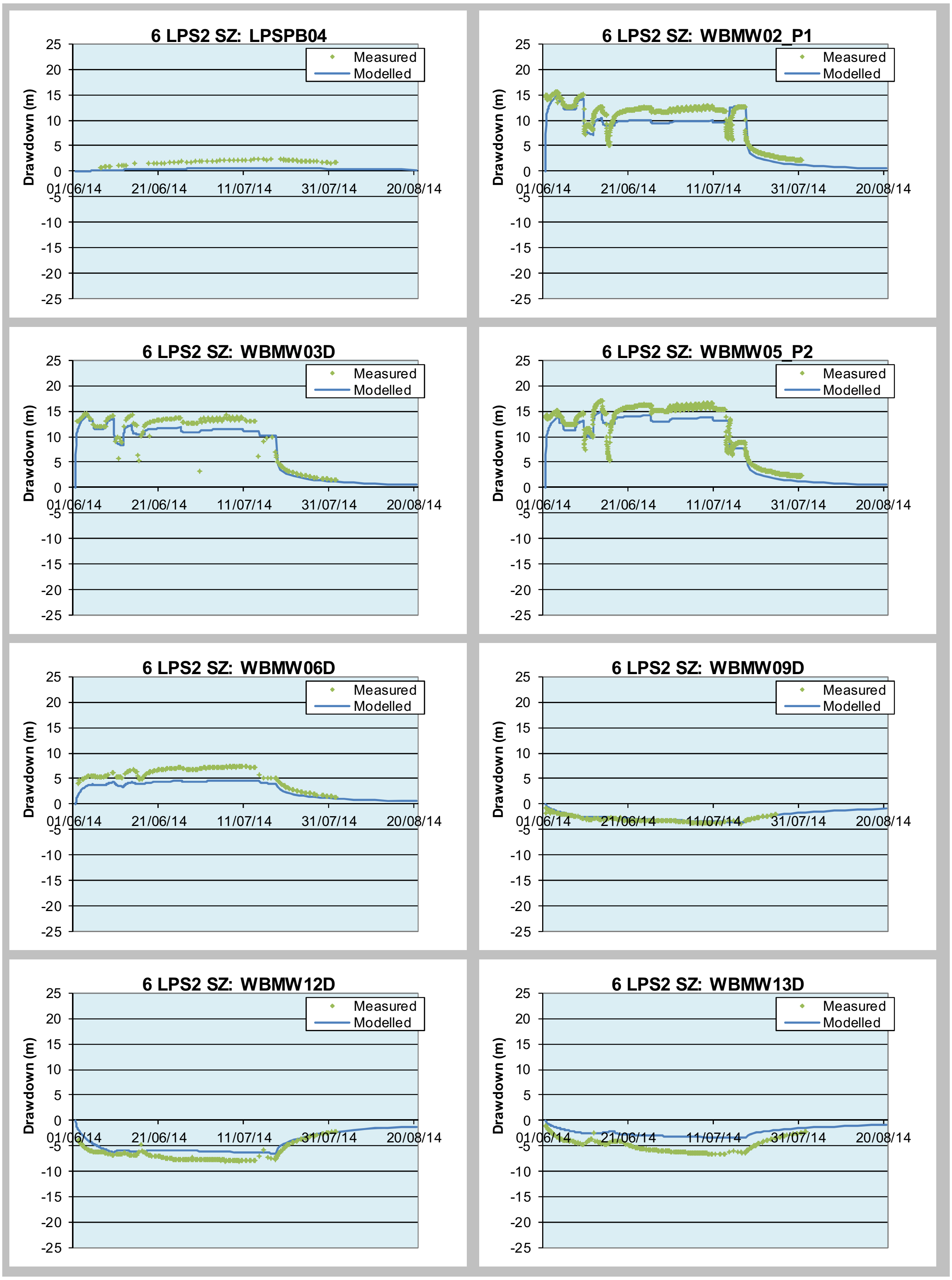


Figure 4.9 : LTT measured and modelled hydrographs

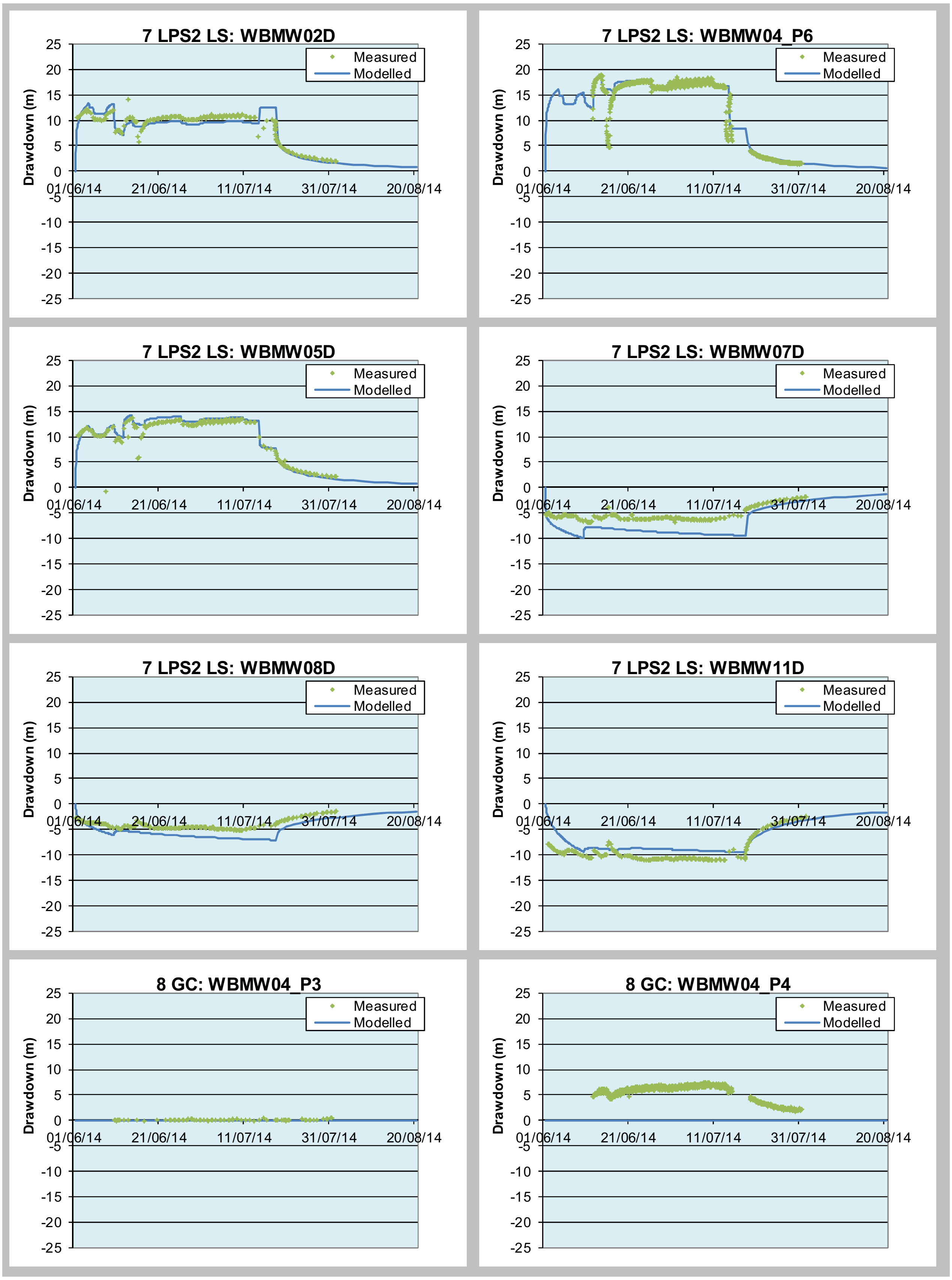


Figure 4.10 : LTT measured and modelled hydrographs

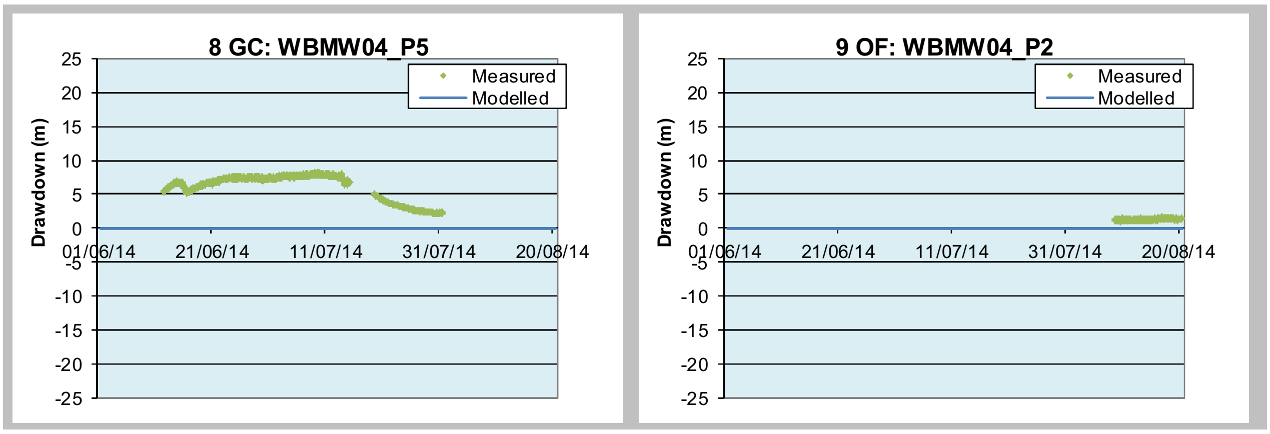


Figure 4.11 : LTT measured and modelled hydrographs

4.2.2 Turkeys Nest 1

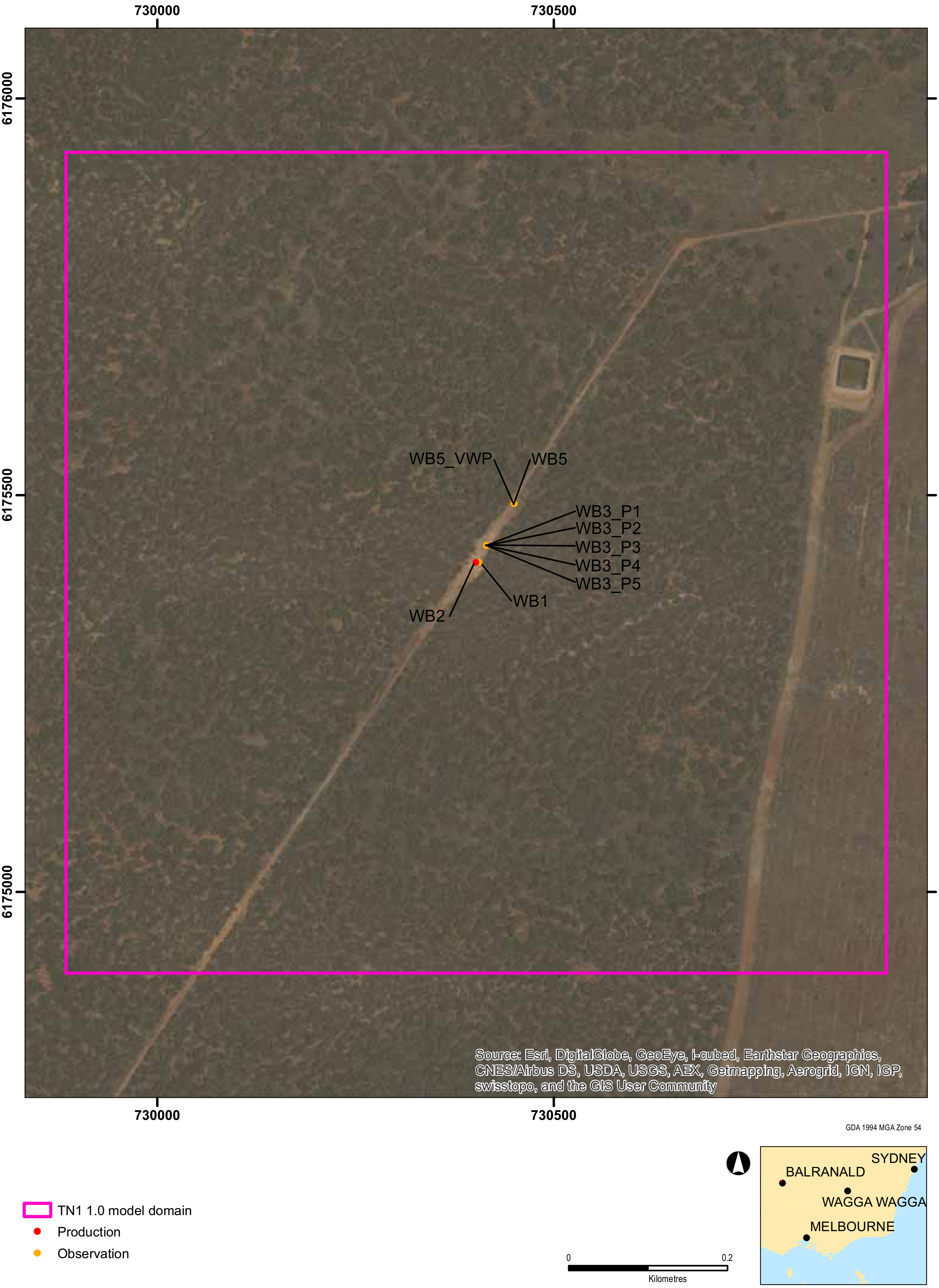
A pumping test was carried out at Turkeys Nest 1 (TN1) during the PFS. The test consisted of production pumping from well WB2 for a duration of 16 hours. It was intended to continue the test for a longer period and the relatively short test duration was a result of pump failure (URS, 2012). Water produced during the test was not reinjected. The TN1_1.0 model domain and location of production and monitoring wells are presented in Figure 4.12. Measured and modelled production rates are presented in Figure 4.13.

4.2.2.1 Calibrated aquifer parameters

The calibrated aquifer parameter values obtained through calibration to transient drawdown data obtained during the pumping test at TN1 are presented in Table 4.2.

Table 4.2 : TN1 calibrated aquifer parameters

Layer / hydrostratigraphic unit/s	Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)
1 & 2 Shepparton Formation	1	0.001	0.15	3×10^{-5}
3 LPS1 foreshore	0.9	0.001	0.15	3×10^{-5}
4 LPS1 surf zone	20	0.1	0.15	3×10^{-5}
5 LPS1 lower shore / LPS2 foreshore	0.9	0.001	0.15	3×10^{-5}
6 LPS2 surf zone	20	0.1	0.15	3×10^{-5}
7 LPS2 lower shore	0.13	0.001	0.15	3×10^{-5}
8 Geera Clay	0.0001	0.00001	0.15	3×10^{-5}
9 Olney Formation	3	0.3	0.15	3×10^{-5}



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TN1 1.0 groundwater wells

Figure 4.12

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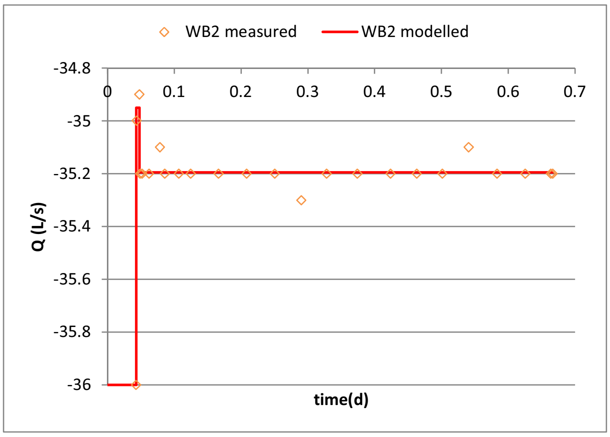


Figure 4.13 : TN1 measured and modelled production

4.2.2.2 Performance

A scatter plot of modelled versus measured drawdown for all monitoring locations and times is presented in Figure 4.14. The limited number of monitoring locations results in a plot that clearly displays the responses of several individual monitoring wells. The scatter is evenly distributed above and below a line of best fit. The Scaled Root Mean Square (SRMS) error associated with this plot is 7.6 %.

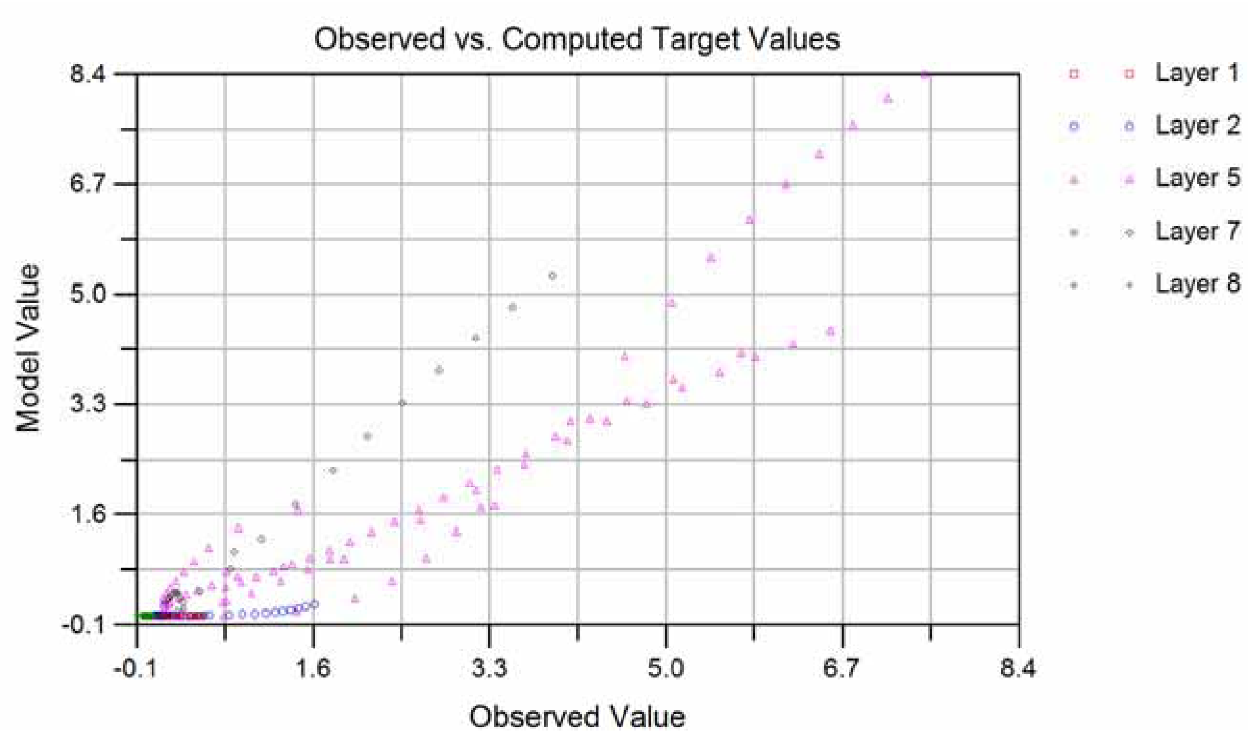


Figure 4.14 : TN1 modelled versus measured drawdown scatter plot

Hydrographs of measured and modelled drawdown for all monitoring sites are presented in Figure 4.15. Good matches to temporal trends and magnitudes are obtained for most monitoring locations. Maps of modelled drawdown in the Shepparton Formation and LPS are presented in Appendix D.

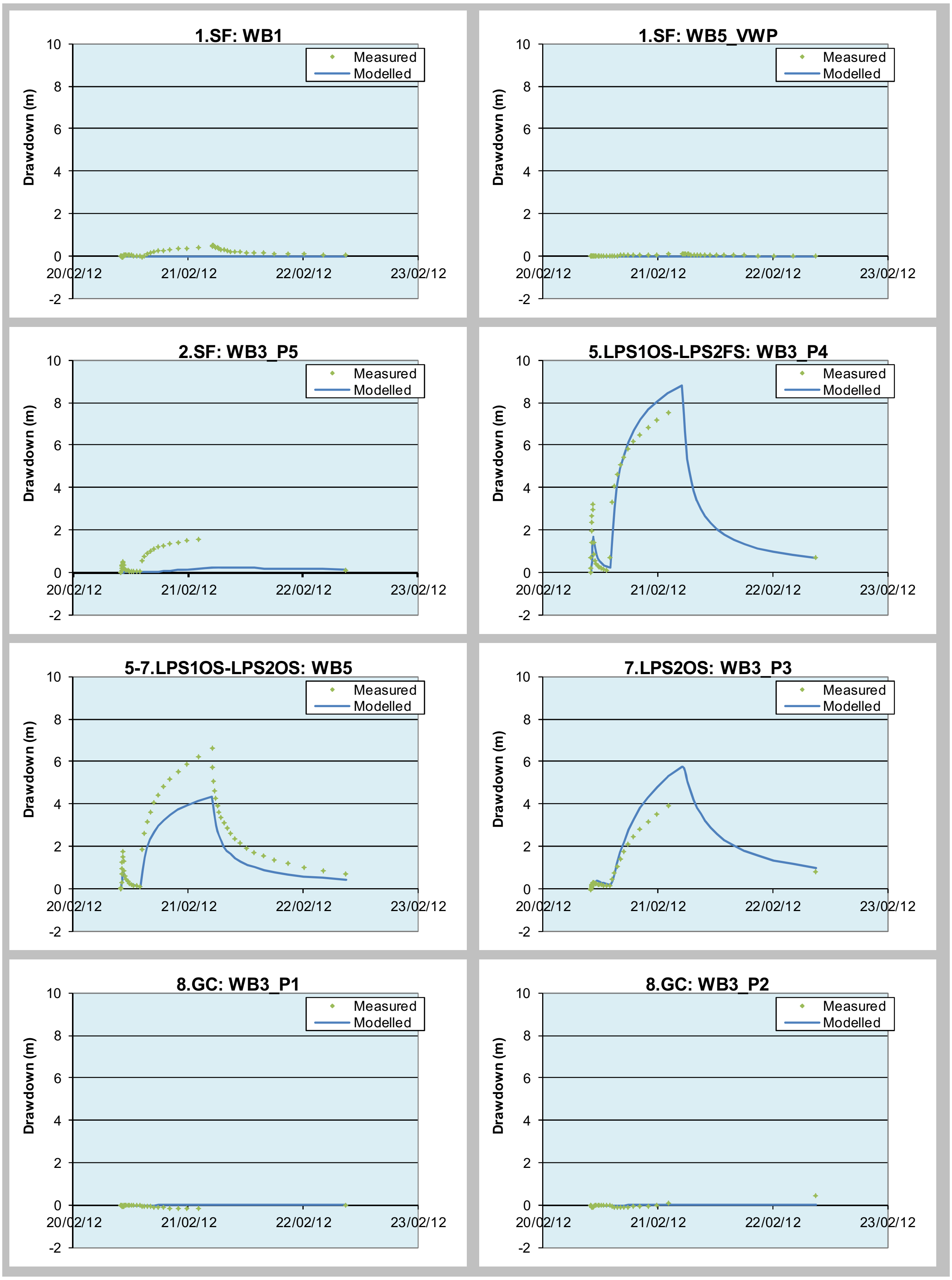


Figure 4.15 : TN1 measured and modelled hydrographs

4.2.3 Turkeys Nest 5

A pumping and injection test was carried out at Turkeys Nest 5 (TN5) during the PFS. The test consisted of production from WB41 for a duration of 7 days and injection of all produced water into WB40. The TN5_1.0 model domain and location of production and monitoring wells are presented in Figure 4.16. Measured and modelled production and injection rates are presented in Figure 4.17.

4.2.3.1 Calibrated aquifer parameters

The calibrated aquifer parameter values obtained through calibration to transient drawdown data obtained during the pumping and injection test at TN5 are presented in Table 4.3.

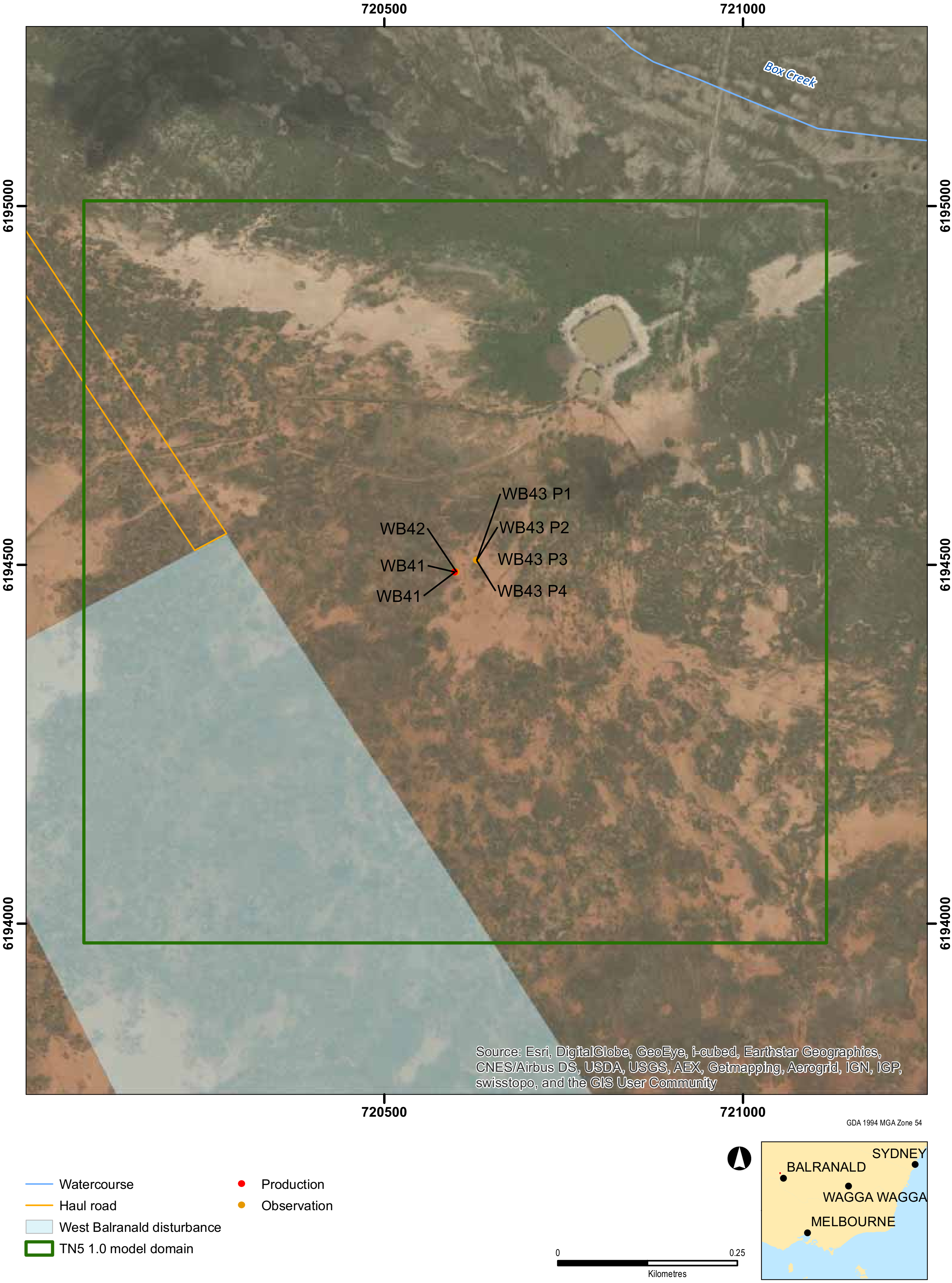
Table 4.3 : TN5 calibrated aquifer parameters

Layer / hydrostratigraphic unit/s	Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)
1 & 2 Shepparton Formation	1	0.001	0.15	3×10^{-5}
3 LPS1 foreshore	0.9	0.001	0.15	3×10^{-5}
4 LPS1 surf zone	24	0.1	0.15	3×10^{-5}
5 LPS1 lower shore / LPS2 foreshore	0.9	0.001	0.15	3×10^{-5}
6 LPS2 surf zone	24	0.1	0.15	3×10^{-5}
7 LPS2 lower shore	0.012	0.001	0.15	3×10^{-5}
8 Geera Clay	0.0001	0.00001	0.15	3×10^{-5}
9 Olney Formation	3	0.3	0.15	3×10^{-5}

4.2.3.2 Performance

A scatter plot of modelled versus measured drawdown for all monitoring locations and times is presented in Figure 4.18. The limited number of monitoring locations results in a plot that clearly displays the responses of several individual monitoring wells. There is a fairly high degree of scatter away from a line of best fit. The Scaled Root Mean Square (SRMS) error associated with this plot is 13.2 %.

Hydrographs of measured and modelled drawdown for all monitoring sites are presented in Figure 4.19. Generally good matches to temporal trends and magnitudes are obtained. However, WB43_P3 responds more rapidly to commencement and cessation of pumping than observed (yet matches the equilibrium drawdown magnitude very well) whilst WB43_P2 (the same horizontal distance as WB43_P3 from the pumped well) responds more slowly than observed. Maps of modelled drawdown in the Shepparton Formation and LPS are presented in Appendix D.



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TN5 1.0 groundwater wells

Figure 4.16

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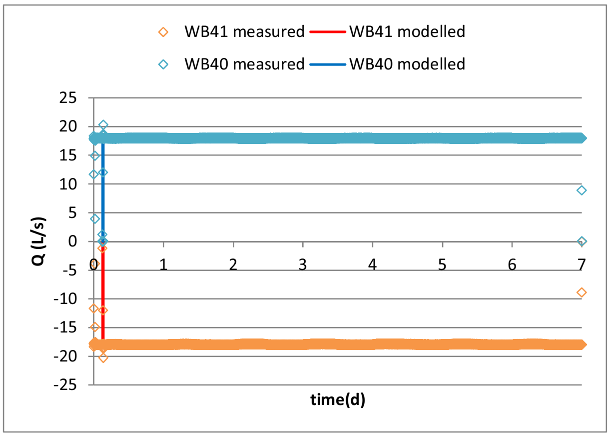


Figure 4.17 : TN5 measured and modelled production and injection

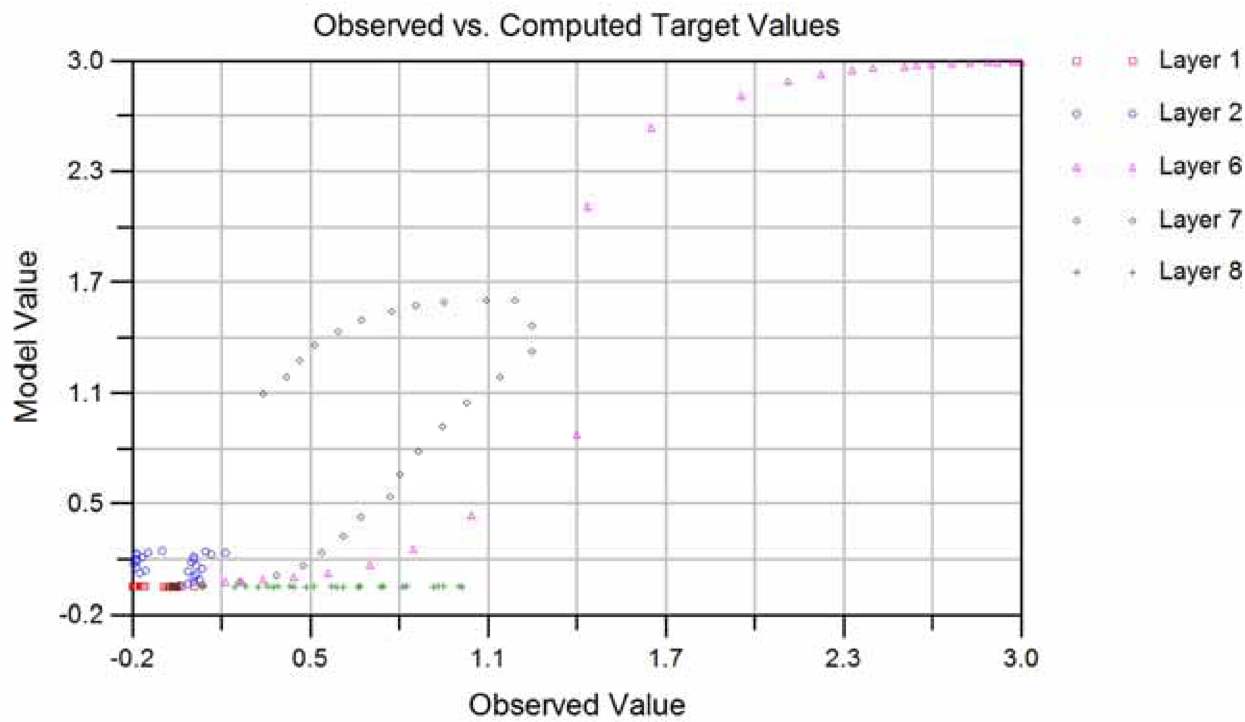


Figure 4.18 : TN5 modelled versus measured drawdown scatter plot

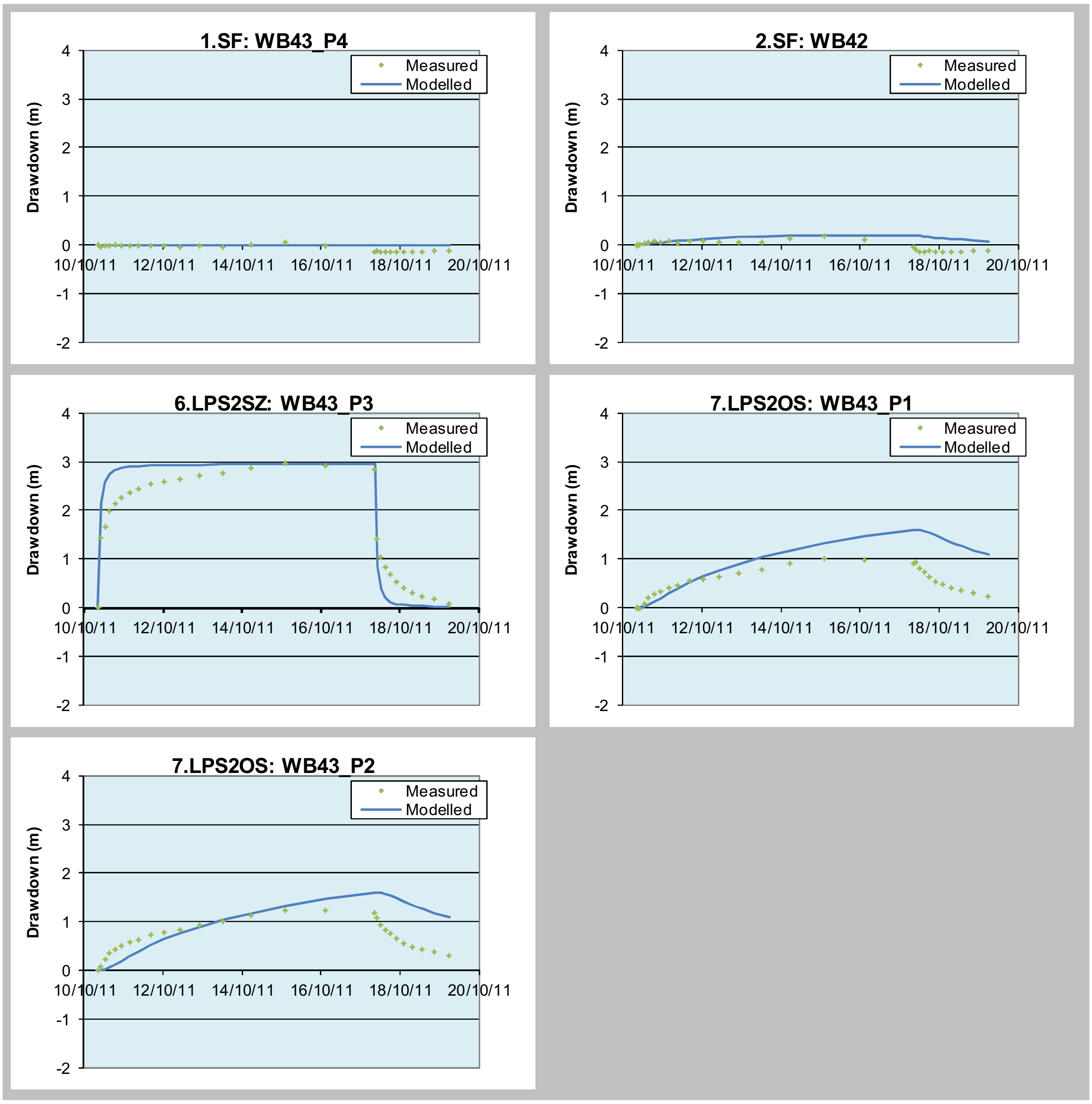


Figure 4.19 : TN5 measured and modelled hydrographs

4.2.4 Nanda

A production and injection test was carried out at "Nanda" during the DFS. The test consisted of production from well WBIW15 for a duration of 4.77 days. Water produced during the test was injected into well WBPW04. The Nanda1.0 model domain and location of production, injection and monitoring wells are presented in Figure 4.20. Measured and modelled production and injection rates are presented in Figure 4.21.

4.2.4.1 Calibrated aquifer parameters

The calibrated aquifer parameter values obtained through calibration to transient drawdown data during the pumping and injection test at "Nanda" are presented in Table 4.4. The calibration process indicated that the aquifer properties at the injection site must be significantly different to those at the production site. Consequently, the LPS2 surf zone was assigned different values at each location. With no obvious structural or spatial drawdown data to indicate where this transition should occur, the surf zone was simply split into two equally sized zones; one for the northern half and one for the southern half of the model domain.

Table 4.4 : "Nanda" calibrated aquifer parameters

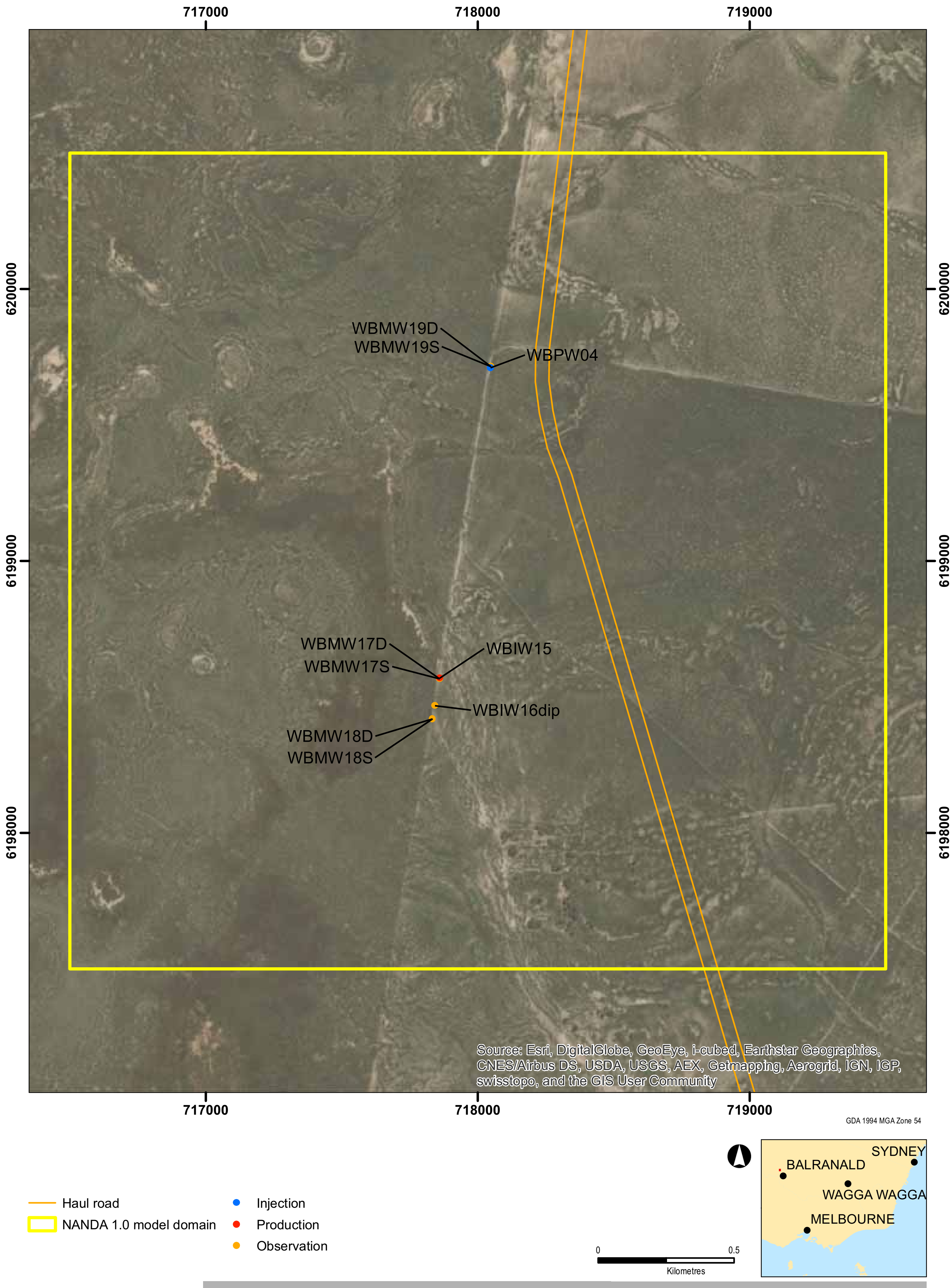
Layer / hydrostratigraphic unit/s	Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)
1 & 2 Shepparton Formation	1	0.001	0.15	3×10^{-5}
3 LPS1 foreshore	0.9	0.001	0.15	3×10^{-5}
4 LPS1 surf zone	20	0.1	0.15	3×10^{-5}
5 LPS1 lower shore / LPS2 foreshore	0.9	0.001	0.15	3×10^{-5}
6 LPS2 surf zone	$10^{\#}$, 40*	0.1	0.15	3×10^{-5}
7 LPS2 lower shore	0.9	0.001	0.15	3×10^{-5}
8 Geera Clay	0.0001	0.00001	0.15	3×10^{-5}
9 Olney Formation	3	0.3	0.15	3×10^{-5}

assigned to southern half of "Nanda", * assigned to northern half of "Nanda"

4.2.4.2 Performance

A scatter plot of modelled versus measured drawdown for all monitoring locations and times is presented in Figure 4.22. Generally a good fit to measured drawdown is produced. However, modelled drawdown at several individual locations can be seen to deviate further from measured values with increased drawdown magnitude (i.e. early time data matches better than data as the system approaches equilibrium under pumped conditions). The Scaled Root Mean Square (SRMS) error associated with this plot is 7.5 %.

Hydrographs of measured and modelled drawdown for all monitoring sites are presented in Figure 4.23. Generally good matches to temporal trends are obtained. However, drawdown magnitude at several wells is not matched particularly well. Whilst the match to an individual well could be improved, it resulted in a poorer match at other wells. The accepted calibration represents a compromise such that all affected wells are equally well calibrated. Plan view modelled drawdown in the Shepparton Formation and LPS are presented in Appendix D.



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Nanda1.0 groundwater wells

Figure 4.20

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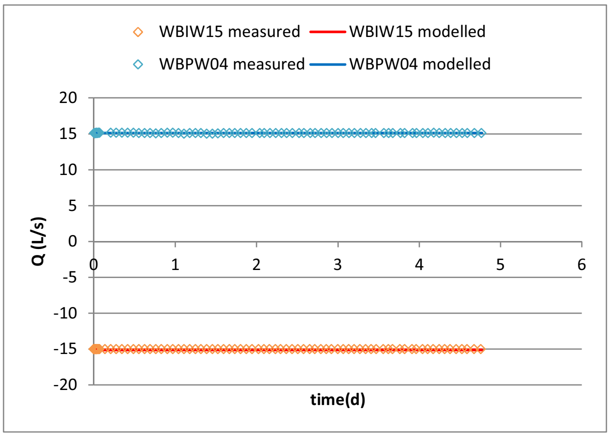


Figure 4.21 : "Nanda" measured and modelled production and injection

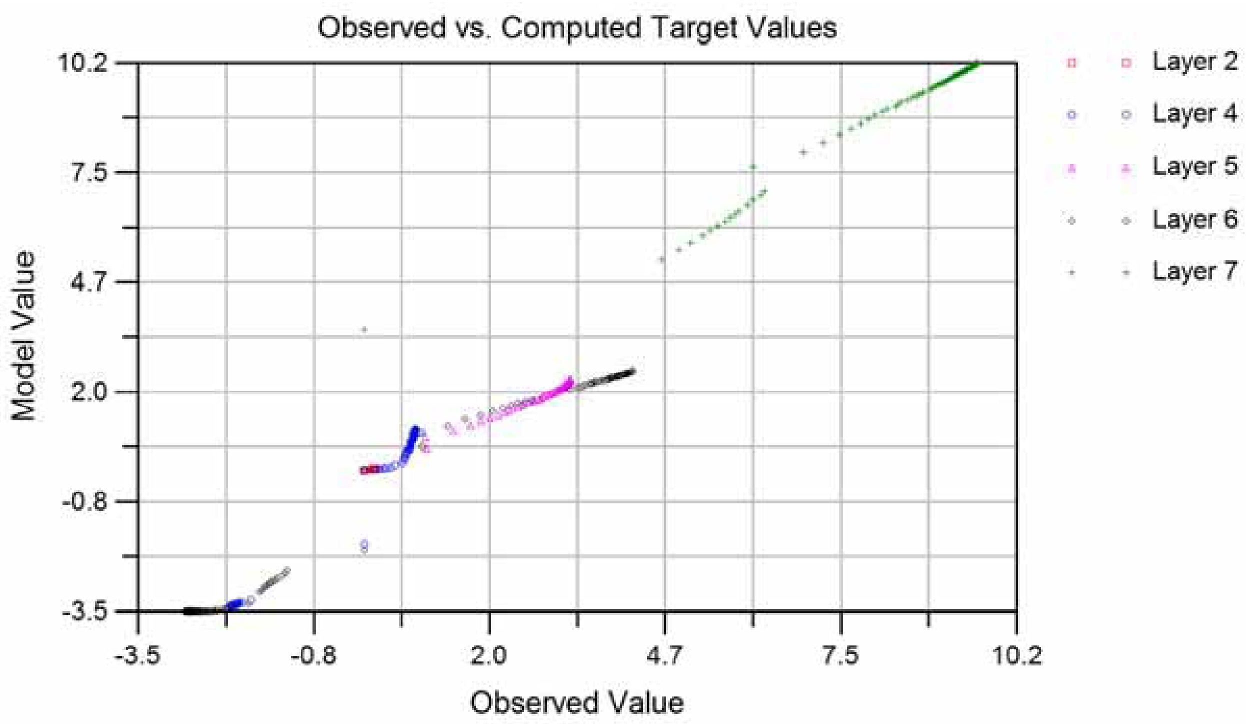


Figure 4.22 : "Nanda" modelled versus measured drawdown scatter plot

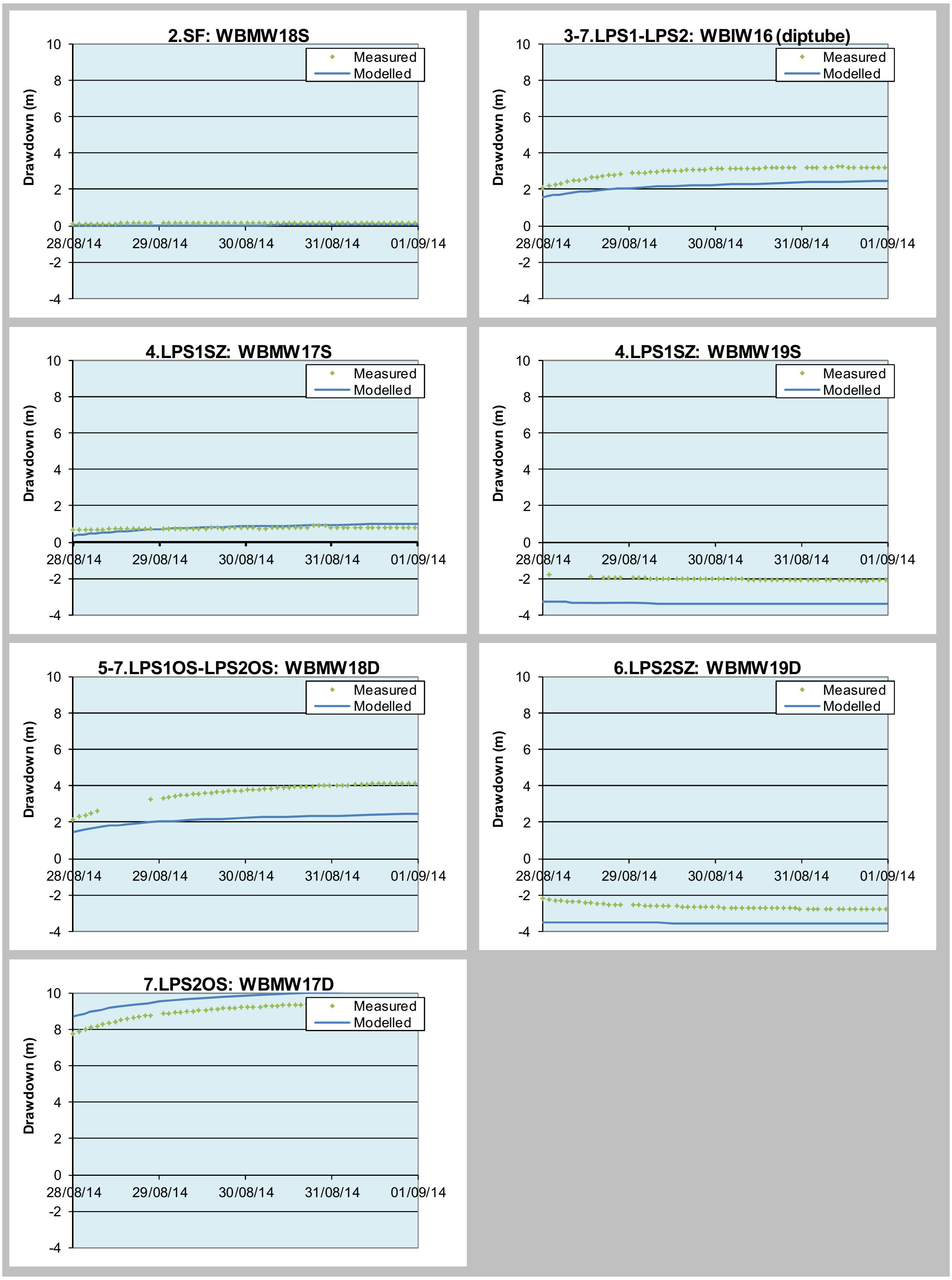


Figure 4.23 : "Nanda" measured and modelled hydrographs

4.2.5 Upson Downs

A production and injection test was carried out at “Upson Downs” during the DFS. The test consisted of production pumping from well WBPW03A for a duration of 6.8 days. Water produced during the test was injected into well WBIW13. The UD1.0 model domain and location of production, injection and monitoring wells are presented in Figure 4.24. Measured and modelled production and injection rates are presented in Figure 4.25.

4.2.5.1 Calibrated aquifer parameters

The aquifer parameter values obtained through calibration to transient drawdown data obtained during the pumping and injection test at “Upson Downs” are presented in Table 4.5.

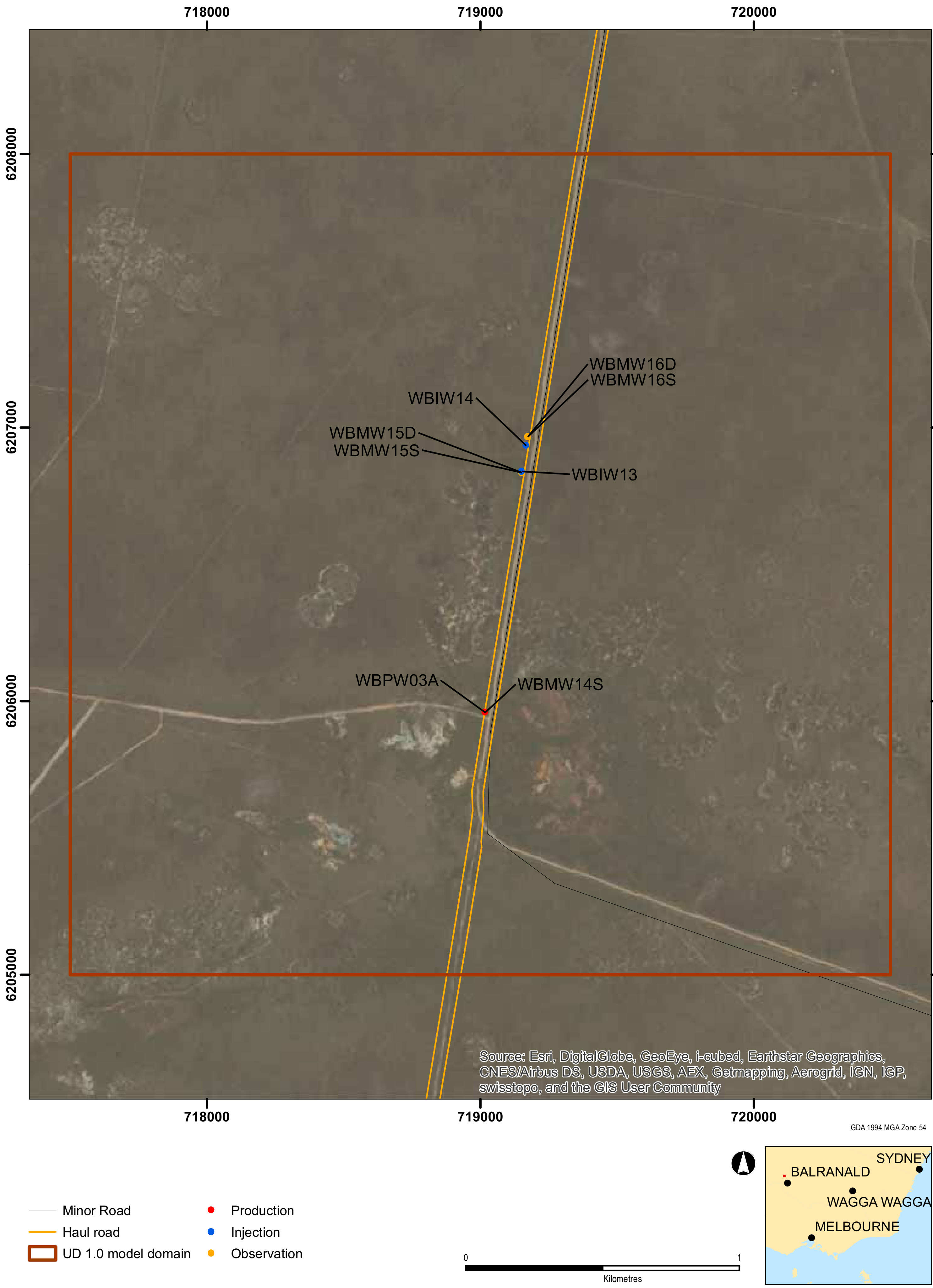
Table 4.5 : “Upson Downs” calibrated aquifer parameters

Layer / hydrostratigraphic unit/s	Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)
1 & 2 Shepparton Formation	1	0.001	0.15	3×10^{-5}
3 LPS1 foreshore	0.9	0.005	0.15	3×10^{-5}
4 LPS1 surf zone	20	0.1	0.15	3×10^{-5}
5 LPS1 lower shore / LPS2 foreshore	0.9	0.001	0.15	3×10^{-5}
6 LPS2 surf zone	17	0.1	0.15	3×10^{-5}
7 LPS2 lower shore	0.9	0.001	0.15	3×10^{-5}
8 Geera Clay	0.0001	0.00001	0.15	3×10^{-5}
9 Olney Formation	3	0.3	0.15	3×10^{-5}

4.2.5.2 Performance

A scatter plot of modelled versus measured drawdown for all monitoring locations and times is presented in Figure 4.26. Modelled data generally correlate well with measured data. The exceptions are the data for model layer 9 which are all for WBMW15D (discussed below). The Scaled Root Mean Square (SRMS) error associated with this plot is 11.8 %.

Hydrographs of measured and modelled drawdown for all monitoring sites are presented in Figure 4.27. Most wells display an excellent match to temporal responses and a good match to drawdown magnitudes. However, a poor match is obtained for WBMW15D. Preliminary log data available at the time of calibration suggested this well was screened in the Geera Clay, yet a mounding of approximately 1 m is observed during the trial. Iluka has since carried out thorough analysis and it is now known that the well is screened in the LPS2 lower shore. The results presented here are for the well screen modelled in the Geera Clay, as it was thought to be. Calibration performance would probably improve if the modelled well screen location was moved to the LPS2 lower shore, where a greater drawdown response is modelled. Maps of modelled drawdown in the Shepparton Formation and LPS are presented in Appendix D.



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UD1.0 groundwater wells

Figure 4.24

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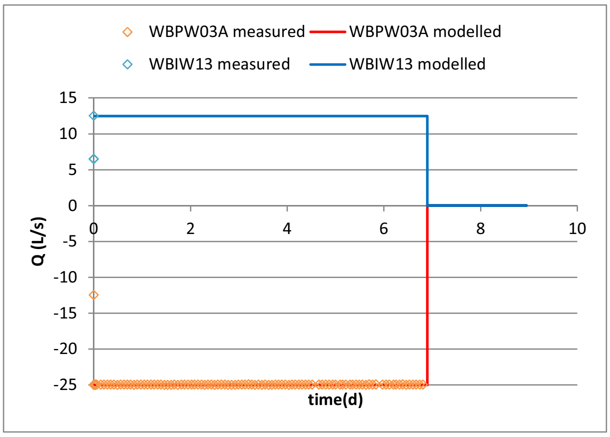


Figure 4.25 : “Upson Downs” measured and modelled production and injection

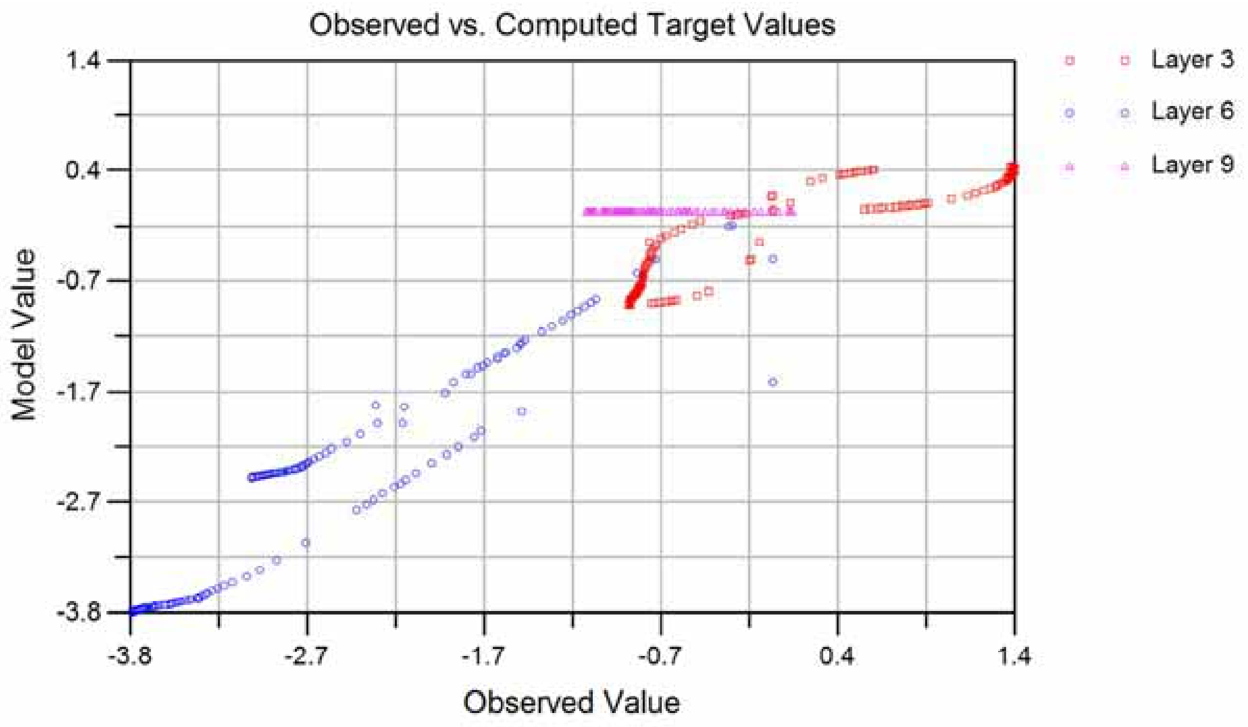


Figure 4.26 : “Upson Downs” modelled versus measured drawdown scatter plot

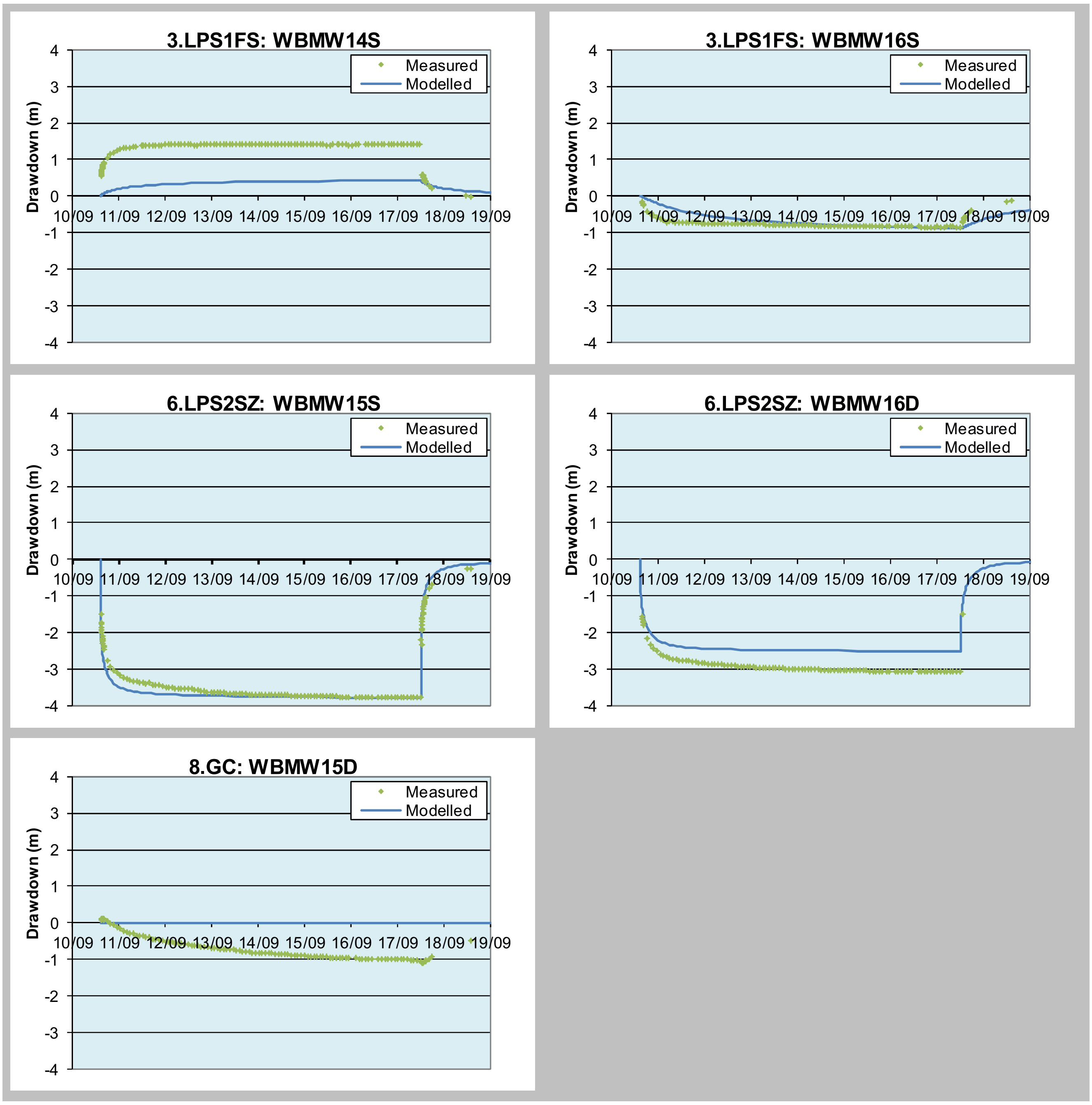


Figure 4.27 : “Upson Downs” measured and modelled hydrographs

4.3 Steady state calibration

Monitoring wells with long-term records suggest that, on a regional scale, the pre-development groundwater system is currently in a pseudo steady state, with no significant seasonal variations or long term trends in potentiometric surfaces (see Figure 2.11). Steady state hydraulic head calibration targets were prepared by averaging observations over the unstressed periods of measurement at individual wells located across the study area. Aquifer parameters were obtained from the local-scale transient calibration models and applied to the regional model domain. The model was run in steady state to validate the selected aquifer parameter values and to calibrate the modelled boundary conditions, recharge and discharge features.

4.3.1 Aquifer parameters

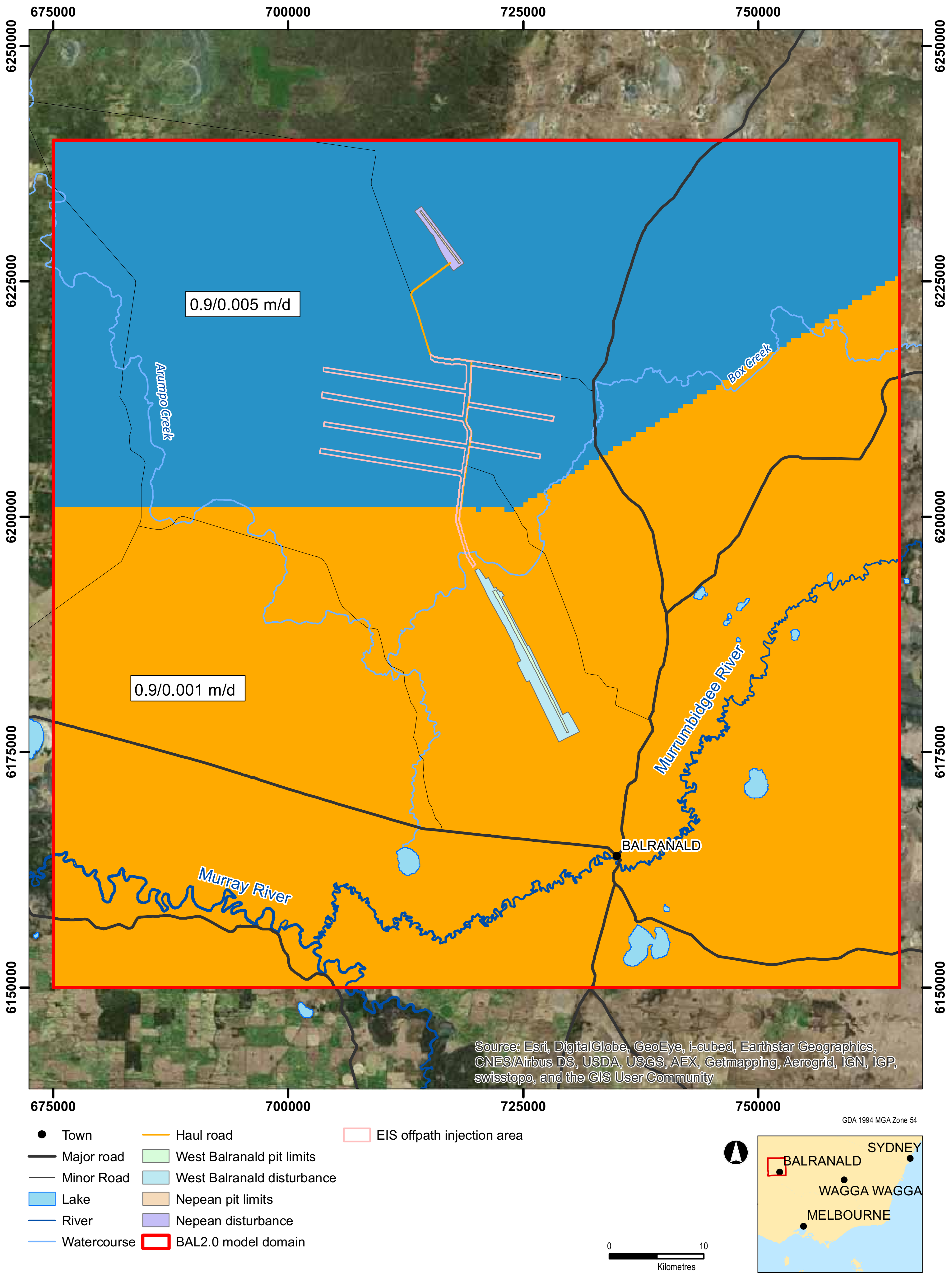
Steady state calibration is insensitive to the values assigned to storage properties. However, for completeness it is mentioned here that predictions made using the BAL2.0 model employ uniform distributions of the storage properties used/identified in the local-scale transient calibration models. Specific yield (Sy) is assigned a value of 0.15 and specific storage (Ss) a value of 3×10^{-5} 1/m.

The aquifer parameter values determined through calibration to transient drawdown data in the local-scale models are presented in Table 4.6. Where uniform parameter values were not obtained for a model layer, the values obtained at the local-scale trial sites were interpolated and extrapolated across the BAL2.0 model domain via a series of zones. These zones are presented in Figure 4.28 to Figure 4.31.

Table 4.6 : BAL2.0 calibrated aquifer parameters

	LTT		**TN1**		**TN5**		**“Nanda” (south)**		**“Upson Downs”**	
Layer/hydrostratigraphic unit	Kh (m/d)	Kv (m/d)	Kh (m/d)	Kv (m/d)	Kh (m/d)	Kv (m/d)	Kh (m/d)	Kv (m/d)	Kh (m/d)	Kv (m/d)
1 & 2 Shepparton Formation	1	0.001	1	0.001	1	0.001	1	0.001	1	0.001
3 LPS1 foreshore	0.9	0.001	0.9	0.001	0.9	0.001	0.9	0.001	0.9	**0.005**
4 LPS1 surf zone	**16**	0.1	20	0.1	**24**	0.1	20	0.1	20	0.1
5 LPS1 lower shore / LPS2 foreshore	0.9	0.001	0.9	0.001	0.9	0.001	0.9	0.001	0.9	0.001
6 LPS2 surf zone	**16**	0.1	**20**	0.1	**24**	0.1	**10 (40*)**	0.1	**17**	0.1
7 LPS2 lower shore	0.9	0.001	**0.13**	0.001	**0.012**	0.001	0.9	0.001	0.9	0.001
8 Geera Clay	0.0001	0.00001	0.0001	0.00001	0.0001	0.00001	0.0001	0.00001	0.0001	0.00001
9 Olney Formation	3	0.3	3	0.3	3	0.3	3	0.3	3	0.3

* assigned to northern half of “Nanda”, **bold** indicates values that differ from the value applied regionally



JACOBS

Hydraulic conductivity zones (Kh/Kv) applied to LPS1 foreshore

Figure 4.28

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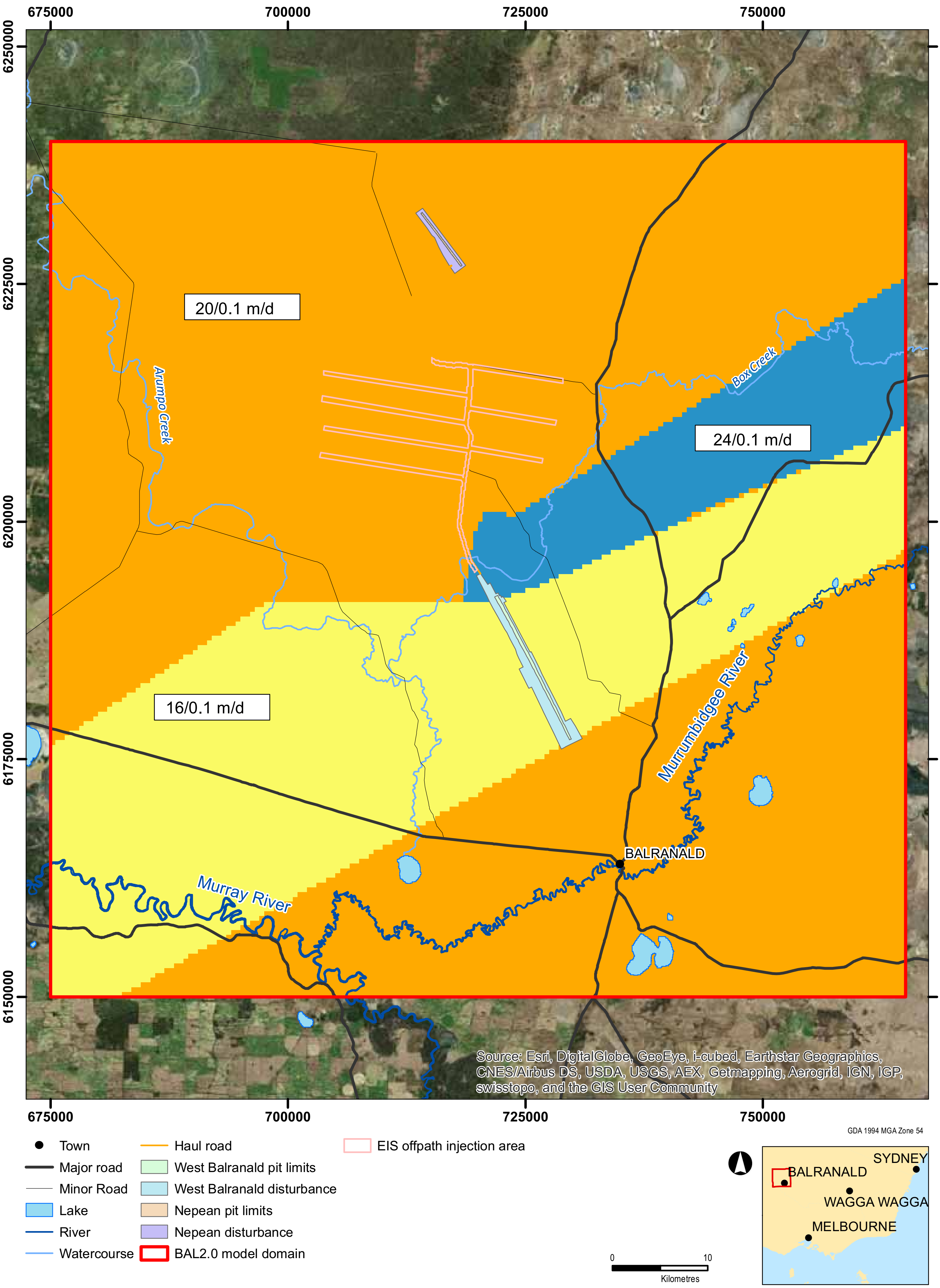

JACOBS

Hydraulic conductivity zones (Kh/Kv) applied to LPS1 surf zone

Figure 4.29

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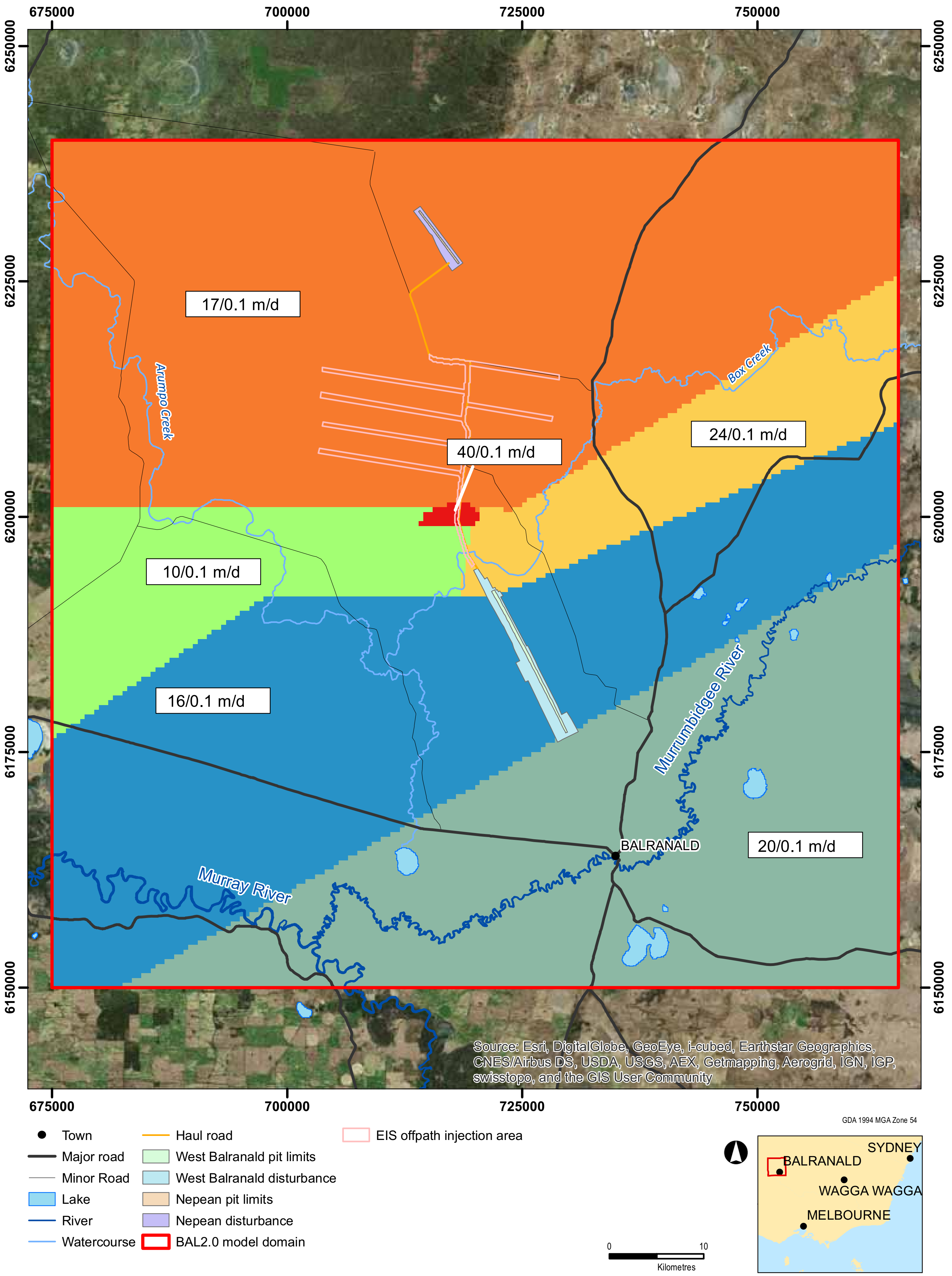

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Hydraulic conductivity zones (Kh/Kv) applied to LPS2 surf zone

Figure 4.30

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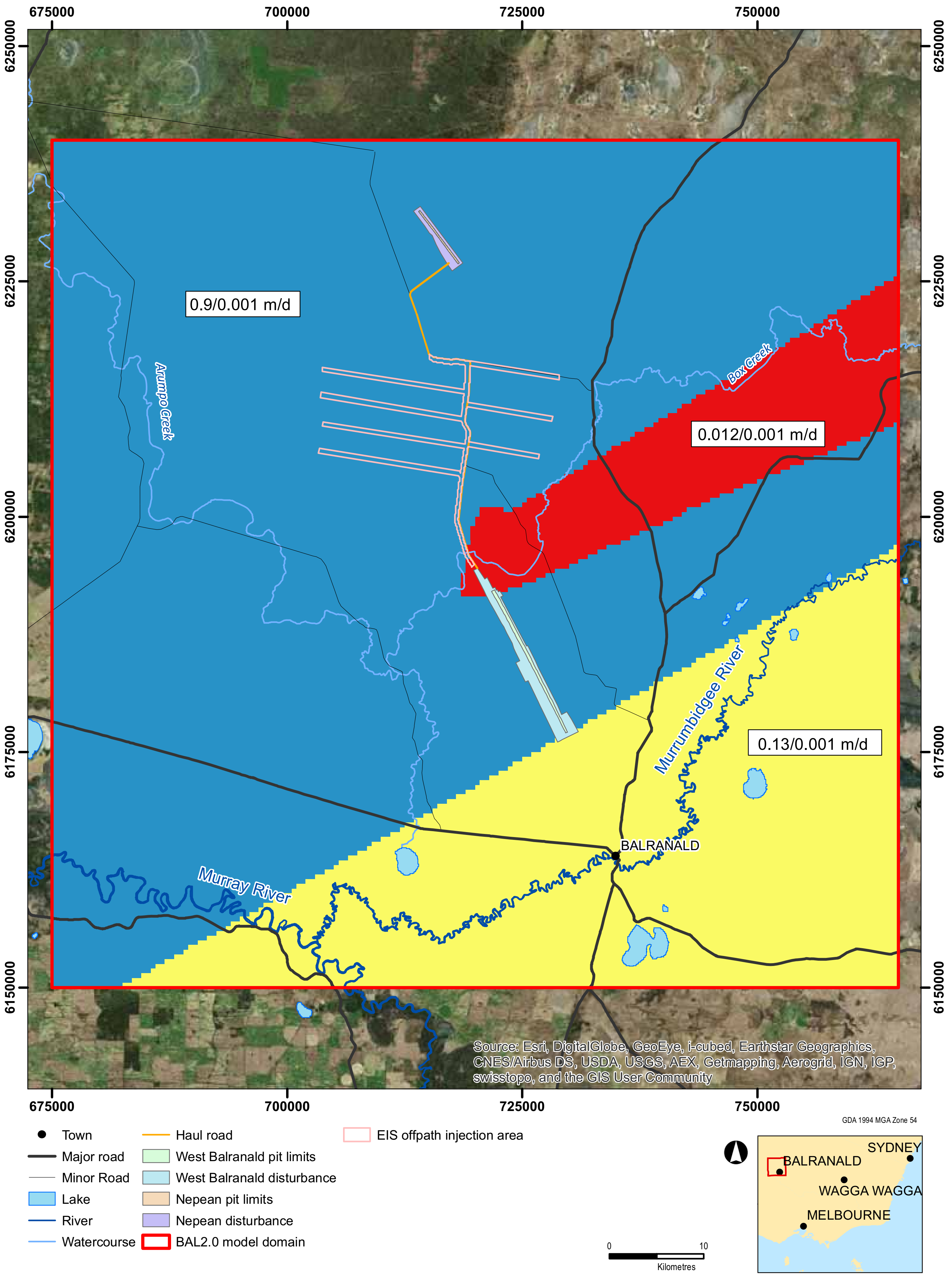

JACOBS

Hydraulic conductivity zones (Kh/Kv) applied to LPS2 lower shore

Figure 4.31

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Rainfall recharge was assigned uniformly across the model at 0.0365 mm/yr. Steady state calibration was very sensitive to this parameter. Increasing this rate even a small amount causes the modelled water table elevation to rise far above the measured heads.

Evapotranspiration was assigned a maximum rate of 2,000 mm/yr and an extinction depth of 3 m. Groundwater is removed by modelled evapotranspiration only at localised features coincident with topographic depressions and/or near the rivers where the water table is relatively shallow (i.e. within 3 m of the surface).

4.3.2 Performance

A scatter plot of modelled versus measured hydraulic heads for all monitoring locations is presented in Figure 4.32. Modelled data generally correlate well with measured data but there is a moderate level of scatter around a line of best fit. The Scaled Root Mean Square (SRMS) error associated with this plot is 11.2 %.

One likely contributing factor to the scatter is the lack of well completion information in the OW groundwater database. Records for many wells do not indicate the screened hydrostratigraphic unit, providing only a total drilled depth with no well log available. In such circumstances the wells are assigned to the model layer in which that depth is encountered. An indicator of the likely errors introduced by this lack of information is the fact that seven wells are modelled as being screened in the Geera Clay. It is very unlikely that many wells screen only the Geera Clay, due to its low conductivity, but without the information to allocate them otherwise this is the where they are modelled. Similar incorrect well screen allocations are likely for other hydrostratigraphic units.

Probably a greater cause of uncertainty in measured potentiometric levels is the fact that many of the wells in the OW groundwater database are not surveyed. The database records a depth to water. For non-surveyed wells this cannot be accurately converted to a potentiometric level. In such cases the groundwater model topography, with 500 m spacing, has been used to provide a “top of casing” reference elevation, from which to subtract the recorded depth to water. This is likely to introduce several metres of error at some wells. Compounding the errors this introduces to the “measured” potentiometric levels is the fact that, for wells that do not have screened hydrostratigraphy recorded, the DEM must also be used to determine the hydrostratigraphic unit to which the data should be assigned. Therefore both the screened unit and potentiometric surface may be affected by several metres of error.

Therefore, with considerable errors likely in the measured potentiometric levels, a greater than desirable degree of scatter is to be expected. Under such conditions the best approach to assessing the calibration performance is to compare the modelled and measured results in terms of regional-scale flow directions and gradients, because significant local-scale discrepancies will arise.

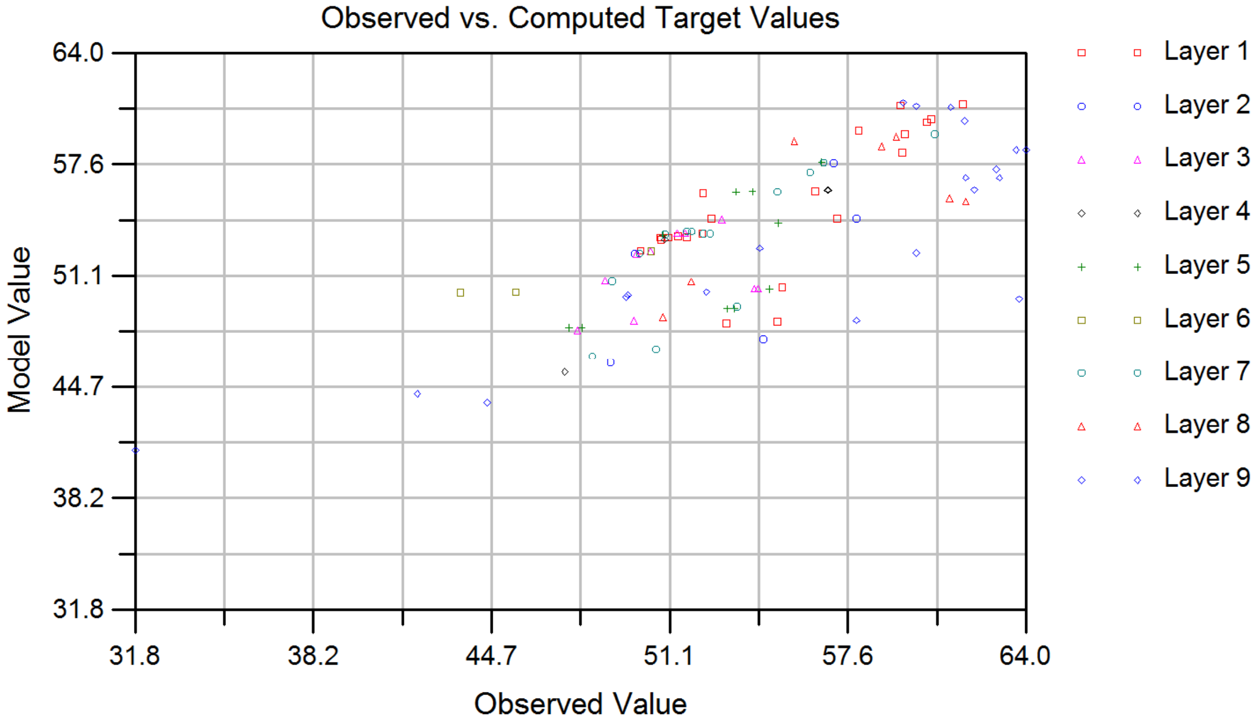


Figure 4.32 : BAL2.0 modelled versus measured steady state hydraulic head scatter plot

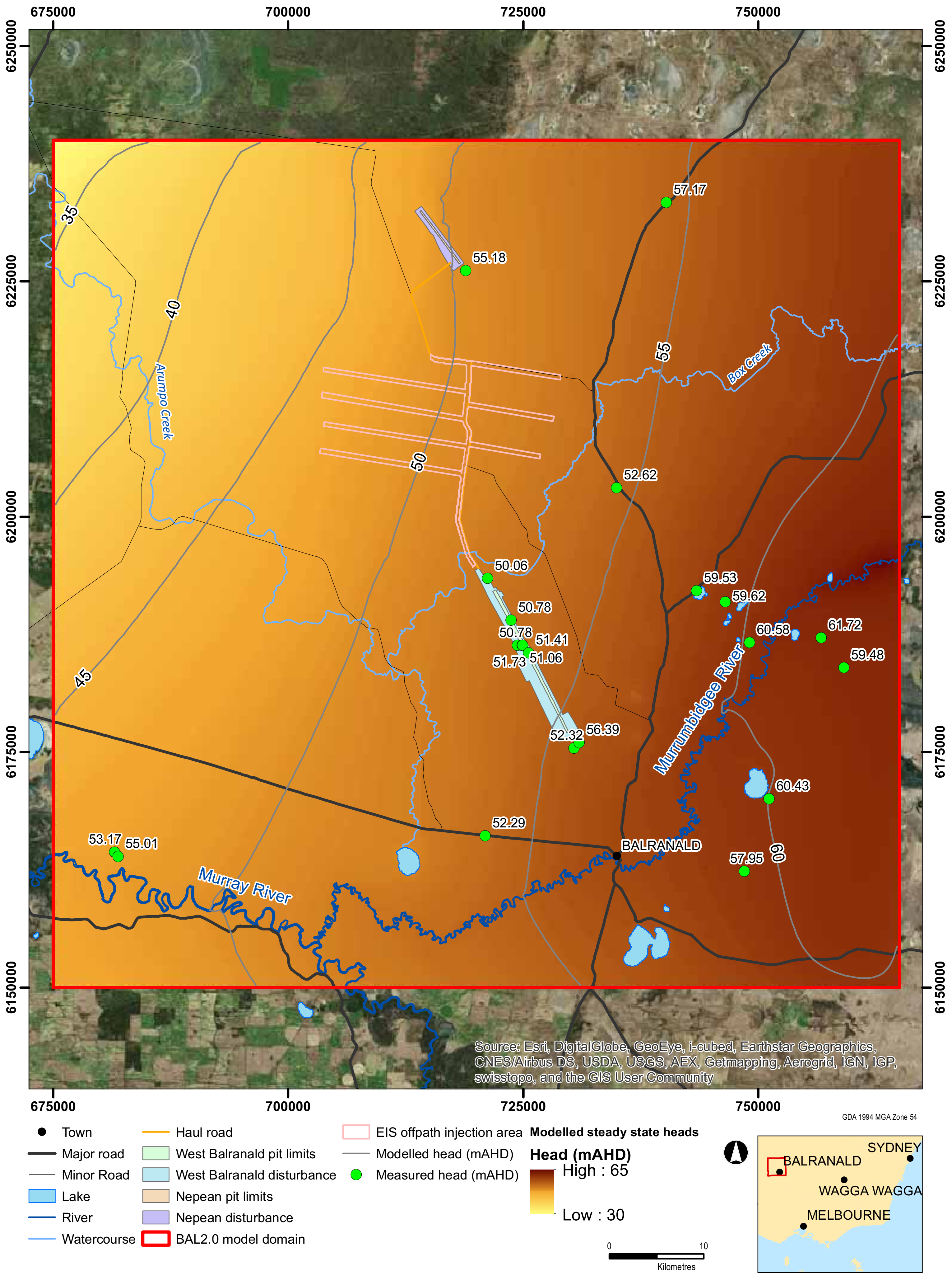
Figure 4.33 to Figure 4.41 present modelled pre-development potentiometric surfaces for the nine model layers. Regional flow directions are consistent with the conceptual model and measured data, with groundwater entering the study area from the east and flowing to the west and north.

Modelled heads in the Shepparton Formation and LPS model layers display evidence of river leakage into the groundwater system across the full width of the model domain.

Heads in the model layers representing the Shepparton Formation and the LPS are very similar, with very little vertical hydraulic gradient evident for the majority of the model area. However, there is a transition in modelled heads through the Geera Clay and, more so, in the Olney Formation. The higher modelled heads in the latter, driven by inflow through the eastern boundary, generate a modelled upward hydraulic gradient through the Geera Clay to the shallower aquifers. This is consistent with observed raw (not modified for groundwater density) hydraulic head data.

Figure 4.42 presents modelled depth to the water table. Along the rivers and for a large area surrounding the West Balranald deposit the water table is shallow, occurring at a depth typically between 5 m and 15 m below ground. Localised areas display modelled depth to water of less than 3 m (indicated by a red contour). These small areas are where modelled evapotranspiration from groundwater occurs, and correspond with locally low topography.

The modelled depth to the water table generally increases towards the north and west. This is a function of two things; water table elevation decreases towards the north-west corner of the study area and topography is elevated around the area of the Iona Ridge which protrudes south into the study area from the northern boundary.



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BAL2.0 cal1 modelled steady state heads in Shepparton Formation (shallow)

Figure 4.33

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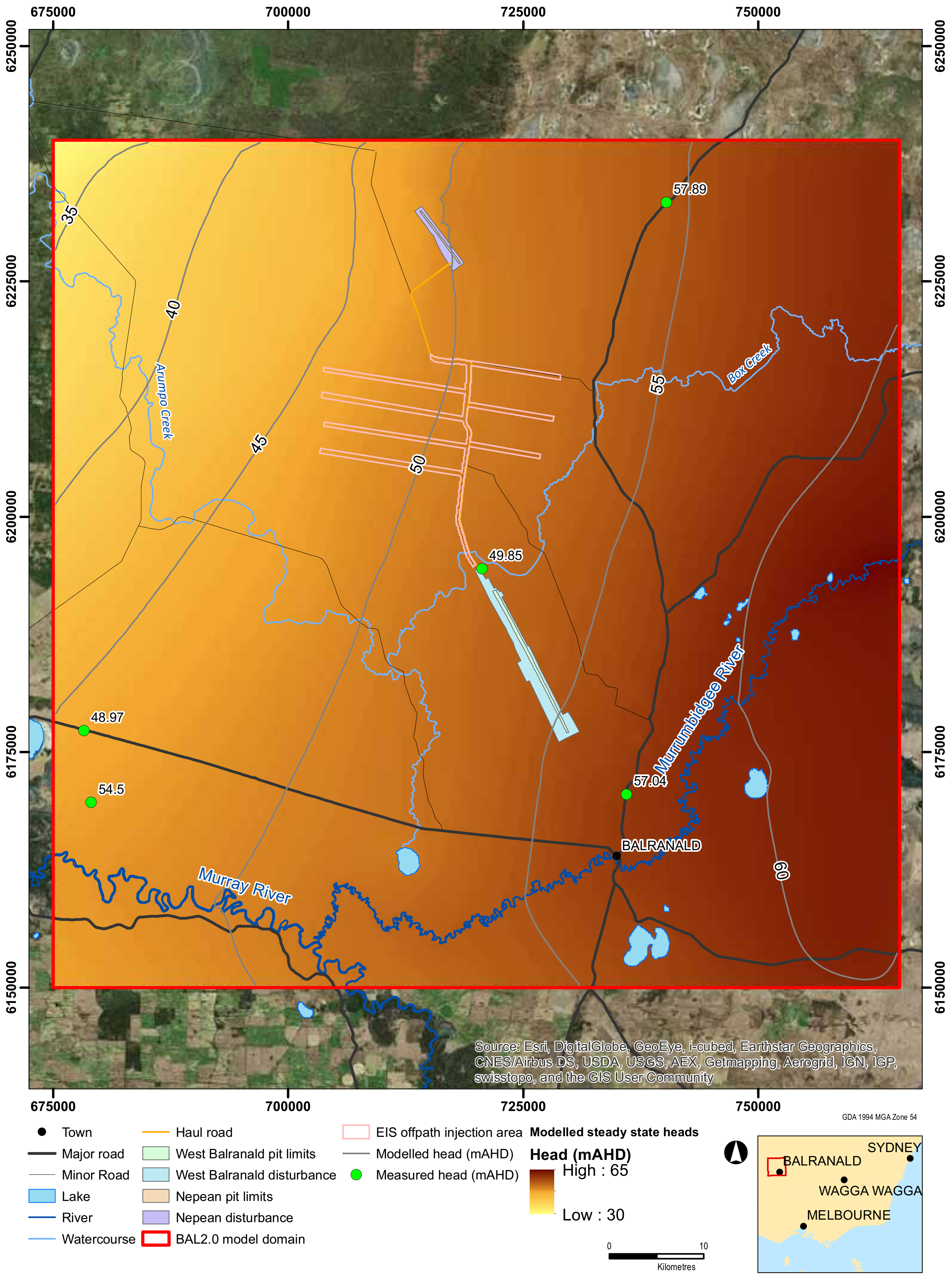

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BAL2.0 cal1 modelled steady state heads in Shepparton Formation (deep)

Figure 4.34

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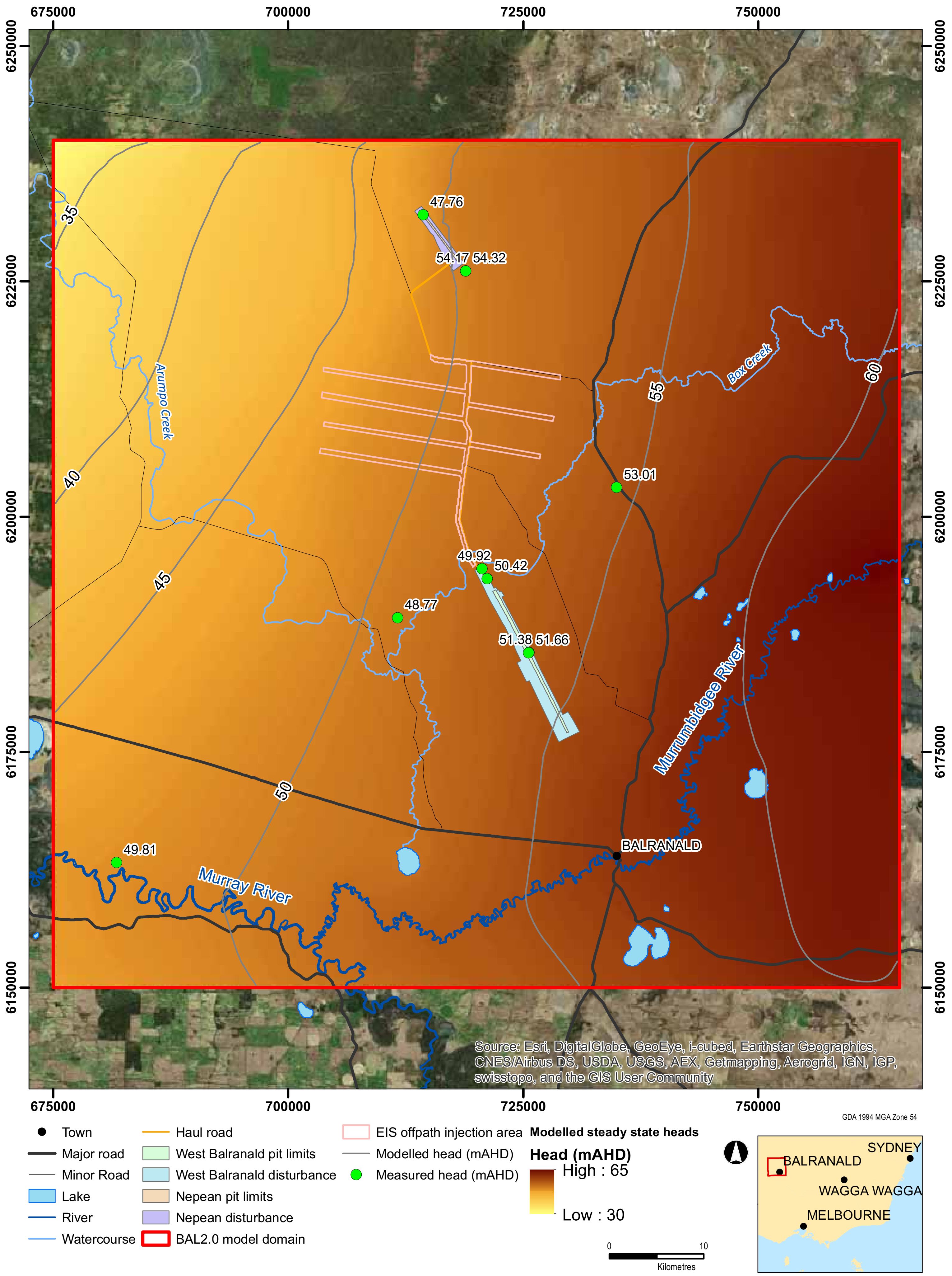

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BAL2.0 cal1 modelled steady state heads in LPS1 foreshore

Figure 4.35

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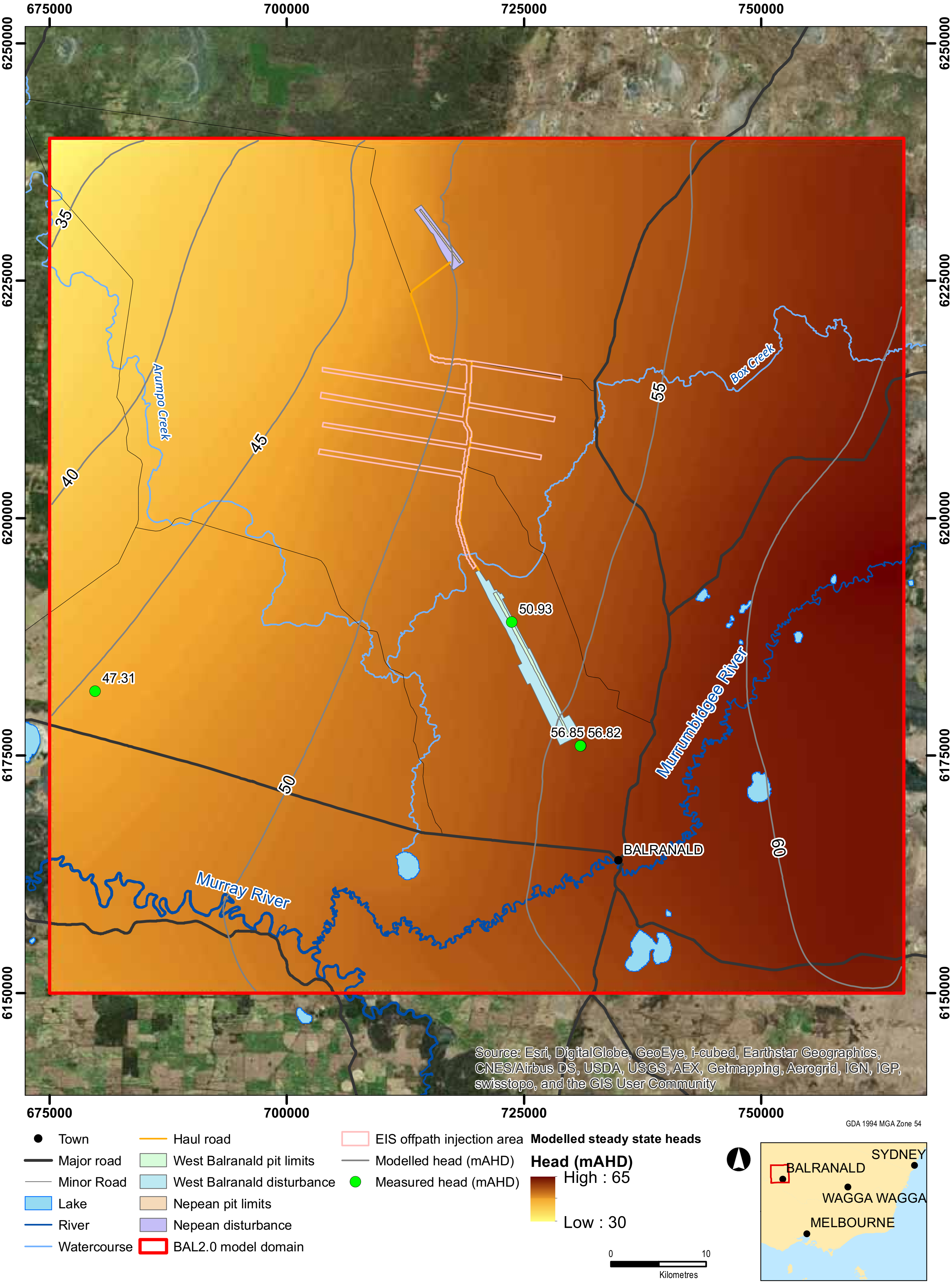

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BAL2.0 cal1 modelled steady state heads in LPS1 surf zone

Figure 4.36

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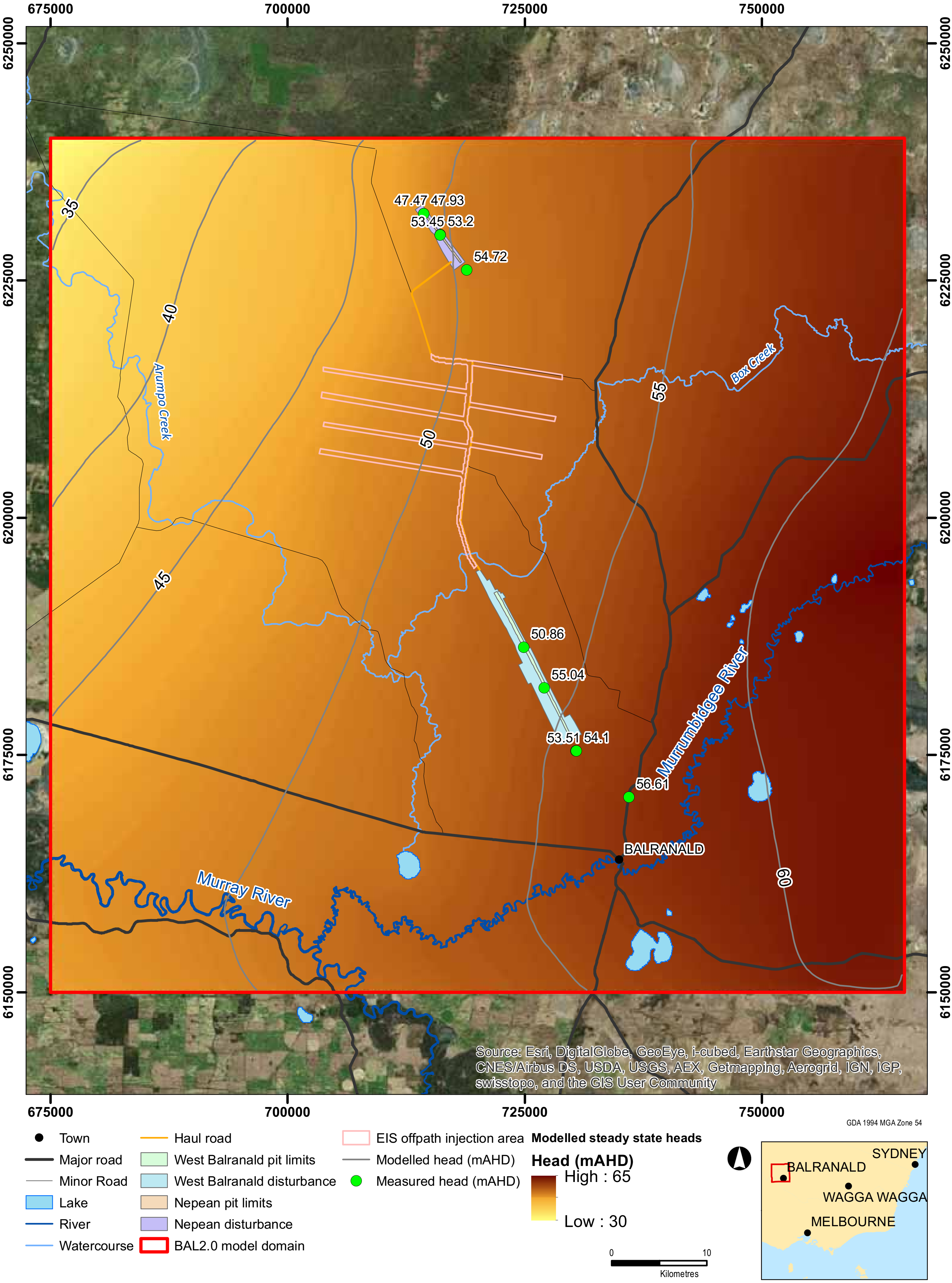

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BAL2.0 cal1 modelled steady state heads in LPS1 lower shore/LPS2 foreshore

Figure 4.37

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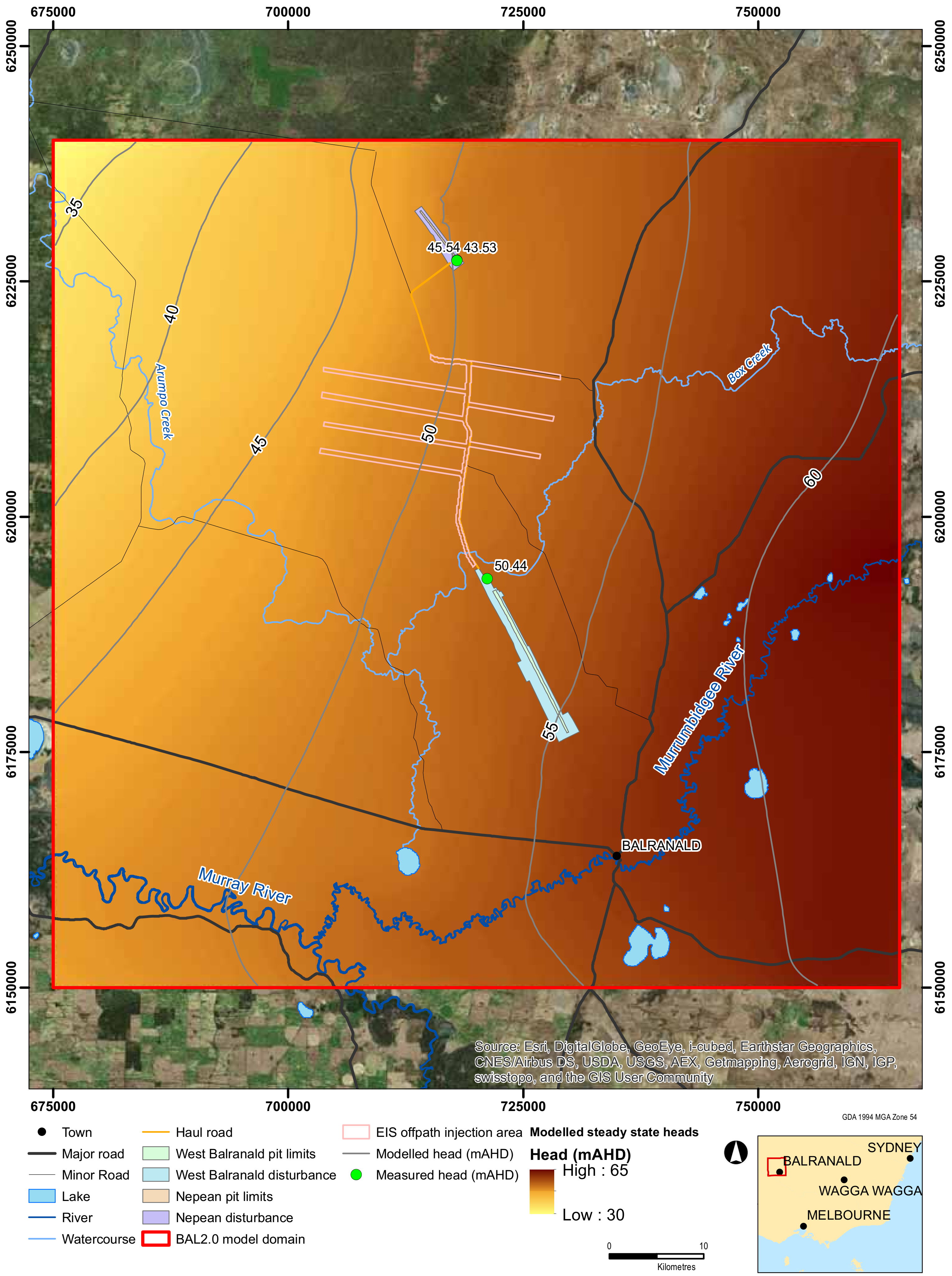

BAL2.0 cal1 modelled steady state heads in LPS2 surf zone

Figure 4.38

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Town
Major road
Minor Road
Lake
River
Watercourse
Haul road
West Balranald pit limits
West Balranald disturbance
Nepean pit limits
Nepean disturbance
BAL2.0 model domain
EIS offpath injection area
Modelled head (mAHD)
Measured head (mAHD)

Modelled steady state heads

Head (mAHD)
High : 65
Low : 30

0 10
Kilometres

JACOBS

BAL2.0 cal1 modelled steady state heads in LPS2 lower shore

Figure 4.39

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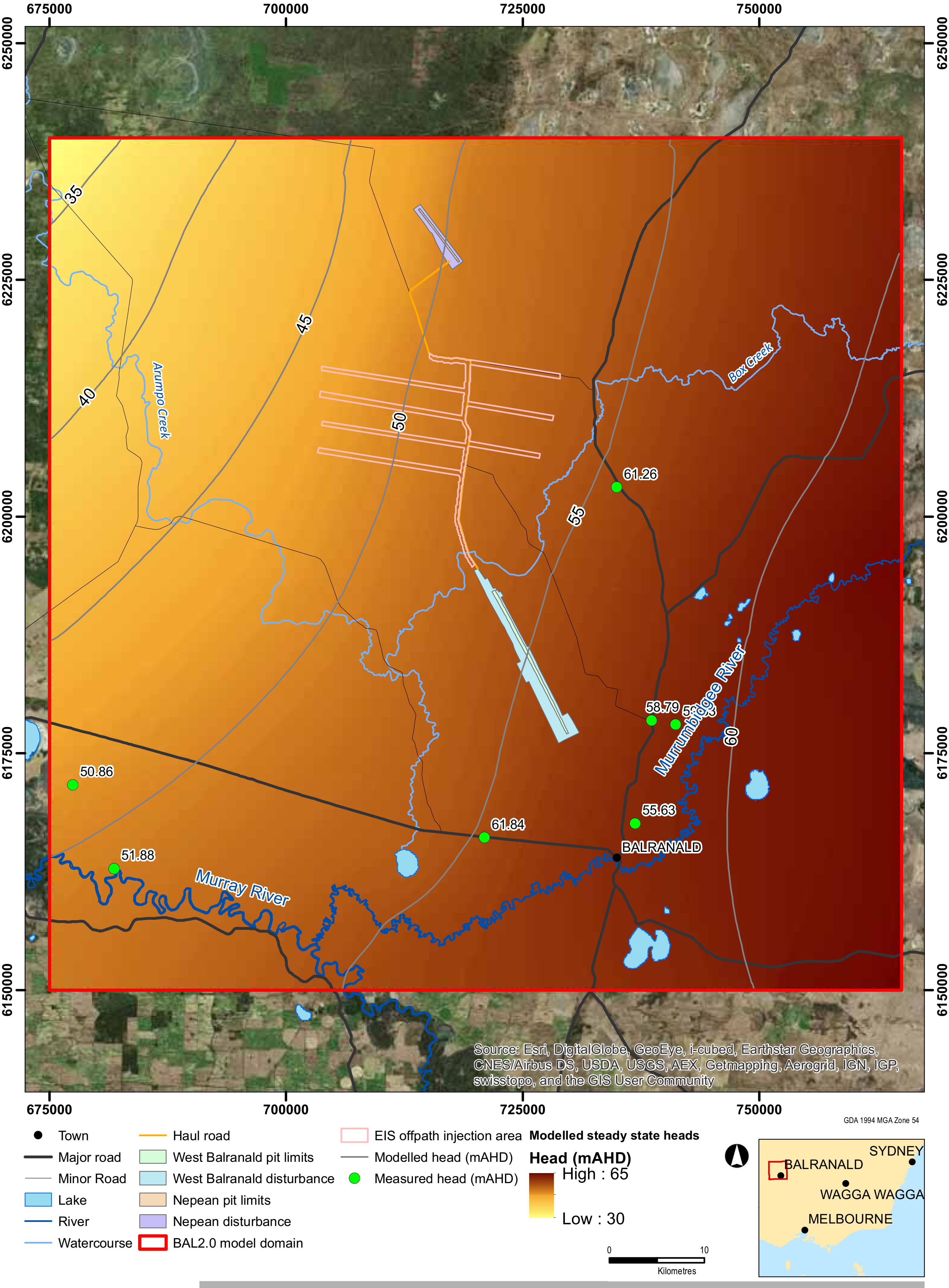

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BAL2.0 cal1 modelled steady state heads in Geera Clay

Figure 4.40

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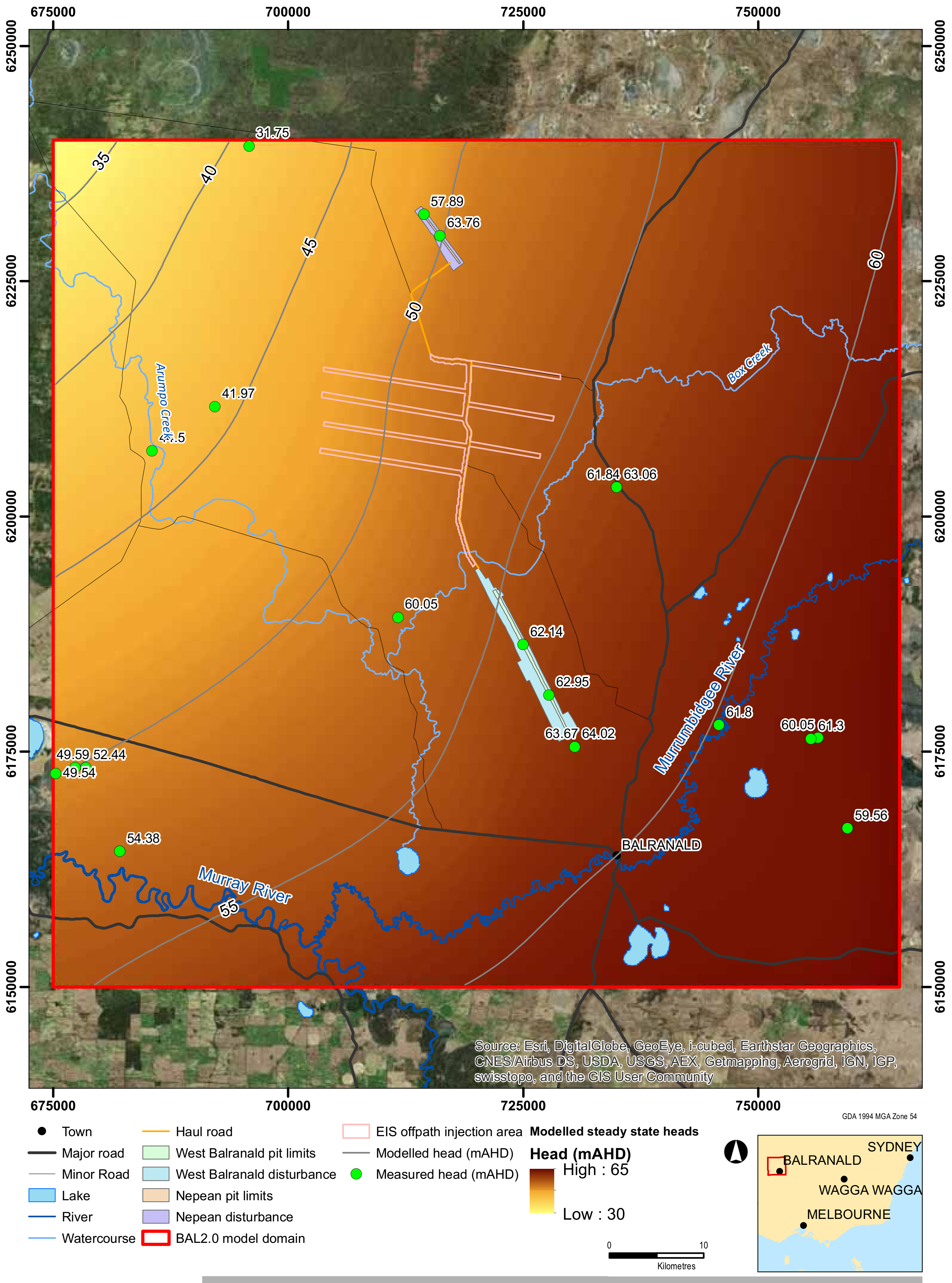

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BAL2.0 cal1 modelled steady state heads in Olney Formation

Figure 4.41

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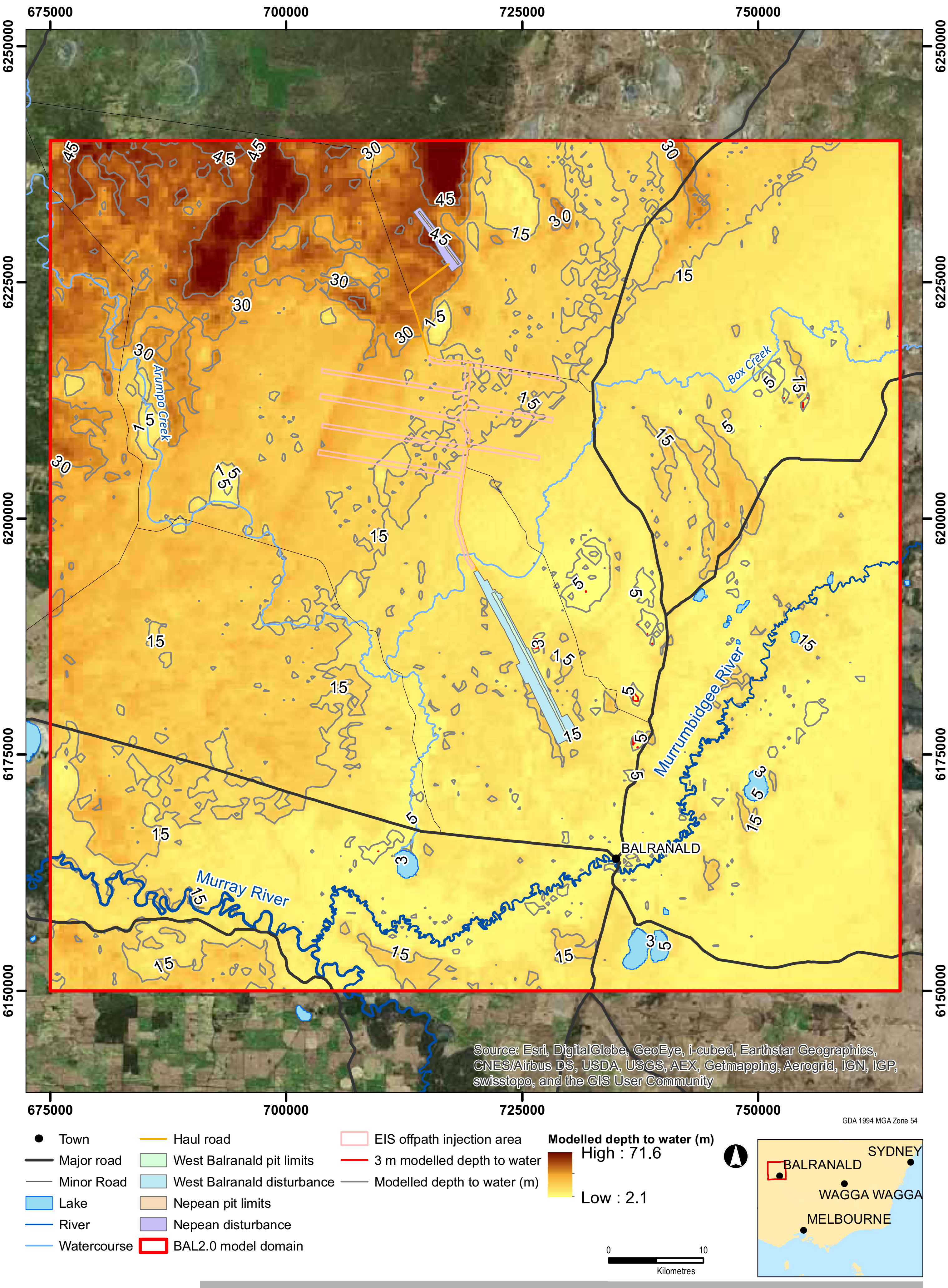

BAL2.0 cal1 modelled depth to water table

Figure 4.42

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4.3.3 Water balance

The modelled pre-development (steady state) water balance is presented in Table 4.7 and graphically in Figure 4.43. Recharge and evapotranspiration are both minor components, indicating that local climate has little effect on the groundwater system. River leakage into the groundwater system is a substantial component, and is much greater than leakage out of the groundwater system into the rivers (i.e. the rivers are modelled as a net losing system). However, by far the greatest component of the water balance is regional throughflow via the model boundaries. This dominates both modelled inflow and outflow. The modelled water balance error is 1 %.

Table 4.7 : Modelled pre-development water balance

	In (ML/yr)	Out (ML/yr)
Recharge	296	-
Evapotranspiration	-	607
River leakage	1,512	97
Boundaries (regional throughflow)	7,831	9,127
TOTAL	9964	10,067

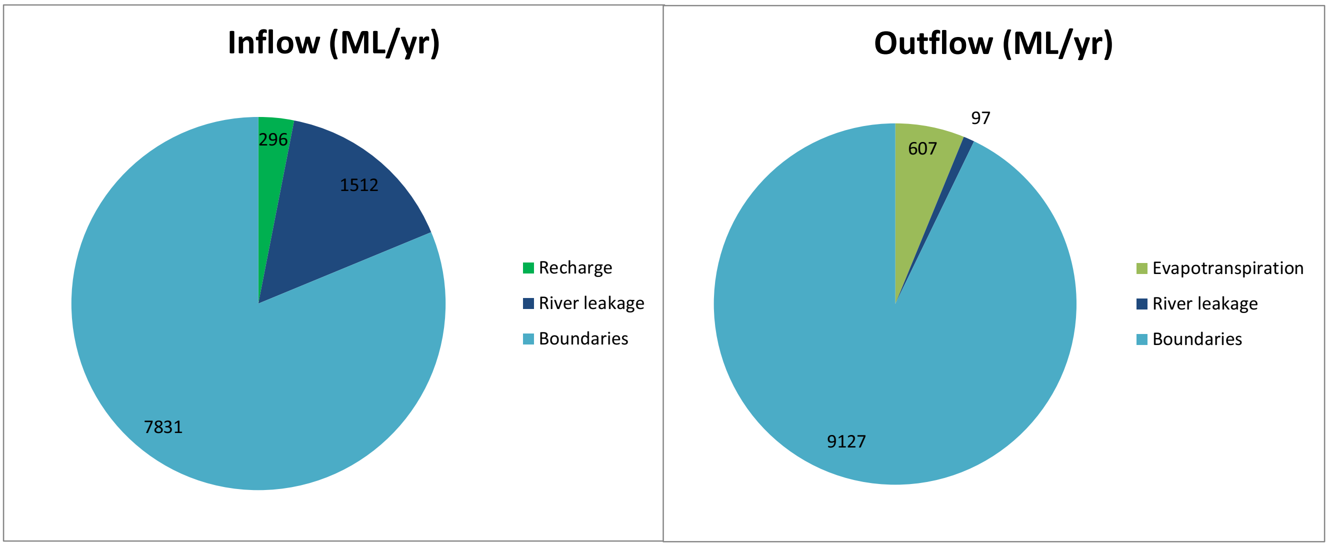


Figure 4.43 : Modelled pre-development steady state water balance

5. Calibration Sensitivity Analysis

5.1 Methodology

An innovative approach to calibration sensitivity analysis was developed to accommodate the calibration method, whereby multiple local-scale models are used to calibrate aquifer parameters by matching modelled and measured drawdown responses to pumping and injection trials. The first step in the analysis involves carrying out individual sensitivity analyses to key aquifer parameters on each of the individual local-scale models. This provides a calibration sensitivity analysis for each of the local-scale models. The SRMS values returned from each of the models are then averaged to provide an indicative quantification of the calibration sensitivity of the regional BAL2.0 model.

The transient calibration approach allows aquifer parameter values to vary from one local-scale model to another and, in the Nanda1.0 model, even within a model. The result is that the BAL2.0 regional model employs a number of spatial zones of differing hydraulic properties within model layers. In order to account for the heterogeneity represented in the model parameterisation, the sensitivity analysis does not test uniform parameter values but, instead, applies a multiplier to the calibrated aquifer parameter values. In this way the sensitivities of the individual local-scale models and, by inference, the BAL2.0 model to scalar changes in parameter values are quantified. The multipliers assigned are 0.2, 0.5, 0.7, 0.8, 1, 1.1, 1.2, 1.5, 2 and 5. The key parameters selected for sensitivity investigation are:

- Shepparton Formation Kh;
- Shepparton Formation Kv;
- LPS surf zones Kh;
- LPS surf zones Kv;
- LPS non-surf zones Kh;
- LPS non-surf zones Kv;
- Geera Clay Kv;
- Olney Formation Kh;
- Sy (uniform across all layers); and
- Ss (uniform across all layers).

5.2 Long Term Trial

Sensitivity of the LTT1.0 transient calibration to the tested parameters is presented in Figure 5.1. For the range of parameter multipliers examined many of the parameters have little effect on the calibration performance. However, LPS surf zones Kh and LPS non surf zones Kh exhibit a strong influence on calibration performance and Ss a relatively weak influence. For these three parameters the minimum SRMS is achieved at the value adopted in the calibrated model. Any deviation away from these values causes deterioration in calibration performance. This suggests that the optimum values have been adopted for these parameters and that for the other parameters, from a statistical calibration performance perspective, alternative values are plausible.

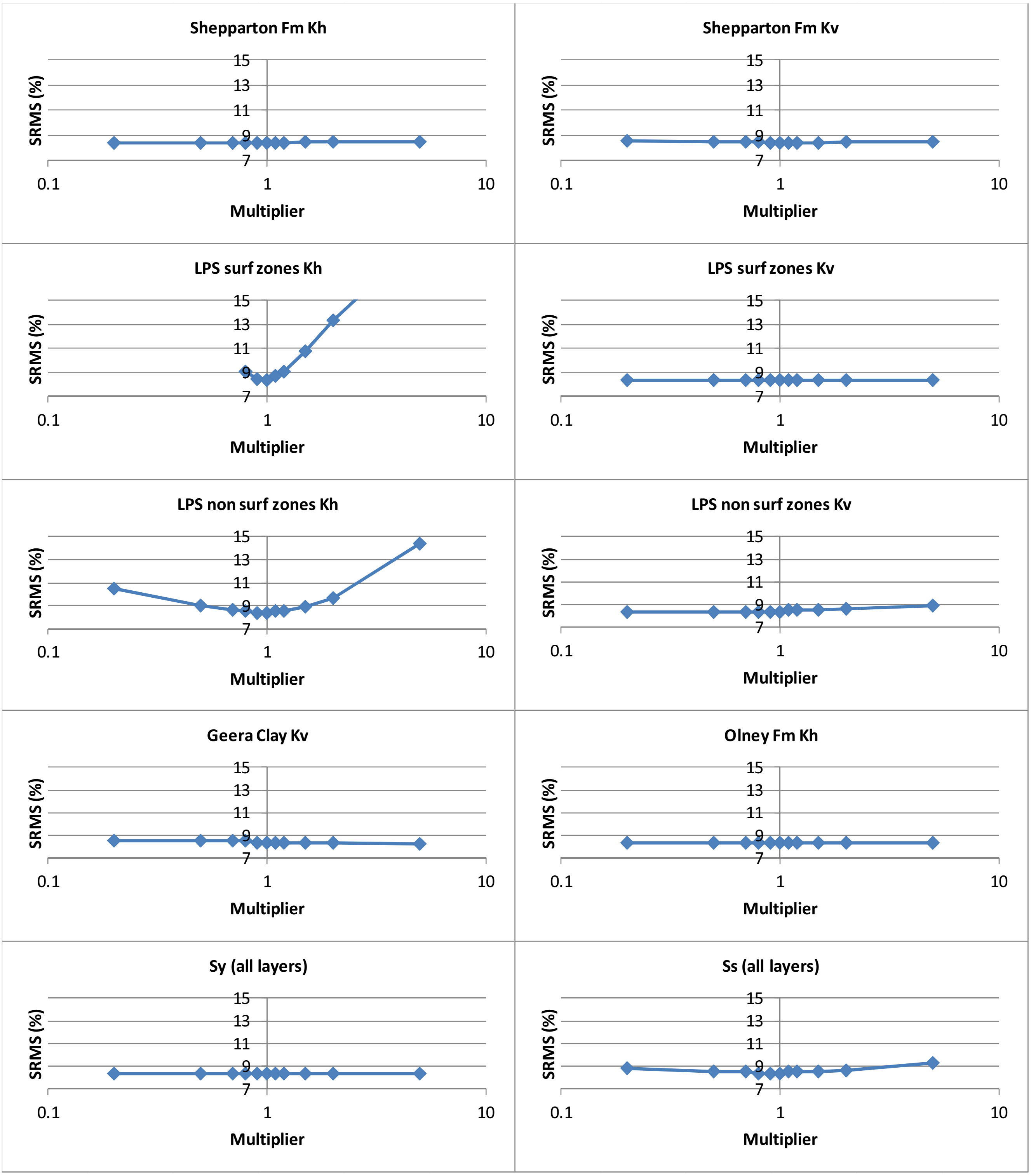


Figure 5.1 : LTT1.0 calibration sensitivity

5.3 Nanda

Sensitivity of the Nanda1.0 transient calibration to the tested parameters is presented in Figure 5.2. For the range of parameter multipliers examined many of the parameters have little effect on the calibration performance. However, as was the case for LTT1.0, LPS surf zones Kh and LPS non surf zones Kh exhibit a strong influence on calibration performance and Ss a relatively weak influence. For the LPS conductivities the minimum SRMS is achieved at slightly higher values than those adopted in the calibrated model. For Ss the performance curve is centred on the adopted value. This suggests that the parameter values adopted for Nanda1.0, from a statistical calibration performance perspective, are very close to optimum and that for several parameters, alternative values are plausible.

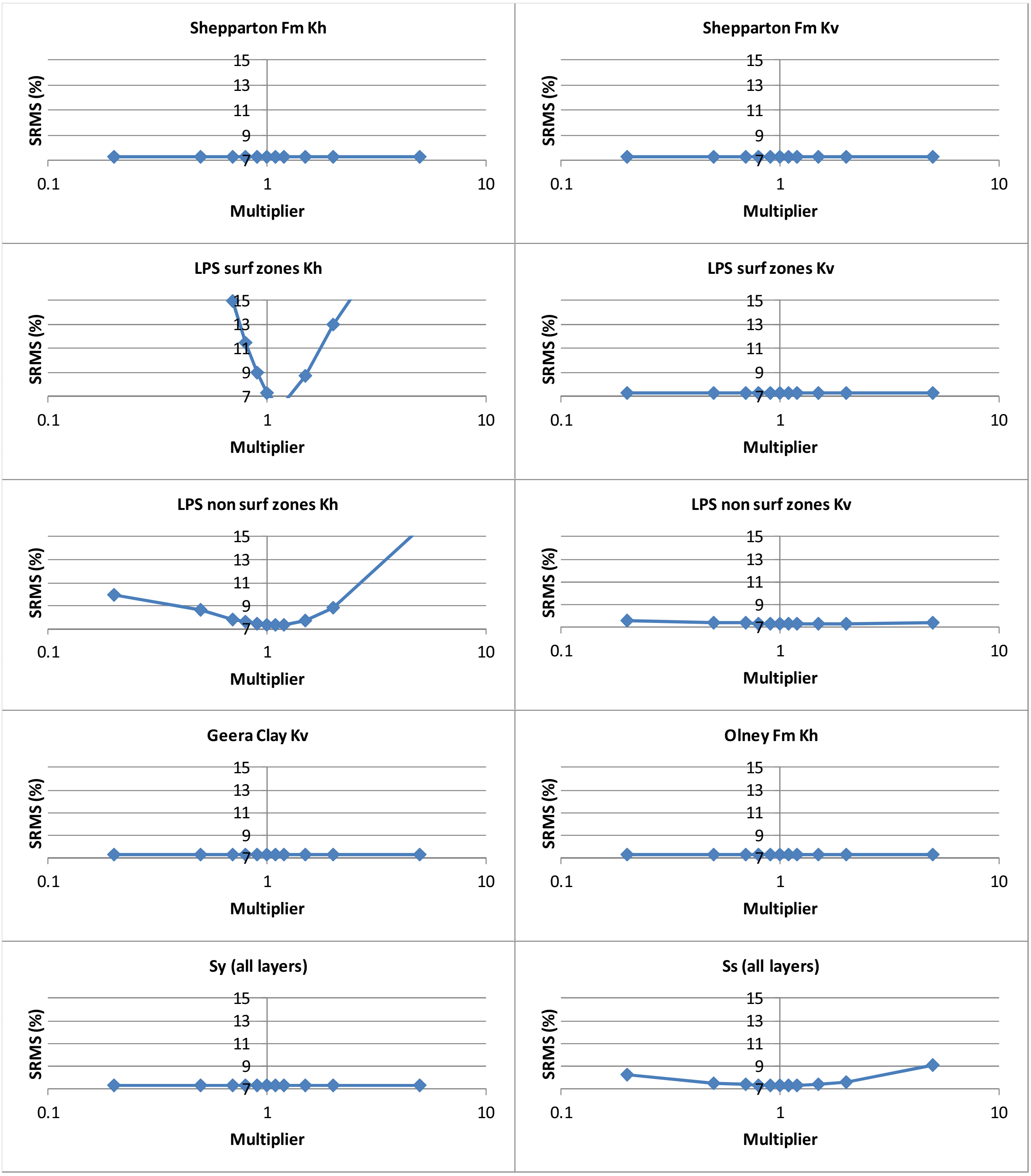


Figure 5.2 : Nanda1.0 calibration sensitivity

5.4 Upson Downs

Sensitivity of the UD1.0 transient calibration to the tested parameters is presented in Figure 5.3. For the range of parameter multipliers examined many of the parameters have little effect on the calibration performance. However, as was the case for LTT1.0, LPS surf zones Kh and LPS non surf zones Kh exhibit a strong influence on calibration performance. At this site LPS non surf zone Kv also exhibits a strong influence on calibration and Ss exhibits a moderate influence. For the LPS surf zone Kh the minimum SRMS is achieved at the adopted calibrated value. Several of the model runs with lower values (multipliers less than one) failed to meet the numerical convergence criteria and are not presented. Results suggest that, statistically, calibration could be improved with adoption of lower LPS non surf zone Kh and higher LPS non surf zone Kv. Whilst Ss does not cause calibration deterioration at lower values, increases above the adopted value do cause the calibration to worsen. Overall, results indicate that the parameter values adopted for UD1.0, from a statistical calibration performance perspective, are generally close to optimum and that for several parameters, alternative values are plausible. Whilst calibration performance could be improved somewhat, a decision was made to maintain consistency between local-scale calibration models where it did not cause a significant deterioration in calibration performance.

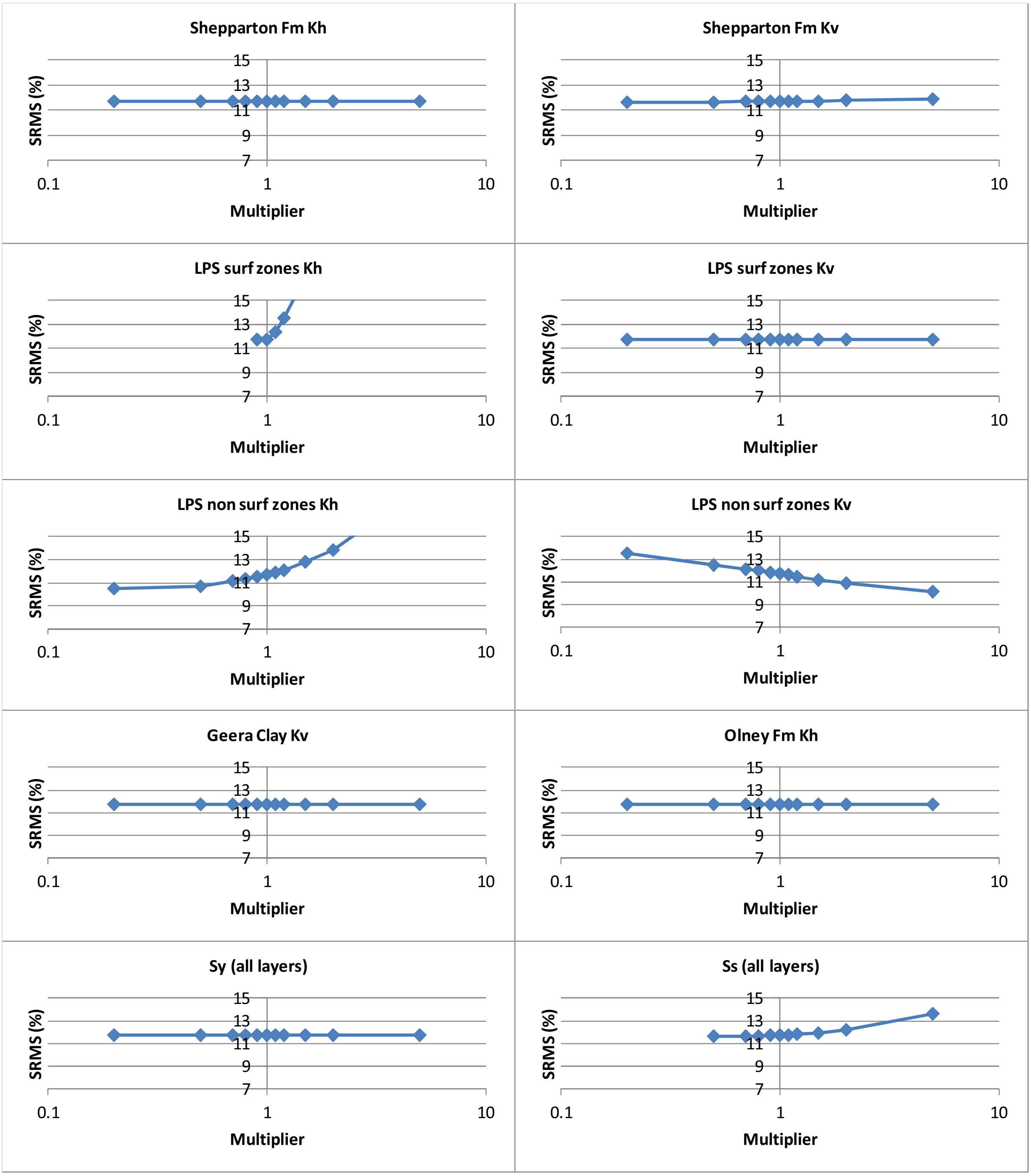


Figure 5.3 : UD1.0 calibration sensitivity

5.5 Turkeys Nest 1

Sensitivity of the TN1_1.0 transient calibration to the tested parameters is presented in Figure 5.4. For the range of parameter multipliers examined many of the parameters have little effect on the calibration performance. As is the case in other local-scale models, LPS surf zones Kh and LPS non surf zones Kh exhibit a strong influence on calibration performance. At this site the adopted values for these parameters appear to be very close to optimum, with minor statistical improvements obtained with slightly lower values. As occurred for UD1.0, several of the model runs for lower values of LPS surf zones Kh (multipliers less than one) failed to meet the numerical convergence criteria and are not presented. Ss demonstrates a strong influence on calibration performance with the performance curve centred on the adopted value. Overall, results indicate that the parameter values adopted for UD1.0, from a statistical calibration performance perspective, are generally close to optimum and that for several parameters, alternative values are plausible.

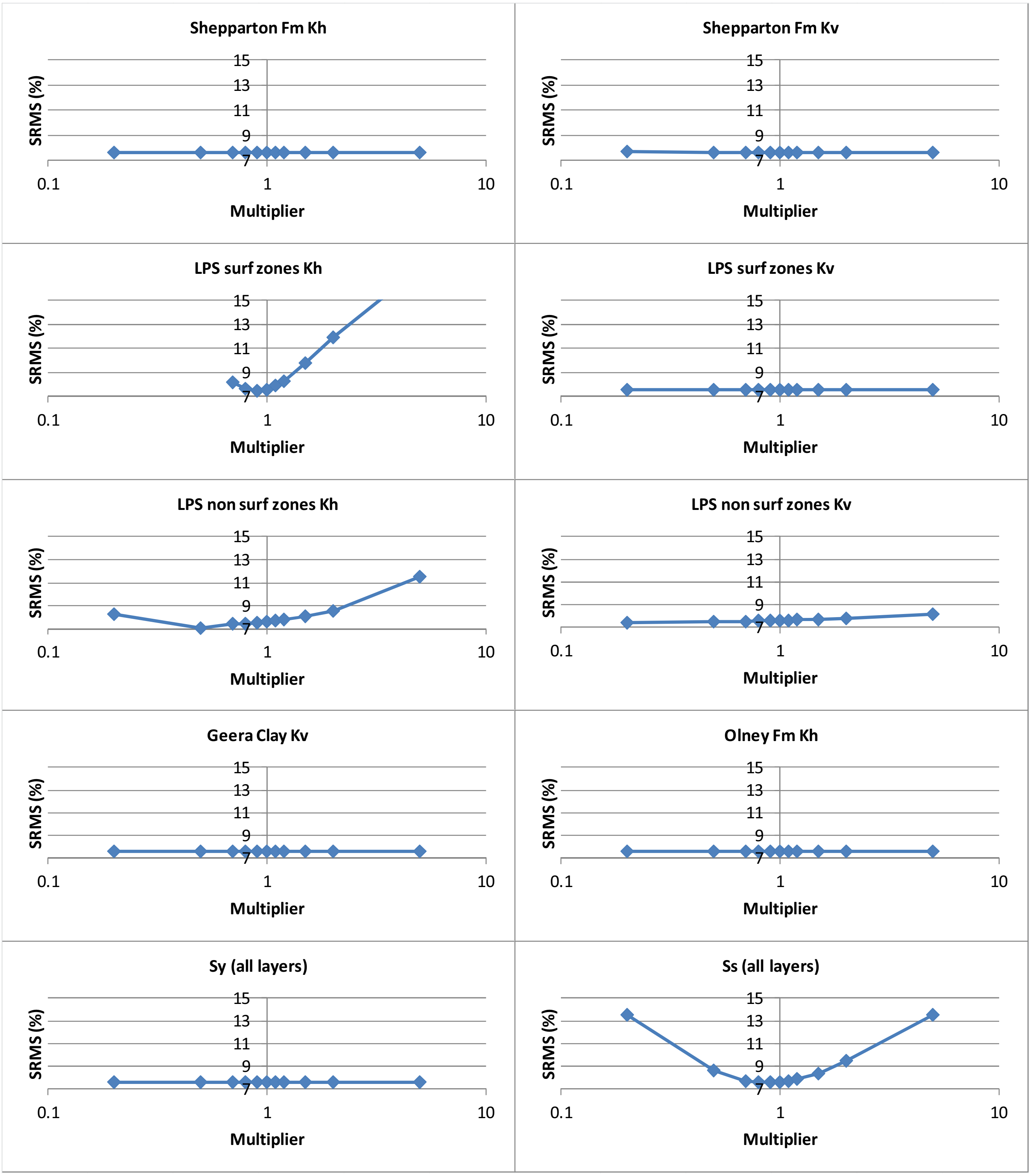


Figure 5.4 : TN1_1.0 calibration sensitivity

5.6 Turkeys Nest 5

Sensitivity of the TN5_1.0 transient calibration to the tested parameters is presented in Figure 5.5. For the range of parameter multipliers examined many of the parameters have little effect on the calibration performance. However, as occurs in the other local-scale calibration models, LPS surf zones Kh exhibits a strong influence on calibration performance. At this site values could be moderately higher than the adopted calibrated value. LPS non surf zone Kh also exhibits less influence at this site than other locations. However the Kv of the LPS non surf zones has a moderate influence with lower values improving calibration and higher values worsening it. Interestingly, results for Ss, which exhibits a strong influence on calibration, suggest that a higher value may be more representative of conditions at this site. Overall, results indicate that the parameter values adopted for TN5_1.0, from a statistical calibration performance perspective, are generally close to optimum and that for several parameters, alternative values are plausible. Whilst calibration performance could be improved somewhat, a decision was made to maintain consistency between local-scale calibration models where it did not cause a significant deterioration in calibration performance.

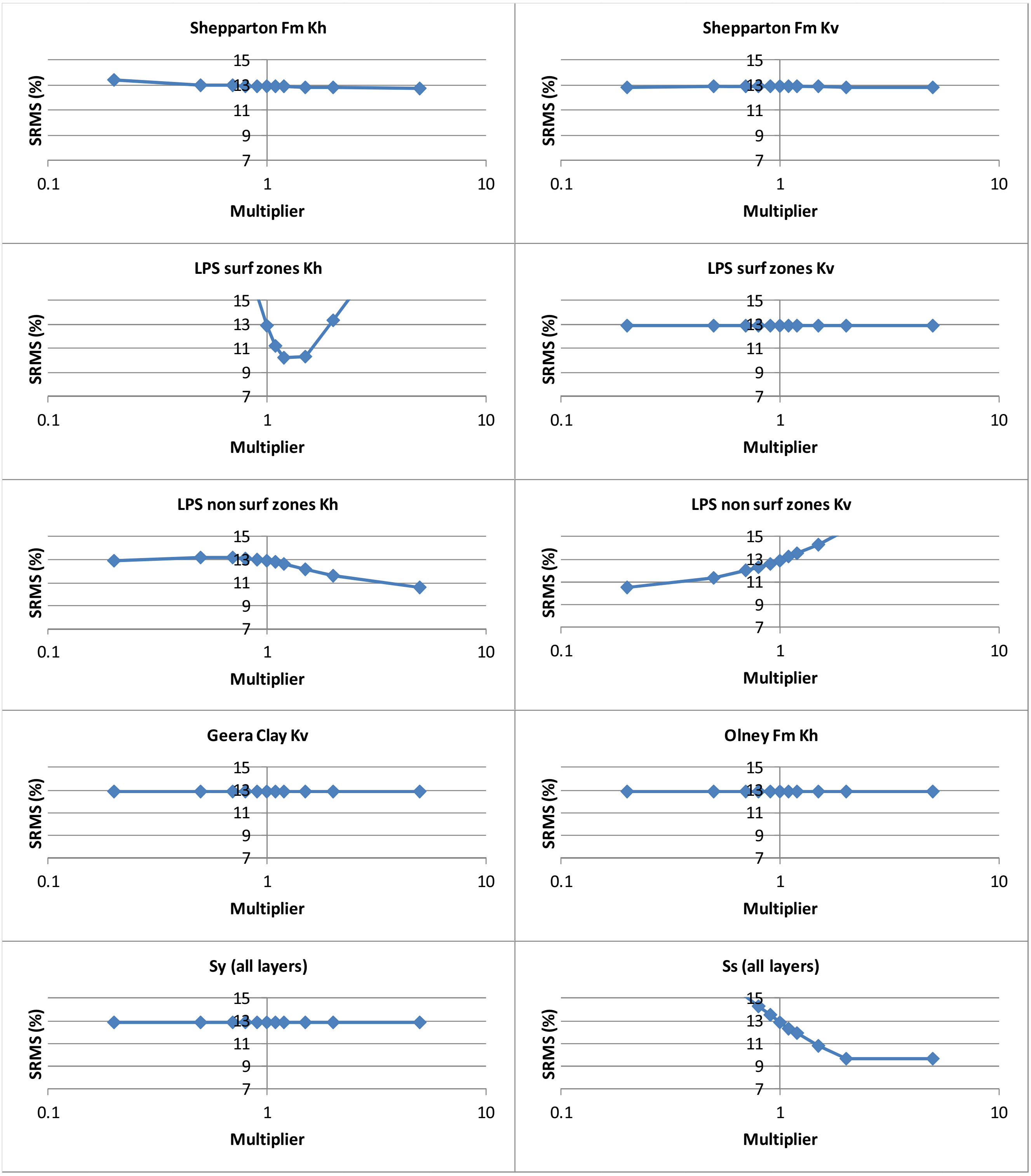


Figure 5.5 : TN5_1.0 calibration sensitivity

5.7 BAL2.0

As an indication of how the BAL2.0 model would behave if the local-scale transient calibration scenarios were modelled using the whole regional model (rather than selected “cookie cut” portions of it), the averaged SRMS values for corresponding parameter multipliers are presented in Figure 5.6. As would be expected, the results provide a generalised summary of the calibration sensitivity presented for the individual local-scale calibration models. That is, for the range of parameter multipliers examined many of the parameters have little effect on the calibration performance but Kh of the LPS surf zones and non surf zones had a strong influence on calibration performance. Ss exhibits a moderate influence. These three appear to be the primary controllers of calibration performance. However, if extreme values, outside the bounds of the conceptual model, were adopted other parameters may significantly influence calibration performance.

Key outcomes of the sensitivity analysis are:

- Overall the local-scale transient calibration models and, by inference, the BAL2.0 regional model have adopted values that cause SRMS to be close to its minimum value. This confirms that the calibration process considered a sufficient range of parameter values such that those adopted are close to optimum, from a statistical measure of calibration performance.
- Calibration is highly sensitive to the adopted Kh values for the LPS surf zones and non surf zones. This is, in part, likely to be due to the large number of data points attributed to these units. However, consistent with the revised conceptualisation developed by Iluka (2015), this is indicative of the dominant role the surf zones (the most sensitive parameter) play in transmitting groundwater during pumping and injection. With calibration deteriorating significantly with small changes in LPS Kh values, this suggests these are not only well calibrated, but well constrained. That is, the sensitivity analysis has provided further confidence in the adopted calibrated values by indicating that values of these parameters cannot be much different from those adopted. Therefore, predictive uncertainty analysis need not consider much variation in LPS Kh.
- Several of the aquifer parameters have little influence on calibration sensitivity. With calibration not deteriorating with variation in these parameters, this suggests that alternative parameter values are entirely plausible and should be considered in predictive uncertainty analysis.

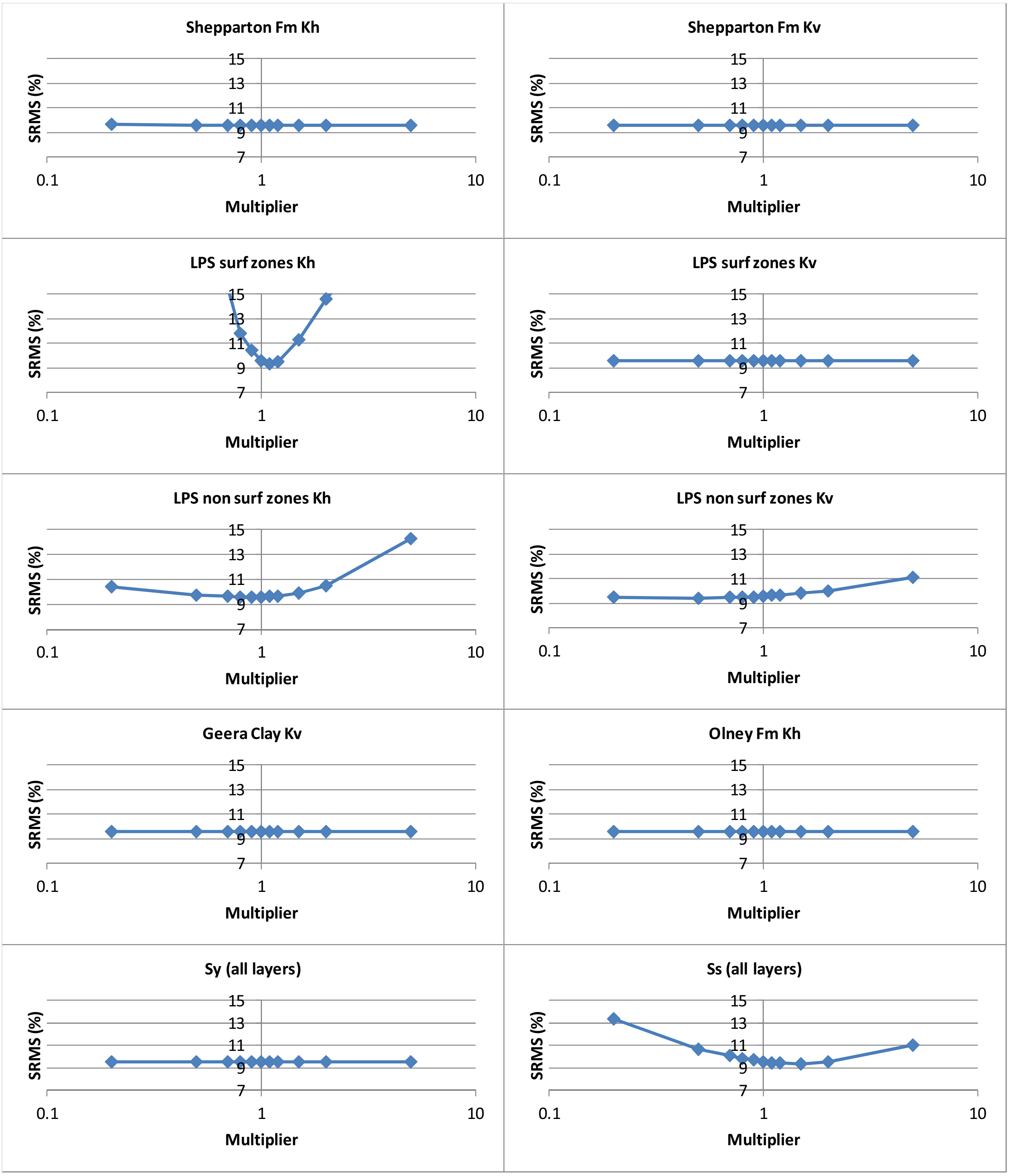


Figure 5.6 : Averaged local-scale calibration sensitivities

6. Scenario Modelling

6.1 Overview

Groundwater management for Iluka's proposed mining scenario is simulated in model run BAL2.0_TS2_opt29. This scenario includes a groundwater supply from three wells for pre-mining construction, dewatering of the West Balranald and Nepean deposits during 'truck and shovel' open cut mining and disposal of all dewatering water via injection into the LPS. A saline groundwater supply is operated from the LPS for a period, after mining year 6, during which dewatering rates alone do not meet requirements for plant make-up water and dust suppression (referred to as makeup water supply). The timing of each of these groundwater stresses is presented in Table 6.1.

The predictive simulation employs stress periods of variable lengths, depending on the timing and scheduling of the mining stresses applied to the groundwater system. The stress period configuration is summarised in Table 6.1.

An initial stress period of 100 years, with no change in stresses from the pre-development conditions in the steady state model, is employed to ensure stable transient conditions prior to simulation of groundwater-affecting activities associated with the Project. The representation of each of the groundwater affecting activities and associated impacts is presented in the following sections.

Impact assessment modelling does not simulate the likely different hydraulic properties of backfill material compared with the current aquifer setting. This is planned for subsequent dewatering optimisation for operational purposes but is not considered necessary for impact assessment.

Table 6.1 : BAL2.0_TS2_opt29 model stresses

Stress period/s	Mining Year	Start date	End date	Stress period length	Groundwater stresses from Project activities
1	n/a	1-Jan-1914	1-Jan-2014	100 yr	None (equilibration)
2	-3.0 to -1.5	1-Jan-2014	1-Jul-2015	1.5 yr	Water supply: wellfield 3
3	-1.5 to -0.5	1-Jul-2015	1-Jul-2016	1 yr	Water supply: wellfield 7 and plant well
4	-0.5 to 0.0	1-Jul-2016	1-Jan-2017	0.5 yr	Water supply: plant well
5	0.0 to 0.25	1-Jan-2017	1-Apr-2017	0.25 yr	West Balranald mining above water table
6-141	0.25 to 5.9	1-Apr-2017	1-Dec-2022	14 d	West Balranald (mining) dewatering and injection
142	5.9 to 6.0	1-Dec-2022	1-Jan-2023	30 d	West Balranald (backfilling) dewatering and Nepean (mining) dewatering
143-146	6.0 to 6.3	1-Jan-2023	1-May-2023	30 d	West Balranald (backfilling) dewatering, West Balranald make-up water supply (56 L/s) and Nepean (mining) dewatering
147-154	6.3 to 7.0	1-May-2023	1-Jan-2024	30 d	West Balranald (backfilling) dewatering, West Balranald make-up water supply (12 L/s) and Nepean (mining) dewatering
155-159	7.0 to 7.5	1-Jan-2024	1-Jul-2024	30 d	West Balranald (backfilling) dewatering and Nepean (mining) dewatering
160-166	7.5 to 8.0	1-Jul-2024	1-Jan-2025	30 d	West Balranald (backfilling) dewatering
167	n/a	1-Jan-2025	1-Jan-2125	100 yr	None (recovery)

6.2 Construction water supply

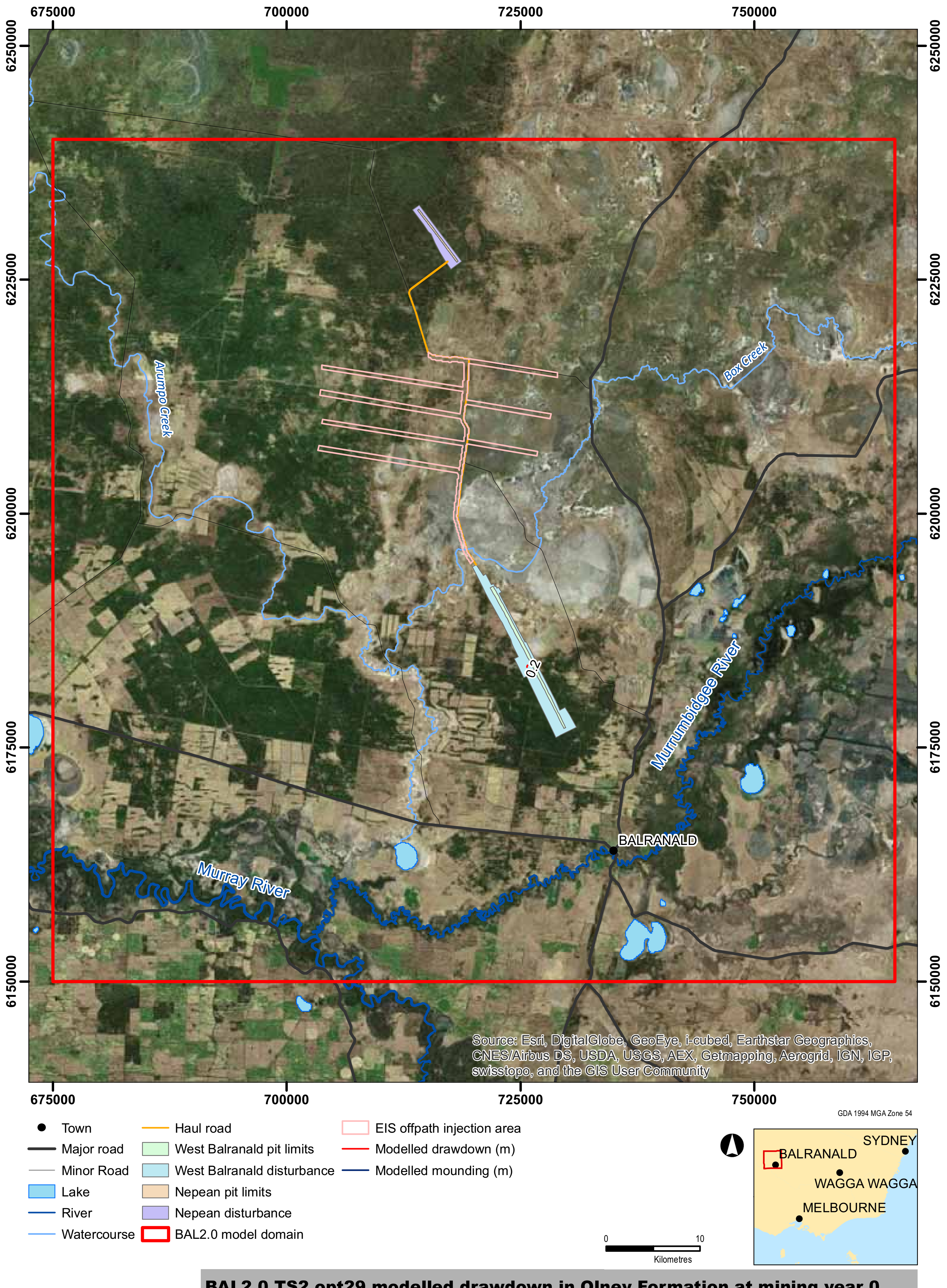
The water supply for pre-mining construction is proposed to be sourced from the brackish Olney Formation. Exact locations of wells have not yet been determined but three general areas have been identified by Iluka from which a groundwater supply may be sourced. These are:

- Wellfield 3, a well located near the haul road on the southernmost spur to the west of the proposed haul road: 75 ML/yr (2.4 L/s) supply for construction of the injection wellfield from mining year -3 to -1.5 (i.e. between 3 and 1.5 years prior to the start of mining);
- Wellfield 7, a well located near the haul road on the northernmost spur to the west of the proposed haul road: 75 ML/yr (2.4 L/s) supply for construction of the injection wellfield from mining year -1.5 to -0.5; and
- Plant, a well located near the plant at West Balranald, approximately halfway along the deposit: 75 ML/yr (2.4 L/s) supply for construction at the West Balranald deposit from mining year -1.5 to 0.

At each of the three sites a single well, simulated with the MODFLOW-SURFACT FWL4 package, is used to represent a groundwater supply. At Wellfield 3 and Wellfield 7 the well is located adjacent to the haul road. At the Plant site it is located immediately south of the mining plant. All wells are assumed to be screened in the Olney Formation.

Three stress periods are employed to represent the timing of operation of the three water supply wells. These have durations of 1.5 yr, 1 yr and 0.5 yr. Total production is 75 ML/yr for the first 1.5 years. This increases to 150 ML/yr for the period between mining year -1.5 and -0.5, when two wells are operational, then reduces back to 75 ML/yr for the final half year of pre-mining construction.

Figure 6.1 presents model-predicted drawdown in the Olney Formation at the end of the construction period, immediately prior to commencement of mining. Residual drawdown from wells at Wellfield 3 and Wellfield 7 is less than 0.2 m and, hence, not evident in the figure. Groundwater extraction from the plant well creates a localised drawdown impact, with the 0.2 m drawdown contour constrained to a small area within the footprint of the West Balranald disturbance area.



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BAL2.0 TS2 opt29 modelled drawdown in Olney Formation at mining year 0 (end of construction) **Figure 6.1**

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6.3 West Balranald dewatering

Iluka plans to mine the West Balranald deposit using a truck and shovel open cut mining method. This involves excavating and mining an active pit area that advances along the deposit. After overburden and ore are removed from an area it is progressively backfilled. The result is a pit that moves from south-east to north-west along the deposit. At any time during mining the open pit floor, between the advancing face and the toe of the backfill, is 900 m long (Figure 6.2).

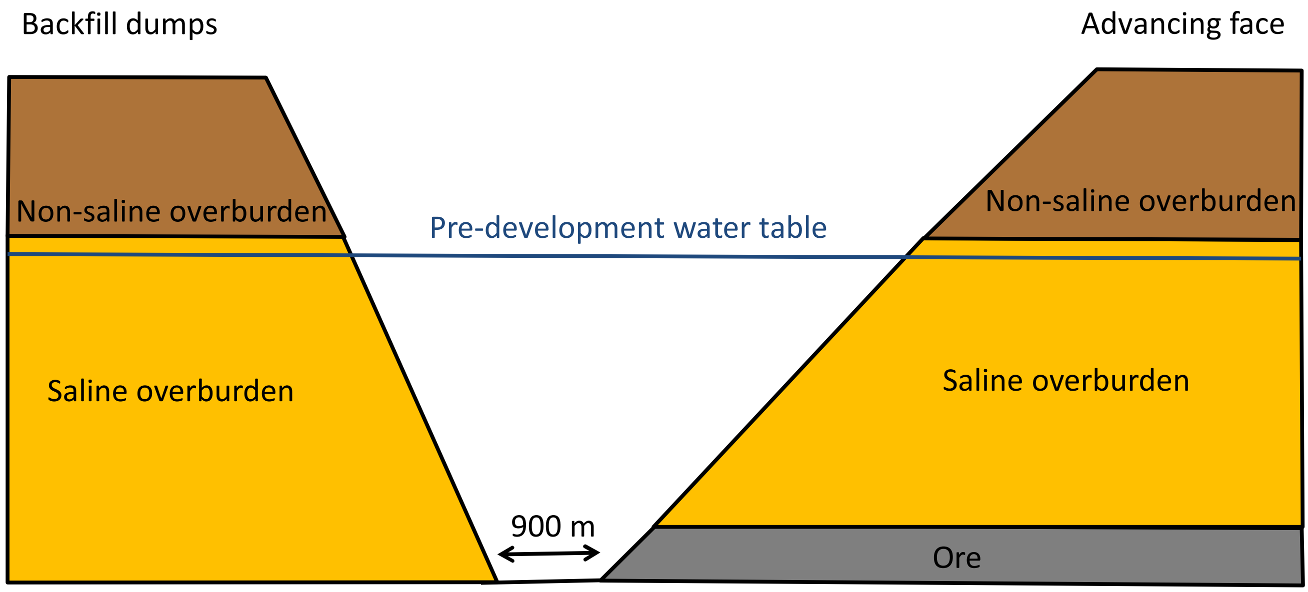


Figure 6.2 : West Balranald pit void

A mine plan, containing chainages for the advancing face and toe of the backfill along with associated pit floor elevations, was provided by Iluka to define the dewatering requirements for the progression of the mining pit along the deposit. The mine plan contained monthly chainages and quarterly elevations. These were interpolated to produce fortnightly values to align with the stress periods employed in the model during mining at West Balranald. Whilst monthly stress periods would have sufficed for impact assessment, when trialled these proved numerically unstable and, hence, fortnightly stress periods were adopted. Monthly stress periods are used for the duration of backfilling at West Balranald.

Iluka plans to dewater the West Balranald pit primarily via ex-pit wells aligned parallel to the deposit and screened in the LPS. Whilst some in-pit dewatering may be required, in-pit dewatering rates are expected to be much lower than those of ex-pit dewatering infrastructure.

Post-mining, a dry pit is required for a further two years whilst the final pit void, located at the northern end of the deposit, is backfilled to an elevation of 52 m AHD. Iluka identified this final elevation based on backfilling to provide fill cover above the pre-mining water table elevation at this location. Given the planned final backfill level is approximately 13 m below the initial and surrounding ground surface elevation of approximately 65 m AHD, any rainfall is likely to cause surface flooding within the remaining depression. This is likely to lead to increased recharge to the water table below the remaining depression and, therefore, mounding of the water table at this point. Some consideration of rainfall capture in the remnant depression, and capillary rise from a shallow water table should be given in the water assessment.

For each stress period of mining below the water table a MODFLOW drain boundary condition is applied to the footprint of the area between the advancing face and toe of backfill. The drain covers the full width of the pit and out to approximately 50 m outside the pit crest. Dewatering wells will be located inside this footprint, as close to the pit crest as possible (expected to be about 25 m from the crest). The drain boundary conditions are assigned to all Shepparton Formation and LPS model layers (layers 1 to 7). Drain invert elevations are set 5 m below the elevation of the pit floor provided in the mine plan. A conductance of 10,000 m^2/d is assigned to all drains to ensure lowering of the potentiometric surface to the desired elevation 5 m below the pit floor within the stress period. This approach is considered to be conservative in two ways. Firstly, the water table will be less than 5 m below the pit floor elevation for the majority of the area over which the drains are applied. Whilst the head at, and in the vicinity of, ex-pit dewatering wells is likely to be more than 5 m below the adjacent pit floor, this is still considered to be a conservative approach. Secondly, the area to which the drains have been applied is conservative in that it extends beyond the pit crest and ex-pit well locations.

Model-predicted potentiometric surface below the pit, along with dewatering rates, are presented in Figure 6.3. Monitoring wells, simulated every 100 m along the centre-line of the deposit, are used to report the hydraulic head in the LPS at the advancing face, the toe of the backfill and the midpoint of these two at time and location of the mine plan. By monitoring heads at these three locations and comparing them with the pit floor elevation, the ability of a particular modelling scenario to meet the requirement for a dry pit can be determined. The modelled potentiometric surface in the LPS is maintained approximately 5 m below the pit floor at the advancing face and the centre of the pit. At the toe of the backfill it oscillates around the elevation of the pit floor. This is thought to be a function of the model grid resolution (monitoring wells being either slightly inside or outside the area to which drains area assigned). Model results suggest the drains have effectively dewatered the pit to enable dry mining conditions. There is an expectation, however, that the low vertical conductivity in the Shepparton Formation and, to a lesser extent, the LPS1 foreshore will act as a barrier between the water table and the dewatering wells that are screened in the underlying LPS. This is expected to result in residual waterlogging in the Shepparton Formation and potentially a perched water table in the vicinity of dewatering operations.

The model predicts an average dewatering rate of 746 L/s for the six years of mining and an average of 95 L/s during the two years of backfilling. The predicted peak fortnightly dewatering rate is 1,309 L/s. It can be seen that the modelled dewatering rate (groundwater removed by drains) fluctuates considerably. With a 900 m chainage over which drains area applied, 100 m x 100 m model cells do not allow very precise specification of the pit chainage to which drains are assigned. Hence, the number of drain cells assigned may vary considerably from one stress period to the next. This gives rise to a ‘noisy’ dewatering time series.

Dewatering rates are predicted to increase over the life of the West Balranald mining operation. The primary reason for this is that the pit deepens over time as it moves northward. The pit floor at the commencement of ore production (1 April 2017) is 9.5 mAHD. This is 22 m higher than the final pit floor elevation of -12.5 mAHD (1 December 2022).

During backfilling the potentiometric surface rises more slowly than the assumed backfilling operation. Hence, the latter part of the backfilling operation requires no dewatering to maintain a dry pit. It should be noted that, should the increase in pit floor elevation not follow the simple linear assumption made here, then the temporal dewatering requirements during backfilling may vary. Similarly the different properties of the backfill material compared to that of the in-situ, pre-mining sediments, may cause a slight difference in the predicted rate of groundwater recovery in the immediate vicinity of the pit.

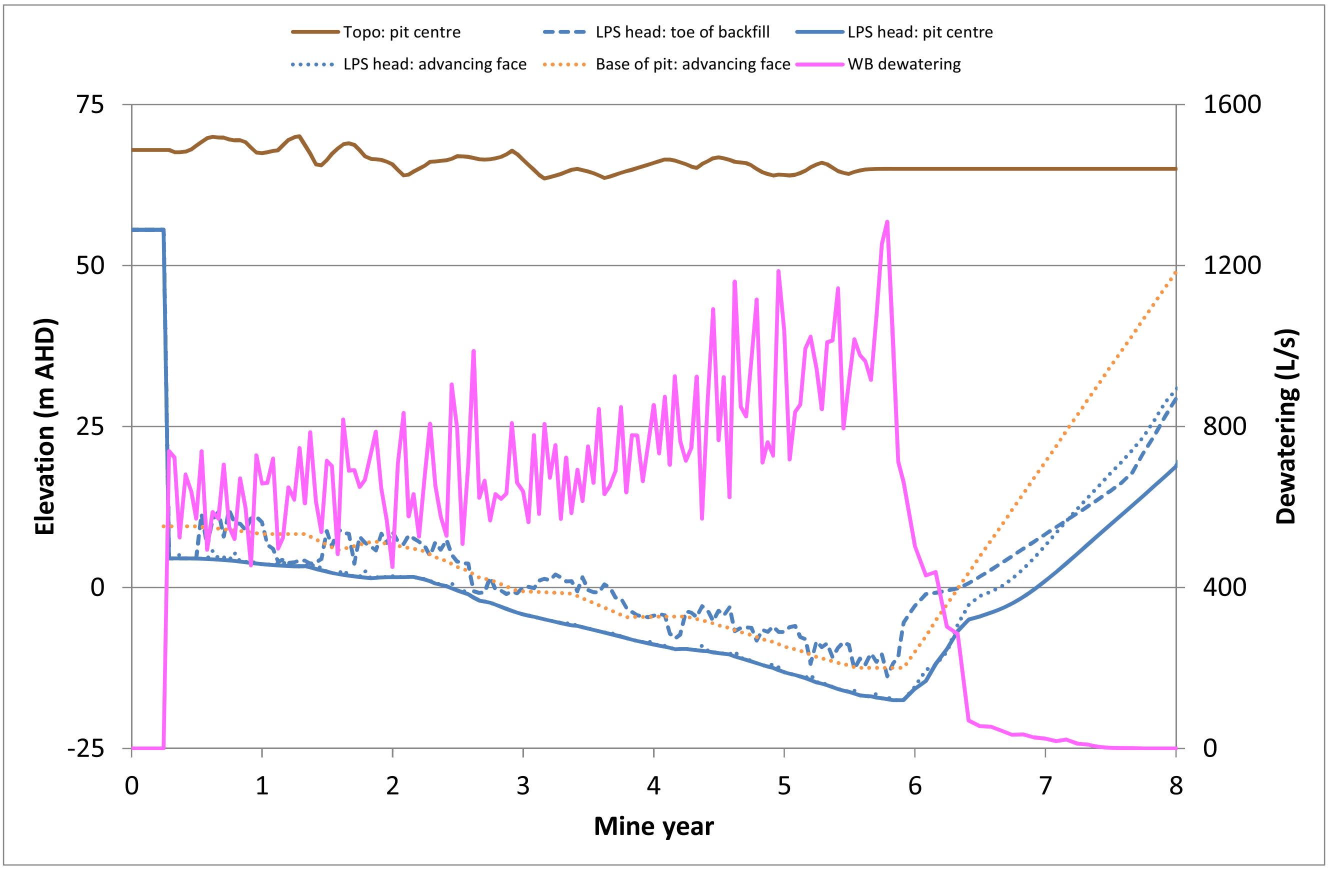
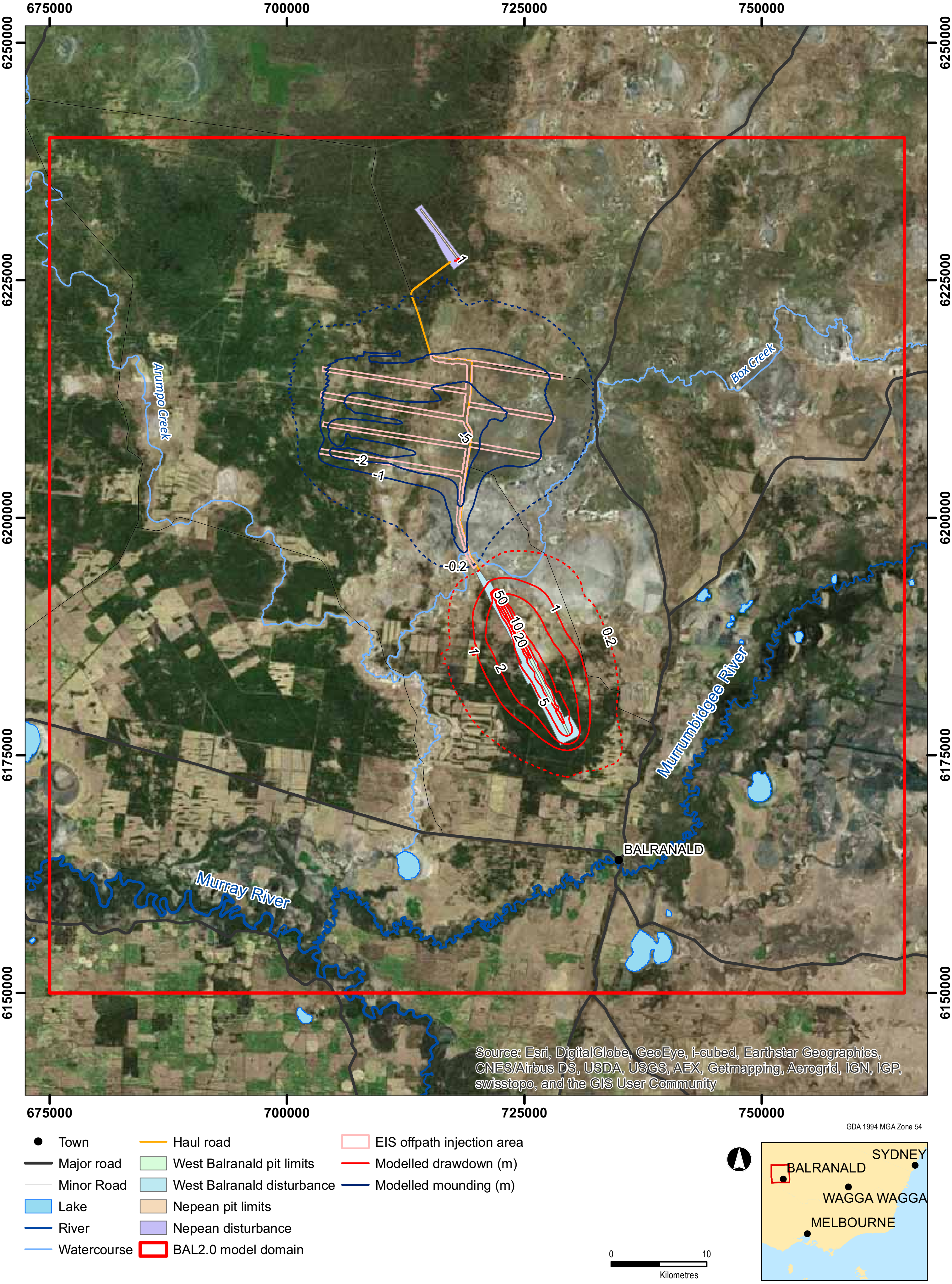


Figure 6.3 : Modelled in-pit potentiometric surface and dewatering rates for West Balranald

Model-predicted drawdown in the Shepparton Formation and LPS1 foreshore at the end of mining the West Balranald deposit and prior to backfilling the final pit (Mining Year 6) are presented in Figure 6.4 and Figure 6.5. Drawdown in the LPS1 foreshore is representative of drawdown in the other LPS sub-units. Results are not presented for the Olney Formation as drawdown does not exceed the minimum (0.2 m) drawdown contour used. A drawdown cone can be seen extending the length of the deposit. The size, shape and location of this drawdown cone are predicted to change with time during mining. Figure 6.4 and Figure 6.5 illustrate the drawdown at an instant in time (six years after the start of mining). In the Shepparton Formation impacts extend up to around 10 km laterally from the strike of the deposit. In the more transmissive LPS the drawdown extends up to around 15 km laterally from the deposit. The associated modelled depths to water (or potentiometric surface) at the end of mining are presented in Figure 6.6 and Figure 6.7. These illustrate that the depth to water in both aquifers has been lowered at the pit to be around the deepest in the study area. However, 10 km (Shepparton Formation) or 15 km (LPS) away from the deposit the pre-mining depth to water condition is unchanged. Further figures presenting model-predicted drawdown and depth to water in the Shepparton Formation and LPS during and after mining are provided in Appendix E



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BAL2.0 TS2 opt29 modelled drawdown in Shepparton Formation at mining year 6

Figure 6.4

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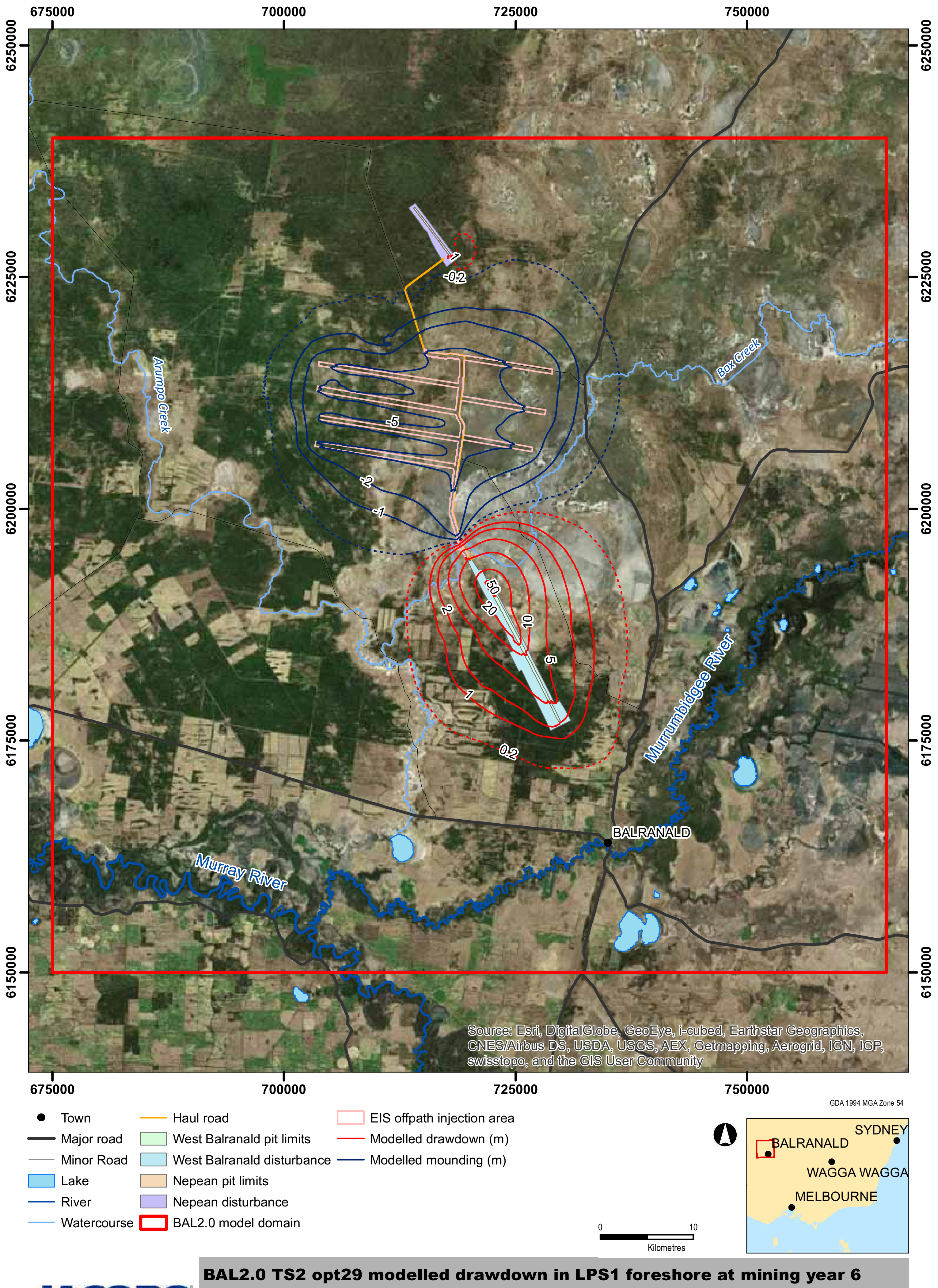

BAL2.0 TS2 opt29 modelled drawdown in LPS1 foreshore at mining year 6

Figure 6.5

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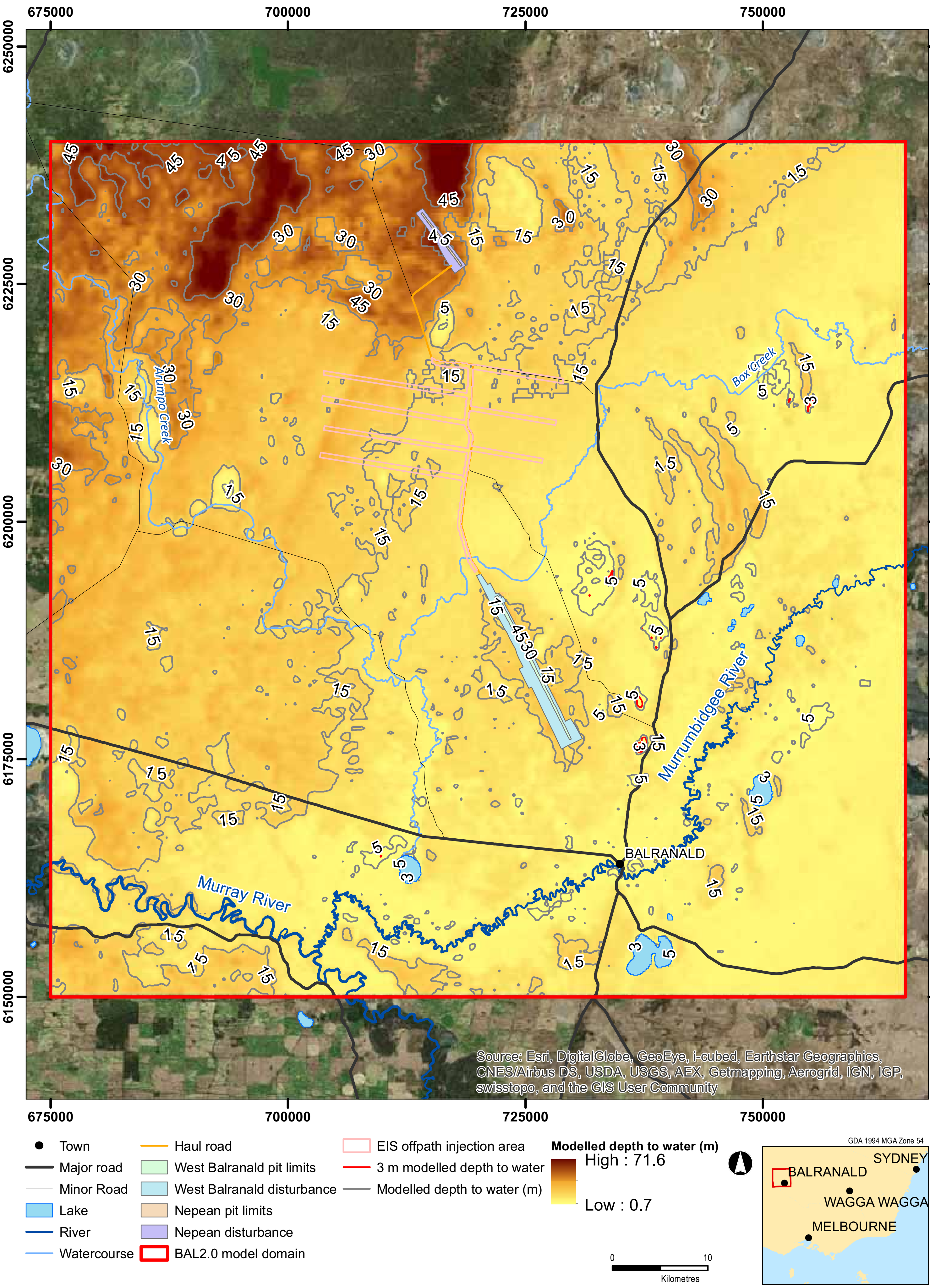

BAL2.0 TS2 opt29 modelled depth to water in Shepparton Formation at mining year 6

Figure 6.6

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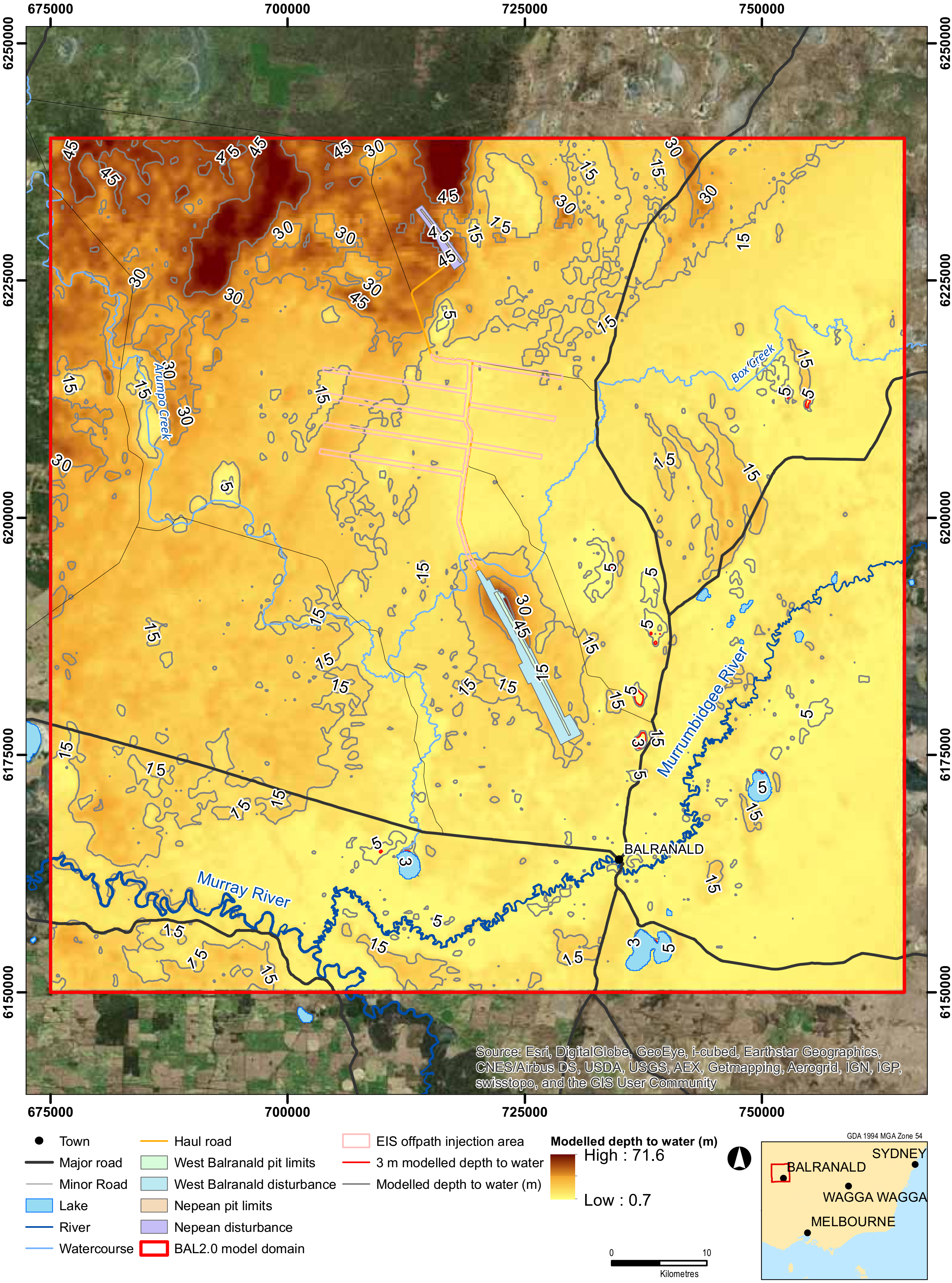

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BAL2.0 TS2 opt29 modelled depth to water in LPS1 foreshore at mining year 6 **Figure 6.7**

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6.4 Nepean dewatering

Dewatering of the Nepean deposit is simulated in a similar manner to dewatering of the West Balranald deposit. Drains are assigned 5 m below the pit floor indicated in the mine plan provided by Iluka. However, during mining of Nepean, stress periods of monthly duration are employed, rather than the fortnightly timing used for West Balranald. The longer periods are sufficient for Nepean because the mine does not excavate as far below the water table as at West Balranald and, hence, the stresses being simulated are smaller resulting in more numerically stable solutions. No post-mining dewatering for backfilling operations is planned for Nepean.

Model-predicted potentiometric surface below the pit, along with dewatering rates, are presented in Figure 6.8. The modelled potentiometric surface in the LPS is maintained approximately 5 m below the pit floor, suggesting the drains have effectively dewatered the pit to enable dry mining conditions.

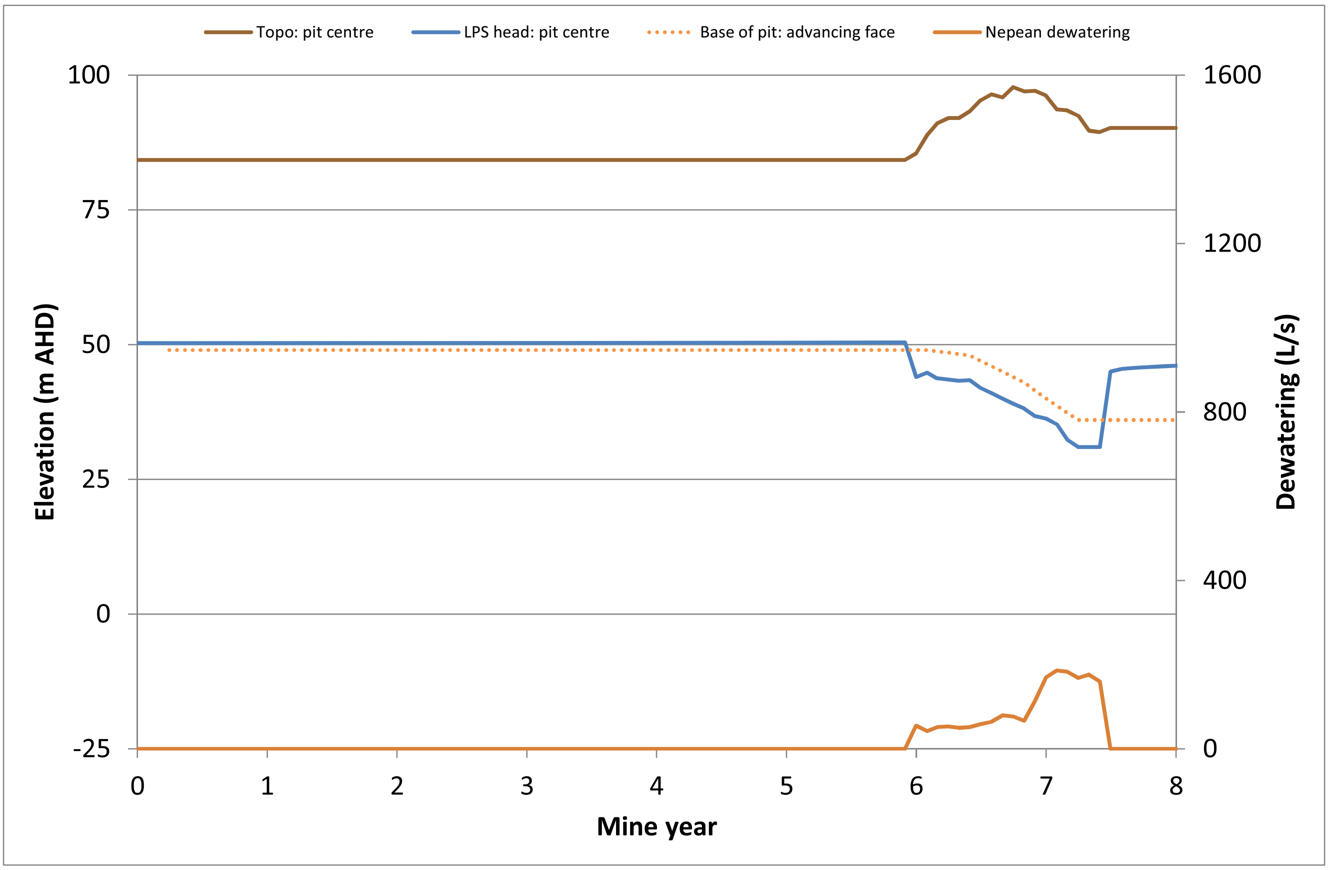
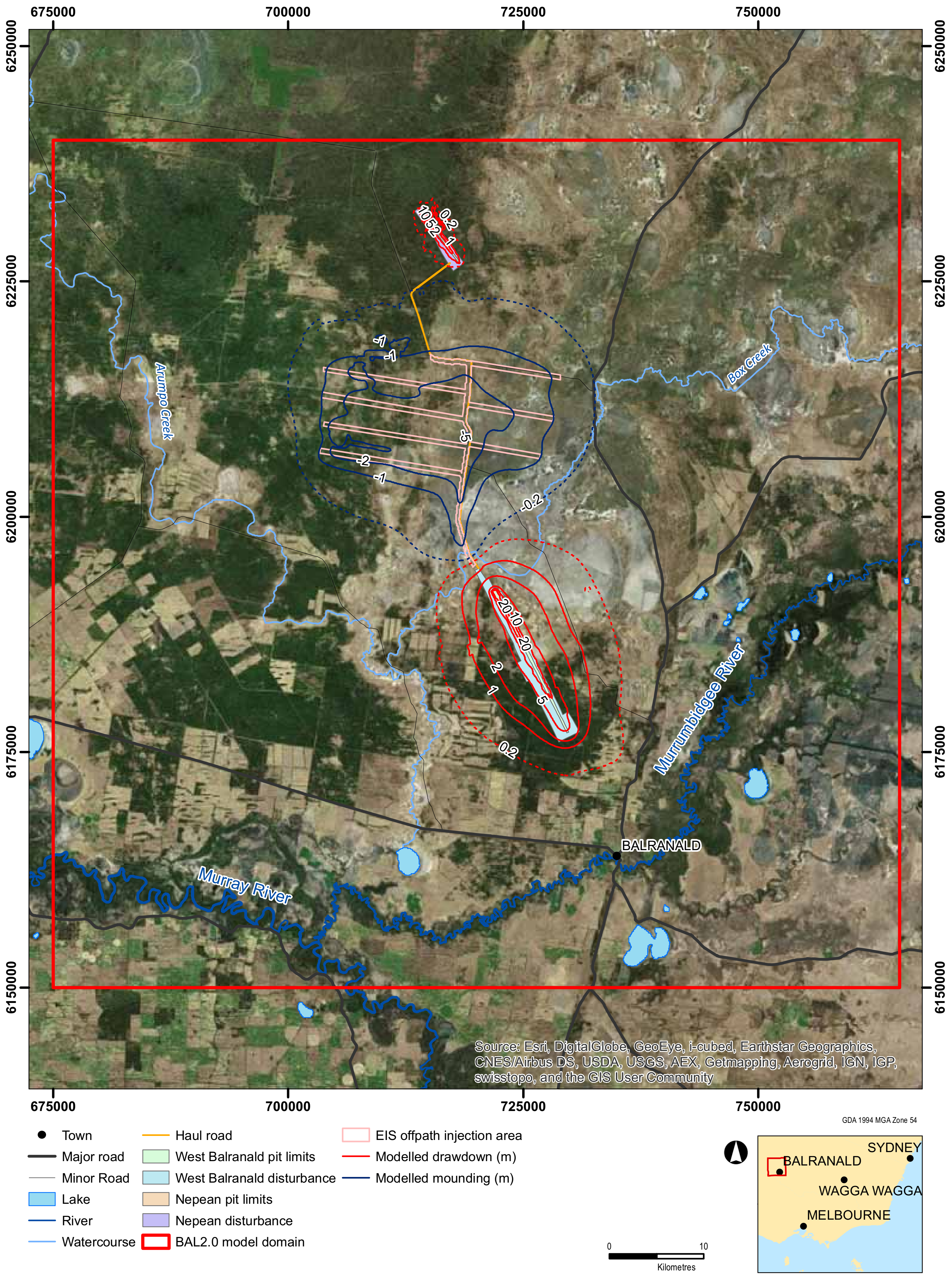


Figure 6.8 : Modelled in-pit potentiometric surface and dewatering rates for Nepean

Model-predicted dewatering rates are presented in Figure 6.8. The model predicts an average dewatering rate of 100 L/s for the 1.5 years of mining. The predicted peak monthly dewatering rate is 186 L/s. Dewatering rates are predicted to increase over the life of the Nepean mining operation. As is the case for West Balranald, the primary reason for this is that the pit deepens below topography and the pre-mining water table over time as it moves northward. At the commencement of ore production the pit floor is at 49 mAHD and progressively deepens to 36 mAHD by the end of the mining. The model-predicted dewatering rates are likely to be conservative. The model is populated with hydraulic properties obtained from production and injection trials carried out near West Balranald, where the aquifers are more transmissive. Aquifer tests carried out at Nepean during the PFS resulted in very low well yields and even caused production wells to go dry. Hence, dewatering estimates obtained using aquifer properties from tests at West Balranald are likely to be higher than will eventuate.

Model-predicted drawdown in the Shepparton Formation and LPS at the end of mining the Nepean deposit (mining year 7.5) are presented in Figure 6.9 and Figure 6.10. The drawdown cone is localised, extending no more than 2 km from the deposit in both units. These small predicted impacts are consistent with expectations given the shallow depth of the mine below the water table. As mentioned above for dewatering rates, these impacts are expected to be conservative as the model is populated with hydraulic properties obtained from near the West Balranald deposit. Further figures presenting model-predicted drawdown and depth to water in the Shepparton Formation and LPS during and after mining are provided in Appendix E.



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BAL2.0 TS2 opt29 modelled drawdown in Shepparton Formation at mining year 7.4

Figure 6.9

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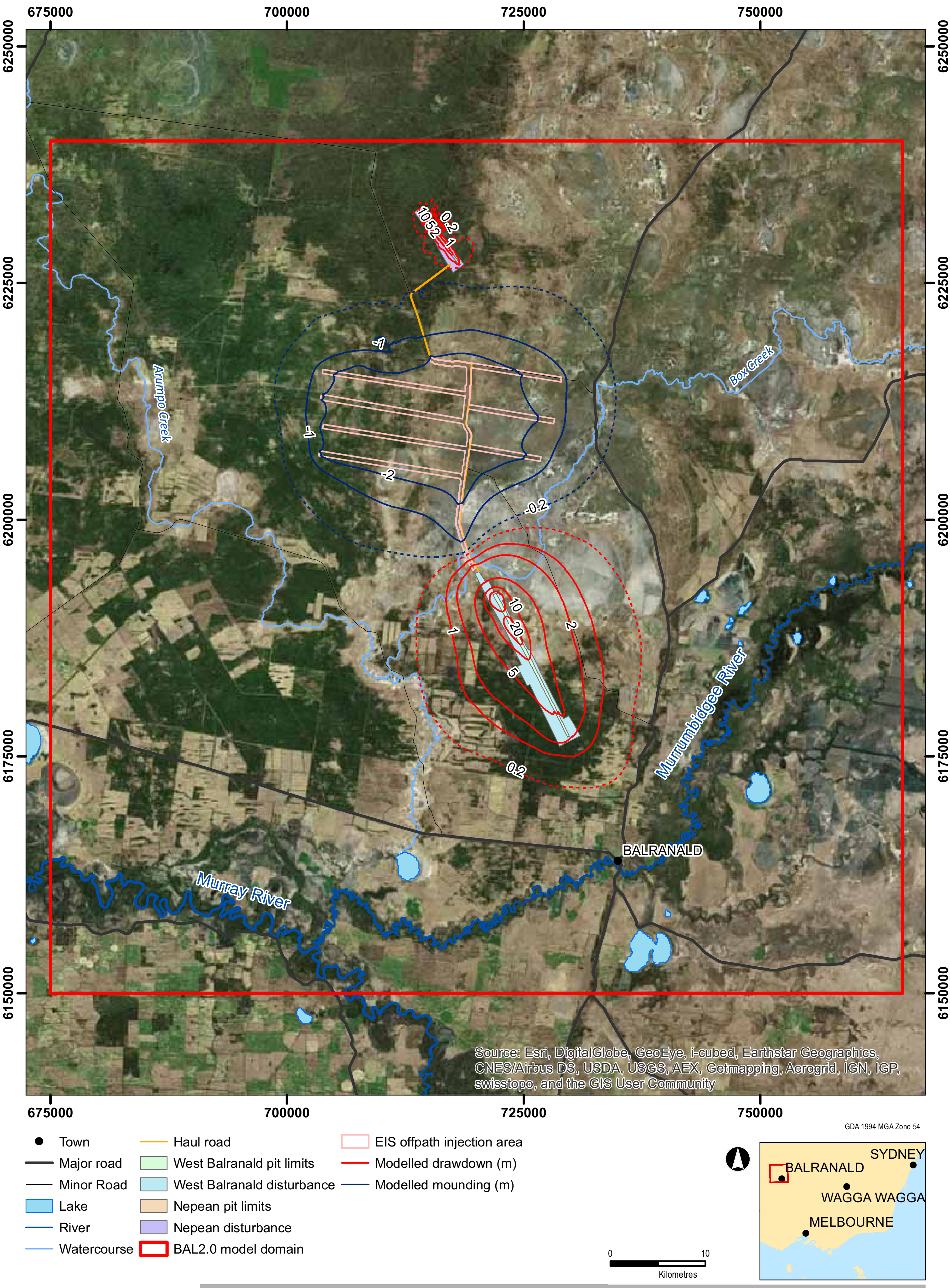

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BAL2.0 TS2 opt29 modelled drawdown in LPS1 foreshore at mining year 7.4

Figure 6.10

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6.5 Disposal

Iluka plans to inject water produced from dewatering operations back into the LPS. Whilst some water may be consumed in mining and processing, the expected losses constitute a minimal proportion of the dewatering volumes. Hence, all dewatering volumes are injected in the groundwater model. This adds to the conservatism of the modelled injection impacts.

During mining of West Balranald some water will be injected into wells that have either been, or will be, used for dewatering when the pit was/is located near them. For the impact assessment a conservative approach has been taken whereby these volumes, which will help to mitigate drawdown impacts, are assumed to be small.

Iluka plans to construct an off-path injection wellfield to receive the majority of water produced by dewatering operations. Wells will be located along the proposed West Balranald-Nepean haul road and on spurs coming off this road. Injection trials at the “Nanda” and “Upson Downs” sites have suggested a highly transmissive aquifer in this region. Bore logs indicate that the surf zones, in particular the LPS2 surf zone, are much thicker here than at the West Balranald deposit.

Many simulations were carried out to identify the size of wellfield necessary to dispose of dewatering volumes produced from West Balranald and Nepean, whilst meeting a constraint defined by Iluka that heads in the LPS should not rise to within 3 m of the ground surface. This constraint is aimed at reducing the risk of waterlogging and salinisation of non-saline shallow soils. This constraint was applied despite the available geological, and to a lesser extent hydrogeological testing, data, suggesting the Shepparton Formation does contain a clay layer and ironstone of relatively low hydraulic conductivity towards its base. The integrity of these cannot be confirmed over a large area. Hence, by maintaining the LPS, on a regional scale, at sub-artesian pressures, the risk of waterlogging and salinisation is negated. Further, this provides operational benefits with regard to maintenance of injection wells. It should be noted that this criterion has been targeted on a 100 m x 100 m model cell scale. Heads and pressures within injection wells will be higher than those modelled in, and averaged over, cells of these dimensions.

All injection is simulated using the MODFLOW-SURFACT FWL4 package into wells screened over the LPS. On-path injection is simulated using wells located along the edges of the West Balranald mine pit, running the full chainage of the deposit. Wells are considered available for injection only when they are a minimum of 5 km from the pit. This restriction is applied to avoid excessive recirculation of injected water towards dewatering infrastructure at the pit. Off-path injection is simulated into wells located in neighbouring 100 m x 100 m model cells along the footprint of the off-path wellfield. For each spur, wells are simulated on the northern and southern sides of the spur. The assumed well layout has been adopted for modelling purposes and is unlikely to represent the optimised wellfield layout that will be chosen for actual injection operation. The modelled layout is conservative in that it includes more bores than are likely to be required. The approach used in the impact assessment modelling is used simply to get the necessary volumes of water into the footprint. It represents a volume that can be injected per 100 m of spur length.

Water is distributed equally amongst all off-path wells. Therefore, there is currently no targeting of more transmissive parts of the aquifer to receive greater volumes of water. This adds to the conservative nature of the impact assessment. Simulated injection rates during mining of West Balranald and Nepean are presented in Figure 6.11. Injection peaks at about 1,300 L/s. Injection continues once mining at West Balranald ceases, but the necessary volumes to maintain dry pits for backfilling of West Balranald and mining at Nepean are substantially reduced when compared to those required during active mining operations at West Balranald.

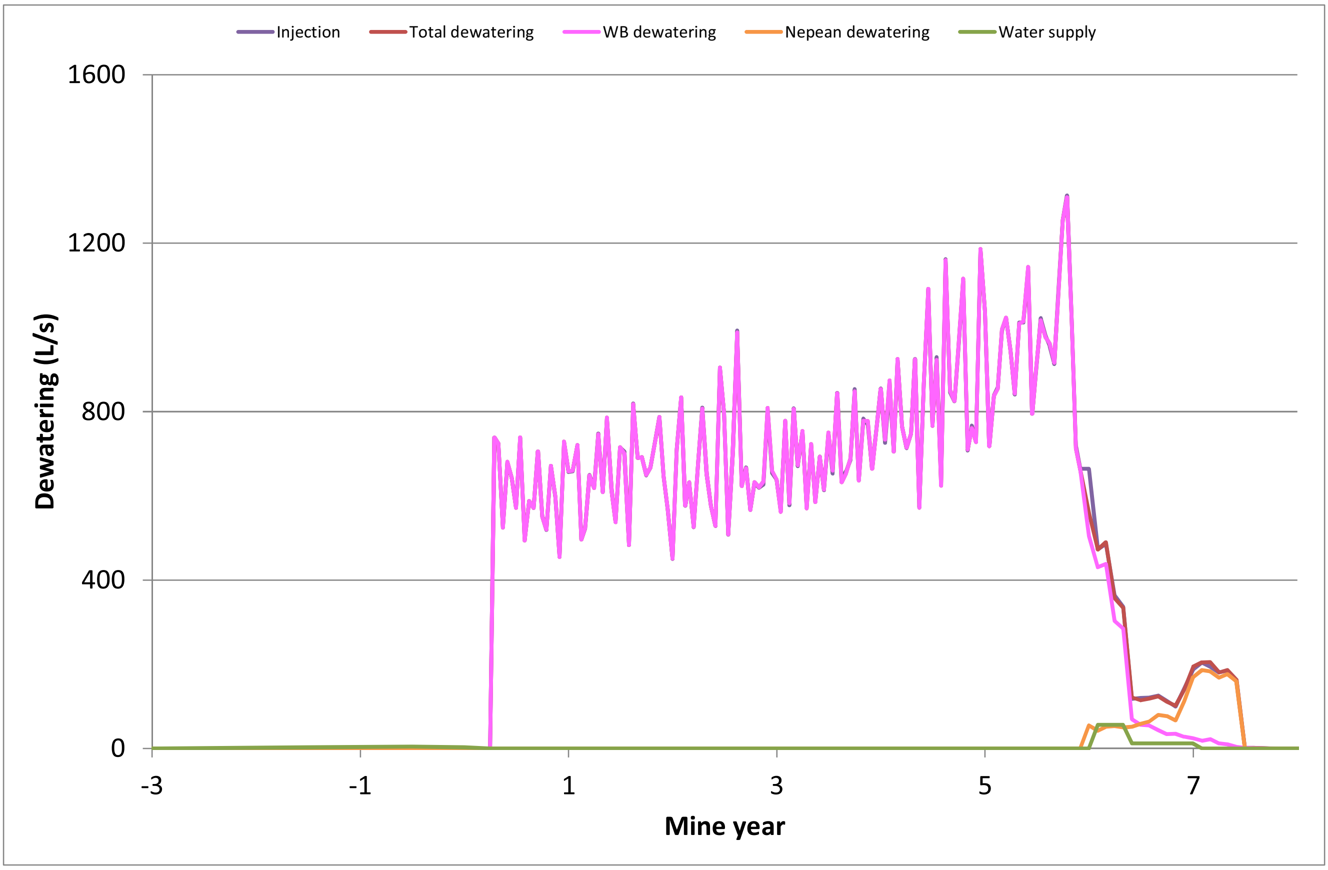


Figure 6.11 : Modelled groundwater management strategy for the Project

Model-predicted mounding (negative drawdown) in the Shepparton Formation and LPS at the end of West Balranald mining are presented in Figure 6.4 and Figure 6.5. Heads in the LPS are seen to increase by more than 5 m above the pre-mining levels. However, the impact in the overlying Shepparton Formation is lower, on the order of 2 m, due to the poor hydraulic connection between the two aquifers. Whilst localised elevated heads can be seen along the West Balranald-Nepean haul road and spurs coming off it, the mounding creates a large 'bubble' of regional elevated heads. This occurs as a result of two factors. Firstly, the wellfield is operated using a head constraint of 3 m below topography. This necessitates a wellfield covering a large area (around 25 km x 20 km) that injects water in a diffuse manner. Secondly, the LPS in the region is highly transmissive, enabling rapid transmission of injected water to the surrounding groundwater system. Predicted mounding, and associated depth to water, throughout mining of both deposits and for 100 years post-mining are presented in Appendix E.

6.6 Post-mining recovery and mitigation

Following cessation of dewatering and injection a 100 year recovery period is simulated. Modelled stresses revert to those simulated for pre-mining conditions.

The modelled water balance for the study area over the period of groundwater-affecting activities and for two years afterwards is presented in Figure 6.12. Fluxes at key times are tabulated in Table 6.2. Upon commencement of mining at West Balranald, dewatering and injection dominate the water balance, along with the associated storage changes. When dewatering and injection reduce and then cease, the water balance is seen to rapidly approach its pre-development condition. Throughout the period of mining, groundwater entering and exiting the model domain via the boundaries remains relatively constant. However, close inspection of the predicted water balance indicates some change in modelled throughflow. Modelled boundary inflow is 7,831 ML/yr prior to development but has a predicted minimum of 7,491 ML/yr, occurring 100 years post-mining. Whilst this maximum fluctuation of 340 ML/yr equates to approximately 4 % of the pre-development magnitude, it is only 0.4 % of the maximum total inflow simulated in the scenario (82,912 ML/yr in mining year 6).Hence, the fluctuation is within the error bounds of the model's water balance and, given that predicted drawdown impacts do not reach the model boundaries, no significant regional throughflow impact is expected.

Similarly, minor fluctuations are evident in modelled river leakage. Maximum deviation from the modelled pre-development leakage rates occurs 100 years post-mining for both leakage from the rivers (varies 111 ML/yr) and leakage to the rivers (varies 5 ML/yr). These equate to 7 % and 5 % of their modelled pre-development values respectively and only 0.1 % and 0.01 % of the maximum inflow and outflow modelled in the scenario (82,912 ML/yr in mining year 6). Monitoring of Murrumbidgee River flow at Balranald for the period 1981 to 2015 indicates an average flow of 926,000 ML/yr, with a minimum of 79,400 ML/yr recorded in 1983 and a maximum of 3,743,000 ML/yr in 1990. As a proportion of average flow in the Murrumbidgee River the maximum fluctuations in modelled river leakages equate to 0.01 % and 0.001 %. Therefore, the modelled variations in river leakage are both within the error bounds of the modelled water balance and very small compared to flow in the river. Furthermore, given that predicted drawdown impacts do not reach the Murray and Murrumbidgee Rivers, no significant impacts are expected on flows in these water bodies.

The lack of significant changes in other components of the water balance suggests that dewatering and injection are balanced almost entirely by changes in storage in their respective locations. Over time, the drawdown at the deposits and mounding at the injection wellfield are expected to return to pre-mining conditions.

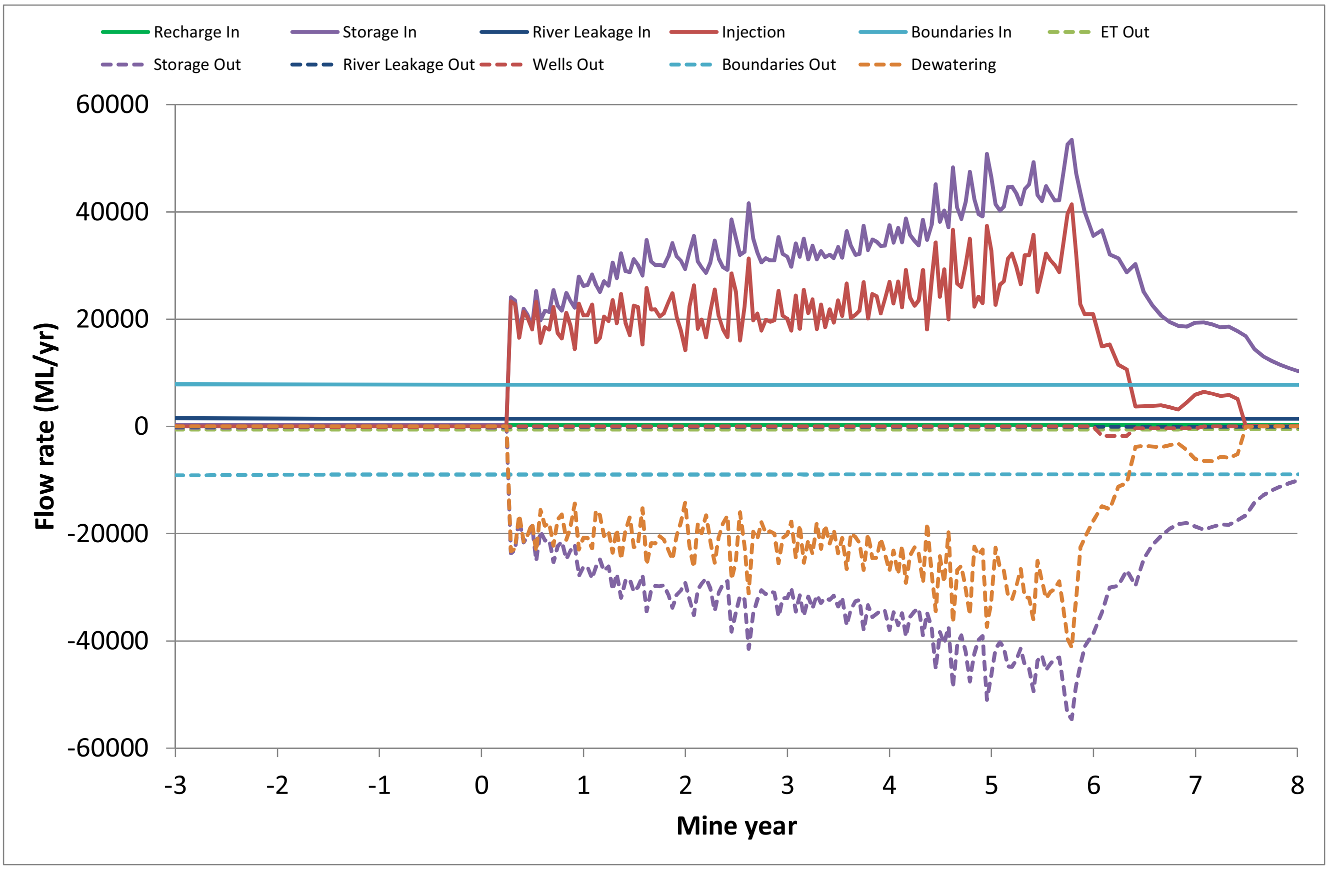


Figure 6.12 : BAL2.0_TS2_opt29 modelled water balance

Table 6.2 : Annual water balances through construction, mining and recovery

	Pre-development		Construction (3 yr)		Mining Year 1		Mining Year 2		Mining Year 3		Mining Year 4	
	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)
Storage	325	236	263	176	22,679	22,481	29,755	29,514	32,623	32,442	33,416	33,836
Recharge	296	-	296	-	296	-	296	-	296	-	296	-
Evapotranspiration	-	607	-	613	-	611	-	599	-	573	-	555
River leakage	1,512	97	1,457	99	1,456	99	1,456	99	1,456	98	1,456	98
Boundaries (throughflow)	7,831	9,127	7,789	8,987	7,783	8,978	7,779	8,966	7,775	8,958	7,772	8,952
West Balranald dewatering	-	-	-	-	-	19,546	-	20,435	-	21,346	-	22,421
Nepean dewatering	-	-	-	-	-	-	-	-	-	-	-	-
Injection	-	-	-	-	19,532	-	20,447	-	21,329	-	22,418	-
Water supply	-	-	-	125	-	-	-	-	-	-	-	-
TOTAL	9,964	10,067	9,804	10,000	51,744	51,715	59,732	59,612	63,479	63,417	65,358	65,862
	Mining Year 5		**Mining Year 6**		**Mining Year 7**		**Mining Year 8**		**Recovery Year 1**		**Recovery Year 100**	
	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)	In (ML/yr)	Out (ML/yr)
Storage	40,057	40,219	43,775	44,573	24,205	23,375	14,799	14,561	7,084	7,054	439	477
Recharge	296	-	296	-	296	-	296	-	296	-	296	-
Evapotranspiration	-	551	-	547	-	545	-	543	-	524	-	495
River leakage	1,456	98	1,456	98	1,456	98	1,456	98	1,407	95	1,401	92
Boundaries (throughflow)	7,770	8,946	7,769	8,944	7,767	8,524	7,768	8,923	7,513	8,627	7,491	8,589
West Balranald dewatering	-	27,004	-	29,461	-	4,730	-	183	-	-	-	-
Nepean dewatering	-	-	-	76	-	2,300	-	2,295	-	-	-	-
Injection	27,144	-	29,616	-	6,269	-	2,065	-	-	-	-	-
Water supply	-	-	-	-	-	841	-	-	-	-	-	-
TOTAL	76,722	76,818	82,912	83,700	39,993	40,414	26,384	26,603	16,290	16,300	9,617	9,653

Model-predicted drawdown and mounding in the Shepparton Formation and LPS 100 years after cessation of groundwater-affecting activities are presented in Figure 6.13 and Figure 6.14. These demonstrate that drawdown impacts in the two aquifers are very similar after such a long period. Both have residual drawdown and mounding of up to 1 m at West Balranald and the off-path wellfield respectively. No residual impact of dewatering at Nepean is evident. Whilst the magnitude of drawdown has reduced substantially by this time, the extent of the 0.2 m contour has expanded outward towards, but not to, the Murrumbidgee River. However, as mentioned earlier, there is no predicted increase in leakage to or from the Murrumbidgee and Murray Rivers.

Given the longevity of drawdown impacts resulting from West Balranald, several attempts were made to mitigate drawdown immediately following cessation of backfilling. These focussed on pumping water from the centre of the off-path injection wellfield back to the northern-most 3 km of the West Balranald deposit, where wells used for dewatering could be readily converted for operation as injection wells. A constraint was applied that, during mitigation injection, heads could not rise to within 3 m of the final backfill elevation (52 mAHD) in the residual pit void. This criterion of 49 mAHD meant that injection rates were highly constrained, in fact injection rates as low as 20 L/s were not possible and, hence, no dedicated drawdown mitigation is planned. In practice, the optimisation of dewatering and injection on-path is expected to firstly reduce dewatering volumes and, secondly, lead to much greater injection on-path such that drawdown is largely mitigated during mining. This would also lead to reduced mounding impacts at the off-path injection wellfield.

6.7 Groundwater users

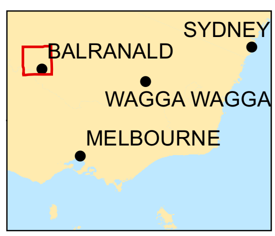
6.7.1 Groundwater dependent ecosystems

An assessment of impacts on potential groundwater-dependent ecosystems (GDEs) has been carried out (CDM Smith, 2015). The groundwater modelling carried out in this study provides inputs to that assessment. Along with spatial datasets of model-predicted drawdown and mounding impacts on the water table, a series of hydrographs at selected sites of potential GDEs has been requested. Model-predicted hydrographs for sites GDE1 to GDE8 and WBMW022 are presented in Appendix F.

6.7.2 Third party wells

EMM is carrying out a water impact assessment, for which modelled groundwater impacts also forms an input. A series of hydrographs at third party wells has been requested for that study. Data on the third party wells was provided by OW. Details of the wells along with model-predicted hydraulic heads for each of them are provided in Appendix G.

- Town
- Major road
- Minor Road
- Lake
- River
- Watercourse
- Haul road
- West Balranald pit limits
- West Balranald disturbance
- Nepean pit limits
- Nepean disturbance
- BAL2.0 model domain
- EIS offpath injection area
- Modelled drawdown (m)
- Modelled mounding (m)



0 10 Kilometres

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BAL2.0 TS2 opt29 modelled drawdown in Shepparton Formation 100 years post-mining

Figure 6.13

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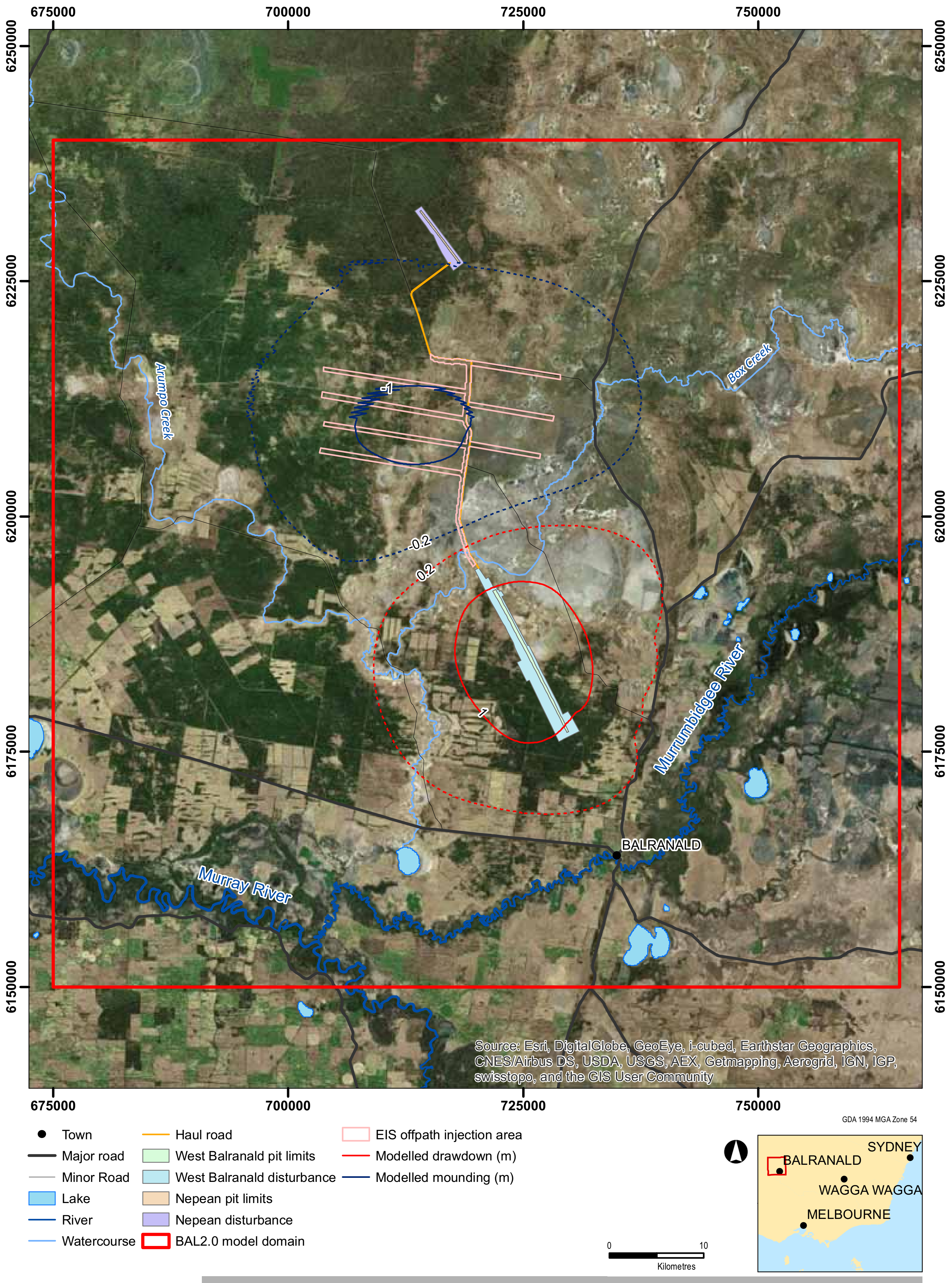

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BAL2.0 TS2 opt29 modelled drawdown in LPS1 foreshore 100 years post-mining

Figure 6.14

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7. Predictive Uncertainty Analysis

Due to their inherent nature as simplified representations of a complex continuous world, all models are “wrong”. The purpose of an uncertainty analysis is to determine how “wrong” a given model prediction may be. That is, the realm of plausible predictions is explored such that a range of outcomes is identified, rather than a single prediction.

Many aspects of a model contribute to the uncertainty associated with a prediction. The available data, conceptual model, spatial and temporal discretisation, adopted parameter values and modelling software all contribute to the “error” in a prediction.

7.1 Methodology

Some aspects of the uncertainty associated with a model prediction are difficult to quantify. The approach taken here is to carry out an uncertainty analysis based on a plausible range of key aquifer properties. Aspects such as alternative conceptualisations, discretisation and software are not considered.

Two sets of alternative parameter values are defined such that they would provide a “high dewatering” case and a “low dewatering” case. The parameter values adopted were selected based on results of the calibration sensitivity analysis and in consultation with Iluka’s Hydrogeology Department.

In the high dewatering case parameter values were selected that were thought to create a more demanding dewatering operation and also that would pose the greatest risk to disposal via injection. It was anticipated this would also generate more extensive and prolonged drawdown and mounding than the base case.

In the low dewatering case the opposite approach was taken, such that parameter values likely to create a less demanding dewatering operation and that would pose the least risk to disposal via injection, were selected. Consistent with the approach of the sensitivity analysis, parameter values were scaled using multipliers. The parameters and associated multipliers used to define the high dewatering and low dewatering cases are presented in Table 7.1.

Table 7.1 : Uncertainty analysis parameter values

Parameter	Base case value	High dewatering multiplier	Low dewatering multiplier
Shepparton Formation Kh (m/d)	1	2	0.2
Shepparton Formation Kv (m/d)	0.001	10	1
LPS surf zones Kh (m/d)	10 - 40	1.5	0.8
LPS non surf zones Kh (m/d)	0.012 – 0.13	2	0.5
LPS non surf zones Kv (m/d)	0.001 – 0.005	10	1
Geera Clay Kv (m/d)	1×10^{-5}	100	1
Ss (1/m)	3×10^{-5}	0.5	2
Sy (-)	0.15	1.33	0.75

Both scenarios were initially run with the base case injection rates. These preliminary model runs provided revised dewatering rates for the duration of the Project. For both cases the simulated injection rates were then revised to match their corresponding dewatering rates. The off-path injection wellfield footprint was assumed the same as for the base case. Production for make-up water supply in mine year 8 was not revised in line with the new dewatering rates. This is a minor component of the mine water balance and expected not to play a significant role in the uncertainty associated with either the operational feasibility or the predicted environmental risks posed by operation of the groundwater management plan.

7.2 Dewatering and disposal requirements

Predicted dewatering requirements for the Project are presented for the high dewatering case and low dewatering case in Figure 7.1 and Figure 7.2 respectively. Average annual dewatering rates for the base case and the two uncertainty analysis runs are shown in Table 7.2. Each of the uncertainty analysis model runs displays the same temporal trend as the base case (refer to Figure 6.11), with dewatering rates generally increasing through the period of mining West Balranald, as the pit moves northward and further below the pre-mining water table. However, the dewatering rates in the high and low dewatering cases are essentially scaled up and down from the base case values. The peak predicted dewatering rates are 2,048 L/s and 934 L/s for the high and low dewatering scenarios.

Analysis of model-predicted hydraulic heads along the West Balranald and Nepean deposits indicates that both uncertainty analysis cases successfully dewater the deposits. Therefore, it is anticipated that, even for the most difficult yet plausible set of aquifer parameter values, the West Balranald deposit could be dewatered (and excess water disposed by injection) with infrastructure capable of operating at a peak capacity of approximately 50 % more than the base case predicted rate of 1,309 L/s. Whilst the dewatering rates at Nepean are much lower than at West Balranald a similar increase in infrastructure capacity is predicted to ensure a dry pit even for the most difficult combination of aquifer parameters.

Table 7.2 : Predicted average annual dewatering uncertainty

Mine Year	Base dewatering (ML/yr)		High dewatering (ML/yr)		Low dewatering (ML/yr)	
	West Balranald	Nepean	West Balranald	Nepean	West Balranald	Nepean
1	19,546	-	31,517	-	12,412	-
2	20,435	-	33,920	-	13,782	-
3	21,346	-	37,625	-	15,093	-
4	22,421	-	37,092	-	15,792	-
5	27,004	-	45,376	-	19,000	-
6	29,461	76	49,301	136	20,922	54
7	4,730	2,300	12,659	3,326	3,867	1,415
8	183	2,295	2,417	2,592	562	1,197

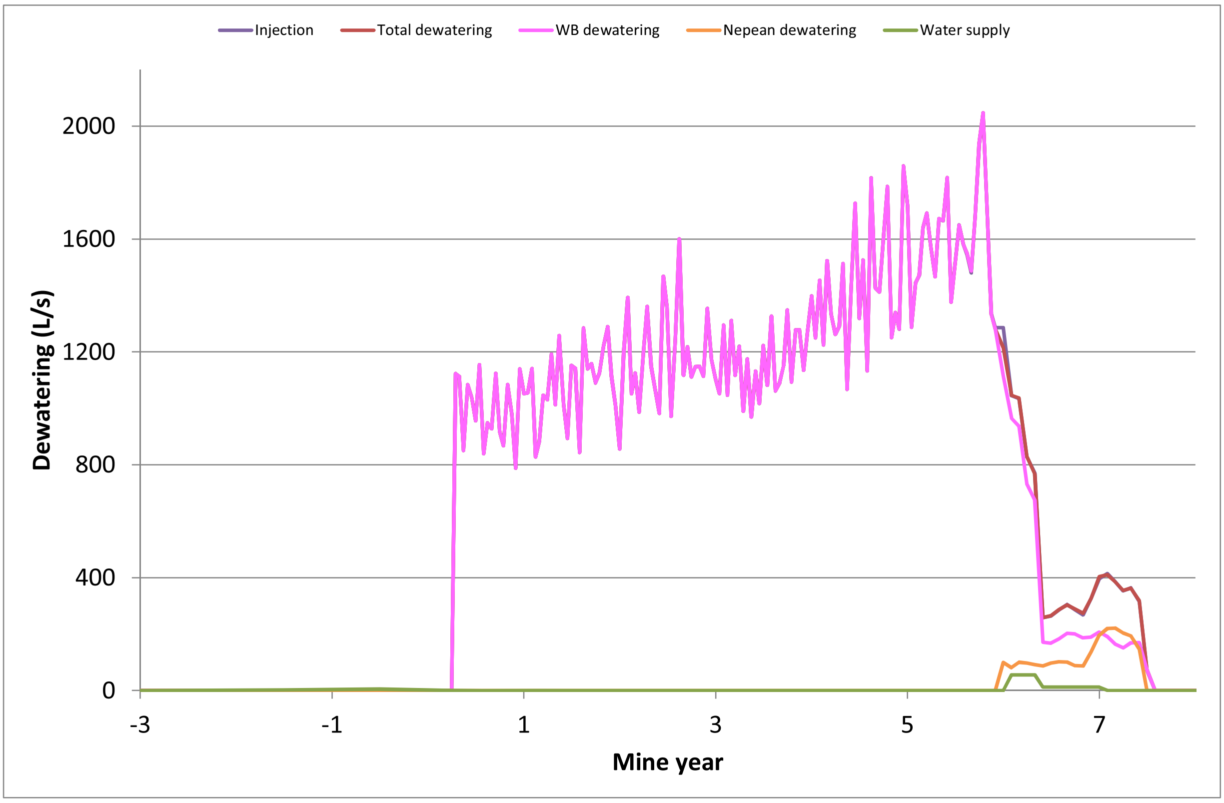


Figure 7.1 : High dewatering modelled groundwater management

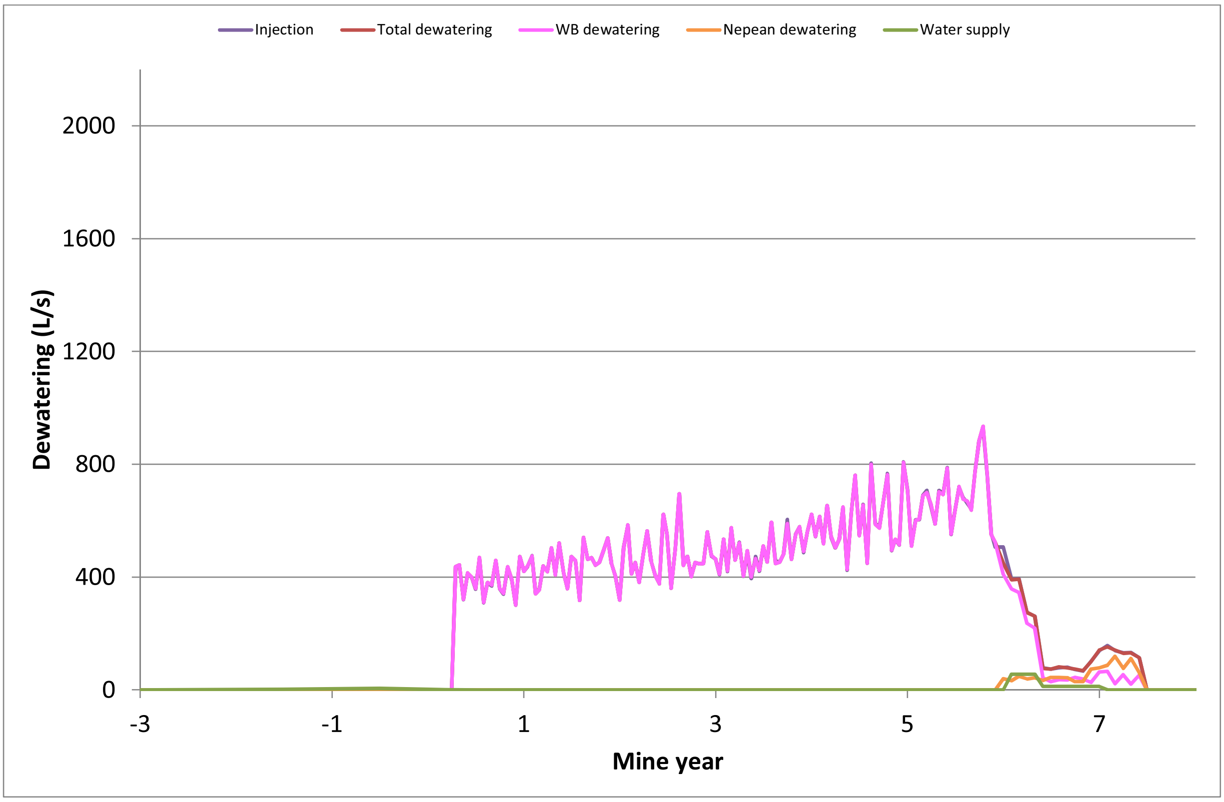


Figure 7.2 : Low dewatering modelled groundwater management

7.3 Drawdown and mounding

Predicted regional drawdown and mounding are presented spatially for the base case and two uncertainty cases in Figure 7.3 to Figure 7.11. Results are presented at the end of mining year 6 (end of mining at West Balranald), mining year 8 (end of backfilling at West Balranald) and 100 years post-mining.

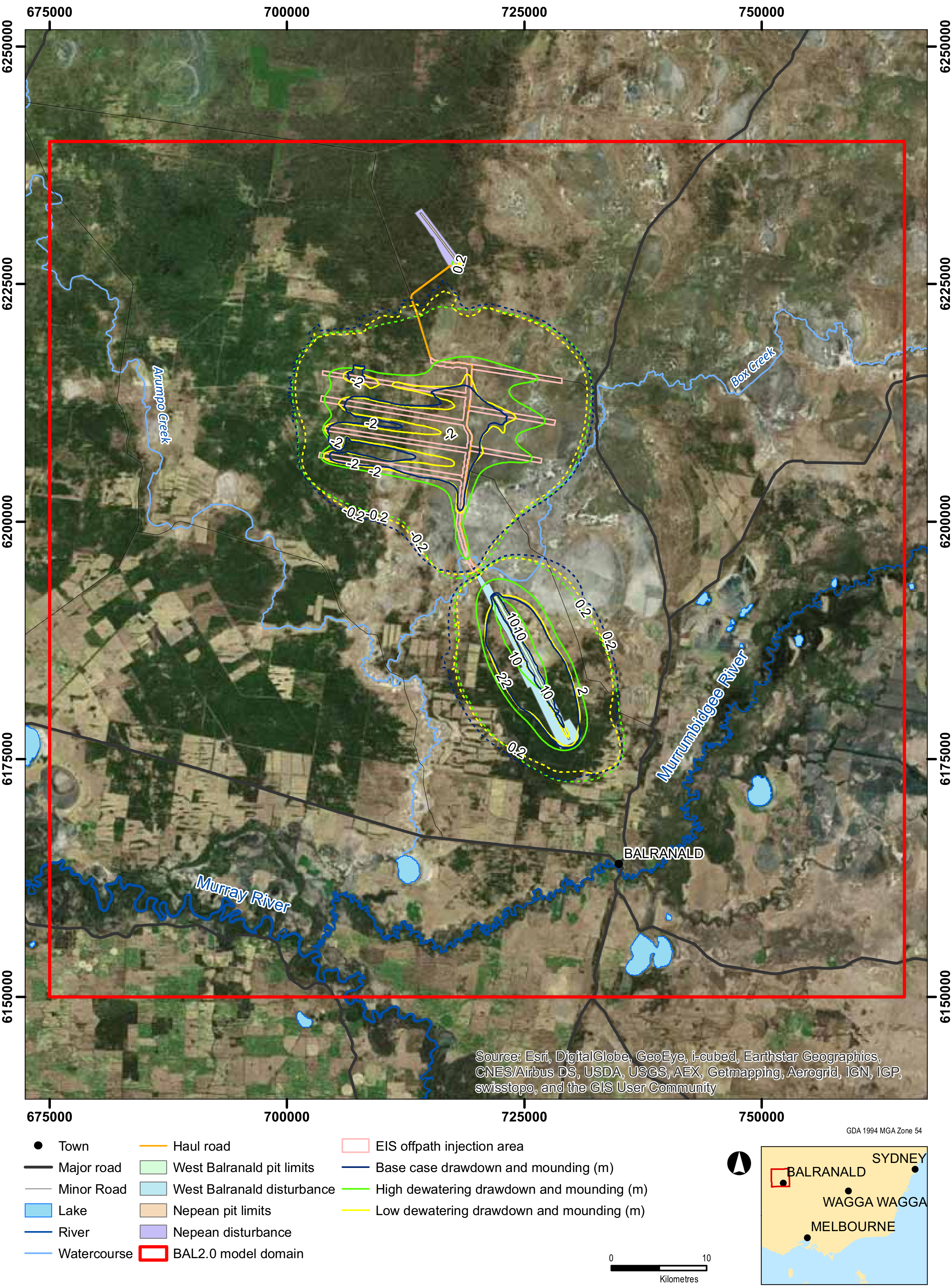
At the end of mining year 6, predicted drawdown and mounding in the Shepparton Formation (Figure 7.3) and LPS1 foreshore (Figure 7.4) are remarkably similar, particularly given the significant difference in dewatering and injection rates between the high and low dewatering cases. It appears that the increased hydraulic conductivities, that are partially responsible for the increased dewatering volumes, enable rapid dispersion of injected groundwater without leading to significant increases in mounding. In fact, impacts from the base case extend further in some directions than the impacts from the two end member cases do.

Predicted drawdown impacts in the Olney Formation at the end of mining year 6 are evident only for the high dewatering case. In the base case and low dewatering case the Geera Clay acts as a sufficient barrier so as to restrict modelled impacts in the Olney Formation to less than 0.2 m. In the high dewatering case the base case Geera Clay Kv of 1×10^{-5} m/d is increased 100 times. This is probably higher than is reasonably expected, even at this much higher conductivity, drawdown and mounding is relatively localised to the West Balranald deposit and off-path injection areas and at levels not much more than 2 m.

Predicted impacts at the end of mining year 8 (refer to Figure 7.6 to Figure 7.8) are very similar in the three reported hydrostratigraphic units to those predicted at the end of mining year 6. The only notable difference is that relatively minor impacts are seen at Nepean. As at year 6, the three cases generate remarkably similar impacts and the only case for which impacts greater than 0.2 m are evident in the Olney Formation is the high dewatering case.

100 years post-mining predicted impacts are again very similar for the three cases tested (Figure 7.9 to Figure 7.11). Drawdown and, in particular, mounding extend furthest outward for the high dewatering case. As is predicted during dewatering, impacts are only predicted to reach 0.2 m in the Olney Formation for the high dewatering case.

Crucially, in all three cases, drawdown of greater than 0.2 m does not reach the Murrumbidgee or Murray Rivers. Further, the remarkable similarity of impacts predicted for the two cases that define the upper and lower bounds of anticipated plausible dewatering suggests that the degree of uncertainty associated with predicted mounding impacts is low. Whilst a little surprising, this outcome suggests that the proposed dewatering and disposal operations required to mine the West Balranald and Nepean deposits can be accommodated within the existing dewatering and injection strategy without adverse environmental impacts.



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BAL2.0 TS2 opt29 drawdown uncertainty analysis in Shepparton Formation at mining year 6

Figure 7.3

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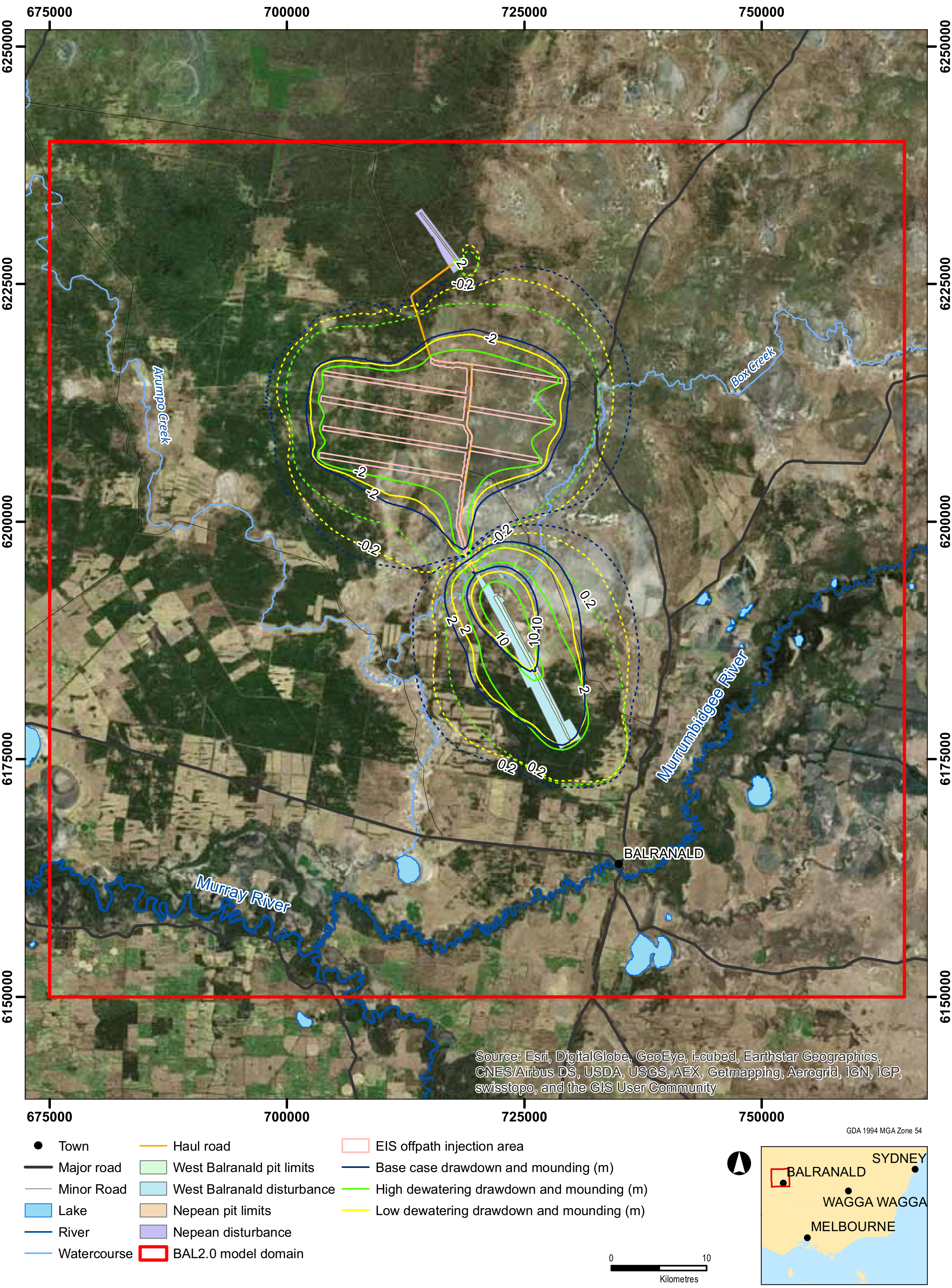

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in LPS1 foreshore at mining year 6

Figure 7.4

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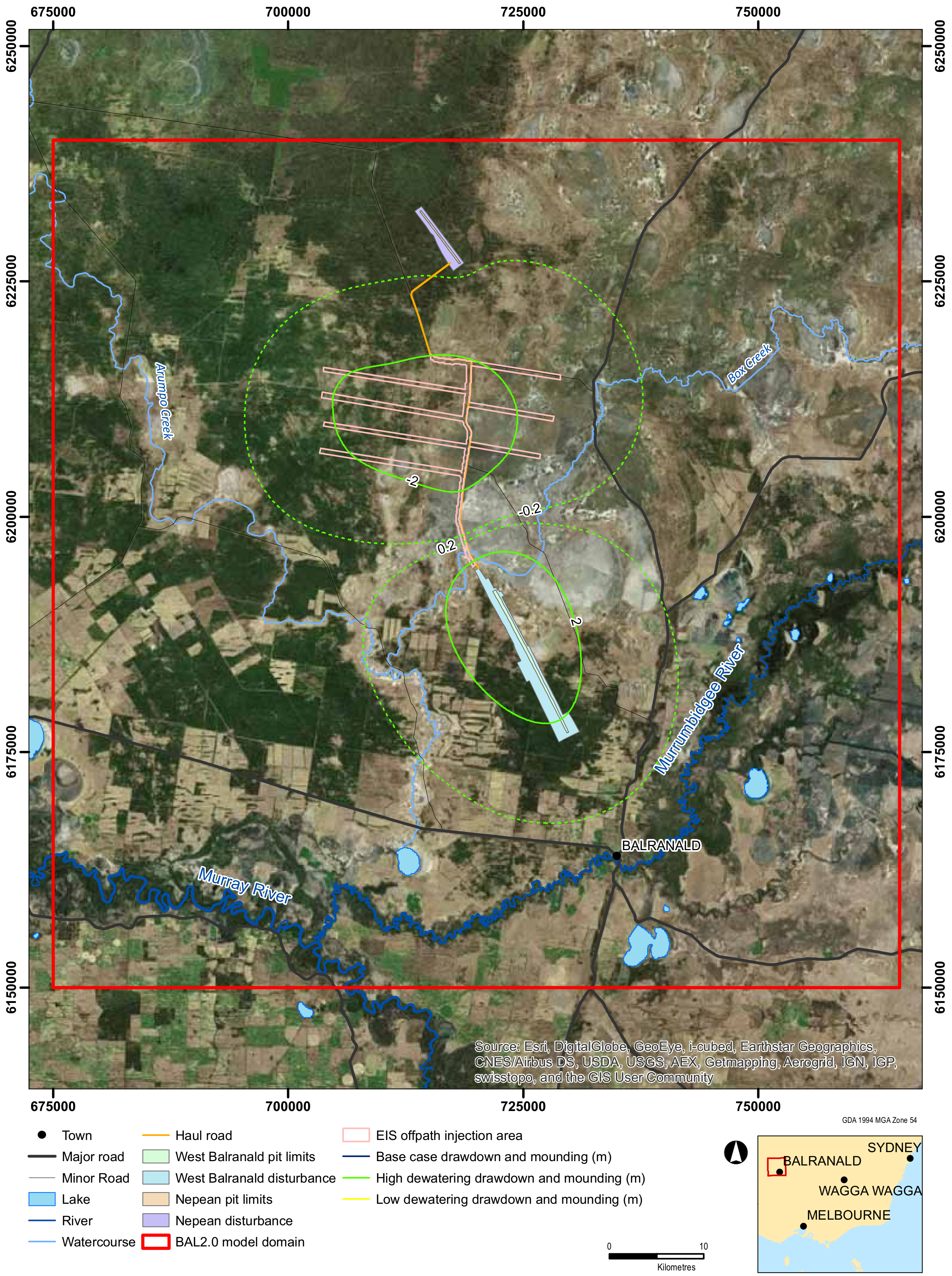

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in Olney Formation at mining year 6

Figure 7.5

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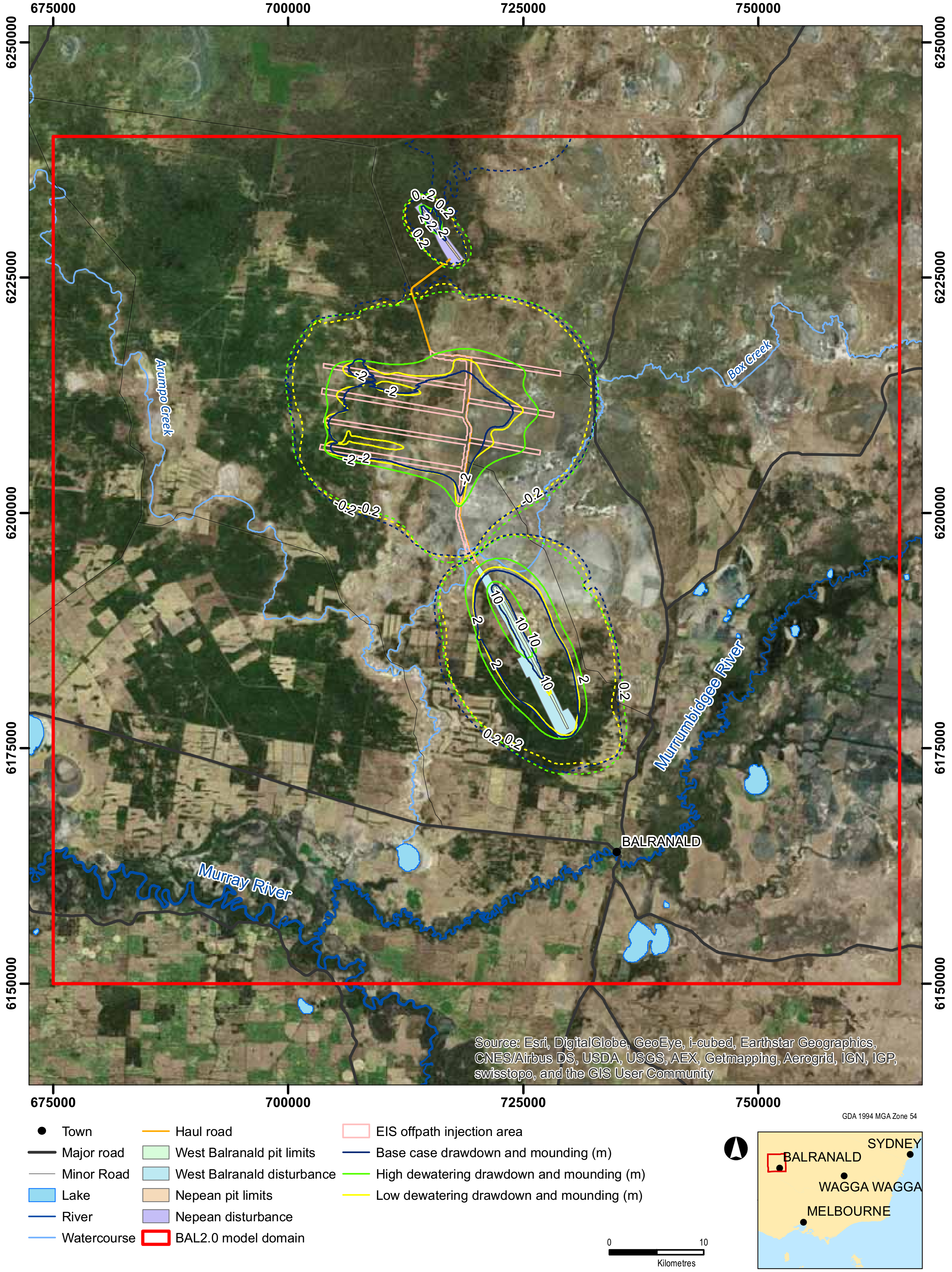

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in Shepparton Formation at mining year 8

Figure 7.6

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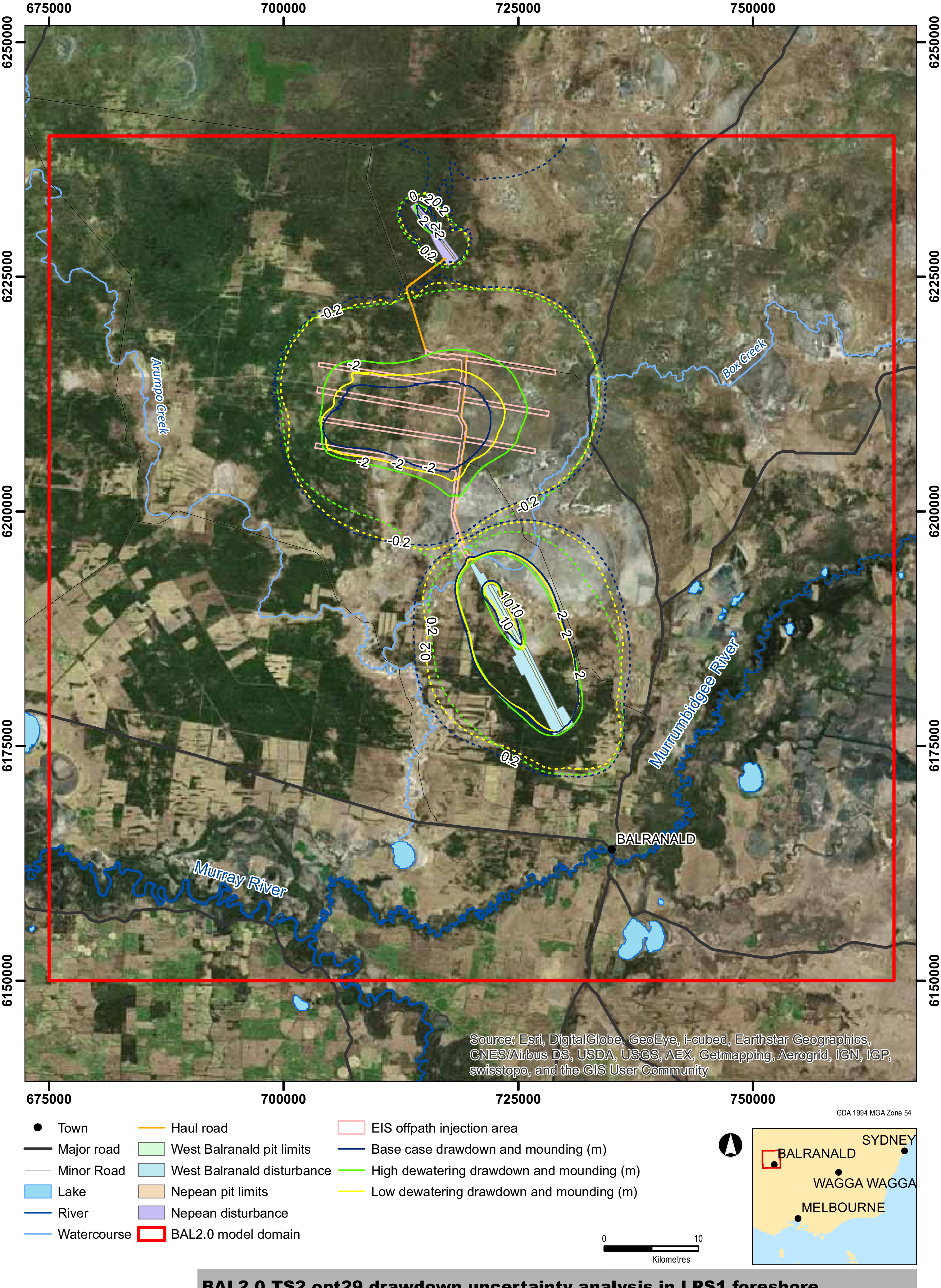

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in LPS1 foreshore at mining year 8

Figure 7.7

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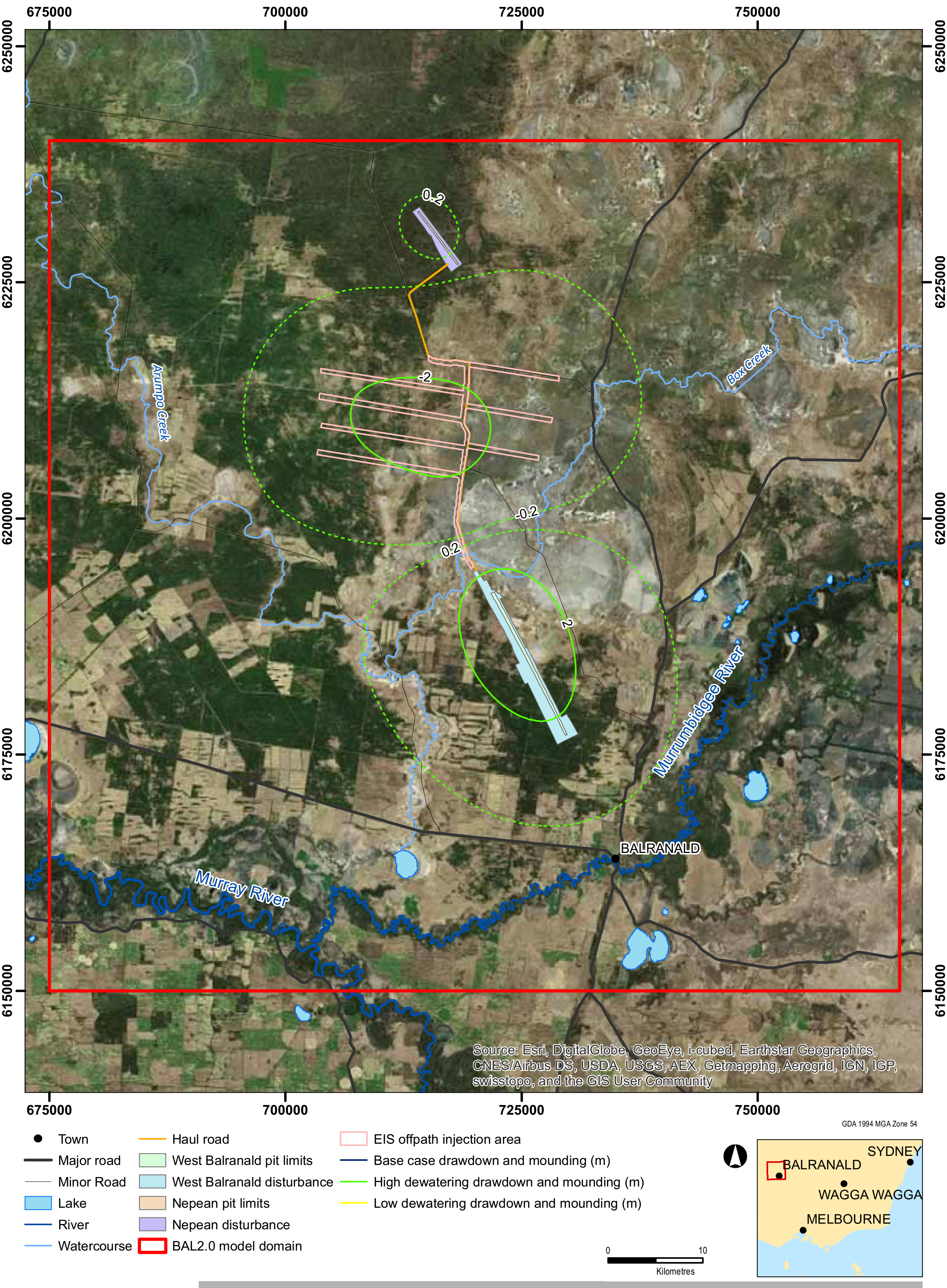

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in Olney Formation at mining year 8

Figure 7.8

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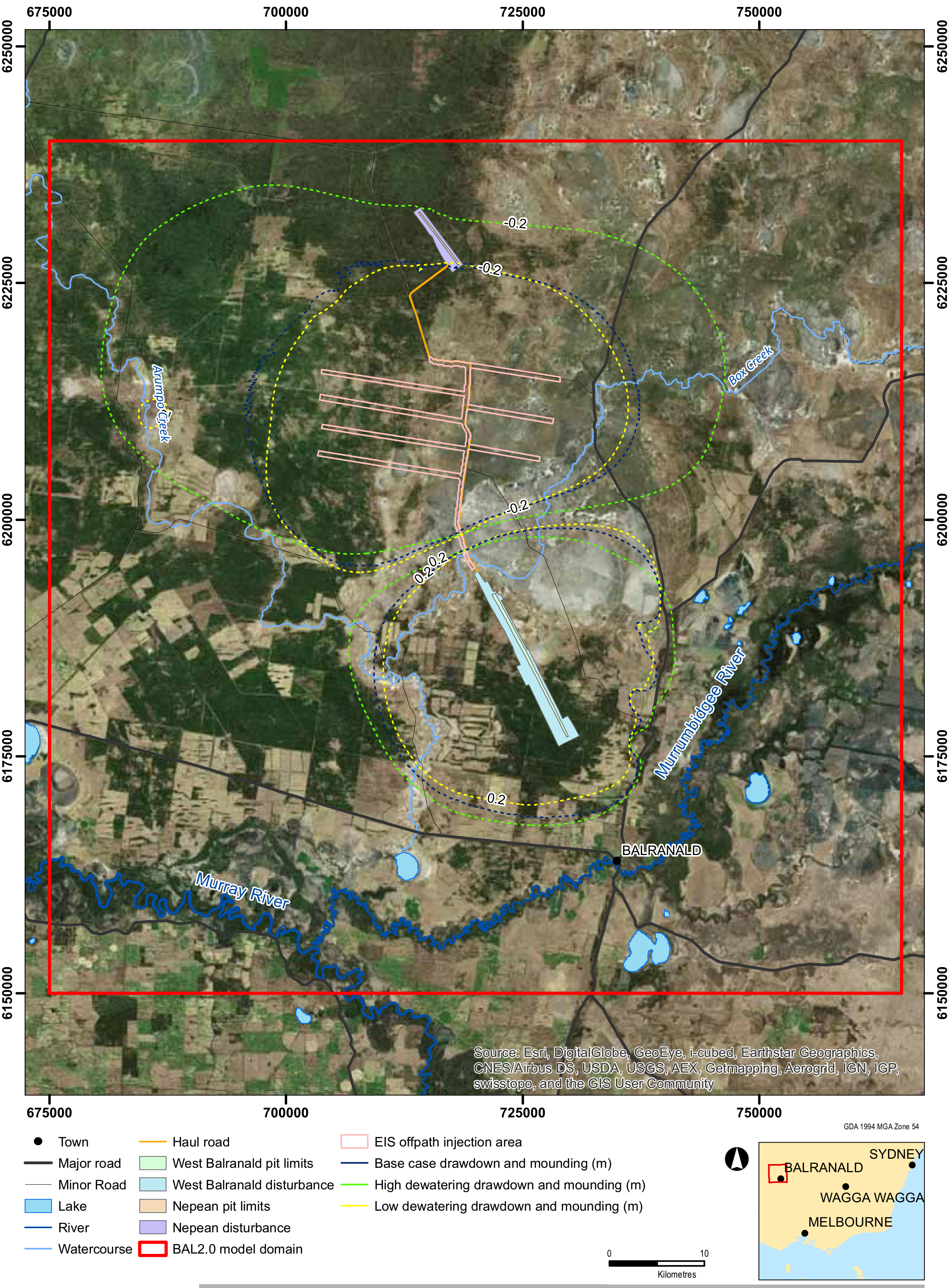

BAL2.0 TS2 opt29 drawdown uncertainty analysis in Shepparton Formation 100 years post-mining

Figure 7.9

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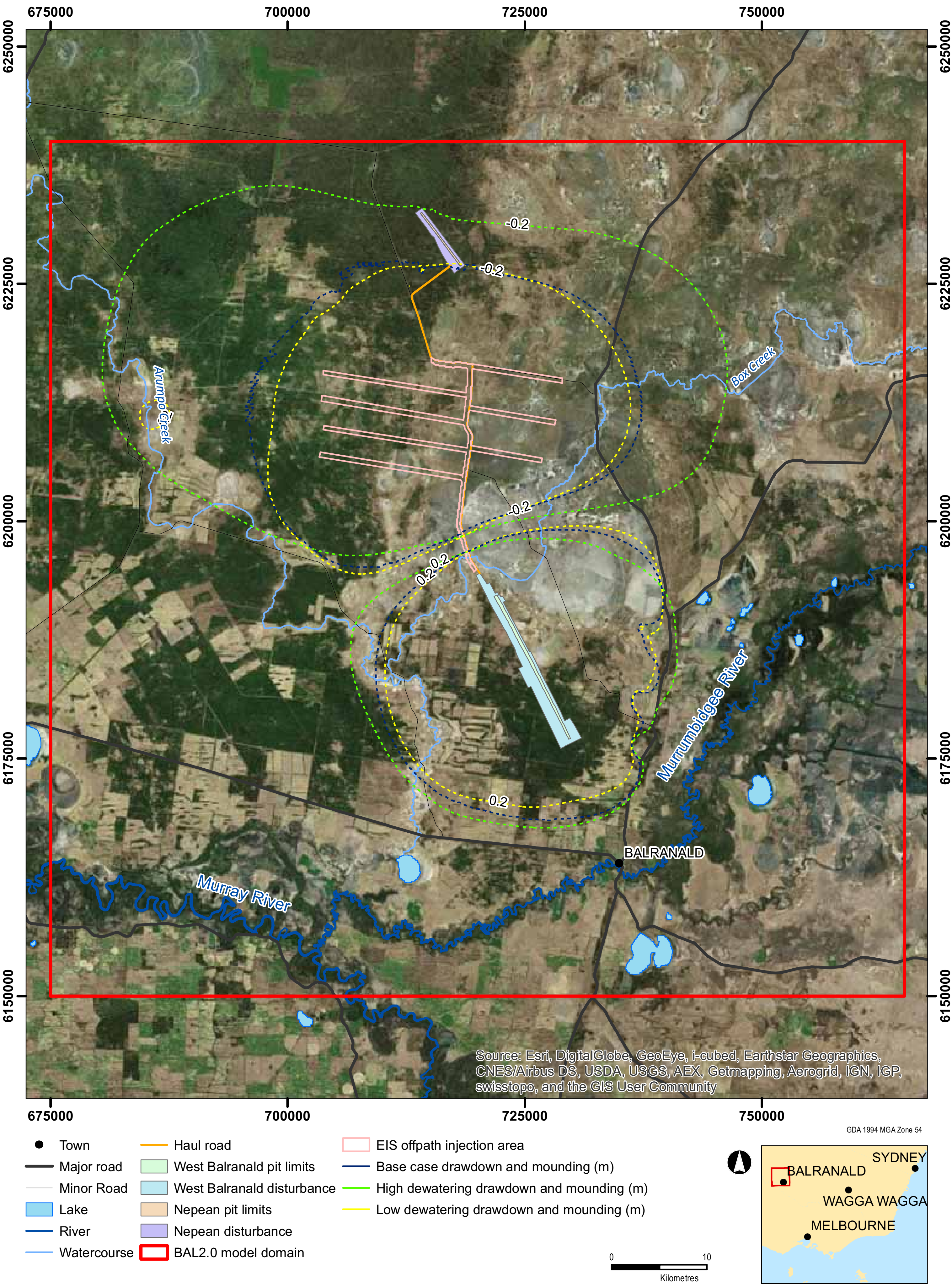

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in Shepparton Formation
100 years post-mining **Figure 7.10**

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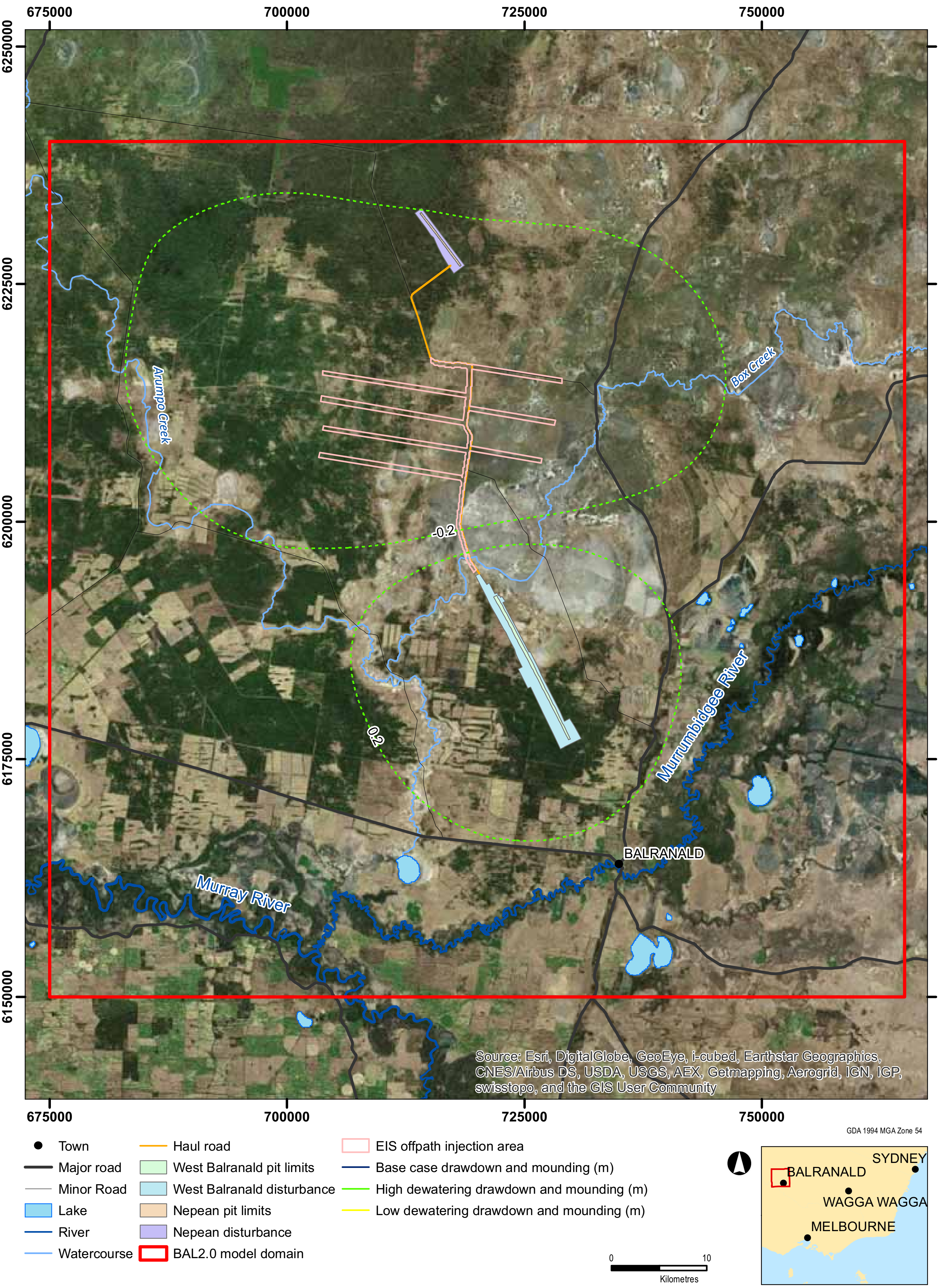

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BAL2.0 TS2 opt29 drawdown uncertainty analysis in Olney Formation 100 years post-mining

Figure 7.11

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8. Model Capabilities and Limitations

The BAL2.0 model presented in this report has been designed to provide regional groundwater impact assessment of groundwater-affecting activities planned for development of the Project. The model has been informed by currently available hydrogeological data. These include a good coverage of bore logs around the deposits, but poorer coverage in areas more remote from the deposits. Of particular interest is the area between the West Balranald and Nepean deposits where the off-path injection wellfield is proposed. Whilst some logs are available for this area, given its importance for injection, Iluka plans to further investigate the presence and properties of the LPS surf zones in this region. The model currently assumes that the thick, highly transmissive LPS2 surf zone encountered in wells near “Nanda” and “Upson Downs” is present across the injection wellfield footprint.

The model is calibrated using data from production and injection tests run at rates of up to 70 L/s and for durations of up to 47 days. These stresses are considerably lower than those planned during operation of the Project and, hence, there is inherent uncertainty with regard to how the groundwater system will respond under different conditions to those to which it is calibrated. Of particular importance is the fact that current pumping and injection test data do not enable identification of the LPS specific yield, which is expected to have a significant influence on the required dewatering pumping rates. A value for this parameter has been obtained from models calibrated to mining stresses at two of Iluka’s other mines in similar settings.

The model is suited to informing high-level dewatering and injection infrastructure design. It does not contain the necessary representation of individual wells to aid design of optimum well spacings and injection rates.

The model does not simulate the temporal changes in aquifer hydraulic properties expected to occur as a result of excavation and subsequent backfilling of the mine pits, as it is considered unnecessary for a regional groundwater impact assessment.

9. Summary and Conclusions

Groundwater modelling has demonstrated that an appropriate groundwater management scheme can be implemented for mining of the West Balranald and Nepean deposits. The scheme involves dewatering at both deposits, at rates of up to around 1,300 L/s at West Balranald (about 700 L/s on average) and around 190 L/s at Nepean (about 100 L/s on average). The model has been constructed in such a way that these are expected to be conservative estimates. Drawdown from dewatering at West Balranald is predicted to extend up to around 15 km from the deposit. Drawdown at Nepean is localised, extending a maximum of around 2 km from the deposit.

Water produced by dewatering operations is reinjected into the LPS via on-path injection wells at West Balranald and an off-path injection wellfield, located on and accessed from the West Balranald-Nepean haul road. Peak injection is around 1,300 L/s. The off-path wellfield has been sized such that injection is spread over a large area. This is done to ensure that mounding of the water table remains a minimum of 3 m below the ground surface to avoid waterlogging and salinisation of non-saline surface sediments.

Predictive uncertainty analysis has explored the sensitivity of model predictions to variability or uncertainty in key hydrogeological parameters included in the model. It has demonstrated that the proposed dewatering and injection plan is capable of delivering acceptable engineering and environmental outcomes under most possible combinations of uncertain model parameters.

Modelling has demonstrated that operation of a water supply during the three years of pre-mining construction, at rates of up to 150 ML/yr, can be supported by the Olney Formation. Drawdown from the water supply wells is localised and not expected to have a significant impact on the regional groundwater system.

The model-predicted water balance suggests that dewatering and injection activities associated with the mine will primarily add and remove water from storage in the groundwater system. No significant impacts are predicted on leakage to or from the Murrumbidgee and Murray Rivers.

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