Appendix A. Independent review by Hugh Middlemis

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MEMO-REPORT

ATTENTION:	Joel Georgiou, Senior Hydrogeologist, Iluka Resources Limited	
FROM:	Hugh Middlemis, Principal Groundwater Engineer, Hydrogeologic	
REFERENCES:	26 March 2015	Balranald_Model_Review_1b_Middlemis_2015.Docx
SUBJECT:	**Balranald Project Groundwater Model Review (BAL2.0, March 2015)**	

1. Overview

This report summarises the outcomes of an independent review of the Balranald Project numerical groundwater flow model developed for Iluka by Jacobs. The focus of this review is the Impact Assessment Modelling (Jacobs, 2015) completed with the BAL2.0 version regional model (engineering design and related risk management issues were not considered).

The review was conducted in accordance with the principles of the 2012 Australian Groundwater Modelling Guidelines (Barnett et al., 2012), as well as the Murray Darling Basin Commission Groundwater Flow Modelling Guideline (Middlemis et al, 2001), which was the foundation for the 2012 guidelines (and remains valid for Murray-Darling Basin projects, such as the Balranald mineral sands mining project). The 2012 guideline suggests a compliance checklist suitable for high-level appraisals, which can also be used to summarise the outcomes of a review. The completed summary checklist is presented at **Error! Reference source not found.**, and justifications for the opinions indicated are summarised in the comments field, with key elements explored in later sections.

In summary, it is my professional opinion that the BAL2.0 model has been developed consistent with best practice for a medium complexity or Class 2 model confidence level classification, meaning that this model is suitable for mining project impact prediction purposes.

Table 1 - Groundwater Model Compliance Checklist: 10-point essential summary

Question	Yes/No	Comments re Balranald groundwater model (BAL2.0)
1. Are the model objectives and model confidence level classification clearly stated?	Yes	A confidence level Class 2 modelling tool is stated as being required to provide information for support the design of and quantify the impacts of a groundwater management scheme for the Balranald mineral sand mining project that includes dewatering and injection wellfields.
2. Are the objectives satisfied?	Yes	The objectives are satisfied via sound model design and calibration performance, including using fine-grid local scale models at pumping test sites for parameter calibration, and applying those parameters to the regional scale model for suitably conservative predictions to evaluate dewatering and related impacts and uncertainties.
3. Is the conceptual model consistent with objectives and confidence level classification?	Yes	The conceptualisation is sound, the key features are appropriately represented in the model design and its implementation, and uncertainties have been considered carefully, appropriate for the impact assessment objectives.
4. Is the conceptual model based on all available data, presented clearly and reviewed by an appropriate reviewer?	Yes	A multi-disciplinary team at Iluka and Jacobs has clearly been involved in the hydrogeological investigations and data analysis undertaken since 2011. Specialist hydrogeologist Ray Evans also contributed his skills and long experience on Mallee zone hydrogeology to address key geological and stratigraphic issues. The hydrogeological data and conceptual model descriptions in the report are excellent.

5. Does the model design conform to best practice?	Yes	The model design, software, extent, cell size, boundaries and parameters are consistent with best practice. The design is innovative in using local scale models for parameter calibration to pumping test data and then applying those parameters to the regional scale model. While the regional model was calibrated with these values in steady state only, the 100-year warm-up period for the transient prediction scenarios essentially forms a 100-year transient calibration, with the pseudo-steady groundwater levels confirming the hydrodynamic equilibrium of the groundwater system under the influence of regional flows and low rainfall recharge. This means that the model calibration period actually exceeds the prediction scenario period by a factor of more than 10, albeit with zero pumping stresses involved (i.e. demonstrating model compliance with a key Class 2 criterion).
6. Is the model calibration satisfactory?	Yes	Model calibration performance is good in terms of statistical measures, matches of modelled contours to regional bore spot height data, and modelled groundwater level matches to time series data from pumping and injection tests at various sites. The regional bore time series data shows a slight long term recession (order of mm to cm per year, consistent with the findings of a recent review of Mallee zone groundwater levels undertaken by the author for the MDBA; in press). This is also consistent with the results from the 100-year warm up modelling period prior to the prediction scenarios.
7. Are the calibrated parameter values and estimated fluxes plausible?	Yes	Calibration uses measured data on groundwater levels and fluxes for bore extraction and injection. An appropriate level of complexity in parameter distributions has been applied to achieve overall good calibration performance. The parameter values and fluxes are plausible and generally consistent with site-specific testing and also literature values (except for post-closure, as outlined below).
8. Do the model predictions conform to best practice?	Yes	The methods applied were consistent with best practice, except that the post-closure aquifer parameters are unchanged from in-situ values, which could over-estimate aquifer recovery rates and groundwater levels, and specific uncertainty analysis is warranted.
9. Is the uncertainty associated with the predictions reported?	Yes	Aquifer parameter sensitivity was analysed and the results used to evaluate related uncertainties in the model predictions. This was executed very well, consistent with the guidelines, in a manner that addresses the potential effect of uncertainty on the project objectives (which is unusual in this reviewer's experience, and demonstrates the professional approach applied to implementing best practice in this case).
10. Is the model fit for purpose?	Yes	My professional opinion is that the model has been developed in a manner consistent with best practice and that it is indeed fit for the stated purpose of environmental impact assessment in relation to the Balranald mineral sands mining project groundwater management system.

2. Review Approach

For the record, the reviewer (Hugh Middlemis) is an independent groundwater modelling specialist with more than 25 years' experience in this field, was awarded a Churchill Fellowship in 2004 to benchmark groundwater modelling against international best practice, and is principal author of the MDBA groundwater modelling guidelines (Middlemis et al, 2001).

This memo summarises the outcomes of a progressive review of the Balranald Project numerical groundwater flow model developed for Iluka by Jacobs. The aim was to identify whether the model setup and calibration performance is consistent with best practice and forms a good foundation for the prediction runs undertaken to evaluate environmental impacts (engineering design and risk management considerations were not a focus of this review).

It is worth noting that the reviewer was has been involved at various stages of the development of the Balranald project models:

- during the period from May 2012 to March 2013 (when employed at RPS Aquaterra), and
- subsequently during the model refinement and re-calibration of the BAL2.0 model version:
  - the BAL2.0 calibration review was undertaken at Iluka's Kent Town office on 22 October 2014, with Dr Doug Weatherill (Senior Modeller, Jacobs) presenting information on the model and answering questions raised by the reviewer; Dr Weatherill navigated though the model data files and results directly on the modelling computer, while under observation by the reviewer, to demonstrate the calibration model capability, functionality and performance (report documentation was not available)
  - the BAL2.0 prediction scenario review was undertaken on 7 November 2014, in a similar process, to identify whether the model setup and calibration performance is consistent with best practice and forms a good foundation for the prediction runs to be undertaken to evaluate environmental impacts.

During this review, it was not possible to evaluate comprehensively the entire range of hydrogeological data nor every element of the gigabytes of model data files, nor indeed all the background reports. While this review does not consider or address all uncertainties and risks, it aims to investigate any weaknesses relating to the model design and implementation, based on application of the review protocols in modelling guidelines. Given the aim to identify weaknesses, the review process tends to focus on negative aspects. However, it is acknowledged that most elements of the technical modelling process have been very well executed in this case.

3. Modelling Approach

The fundamental model purpose is to assess broad dewatering strategies and the related impacts, requiring a Class 2 or medium complexity model. There are certain high complexity model elements, notably the aquifer structure and parameter values from calibration to pumping and injection tests. While there are some lower complexity model elements (typical for most models), the sensitivity and uncertainty assessment methodologies applied in this case tend to confirm confidence in the model results. It is reasonable to assign the BAL2.0 model an overall medium complexity status (Middlemis et al, 2011) or Class 2 model confidence level (Barnett et al 2012), appropriate for mining project impact prediction purposes.

3.1 Hydrogeological Conceptualisation

The model design, boundary conditions and parameters are based on the substantial hydrogeological investigations and modelling programs undertaken since 2011 (e.g. SKM, 2013). This has been updated with information from drilling, lithology/core inspections and pumping/injection test work programs throughout 2014 (Jacobs, 2015). The layer elevations in particular have been updated substantially and appear to be physically realistic. Specialist hydrogeological advice has been provided by Ray Evans (including notably on the formations below the Loxton-Parilla Sands or LPS), confirming that the geological and stratigraphic conceptualisation is valid and has been implemented appropriately in the model.

The major recharge and discharge processes represented in the model comprise the regional groundwater inflows and outflows via the general head boundaries, and the related groundwater level contours appear to be appropriate, compared to measured bore spot heights.

The River Murray and Murrumbidgee River features in the model act as losing streams forming a small component of the groundwater balance, which is broadly consistent with reports on previous investigations in the region. Given the high salinity of the regional groundwater system, any significant gaining streams should be obvious, and it is noted that this area has not been subject to investment in the salt interception schemes that are prevalent further downstream (Mallee Cliffs) and around Mildura.

The evapotranspiration (EVT) feature has a shallow extinction depth (3m), which is consistent with the parameter applied to many models for salinity management purposes along the Murray. EVT does not constitute a major process in the modelled system (low volume component in the groundwater balance). This was confirmed from a spatial view of active EVT cells in the model, which are isolated in certain low-lying areas and show low discharge rates.

Diffuse rainfall recharge forms a small component of the groundwater balance, based on the uniformly applied low rate (0.1 mm/yr), consistent with uncleared mallee landscapes. The regional bore time series data shows a slight long term recession (order of mm to cm per year), which is consistent with the findings of a recent review of Mallee zone groundwater levels (undertaken by the author for the MDBA; in press).

The design is innovative in using local scale models for parameter calibration to pumping test data and then applying those parameters to the regional scale model. While the regional model was calibrated with these values in steady state only, the 100-year warm-up period for the transient prediction scenarios essentially forms a 100-year transient calibration, with the pseudo-steady groundwater levels confirming the hydrodynamic equilibrium of the groundwater system under the influence of regional flows and low rainfall recharge. This means that the model calibration period actually exceeds the prediction scenario period by a factor of more than 10, albeit with zero pumping stresses involved (i.e. demonstrating model compliance with a key Class 2 criterion).

3.2 Regional and Local Scale Models

The model calibration approach is iterative, providing a sound basis for the prediction scenarios:

- 9-layer regional model with a 90 km square extent and a uniform cell size of 500 m for the calibration model (refined in wellfield areas to 100 m minimum for the prediction scenarios);
- steady state regional model calibration to available long term monitoring bore data, with acceptable statistical performance measures for a remote mining project context, and generally good matches between modelled water level contours and measured spot heights;
- 100-year warm-up period for the transient prediction scenarios essentially forms a 100-year transient calibration, confirming the model design and parameterisation;
- four local scale (fine grid) models were developed using the regional model as a basis for layer structure and boundary conditions; the local model extents are typically 1-3 km square, with minimum cell sizes of about 0.25 m; the purpose is for calibration to the short term (1-7 days) pumping and injection test data at four sites along the mine path; one larger model (8 x 18 km) was developed for calibration to the 7-week long term test; also used to evaluate aquifer pressure responses to pumping and injection;
- remarkably consistent parameter values and strong calibration performance to pumping test data was achieved from the local scale models; the parameter values were applied to the regional model, and the steady state calibration performance was confirmed;
- regional model transient prediction simulations of mine dewatering from the LPS aquifer were modelled via blanket drain cells across the active pit area, with drain invert levels set to 5 m below the target pit floor; while this is not physically realistic (actual dewatering will be implemented via dewatering wells on the pit periphery and pit floor sumps in specific locations), it is a conservative approach that is appropriate for impact prediction purposes as it will tend to over-estimate drawdown impacts; a “truck and shovel” mining method was assumed, which involves a conservative over-estimate of the mine footprint;
- excess water was modelled by injection to the LPS aquifer mostly at a highly transmissive aquifer zone located off-mine-path midway between the West Balranald and Nepean deposits; constraints were applied to keep groundwater levels to less than 3 m below natural surface, a conservative measure designed to reduce waterlogging and/or salinisation risks;
- simulations of post-mine aquifer recovery assumed progressive pit infilling and

rehabilitation, but with aquifer parameter values unchanged from in situ values; as post-closure aquifer parameters are unchanged from in-situ values, aquifer recovery rates and groundwater levels may be over-estimated, and specific uncertainty analysis is warranted

- a comprehensive sensitivity analysis was undertaken on Kh, Kv, Ss and Sy parameters, confirming the well-constrained calibration; the predictive uncertainty analysis used these results to evaluate a high and low dewatering case, demonstrating little material difference in predicted impacts; structural model uncertainty has not been tested, but this is not common in best practice.

3.3 Predicted Impacts on Rivers and Regional Groundwater Flows

The model report shows that the drawdown due to mine dewatering and injection does not extend to the Murrumbidgee River or to the Murray River. However, it also concludes that "*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*." However, careful inspection of the water balance volumes presented in Table 6.2 (copied below, for the record) reveals some interesting insights, outlined below.

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	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	-	286	-	286	-
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	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

- River leakage "out" (groundwater inputs to river) increased very little during mining, from 97 ML/yr pre-development, to 99 ML/yr at construction, and then remained steady at about 98 ML/yr during mining; that indeed demonstrates little impact; this component then falls to 95 ML/yr at post-mining year 1 and to 92 ML/yr at post-mining year 100; this total effect is "only" about 5%, but this may be deemed an accountable impact in terms of the NSW Aquifer Interference Policy.
- River leakage "in" (river inputs to groundwater) decreased somewhat during mining, from 1512 ML/yr pre-development, to 1457 ML/yr at construction, and then remains steady at about 1456 ML/yr during mining; that again demonstrates little impact, and this component then falls further to 1407 ML/yr at post-mining year 1 and to 1401 ML/yr at post-mining year 100 (about 7% effect), leaving the reader confused on these questions:
  - why is there a 55 ML/yr reduction in leakage from the river due to construction, although construction pumping stresses are very low?
  - why is there no subsequent reduction due to mining when stresses are so high?

  - why is there a subsequent further reduction immediately on cessation of mining of 50 ML/yr, and why does this reduce further by 6 ML/yr during the 100-year post-mining period?
- Boundary flows show a similar set of relatively minor changes:
  - Boundary inflow changes during mining, from 7831 ML/yr pre-development, to 7789 ML/yr at construction, and then further reductions during mining from 7783 to 7768 ML/yr (less than 1% effect), and further reductions again post-mining from 7513 to 7491 ML/yr (4% total effect); this indicates that mining project impacts of reducing regional boundary inflows extends throughout mining and beyond the 100-year post-mining period
  - Boundary outflow changes during mining, from 9127 ML/yr pre-development, to 8987 ML/yr at construction, and then further reductions during mining from 8978 to 8524 ML/yr by year 7 (7% effect), before increasing to 8923 in mine year 8 (why?), and then reducing further post-mining from 8627 to 8589 ML/yr (6% total effect); this indicates that the mining project impacts of reducing regional boundary outflow extends throughout mining and beyond the 100-year post-mining period
- Total effects on the water balance comprise about 116 ML/yr for river leakage and 878 ML/yr on boundary flows, or almost 1 GL/yr, applying over a period in excess of 100 years, which this review suggests should be described as significant, although the drawdown impacts do appear to be significant.

Further detailed analysis of model results was undertaken subsequent to the identification of the issue in the draft review report dated 2nd March. The aim was to try to identify the location, extent, magnitude and causative processes of these various effects on river-aquifer interactions. However, as the model is indeed extremely large, some software limitations affected the ability to undertake a comprehensive water balance analysis. The analysis was able to conclude that the volumes of river leakage are indeed very small in relation to typical river flows, and similarly for the boundary flow changes. While the causative processes have not been fully explained, the data has been presented clearly and the impacts are at least contextualised. It is recommended (assumed) that this data (will) be used by others to undertake a detailed analysis in relation to the Aquifer Interference Policy, as that is a notable gap in the scope of the modelling study and the report presented for review.

It is recommended that subsequent modelling work programs should investigate these issues in detail to improve our understanding of the hydrogeological dynamics involved. Further analysis is also required on the boundary inflows and outflows, and it is expected that there is likely to be some interactions between the regional boundaries and the river boundaries (e.g. apparent from inspection of Figures 2.12, 2.14 and 3.3 of the modelling report), and some influence from potentially extensive deep/confined aquifer pressure effects.

3.4 Discussion on Guideline Issue of Model Confidence Level or Complexity

The report sets a Class 2 model confidence level as a target and suggests that it has been achieved. It also identifies several areas where the model needs to be improved to achieve a Class 3 in due course, notably the length of predictions compared to calibration and the level of pumping stresses involved. However, in my view, if one were to apply these two guideline criteria *sensu stricto*, then they would relegate the model to a Class 1 confidence level, given this "guidance" (Barnett et al, 2012): "*if a model falls into a Class 1 classification for either the data, calibration or prediction sectors, it should be given a Class 1 model [classification], irrespective of all other ratings*", and: "*when a predictive model includes stresses that are well outside the range of stresses included in calibration, the reliability of the predictions will be low and the model confidence level classification will also be low*". Other "guidance" is similarly unhelpful, including:

  - *"a model that is calibrated in steady state only will likely produce transient predictions of low confidence"*
  - *"in general, it should be acknowledged that if a model has any of the characteristics or indicators of a Class 1 model it should not be ranked as a Class 3 model, irrespective of all other considerations".*

The following points explore these issues and suggest that it would be appropriate in this case to apply the guideline criteria *sensu lato* and ignore the unhelpful "guidance":

- the reported modelling approach is one of steady state calibration and transient model prediction, whereas the 2012 guidelines suggest low model confidence if only steady state calibration is undertaken; however, the 100-year transient simulation warm-up period effectively forms a transient calibration simulation (albeit with zero pumping stresses involved) and confirms the model performance as a valid predictive tool;
- the predicted dewatering rate (average ~750 L/s) is high compared to the low pumping test rates (<70 L/s), and the dewatering prediction time frame (about 8 years) is long compared to the much shorter pumping test calibration (<7 weeks);
  - the 2012 guidelines suggest a maximum ratio of 10 for the prediction duration compared to the calibration period; while the 8-year dewatering prediction is about 60 times the duration of the 7-week long term pumping test calibration, the 100-year transient simulation warm-up period effectively forms an adequate transient calibration period;
  - the average dewatering rate is more than 20 times the individual bore pumping test rates (15 L/s to 40 L/s per bore), and it is also more than 10 times the total rate for the long term test (70 L/s applied for about 15 days); although the 2012 guidelines suggest a maximum pumping stress ratio of 2-5 times, it is arguably impossible to undertake investigations for a proposed project at one fifth to one half of the full scale of the proposed project and for a duration long enough to achieve the guideline criteria; the criteria are not suitable for an impact prediction context, but could be more applicable to a compliance review of an approved an operational project (i.e. they could be used to guide approval conditions); in this case, the comprehensive sensitivity and uncertainty analysis undertaken addresses any residual risk issues, helping to justify a relaxed approach to applying the guideline criteria;
  - it is also important to note that the Balranald investigation is unusually comprehensive for a greenfields mining project (i.e. demonstrates best practice in a generic sense), extending over more than 4 years, with pumping and injection tests undertaken at five locations including a long term pumping and injection trial.

Further, information and analogues available from Iluka's operations elsewhere in the Murray Basin have been used to support the parameter values applied and to benchmark the aquifer responses to project-scale stresses and mining operations, improving confidence that key uncertainties have been addressed in a best practice manner.

While the BAL2.0 model may not strictly meet certain Class 2 confidence level criteria (Barnett et al, 2012), in my view that is an issue with the 2012 guideline and not an indicator of material flaws in this model or its performance. In terms of the 2001 guidelines (Middlemis et al, 2011), the medium complexity model design and performance is fundamentally sound and it is clearly suitable for impact assessment purposes. These issues have been discussed on several recent projects in Australia, and are planned to be subject to a review workshop at the 2015 IAH national conference.

Alternative approaches that are worth considering to clearly demonstrate that the regional model is directly consistent with the guidelines, as well as helping to address model uncertainty, would involve:

- regional model transient calibration to the available long term regional monitoring data, which should be feasible, given that the data apparently show no upwards or downwards long term trends, and/or
- regional model steady state prediction of mine dewatering impacts (a gross over-estimation method, although the impacts may not be acceptable); this could be undertaken by simulating dewatering of a mine extent equivalent to the maximum mining area that is open at any stage, applied to the middle of the mine path to represent "long term average mining conditions".

4. Conclusion

This independent model review did not identify any material weaknesses in the model design, boundary conditions, parameter values, calibration performance or sensitivity and uncertainty assessments. Further analysis of model results is required to unpack the impact assessment implications of the apparent changes to the water balance components of river-aquifer interaction and regional boundary inflows/outflows.

It is my professional opinion that the BAL2.0 model has been developed consistent with the 2012 best practice guideline for a Class 2 model confidence level classification (medium complexity model in terms of the 2001 guidelines), and is suitable for mining project impact prediction purposes.

The report is a high quality document, which is notable in itself as exemplifying the best practice approach applied, and also as it succeeds so well where modelling studies commonly fail (most reviews identify report documentation as sub-standard).

Yours sincerely,

Hydrogeologic

Hugh Middlemis (Director).

References:

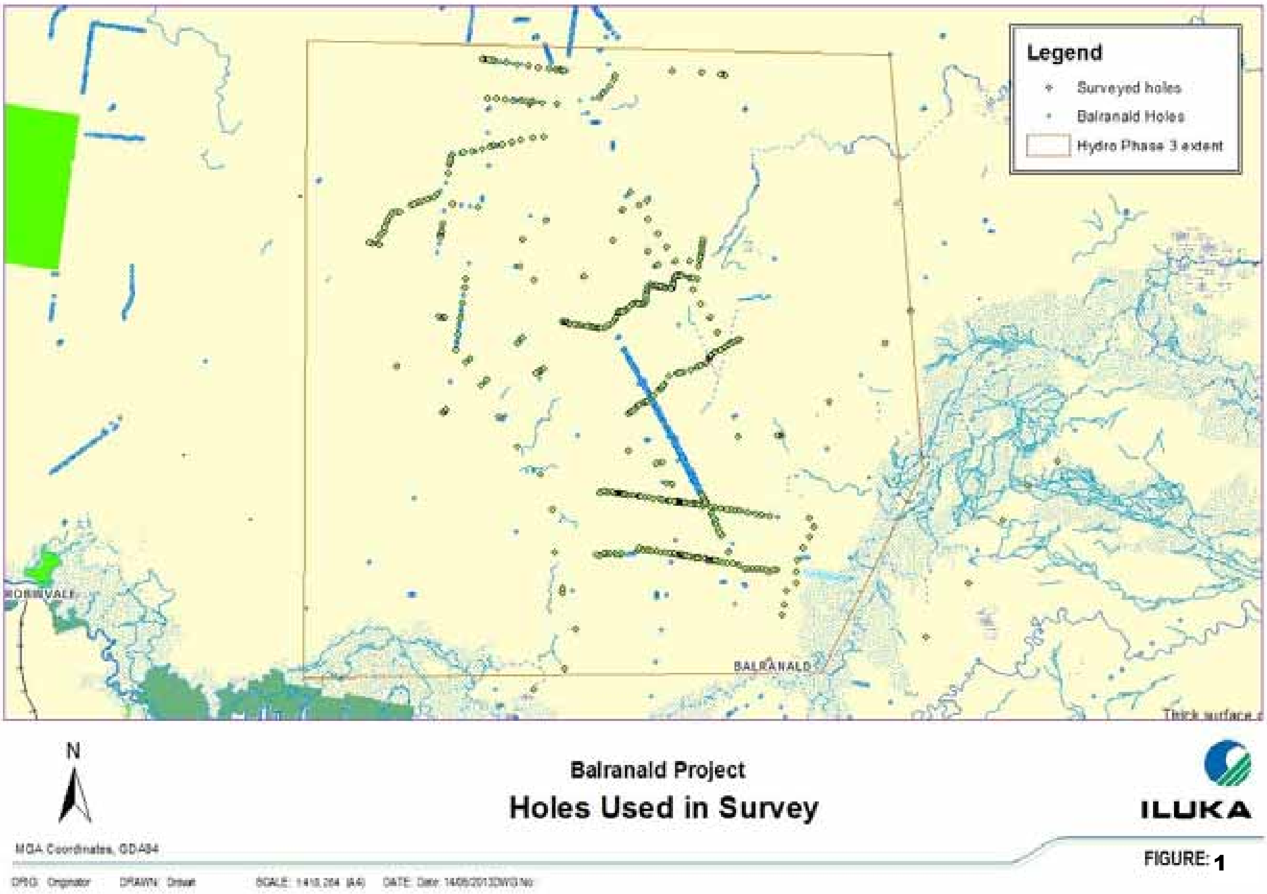
Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). Australian Groundwater Modelling Guidelines. Waterlines report 82, National Water Commission, Canberra. URL: http://archive.nwc.gov.au/library/waterlines/82.

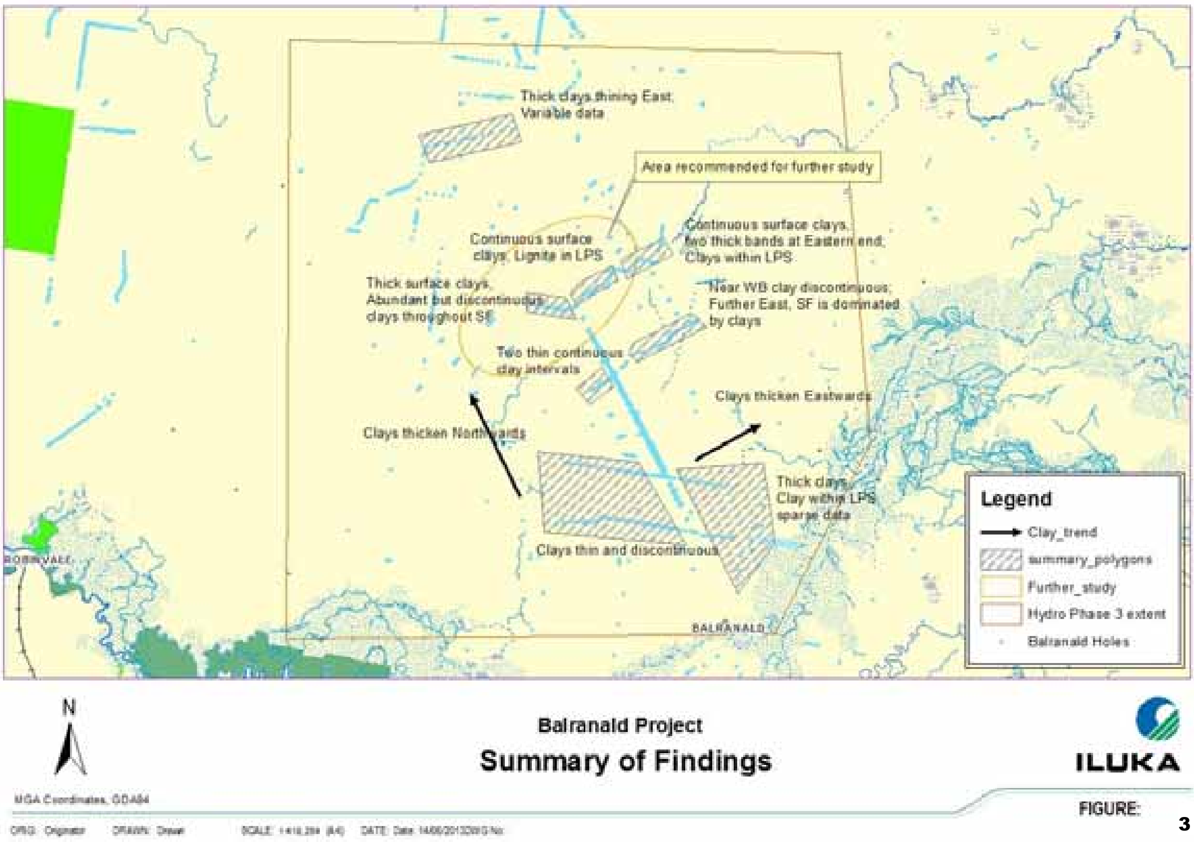
Jacobs (2015). Balranald Project DFS1 Groundwater Modelling. Impact Assessment Modelling. Prepared for Iluka Resources. Jacobs document no. T18466, draft revision B, dated 23 February, 2015.

Middlemis, H., Merrick, N., Ross, J., and Rozlapa, K. (2001). Groundwater Flow Modelling Guideline. Prepared for Murray–Darling Basin Commission by Aquaterra, January 2001. URL: www.mdba.gov.au/sites/default/files/archived/mdbc-GW-reports/2175_GW_flow_modelling_guideline.pdf

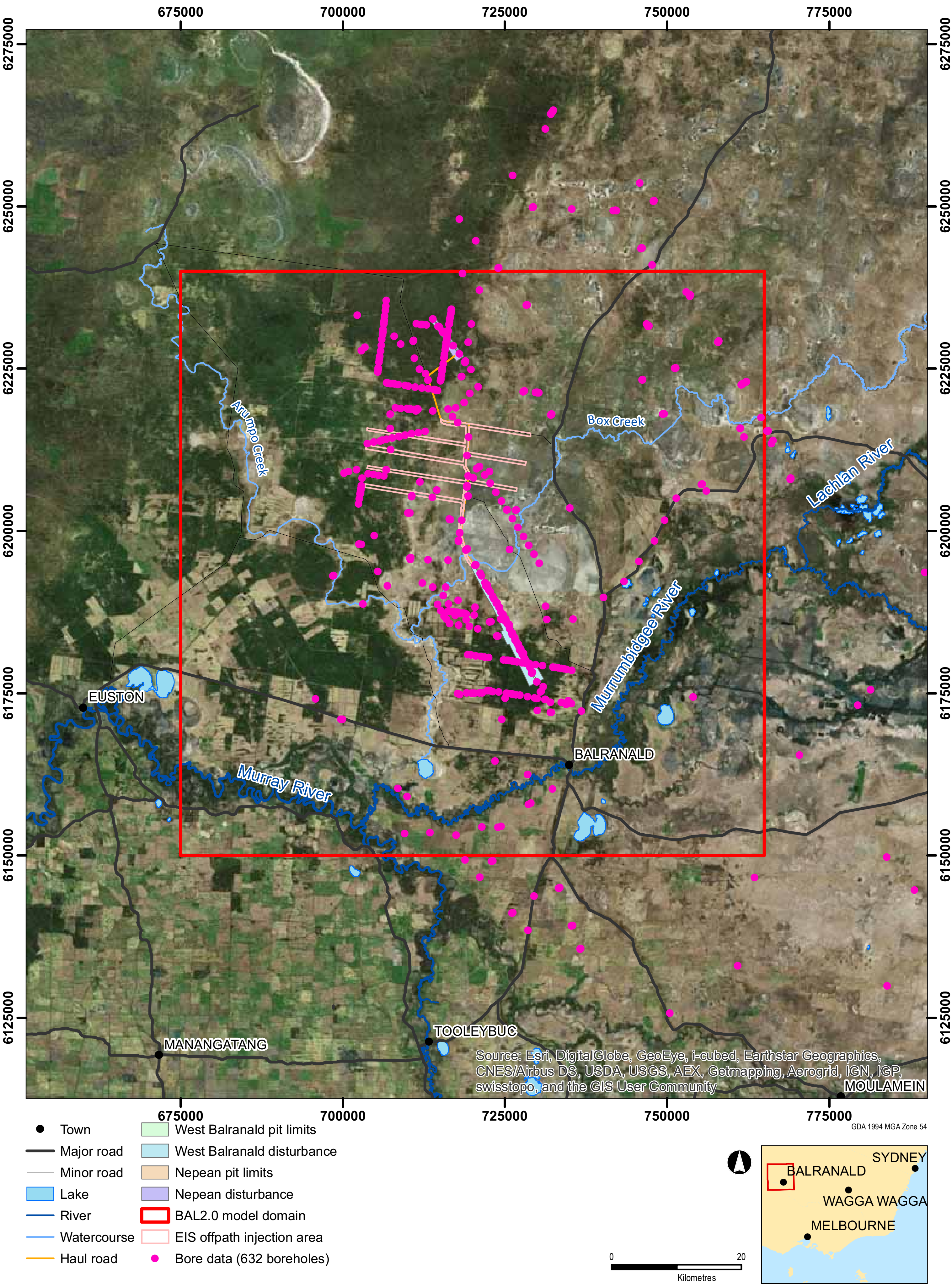
SKM (2013). Balranald Project Groundwater Modelling (version 2). Prepared for Iluka Resources, dated 11 February, 2013.

Appendix B. Hydrostratigraphic data





Locations of bores used and summary results of Iluka (2013)



JACOBS

Top of LPS1 FS elevation data

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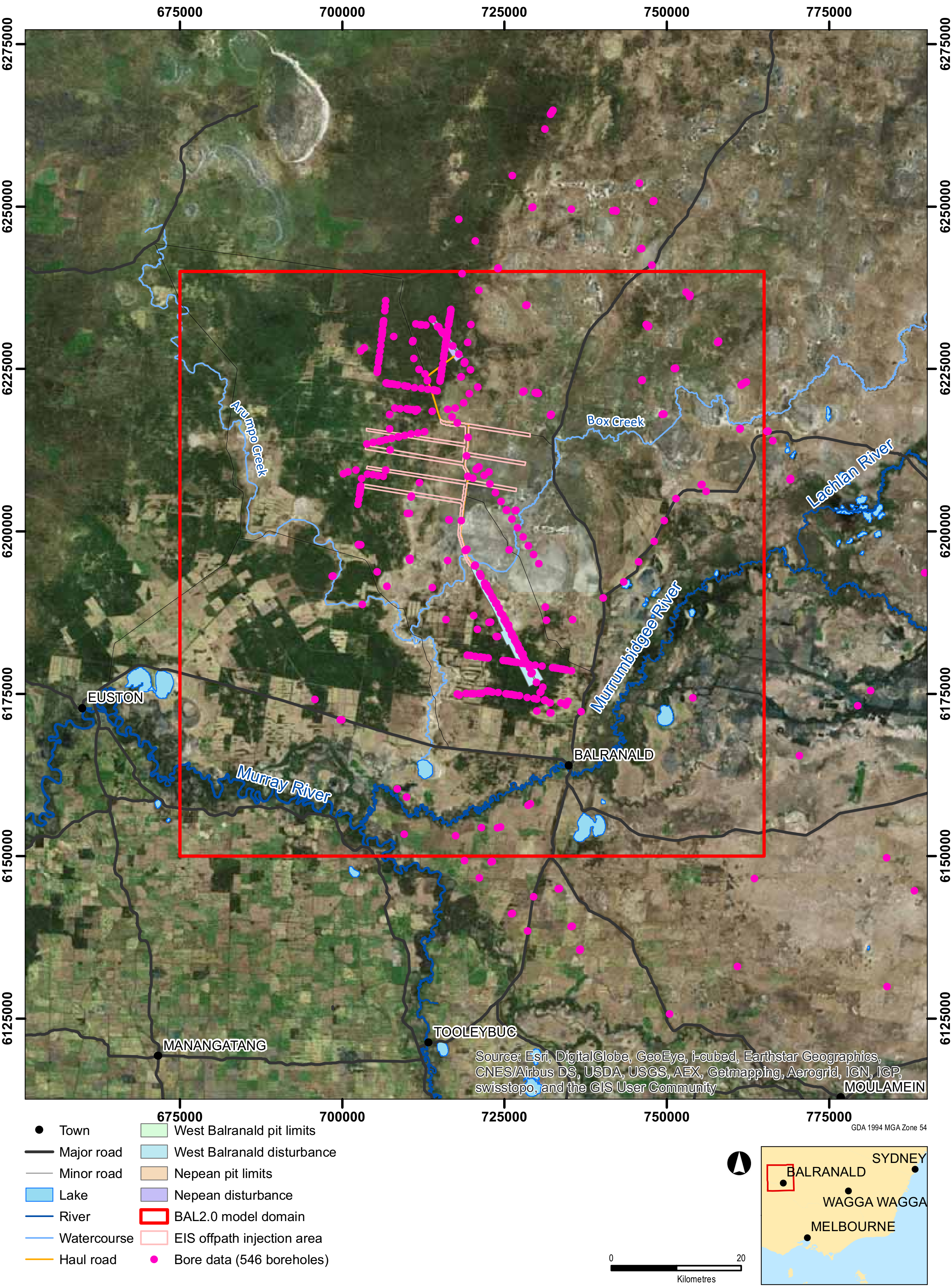

Top of LPS1 SZ elevation data

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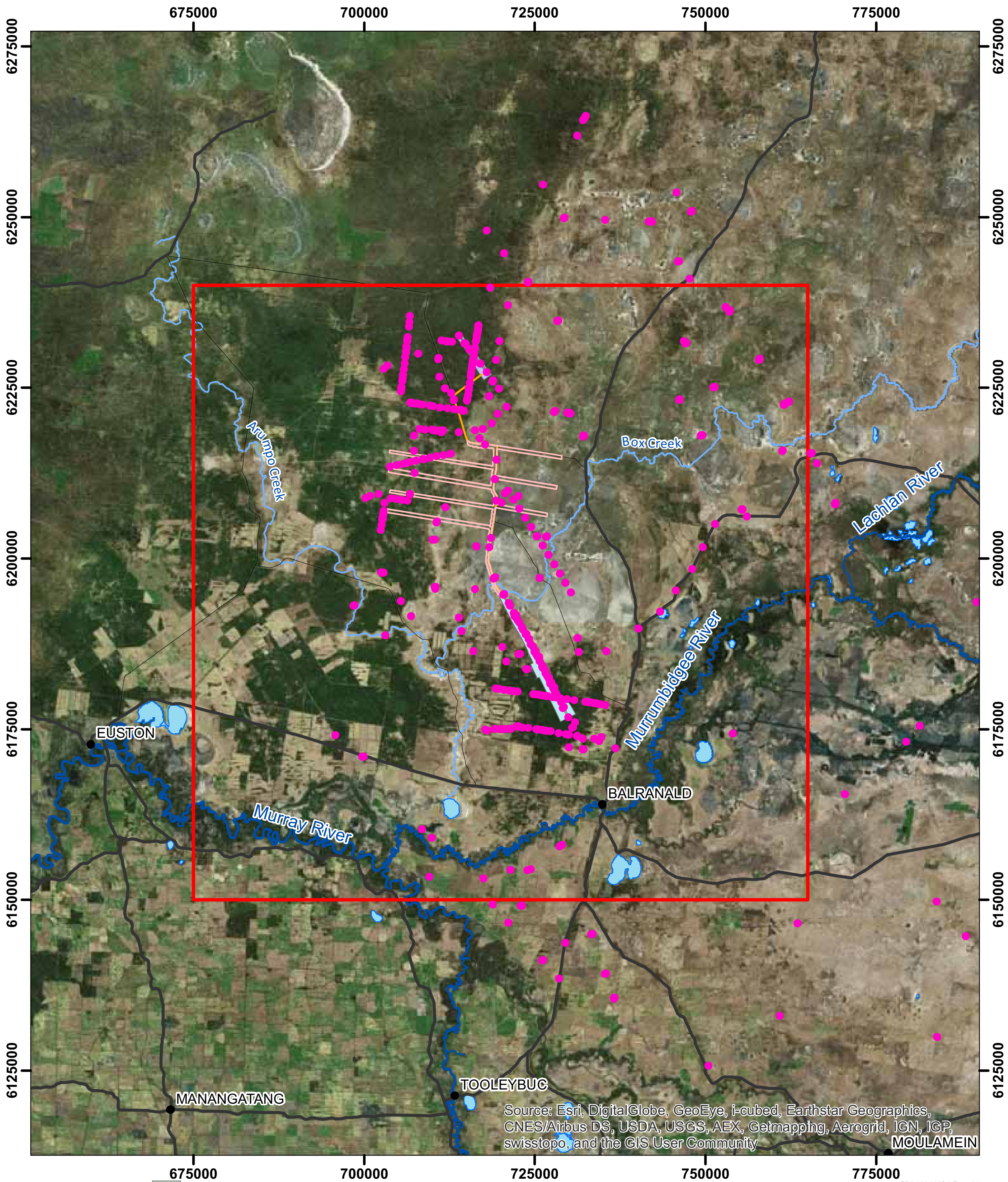
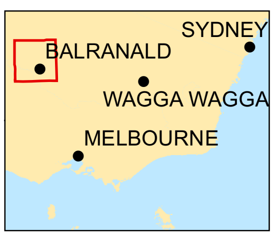


- Town
- Major road
- Minor road
- Lake
- River
- Watercourse
- Haul road
- West Balranald pit limits
- West Balranald disturbance
- Nepean pit limits
- Nepean disturbance
- BAL2.0 model domain
- EIS offpath injection area
- Bore data (548 boreholes)

0 20
Kilometres



JACOBS

Top of LPS1 LS elevation data

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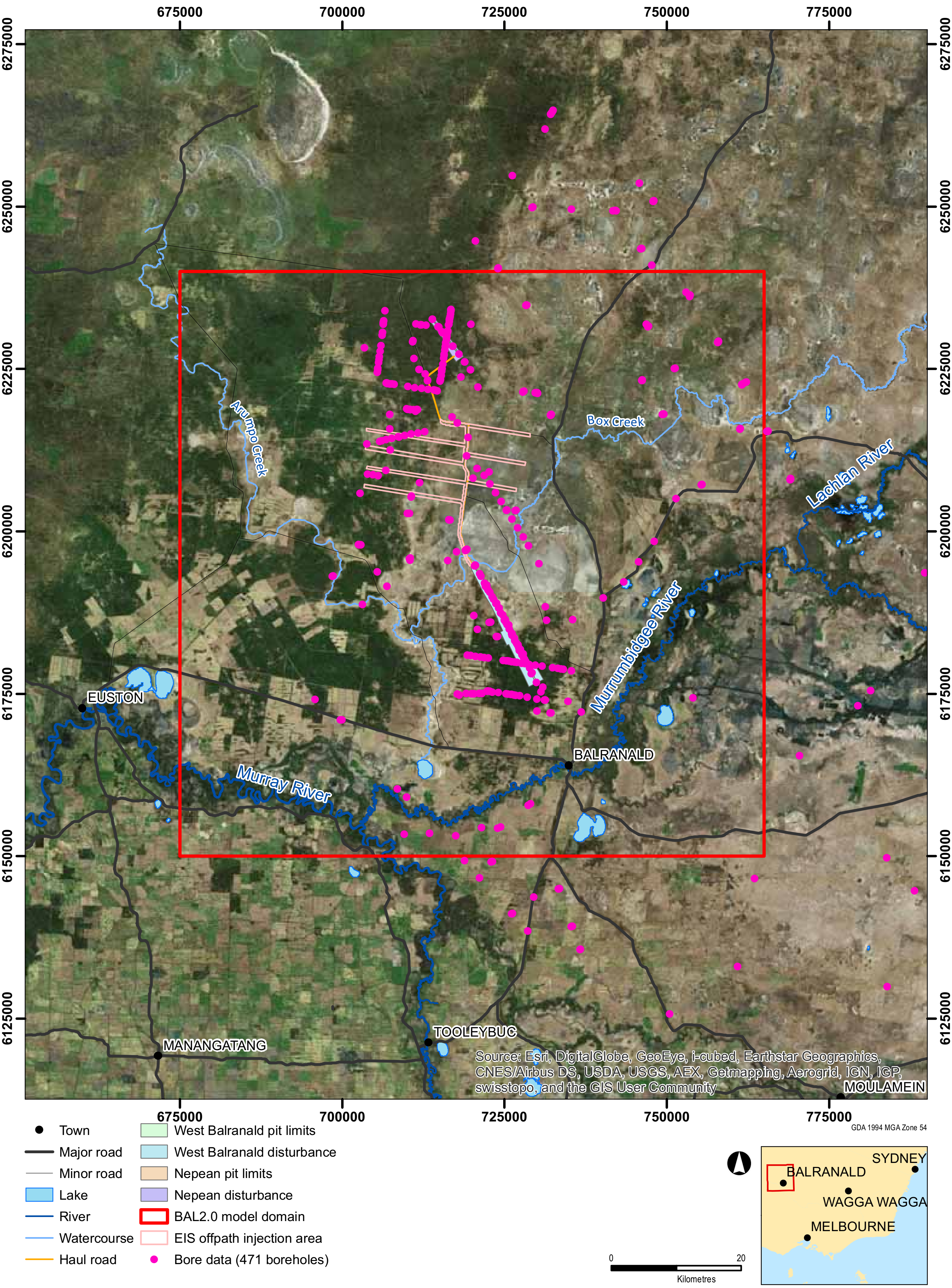

JACOBS

Top of LPS2 SZ elevation data

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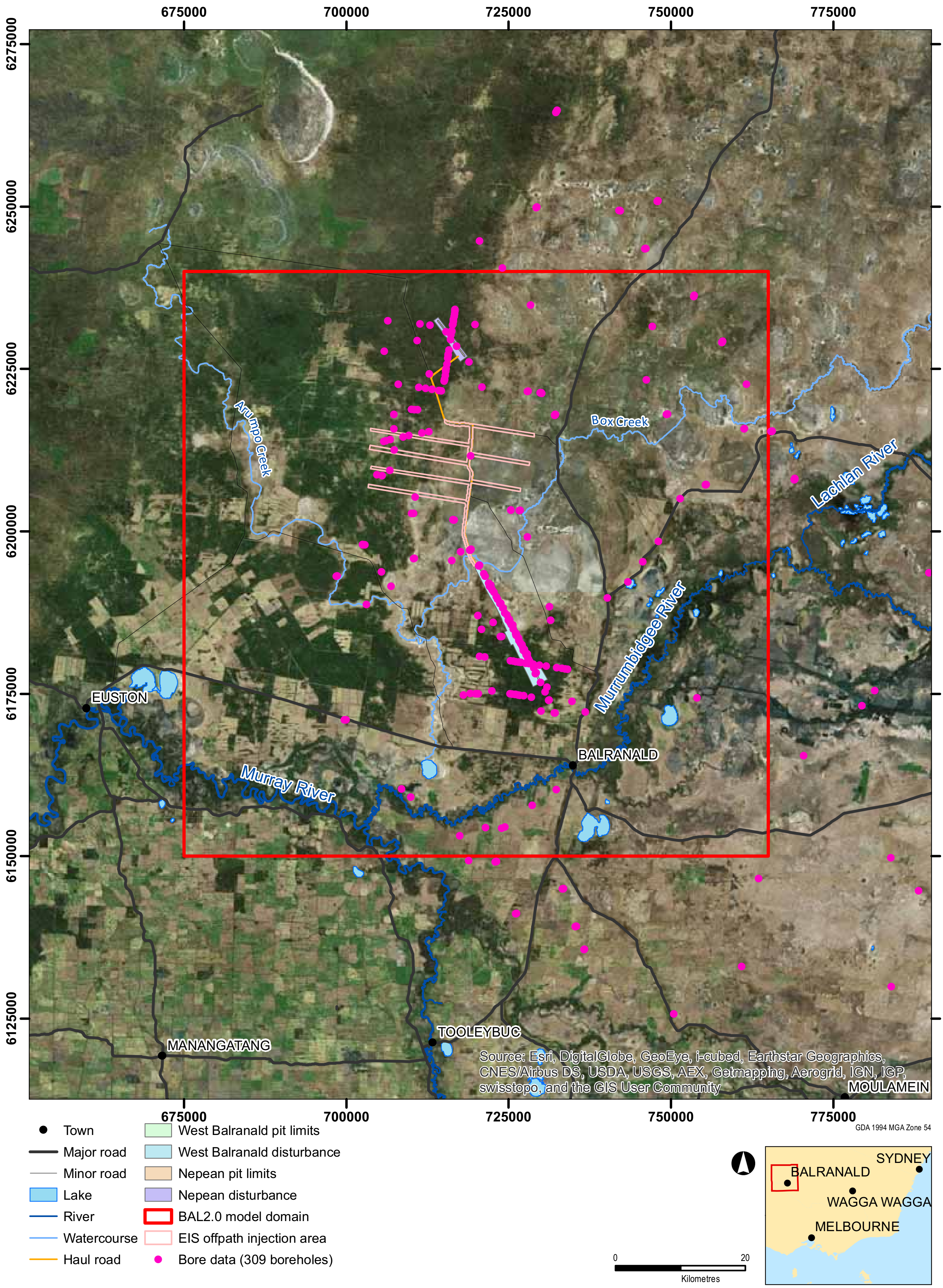

Top of LPS2 LS elevation data

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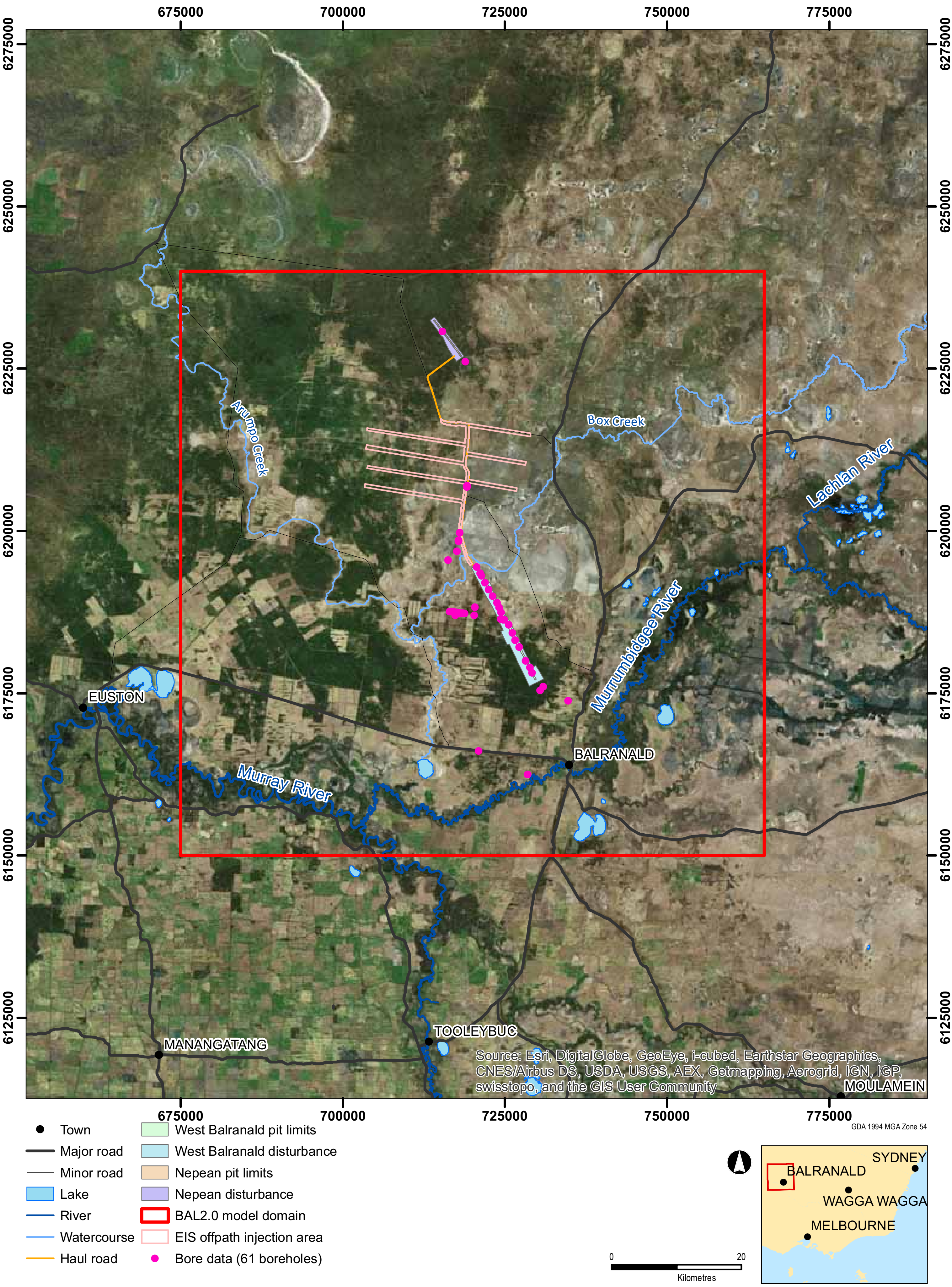
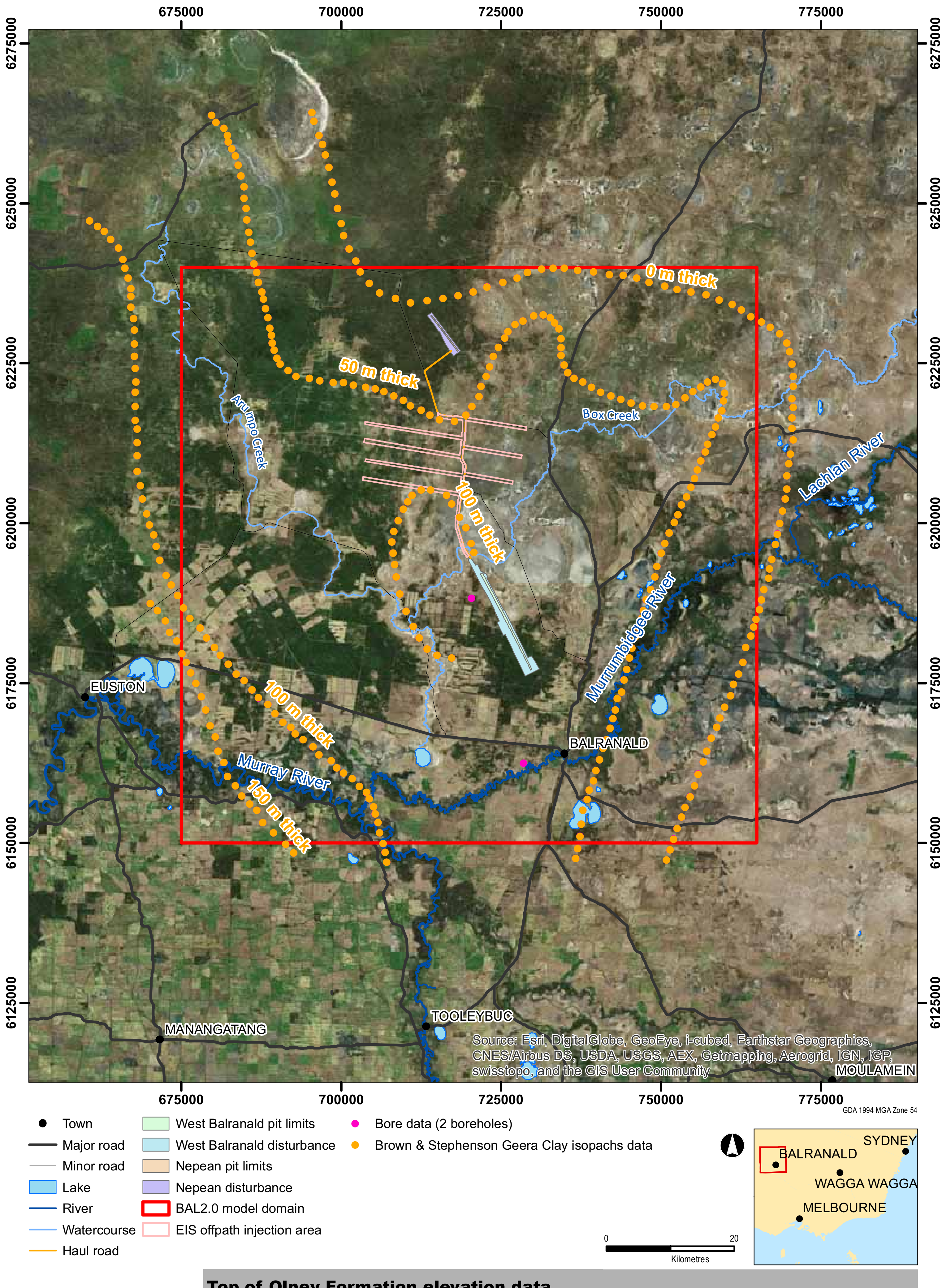


Top of Geera Clay elevation data

JACOBS

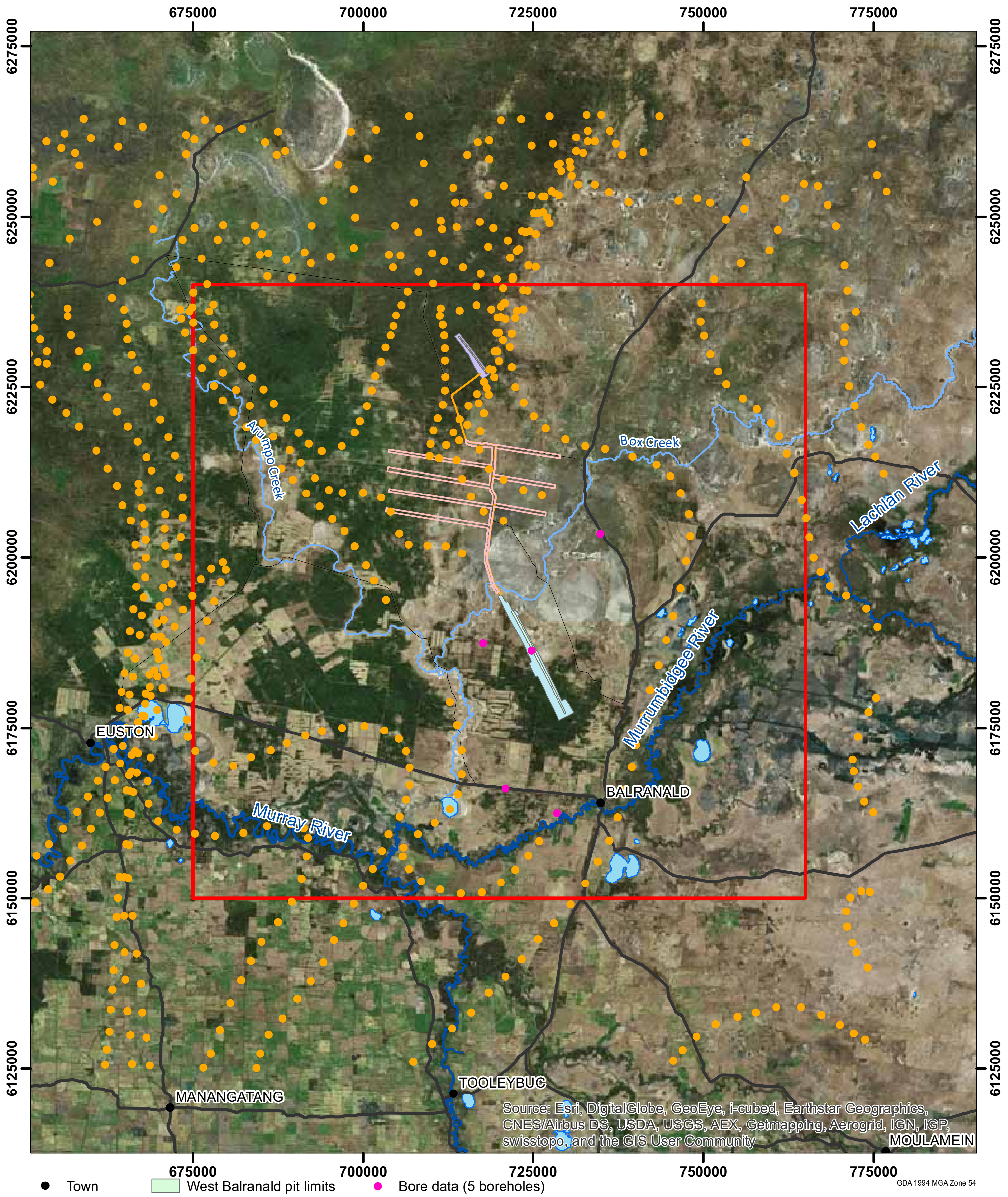
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Data for surface creation\Rev2\Geera Clay_data points.mxd



Top of Olney Formation elevation data

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Data for surface creation\Rev2\Olney fromation_data points.mxd



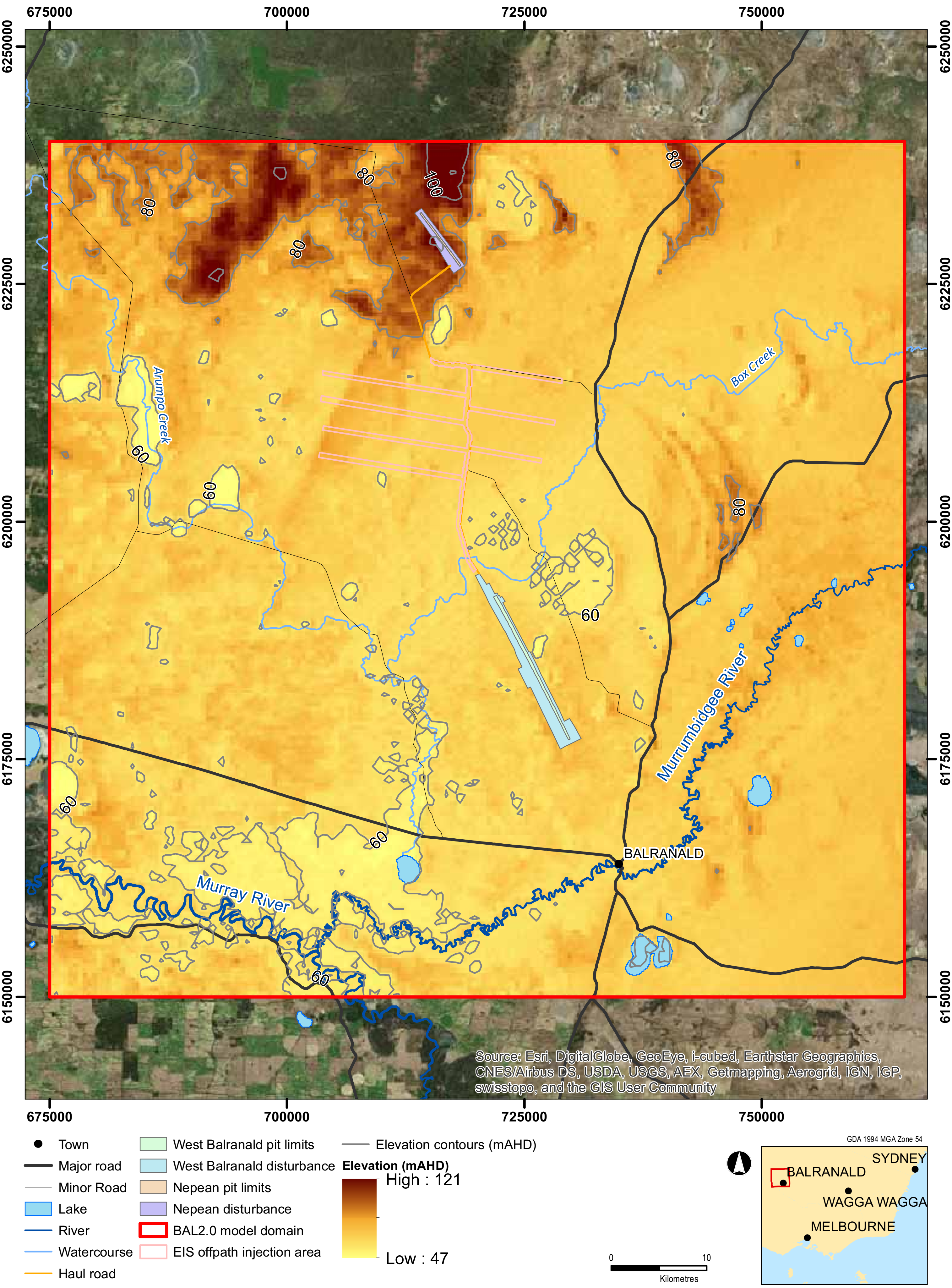
Town
Major road
Minor road
Lake
River
Watercourse
Haul road
West Balranald pit limits
West Balranald disturbance
Nepean pit limits
Nepean disturbance
BAL2.0 model domain
EIS offpath injection area
Bore data (5 boreholes)
Balranald & Pooncarie map sheets data

Top of Basement elevation data

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Data for surface creation\Rev2\Basement_data points.mxd

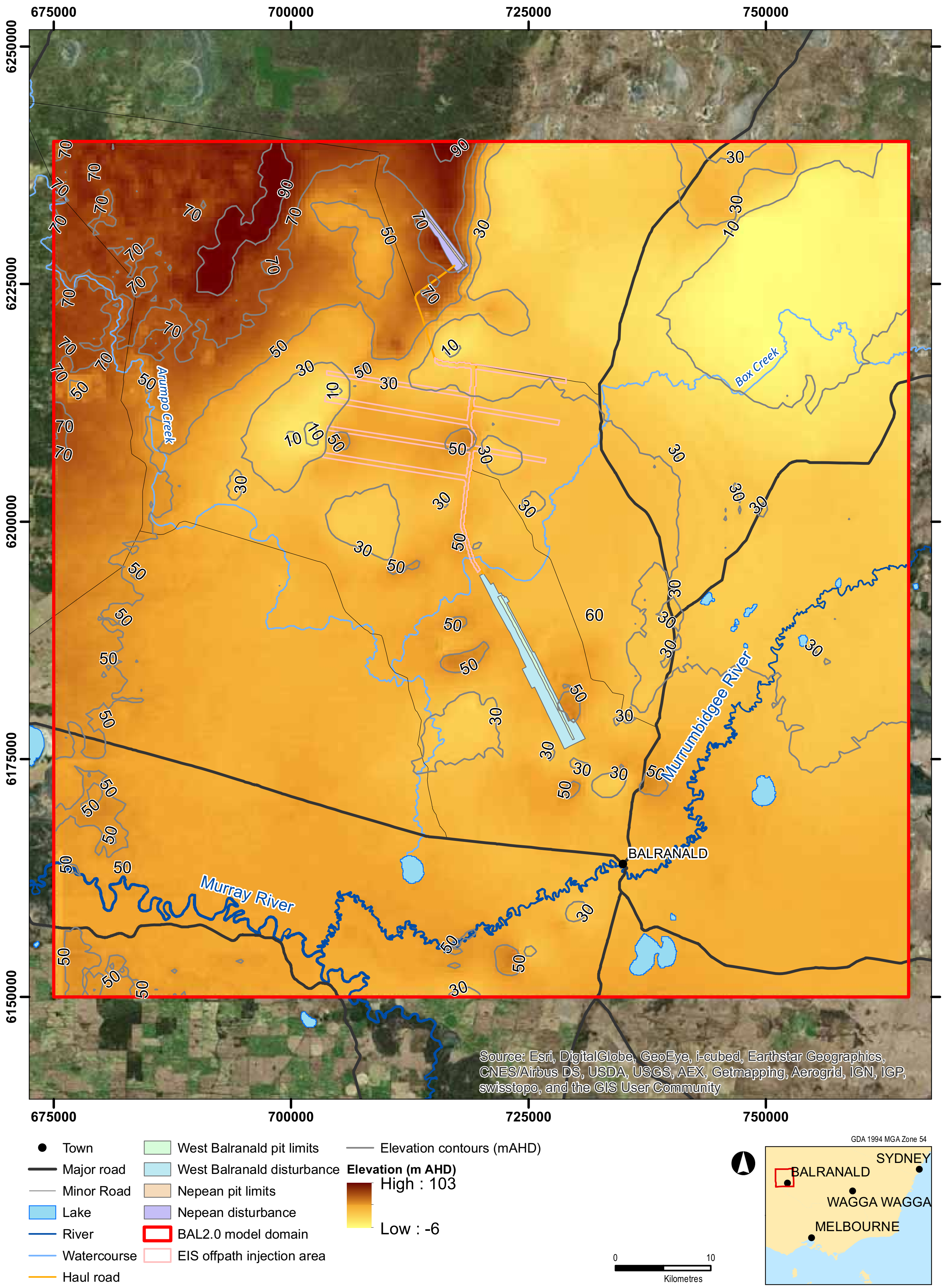
Appendix C. Model layer elevations and thicknesses



BAL2.0 top of Shepparton Formation (shallow) (layer 1)

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 topography (Top of Layer 1) 20141211.mxd



BAL2.0 top of Shepparton Formation (deep) (layer 2)

JACOBS

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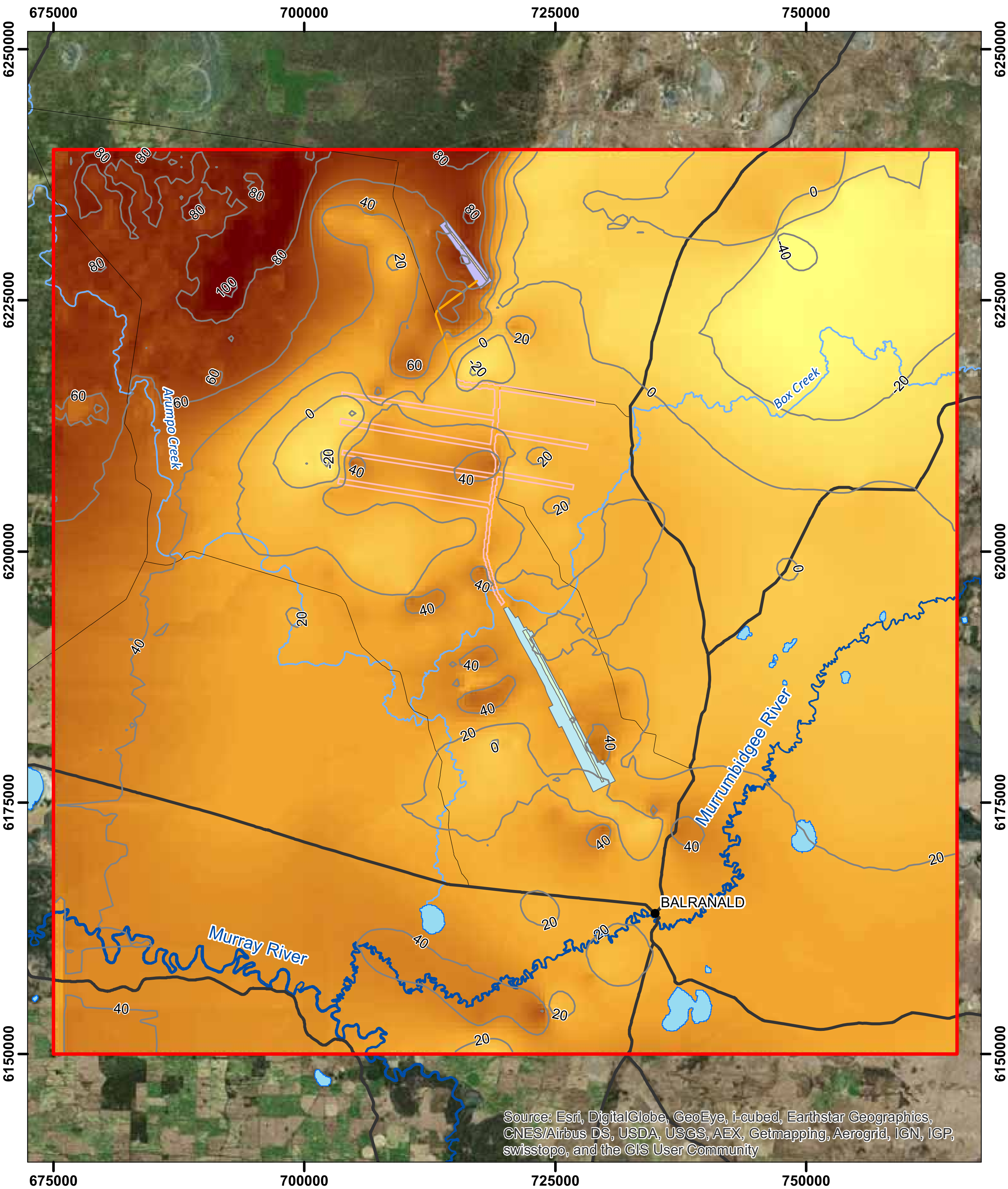
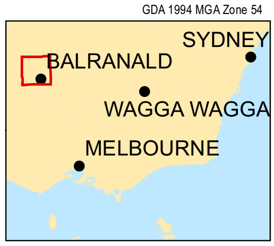


Town
Major road
Minor Road
Lake
River
Watercourse
Haul road
West Balranald pit limits
West Balranald disturbance
Nepean pit limits
Nepean disturbance
BAL2.0 model domain
EIS offpath injection area
Elevation contour (mAHD)
Elevation (mAHD)
High : 103
Low : -45

GDA 1994 MGA Zone 54

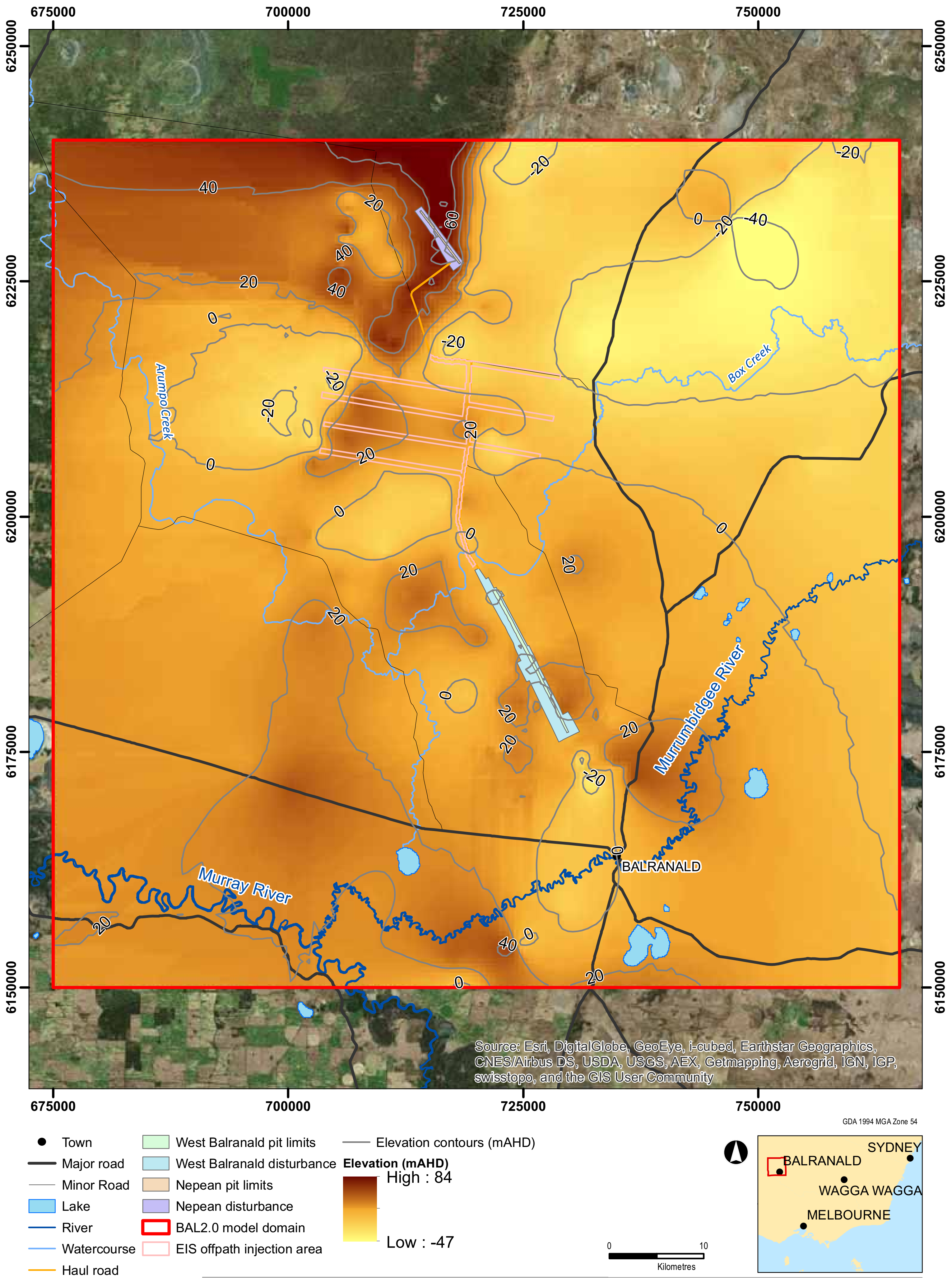


0 10
Kilometres

BAL2.0 top of LPS1 FS (Layer 3)

JACOBS

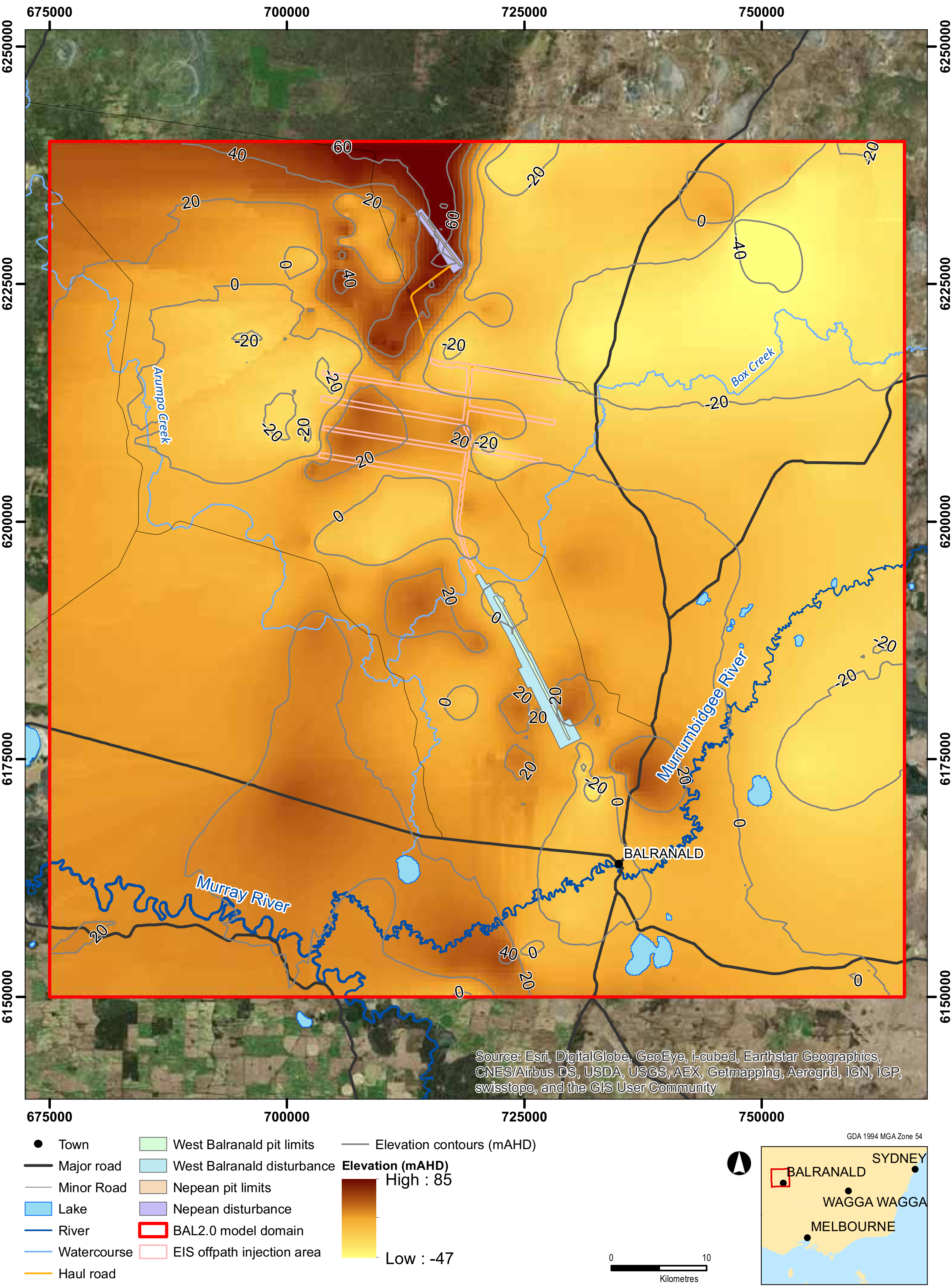
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of LPS1 FS (Layer 3) 20141211.mxd



BAL2.0 top of LPS1 SZ (layer 4)

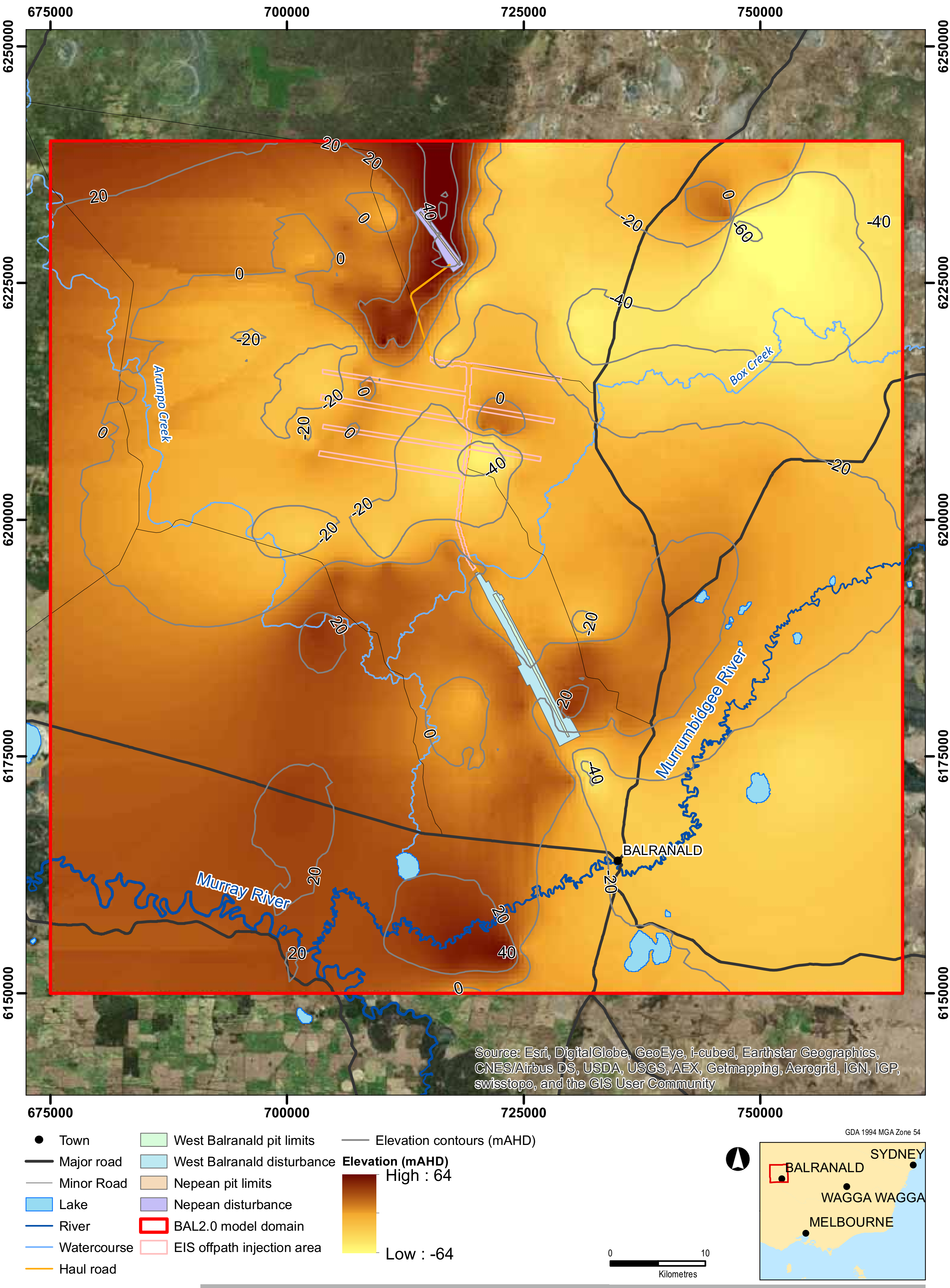
JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of 4 LPS1 SZ 20141211.mxd



BAL2.0 top of LPS1 LS (layer 5)

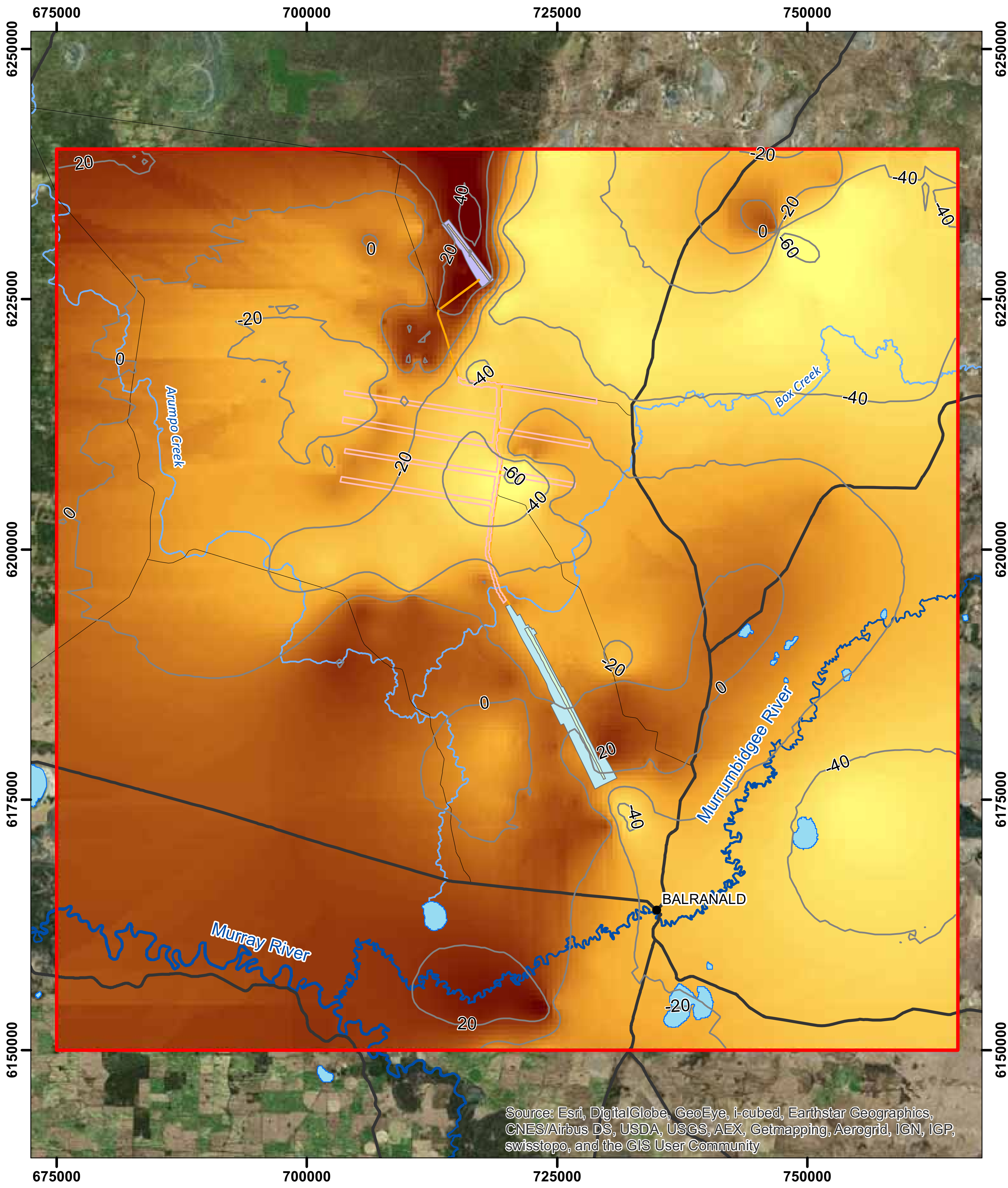
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of LPS1 LS (layer 5)20141211.mxd



BAL2.0 top of LPS2 SZ (layer 6)

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of LPS2 SZ (layer 6)20141211.mxd

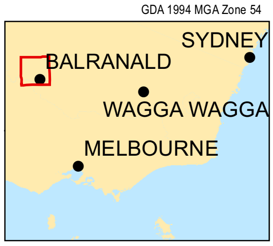


Town
Major road
Minor Road
Lake
River
Watercourse
Haul road
West Balranald pit limits
West Balranald disturbance
Nepean pit limits
Nepean disturbance
BAL2.0 model domain
EIS offpath injection area
Elevation contours (mAHD)

Elevation (mAHD)
High : 58
Low : -64

0 10 Kilometres

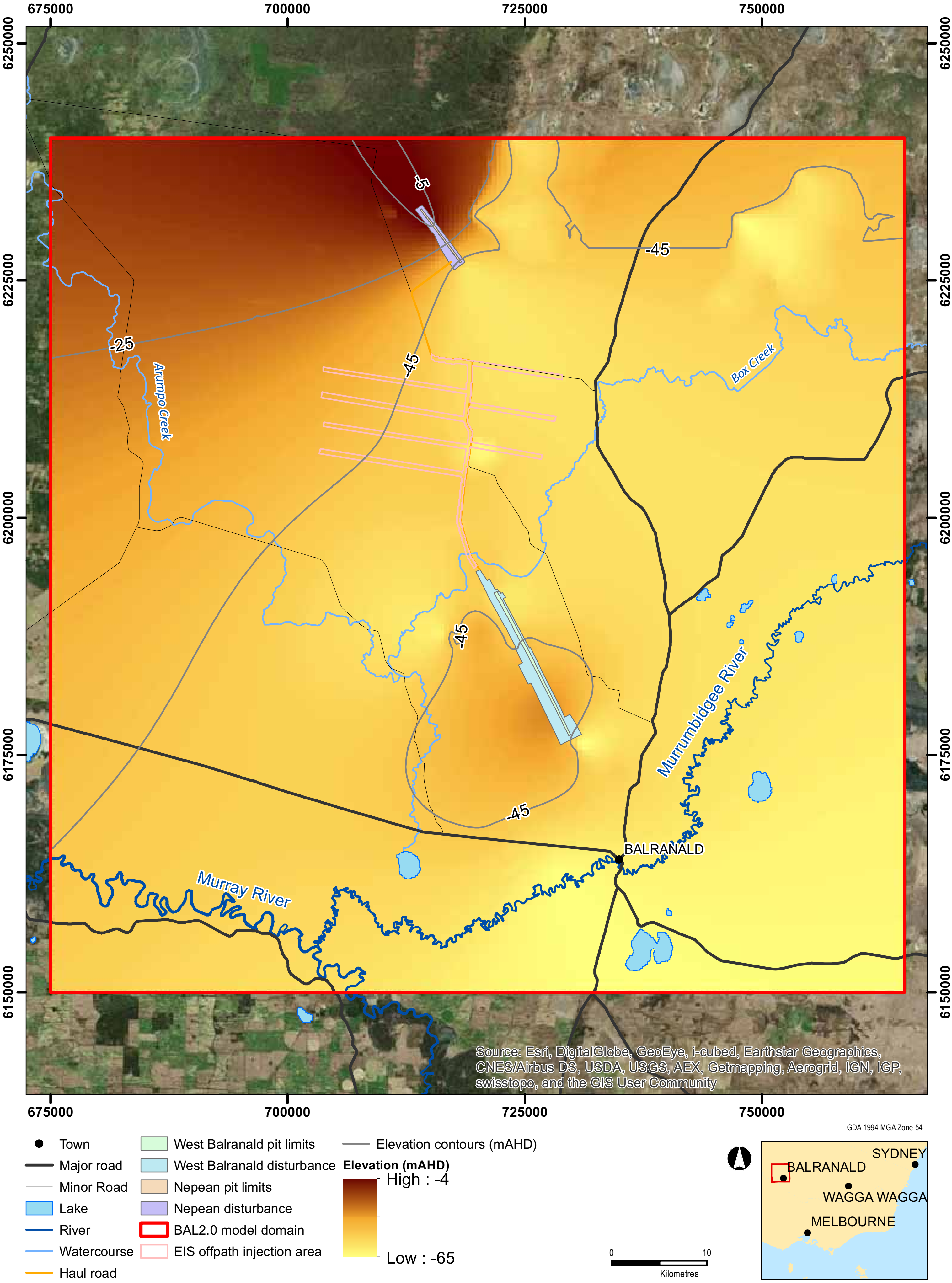
GDA 1994 MGA Zone 54



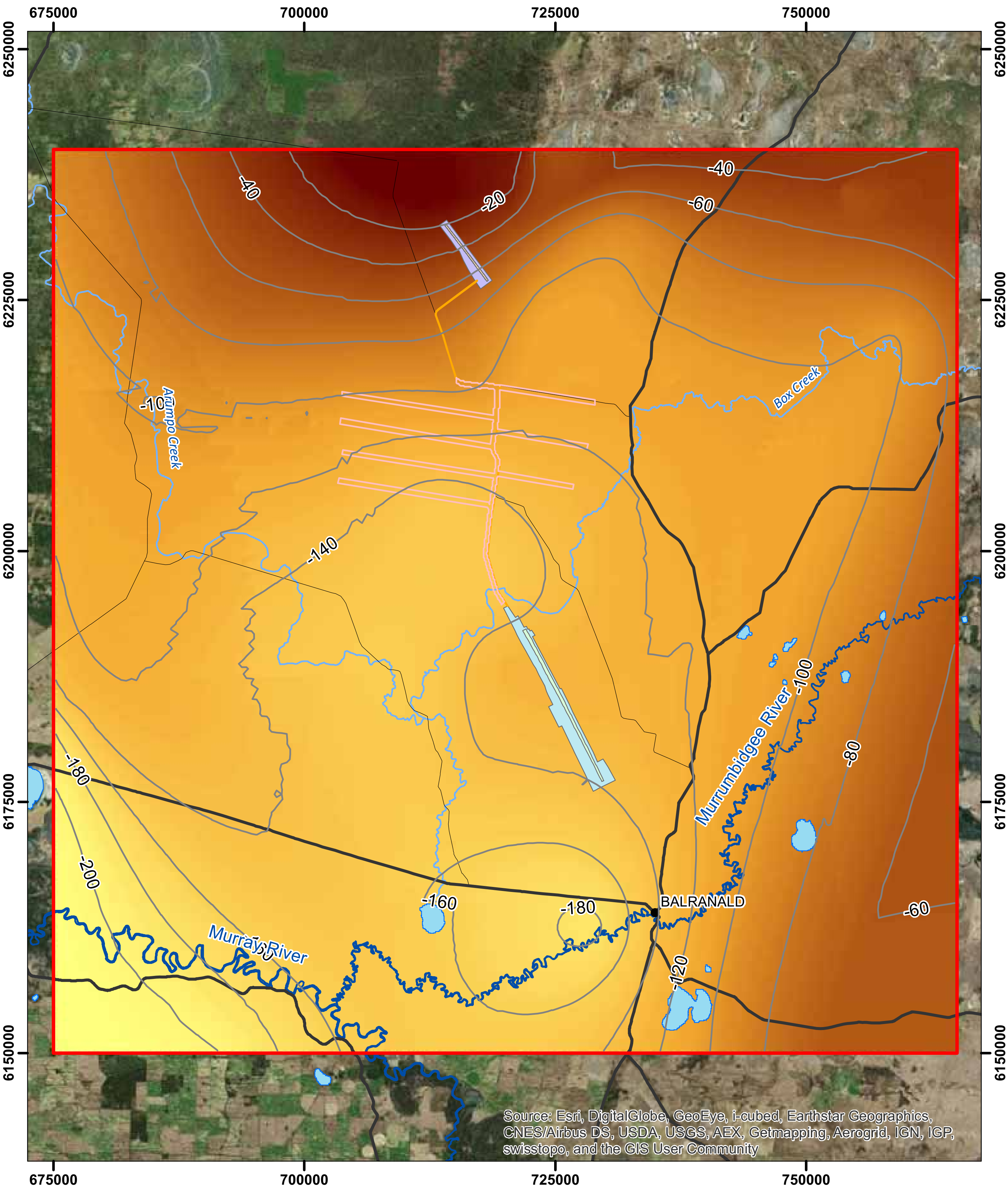
BAL2.0 top of LPS2 LS (layer 7)

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of LPS2 LS (layer 7) 20141211.mxd



BAL2.0 top of Geera Clay (layer 8)



- 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
- Elevation contours (mAHD)

Elevation (mAHD)
High : -4
Low : -216

0 10
Kilometres

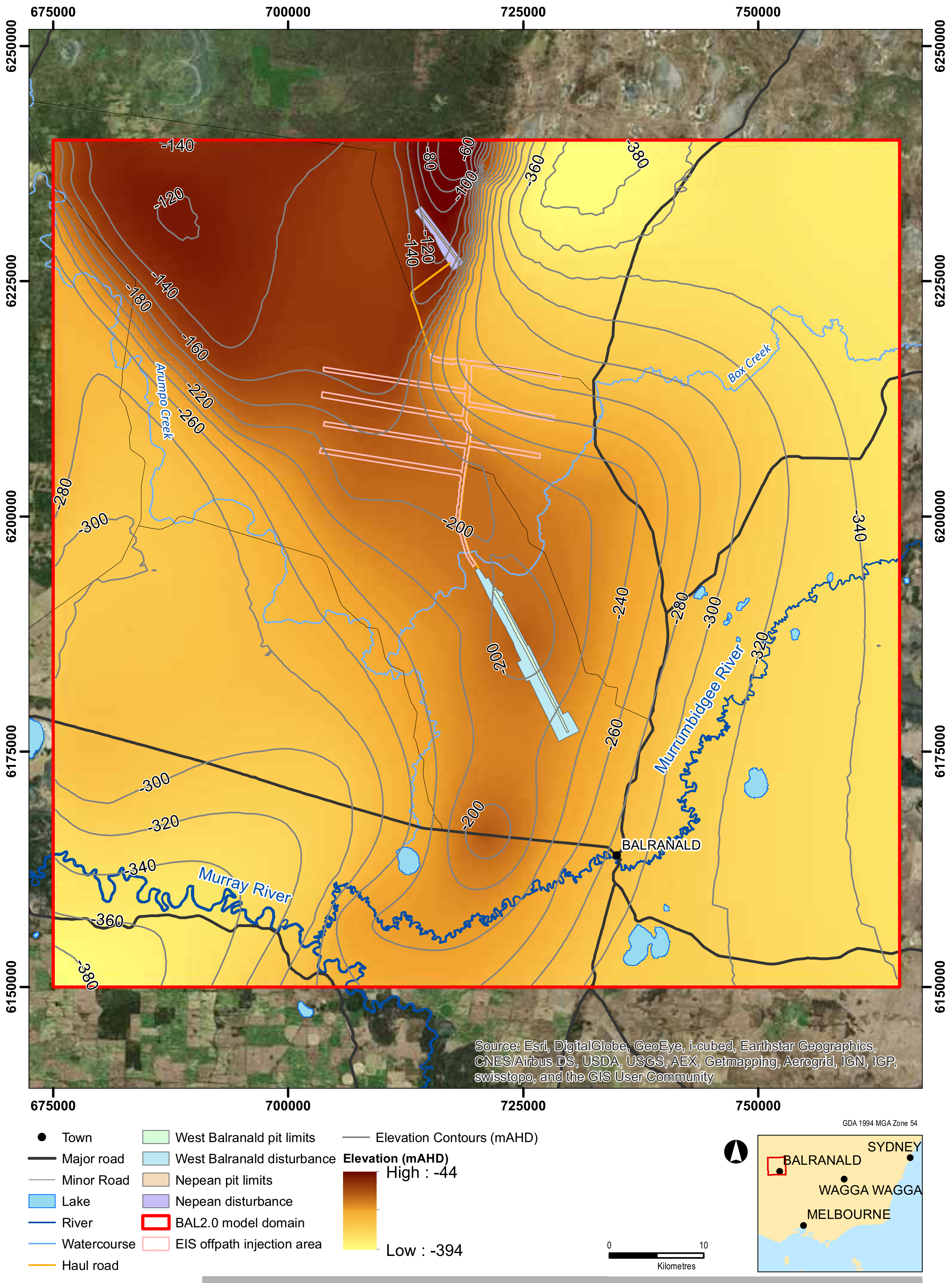
GDA 1994 MGA Zone 54

SYDNEY
BALRANALD
WAGGA WAGGA
MELBOURNE

JACOBS

BAL2.0 top of Olney Formation (layer 9)

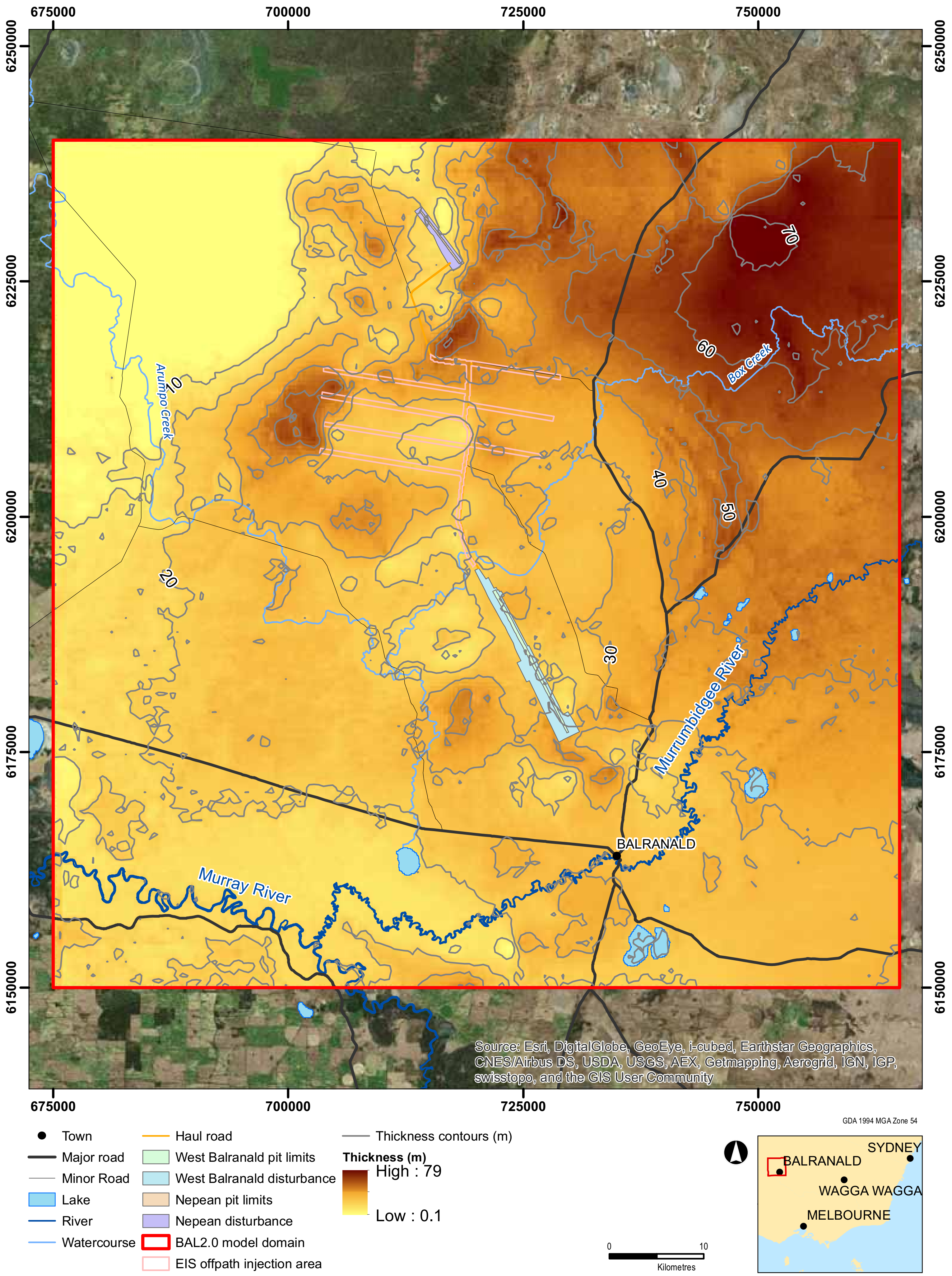
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of Olney Fm (layer 9) 20141211.mxd



JACOBS

BAL2.0 top of basement (bottom of layer 9)

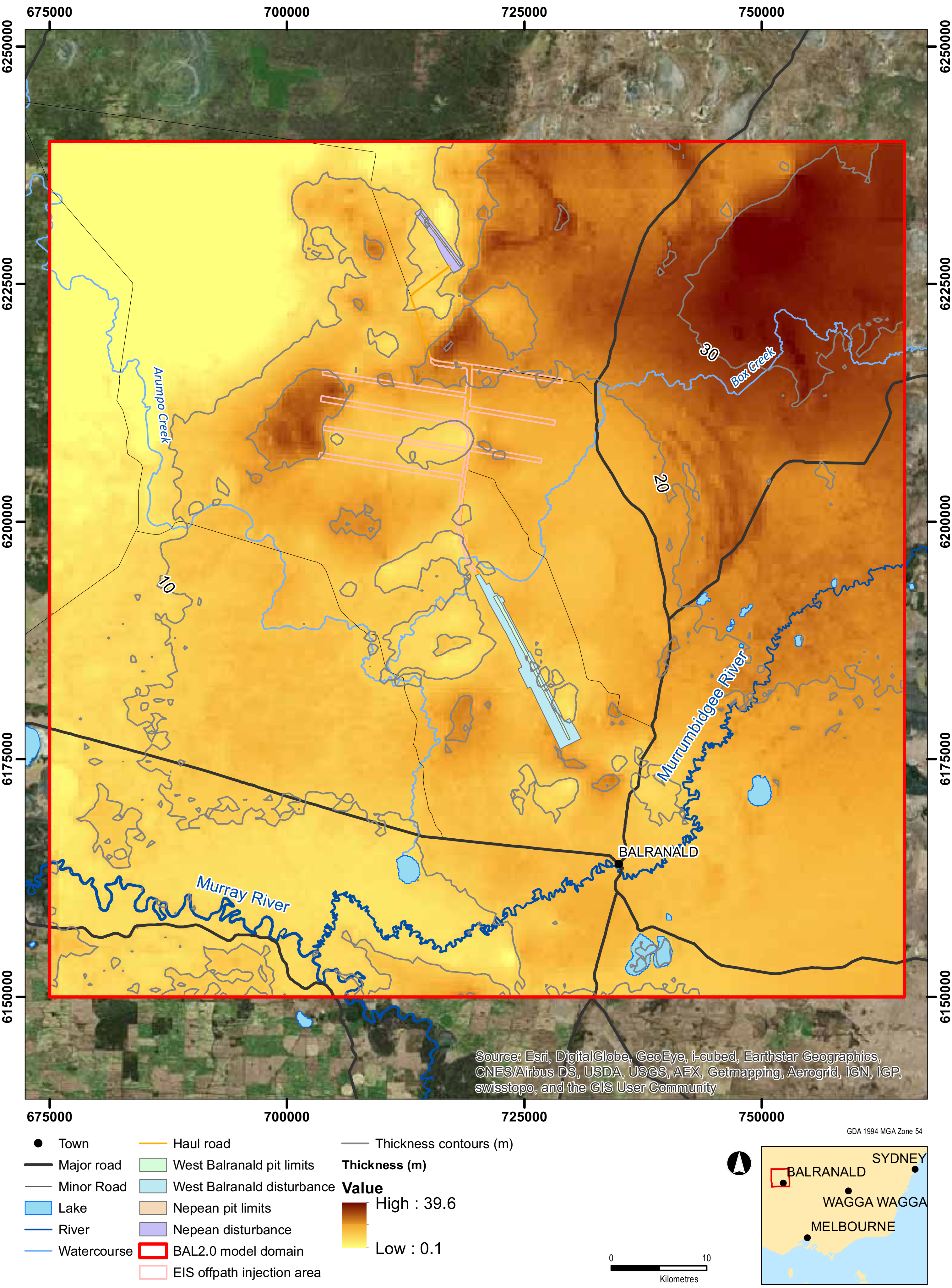
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer surfaces\Rev2\BAL2.0 top of basement (bottom of layer 9) 20141211.mxd



JACOBS

BAL2.0 thickness of Shepparton Formation (shallow) (layer 1)

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer thicknesses\Rev2\BAL2.0 thickness of Shepparton Fm (layer 1)_20141211.mxd



JACOBS

BAL2.0 thickness of Shepparton Formation (deep) (layer 2)

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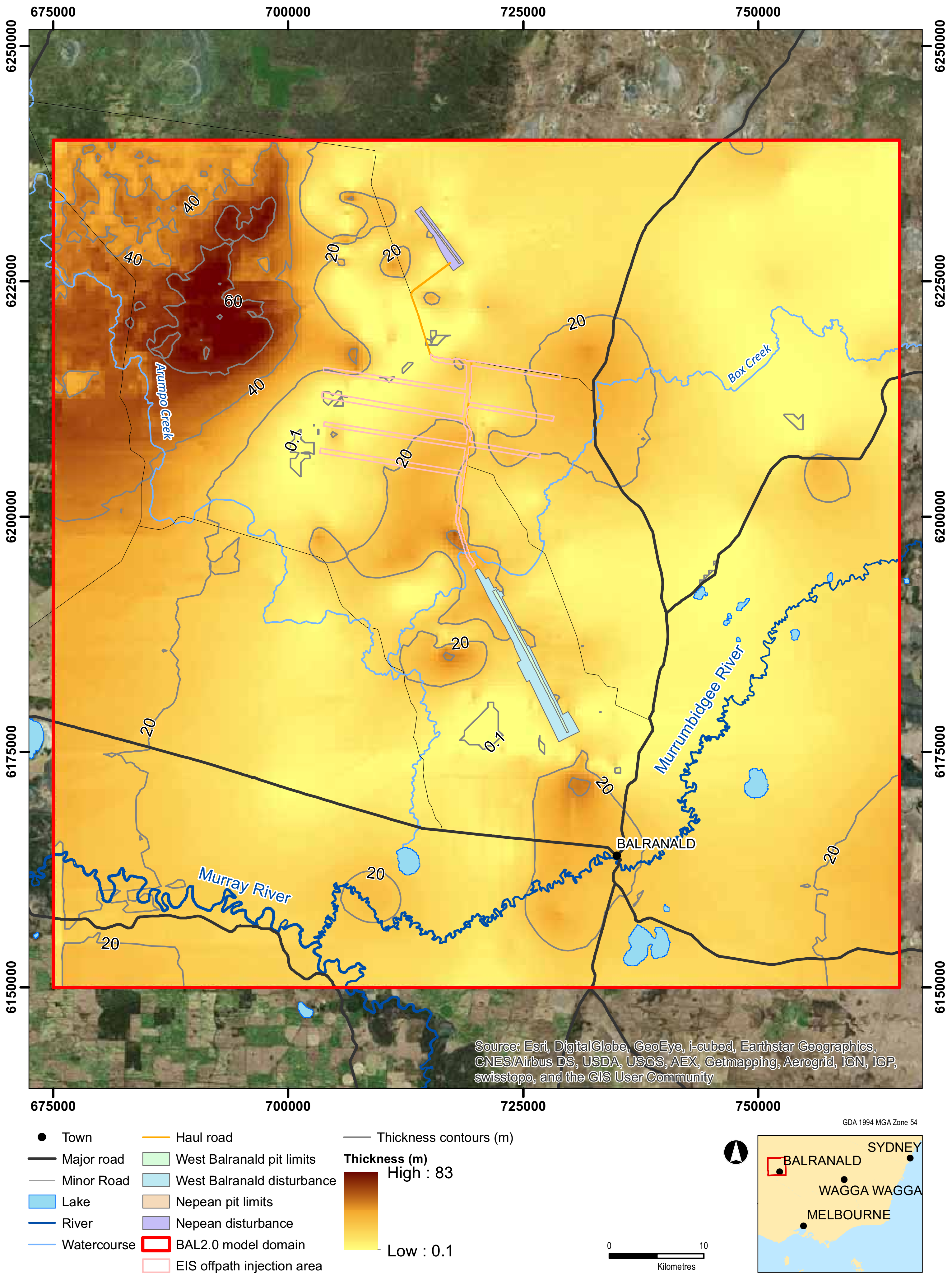
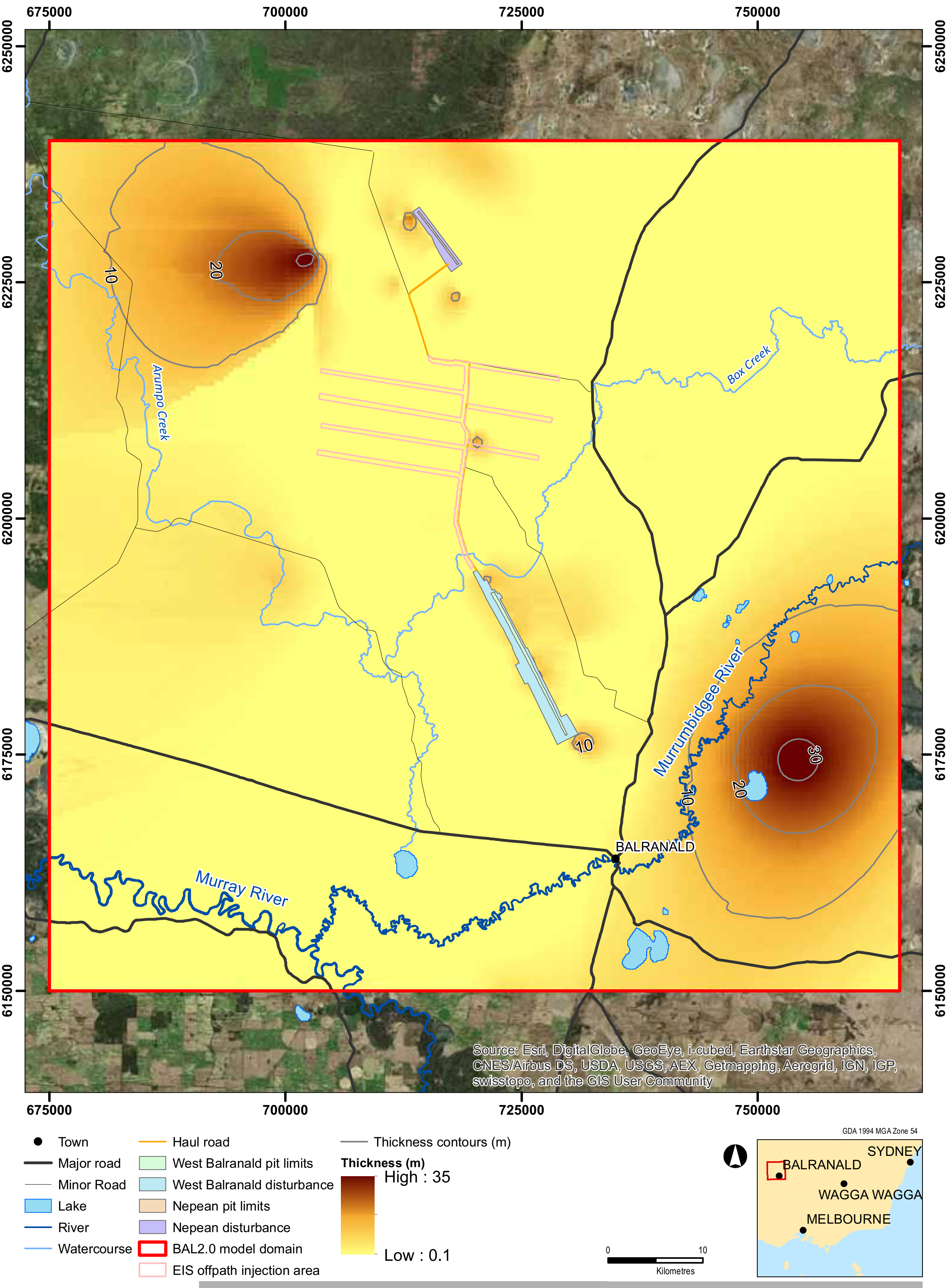


JACOBS

BAL2.0 thickness of LPS1 FS (layer 3)

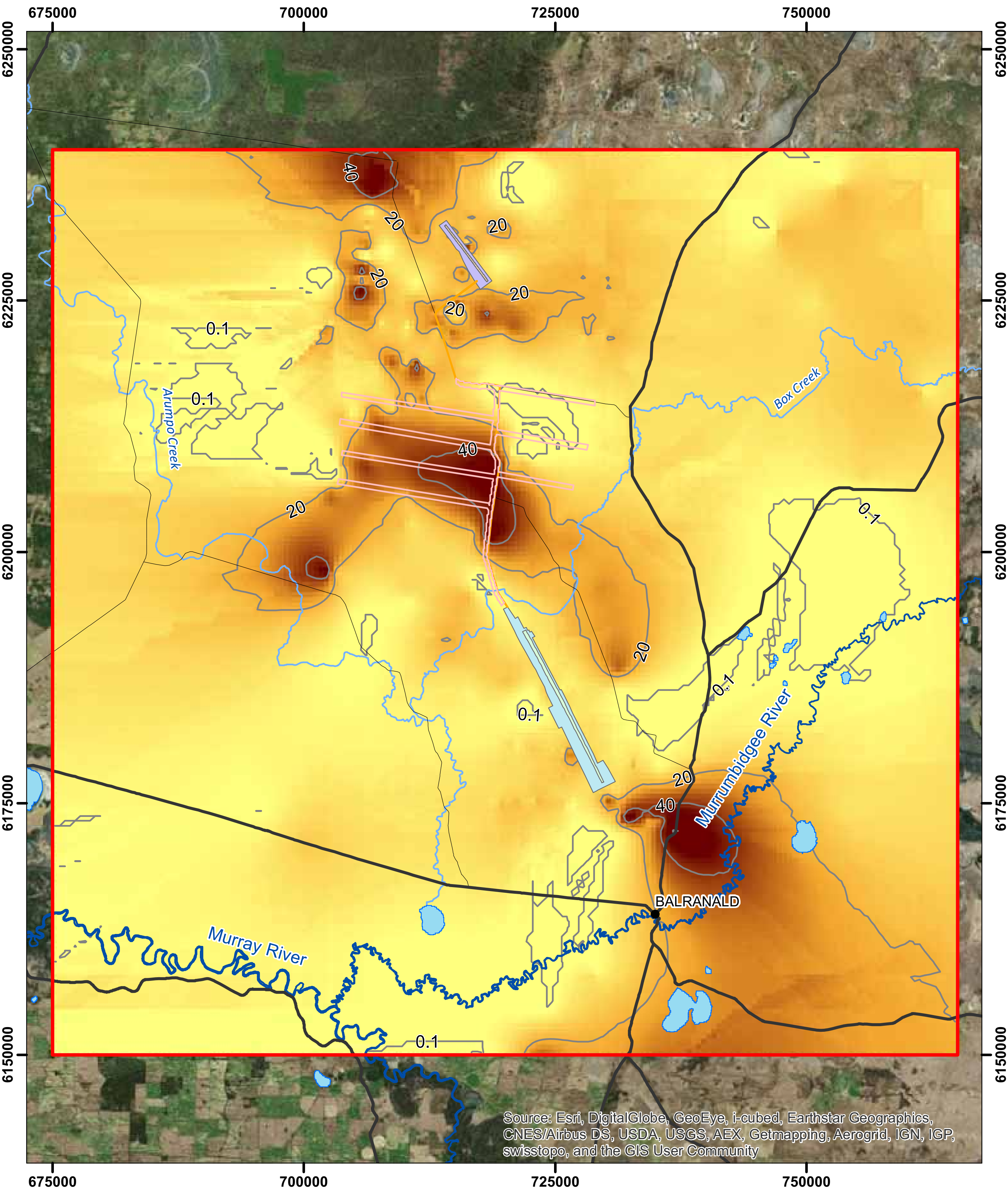
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer thicknesses\Rev2\BAL2.0 thickness of LPS1 FS (layer 3)_20141211.mxd



BAL2.0 thickness of LPS1 SZ (layer 4)

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer thicknesses\Rev2\BAL2.0 thickness of LPS1 SZ (layer 4)_20141211.mxd

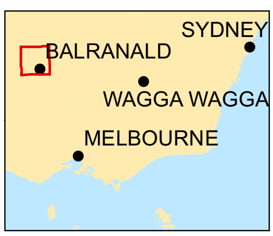


GDA 1994 MGA Zone 54

- 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
- Thickness contours (m)

Thickness (m)
High : 60
Low : 0.1

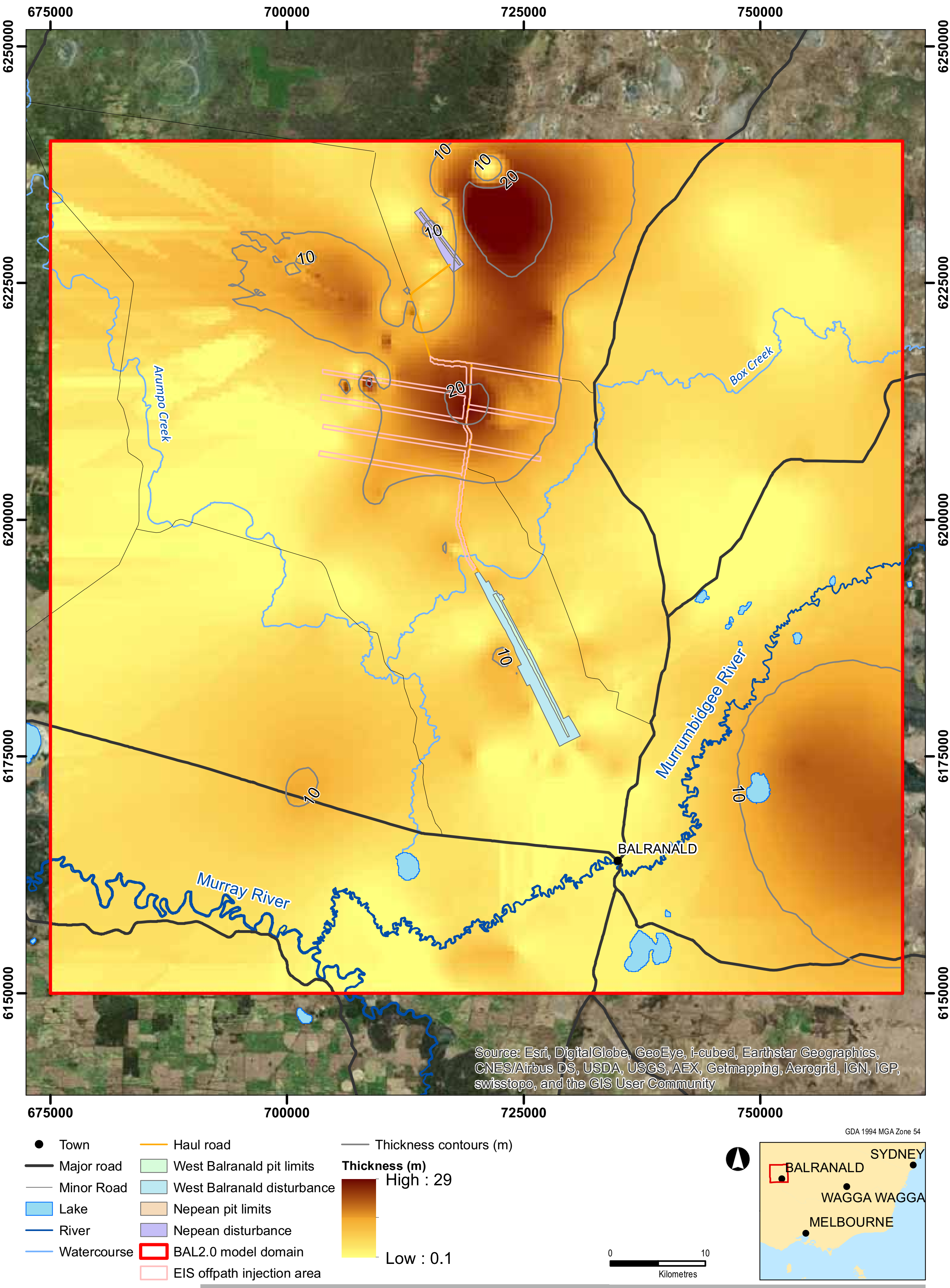
0 10
Kilometres



JACOBS

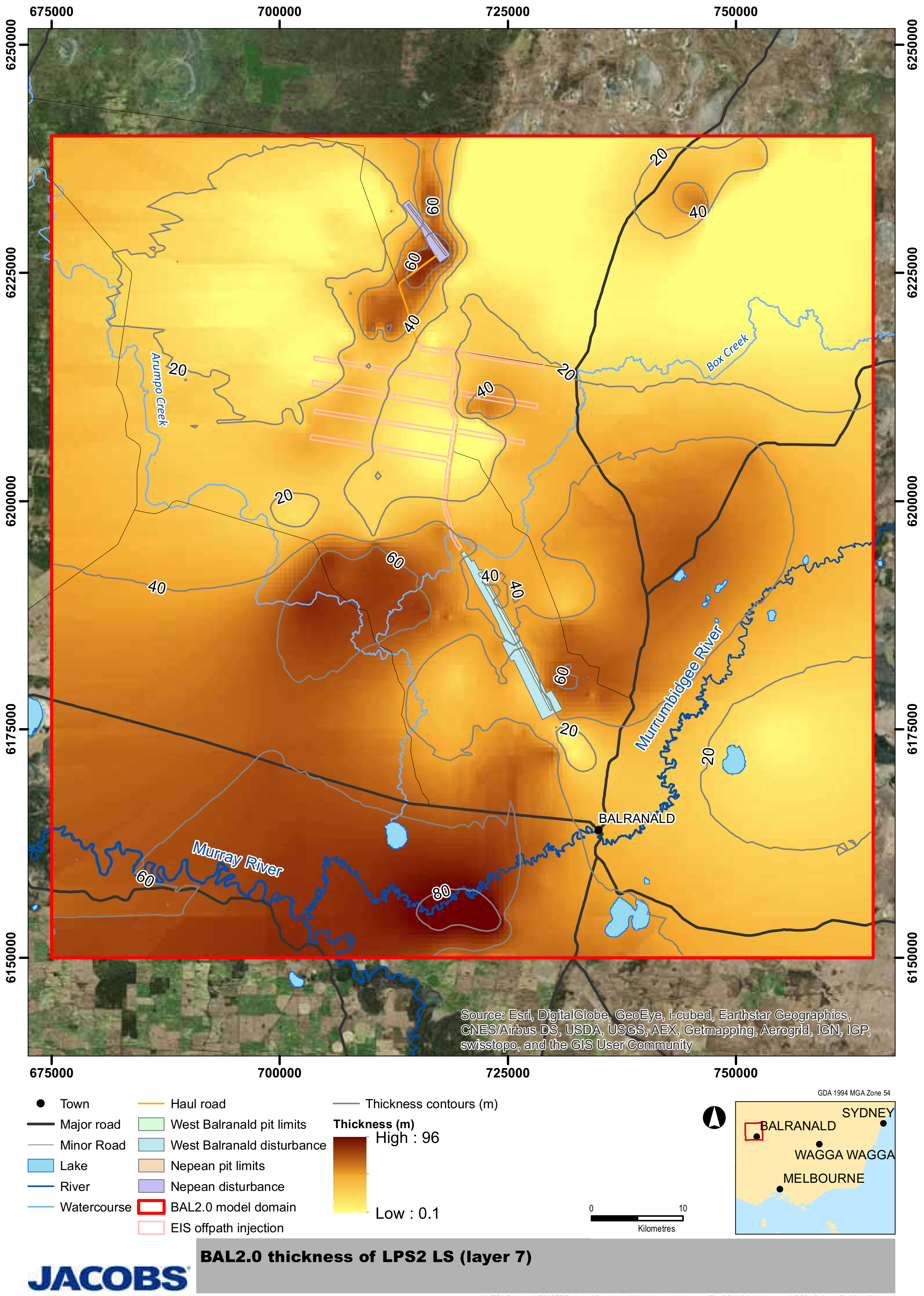
BAL2.0 thickness of LPS1 LS-LPS2 FS (layer 5)

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer thicknesses\Rev2\BAL2.0 thickness of LPS1 LS-LPS2 FS (layer 5)_20141211.mxd



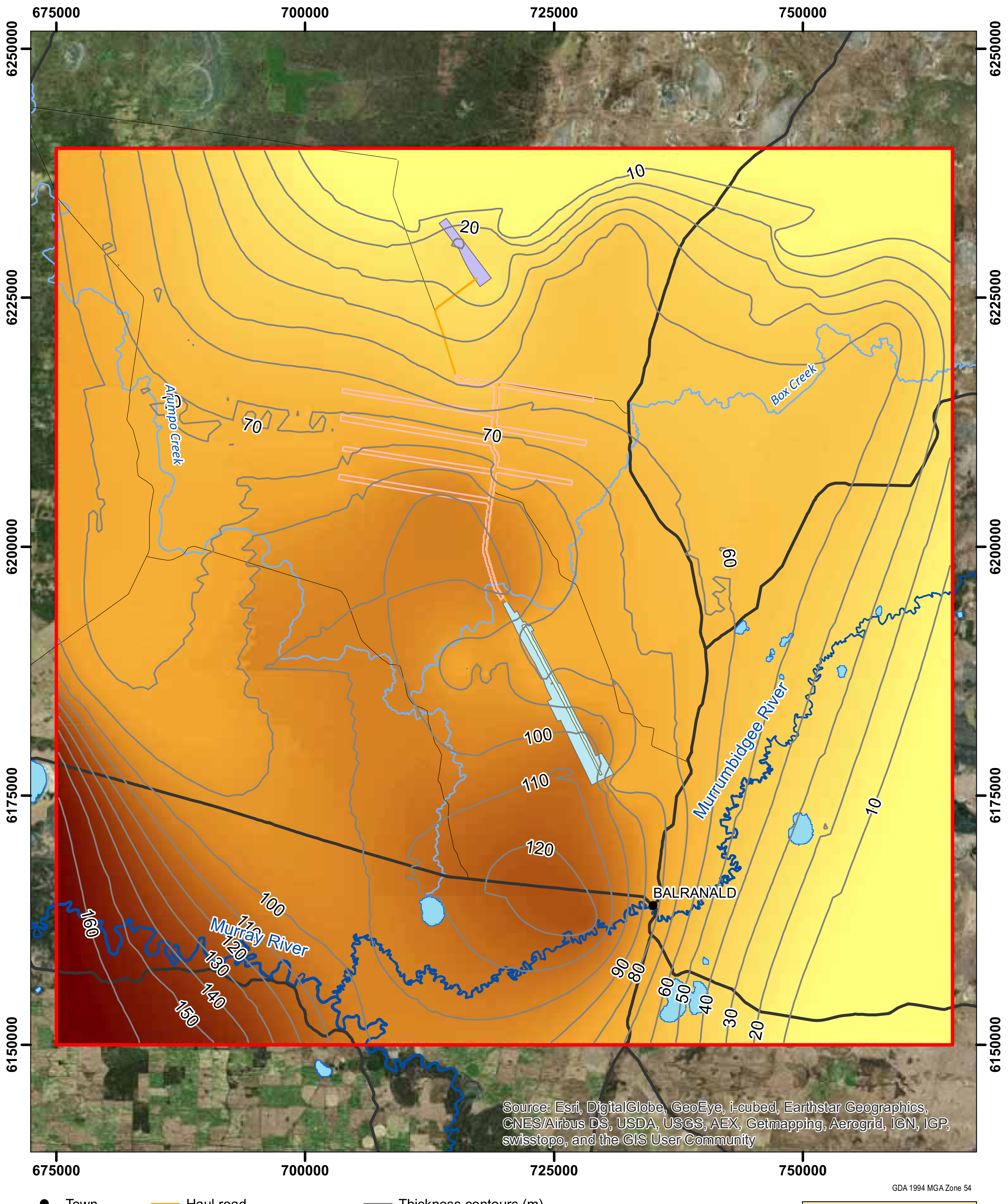
BAL2.0 thickness of LPS2 SZ (layer 6)

JACOBS



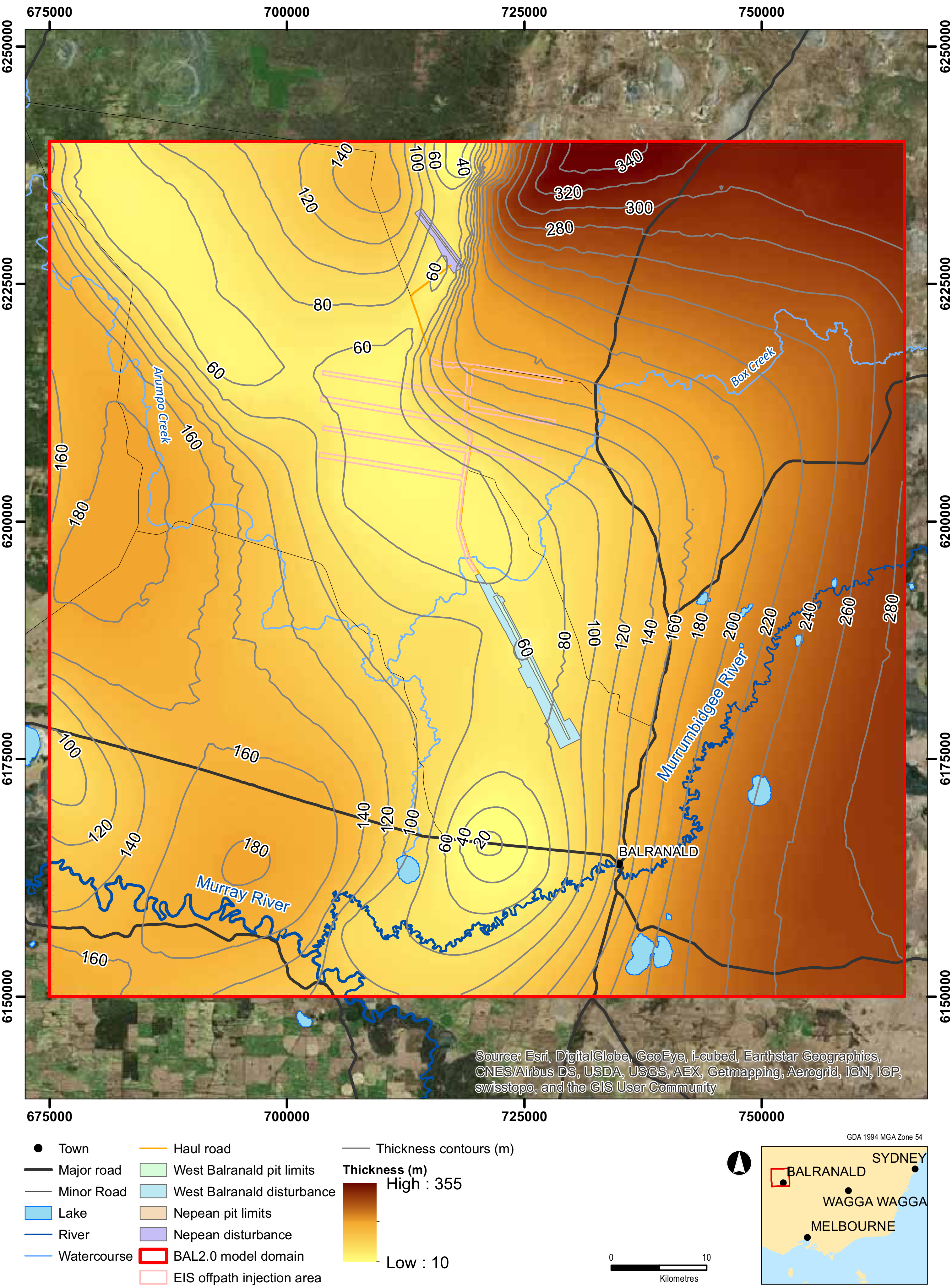
BAL2.0 thickness of LPS2 LS (layer 7)

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer thicknesses\Rev2\BAL2.0 thickness of LPS2 LS (layer 7)_20141211.mxd



BAL2.0 thickness of Geera Clay (layer 8)

JACOBS

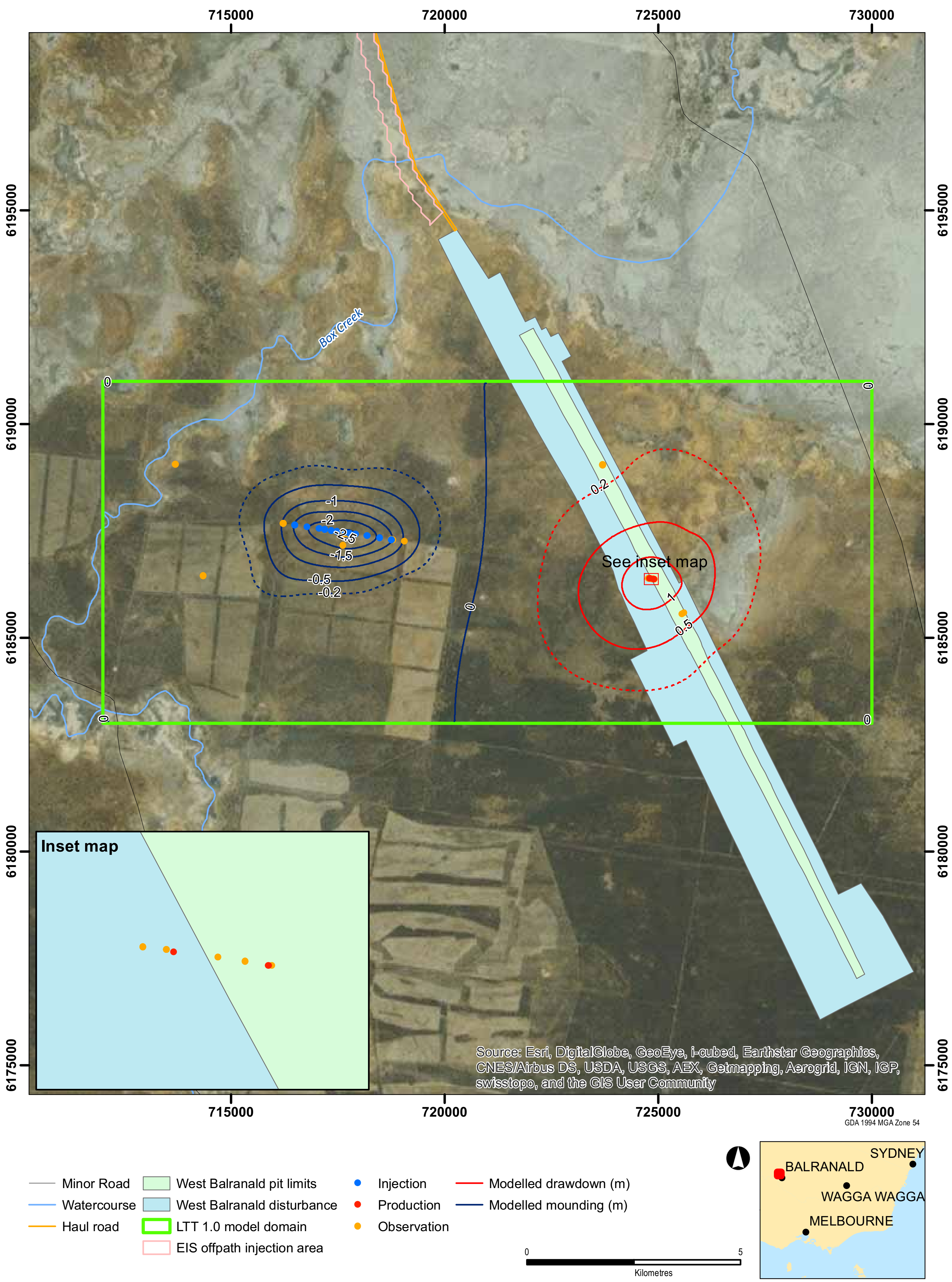


BAL2.0 thickness of Olney Formation (layer 9)

JACOBS

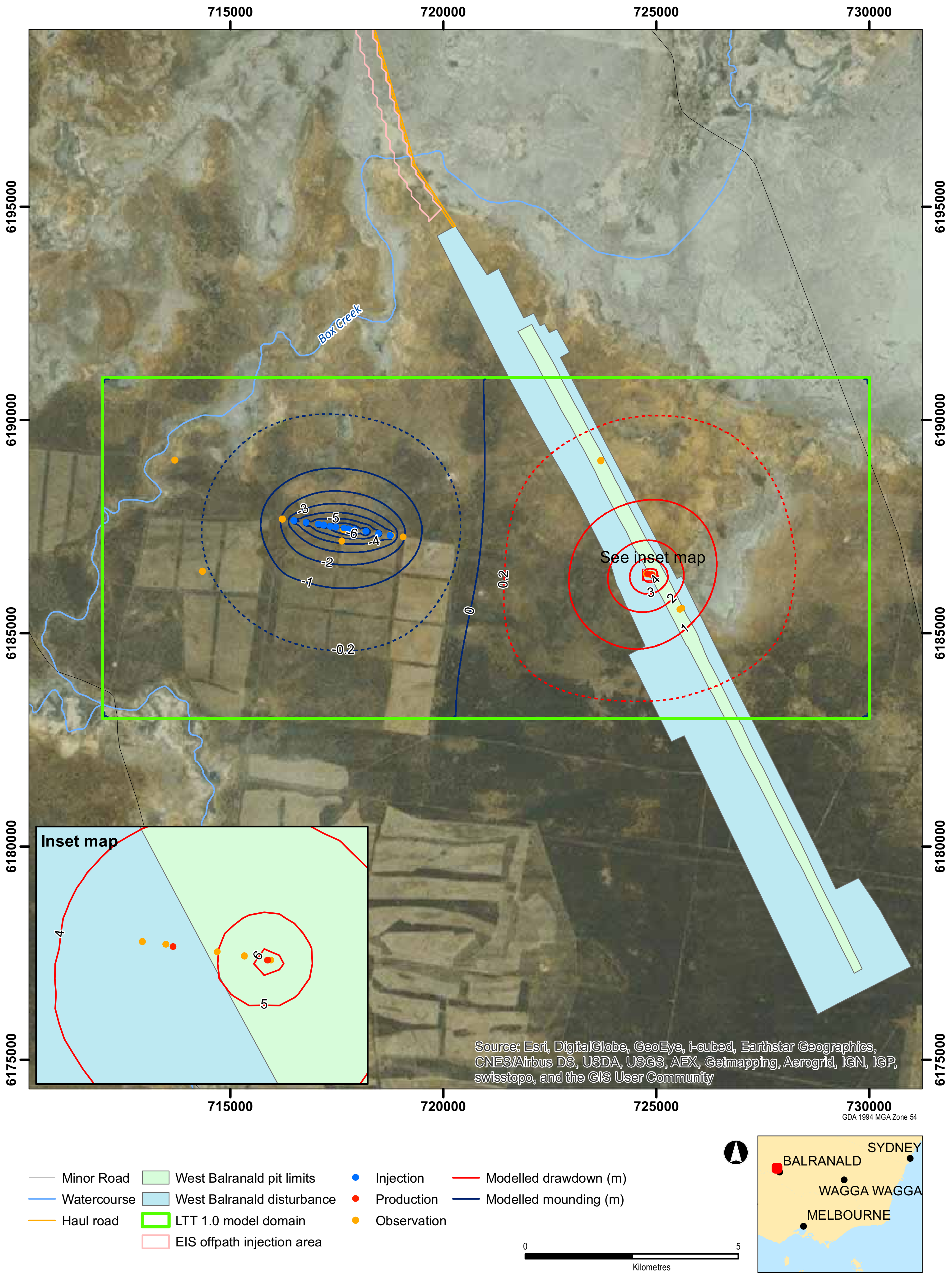
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Model layer thicknesses\Rev2\BAL2.0 thickness of Olney Fm (layer 9)_20141211.mxd

Appendix D. Modelled drawdown for local-scale models



LTT1.0 modelled drawdown in Shepparton Formation (deep) on 10/07/2014

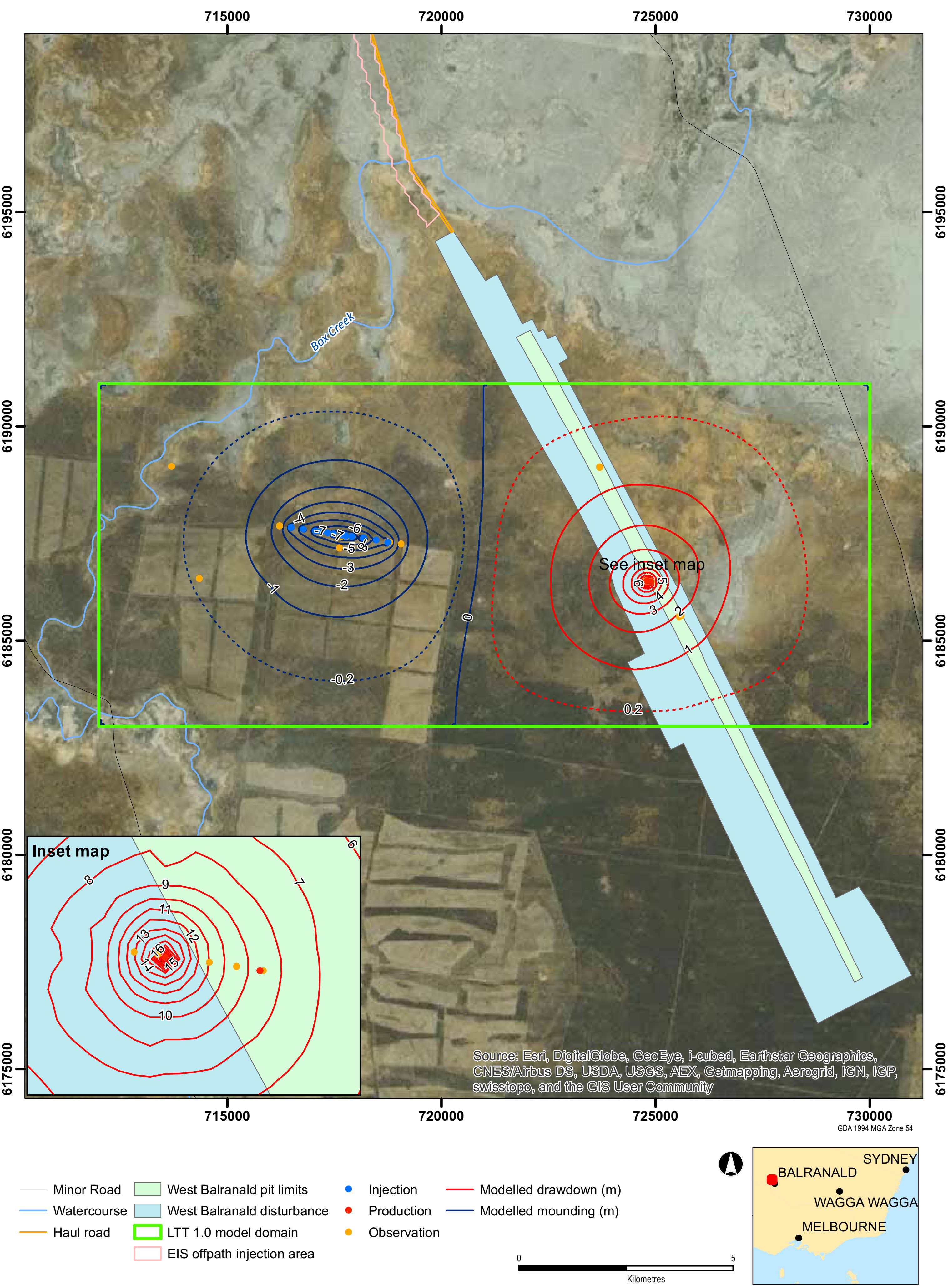
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\LTT1\2 LTT1.0 Drawdown in theShepparton (deep) .mxd



JACOBS

LTT1.0 modelled drawdown in LPS1 FS on 10/07/2014

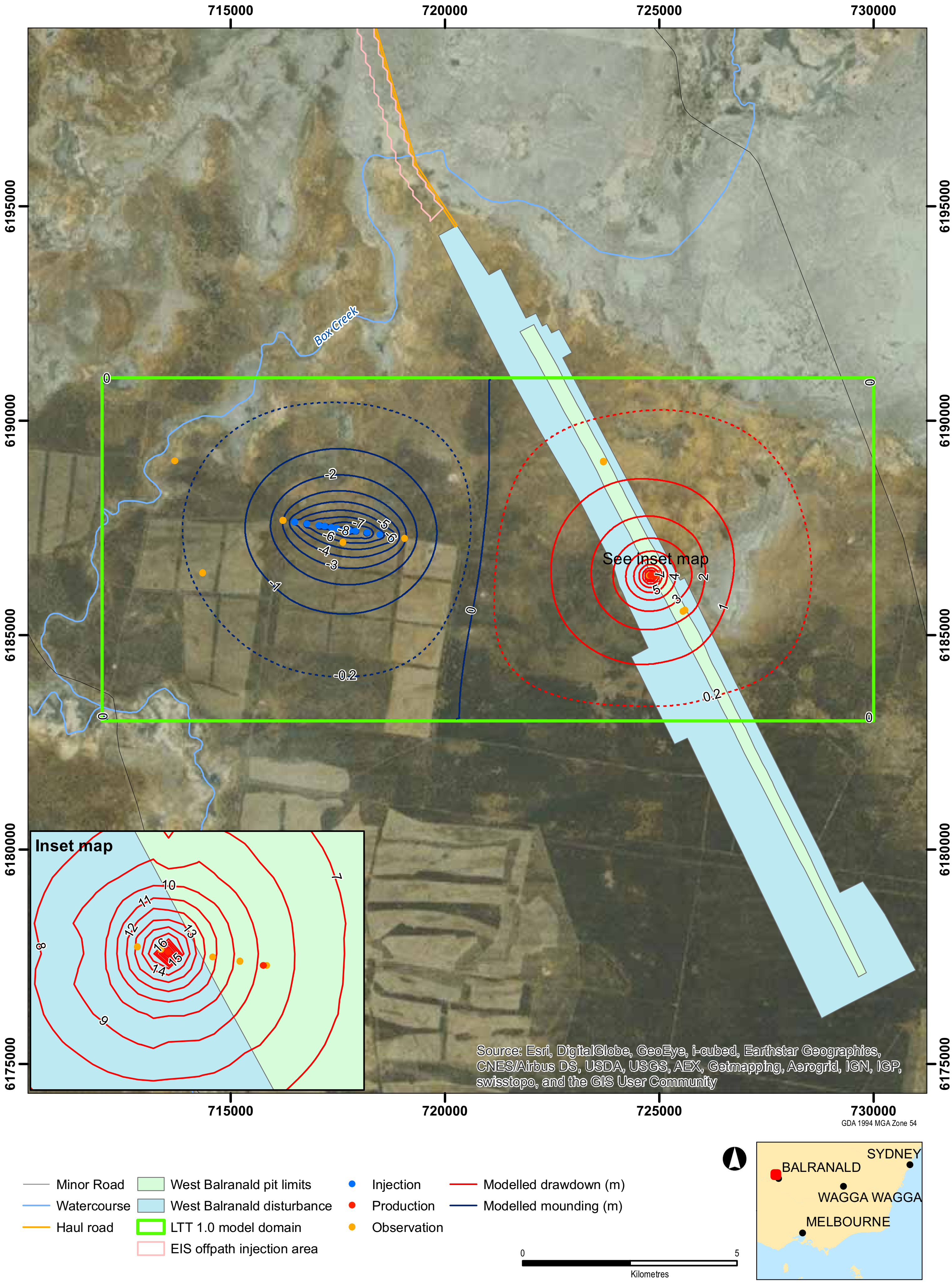
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\LTT1\3 LTT1.0 Drawdown in the LPS1 FS.mxd



LTT1.0 modelled drawdown in LPS1 SZ on 10/07/2014

JACOBS

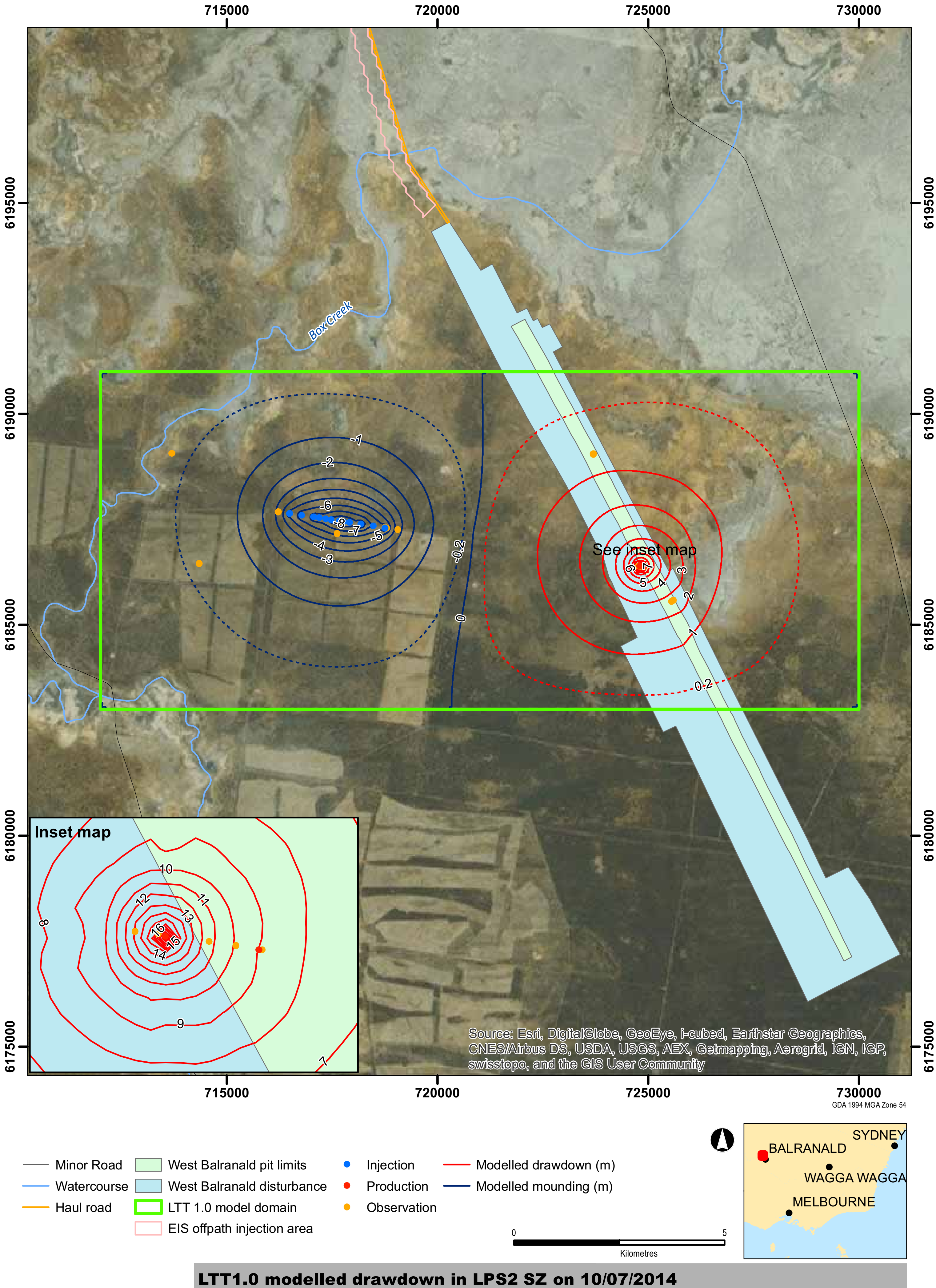
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\LTT1\4 LTT1.0 Drawdown in the LPS1 SZ.mxd



LTT1.0 modelled drawdown in LPS1 LS/LPS2 FS on 10/07/2014

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\LTT1\5 LTT1.0 Drawdown in theLPS1 LS_LPS2 FS.mxd



JACOBS

LTT1.0 modelled drawdown in LPS2 SZ on 10/07/2014

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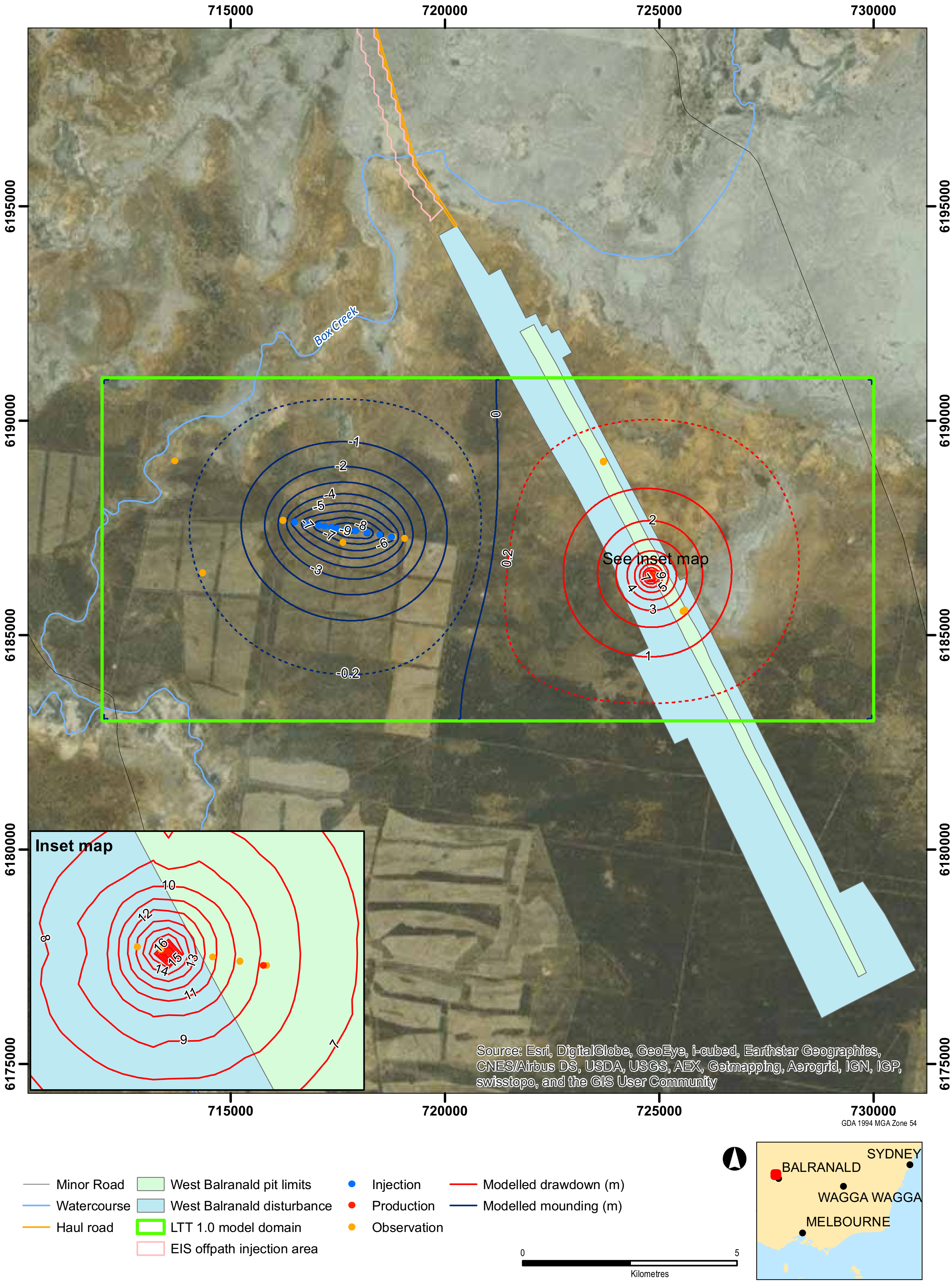
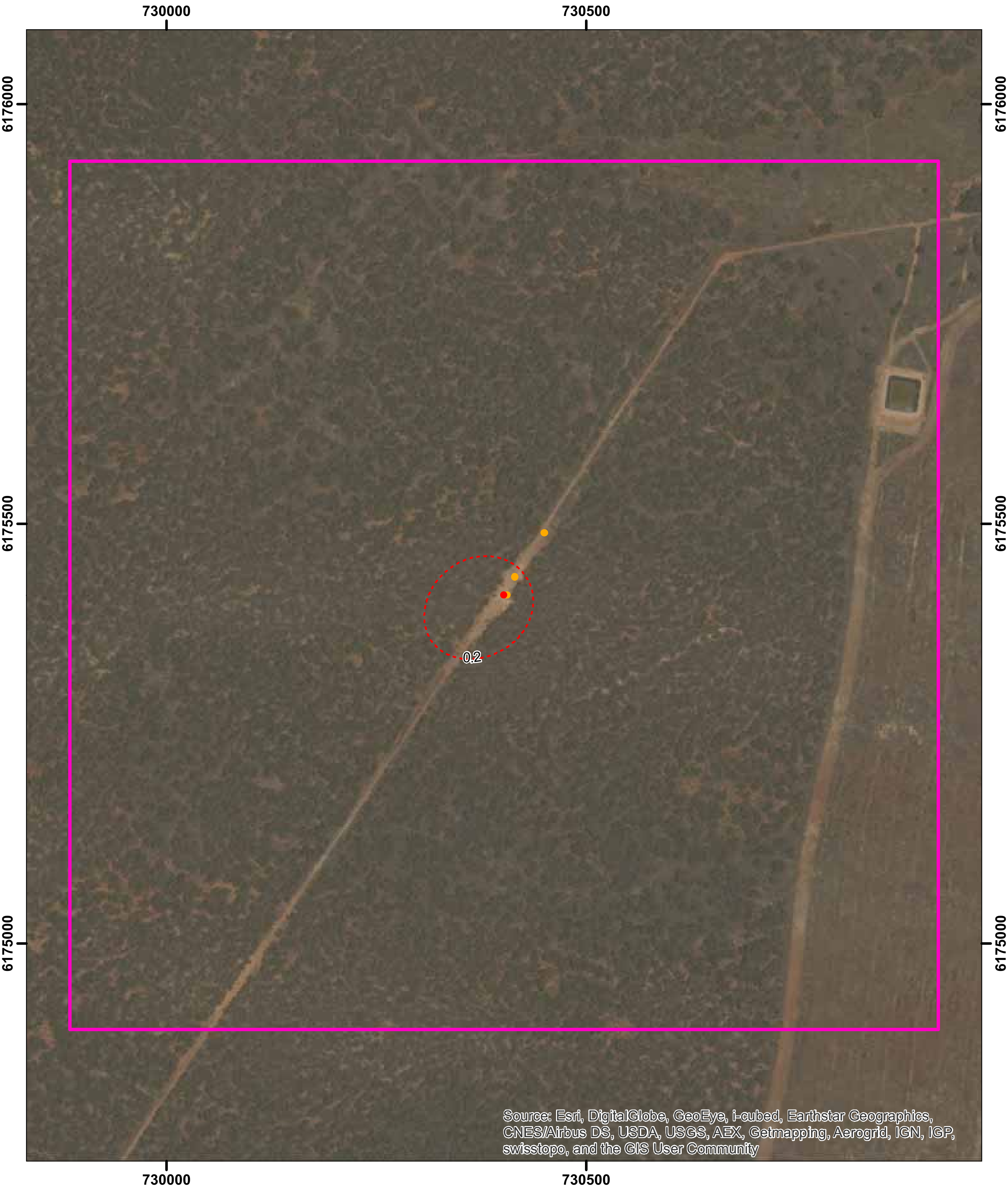


LTT1.0 modelled drawdown in LPS2 LS on 10/07/2014

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\LTT1\7 LTT1.0 Drawdown in theLPS2 LS.mxd



GDA 1994 MGA Zone 54

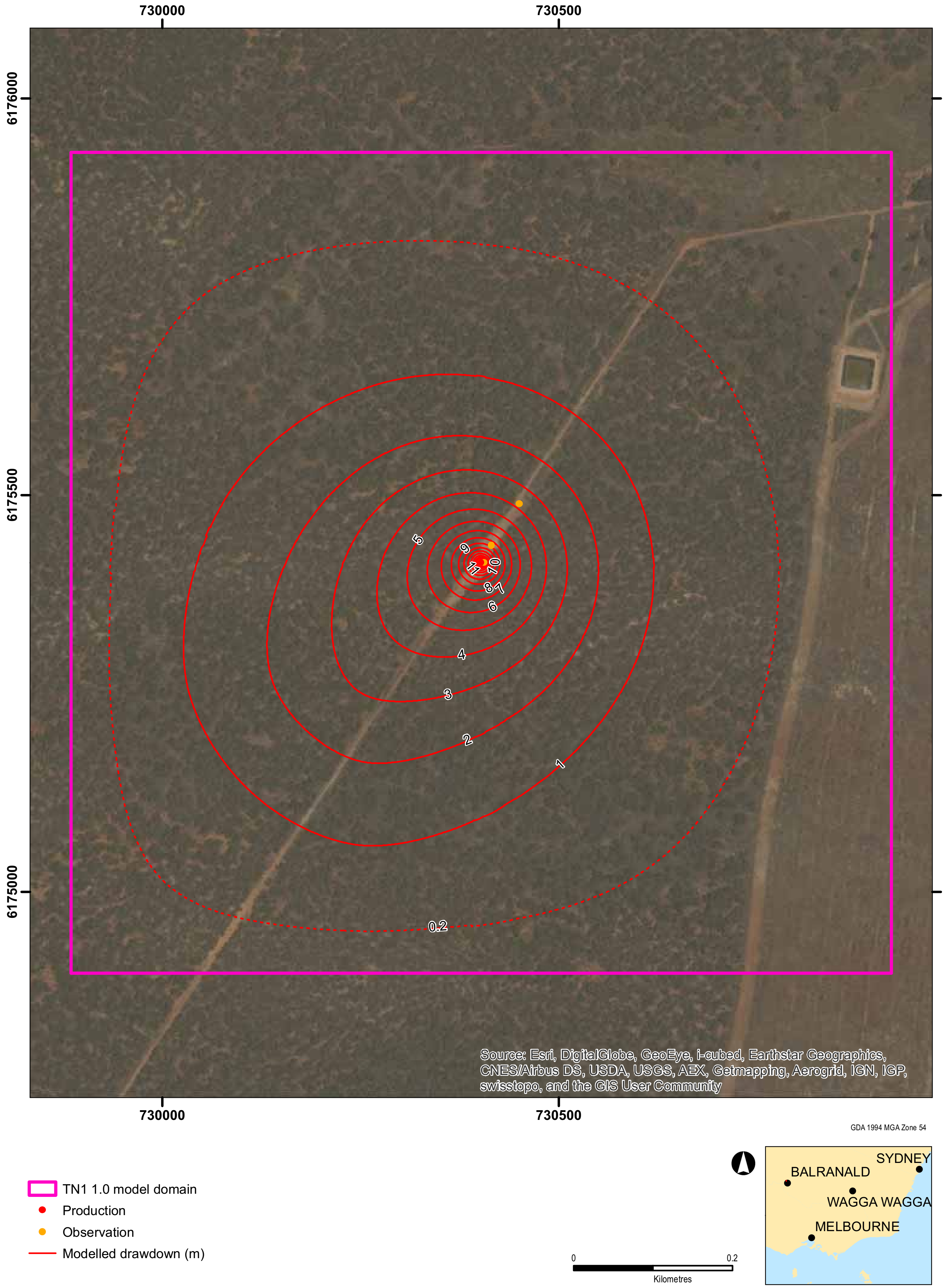
TN1 1.0 model domain
Production
Observation
Modelled drawdown (m)

0 0.2
Kilometres

TN1 1.0 modelled drawdown in Shepparton Formation (deep) on 21/02/2012

JACOBS

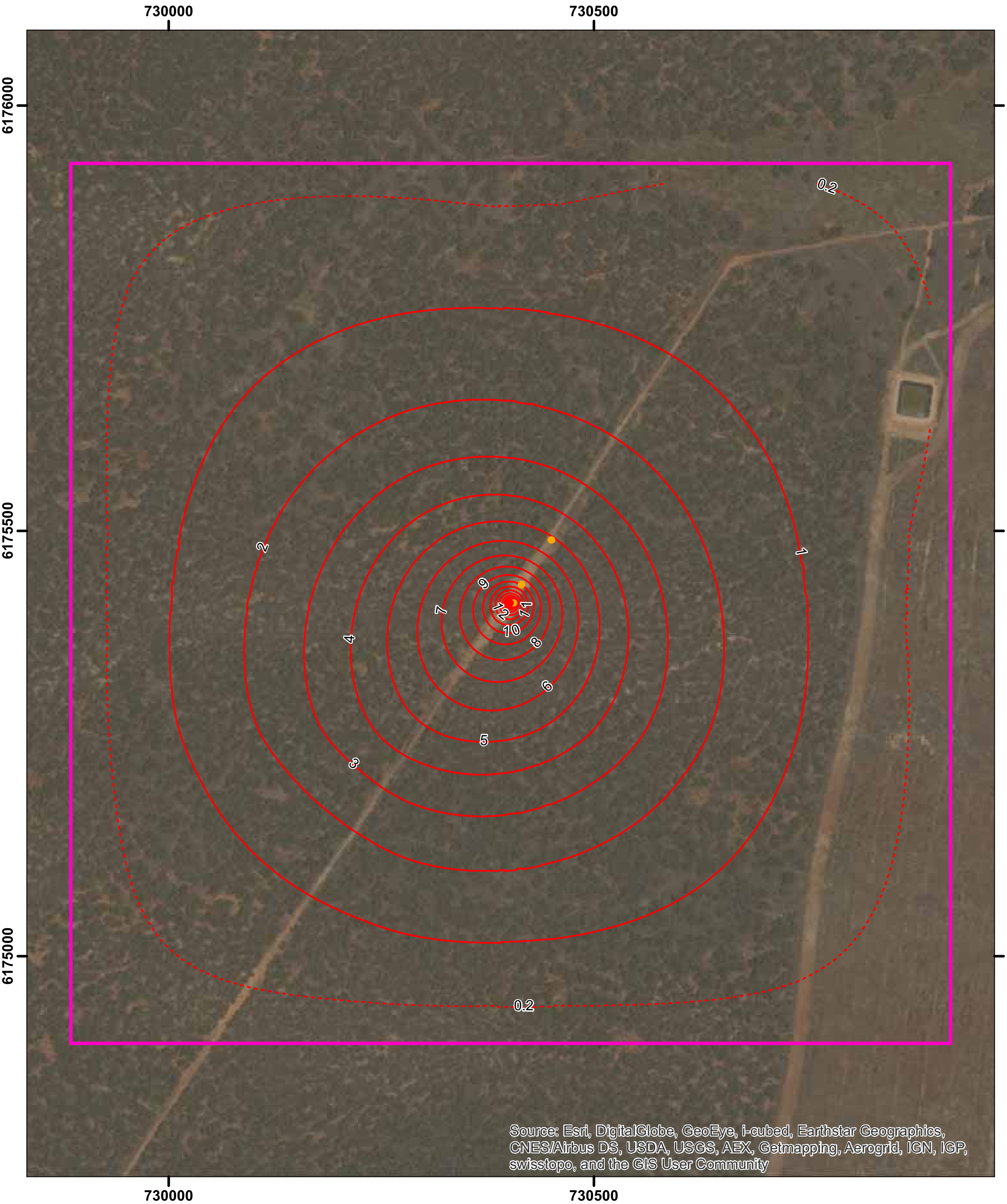
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN1\2 TN1 1.0 Drawdown in the Drawdown in the Shepparton Formation (deep).mxd



TN1 1.0 modelled drawdown in LPS1 FS on 21/02/2012

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN1\3 TN1 1.0 Drawdown in the Drawdown in the LPS1 FS.mxd



GDA 1994 MGA Zone 54

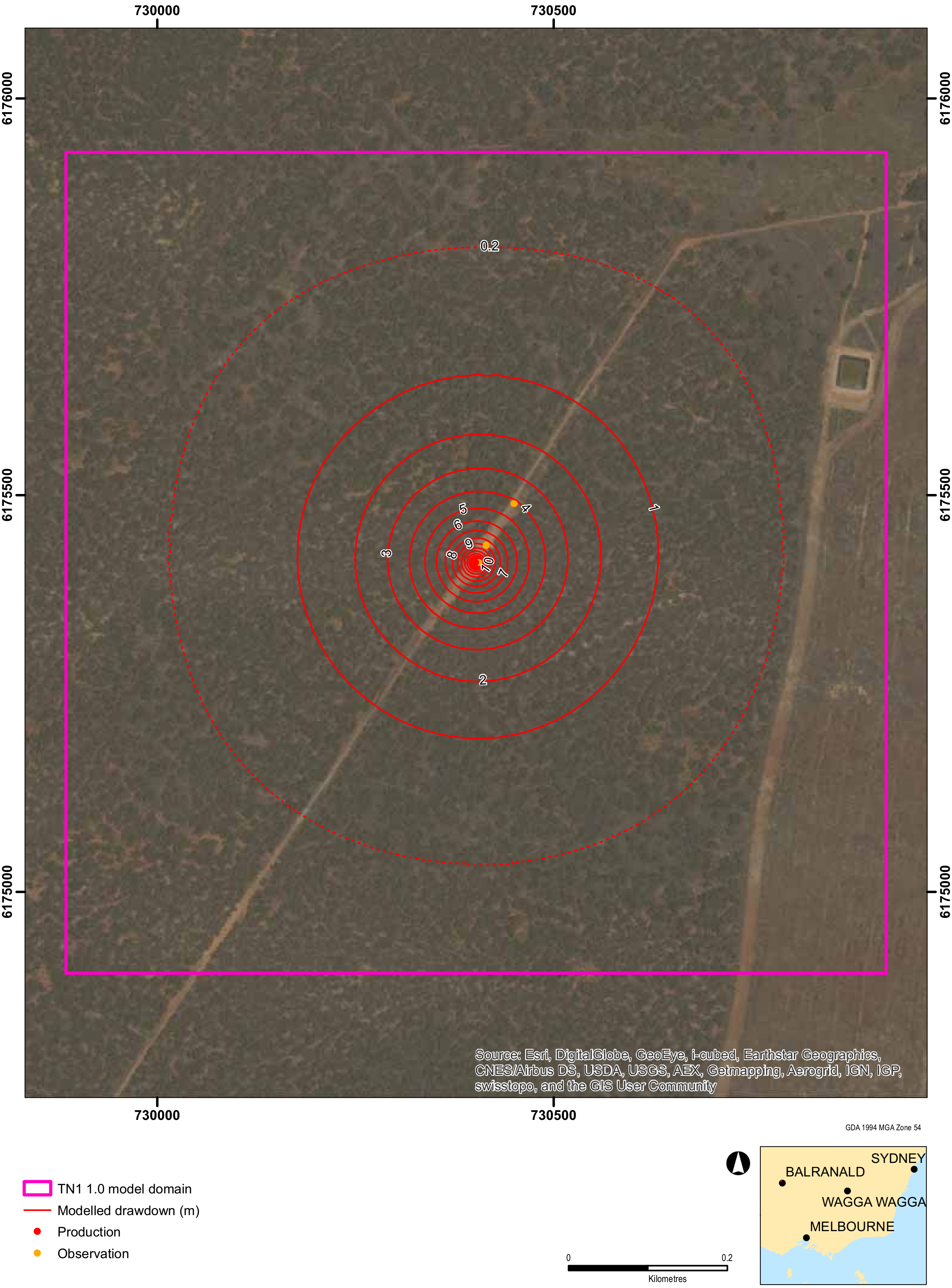
- TN1 1.0 model domain
- Modelled drawdown (m)
- Production
- Observation

0 0.2
Kilometres

TN1 1.0 modelled drawdown in LPS1 SZ on 21/02/2012

JACOBS

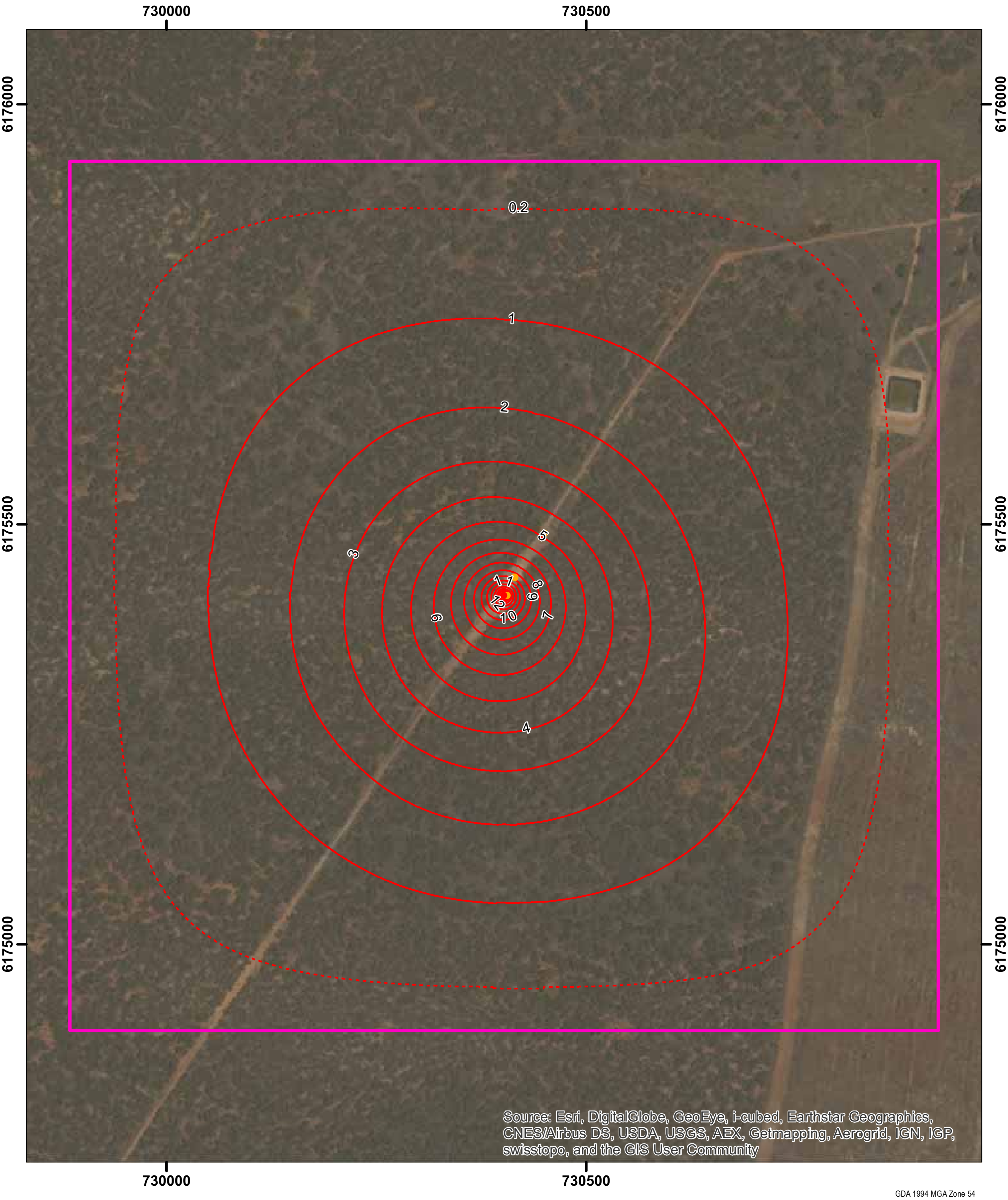
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN1\4 TN1 1.0 Drawdown in the Drawdown in the LPS1 SZ.mxd



TN1 1.0 modelled drawdown in LPS1 LS/LPS2 FS on 21/02/2012

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN1\5 TN1 1.0 Drawdown in the LPS1 LS_LPS2 FS.mxd

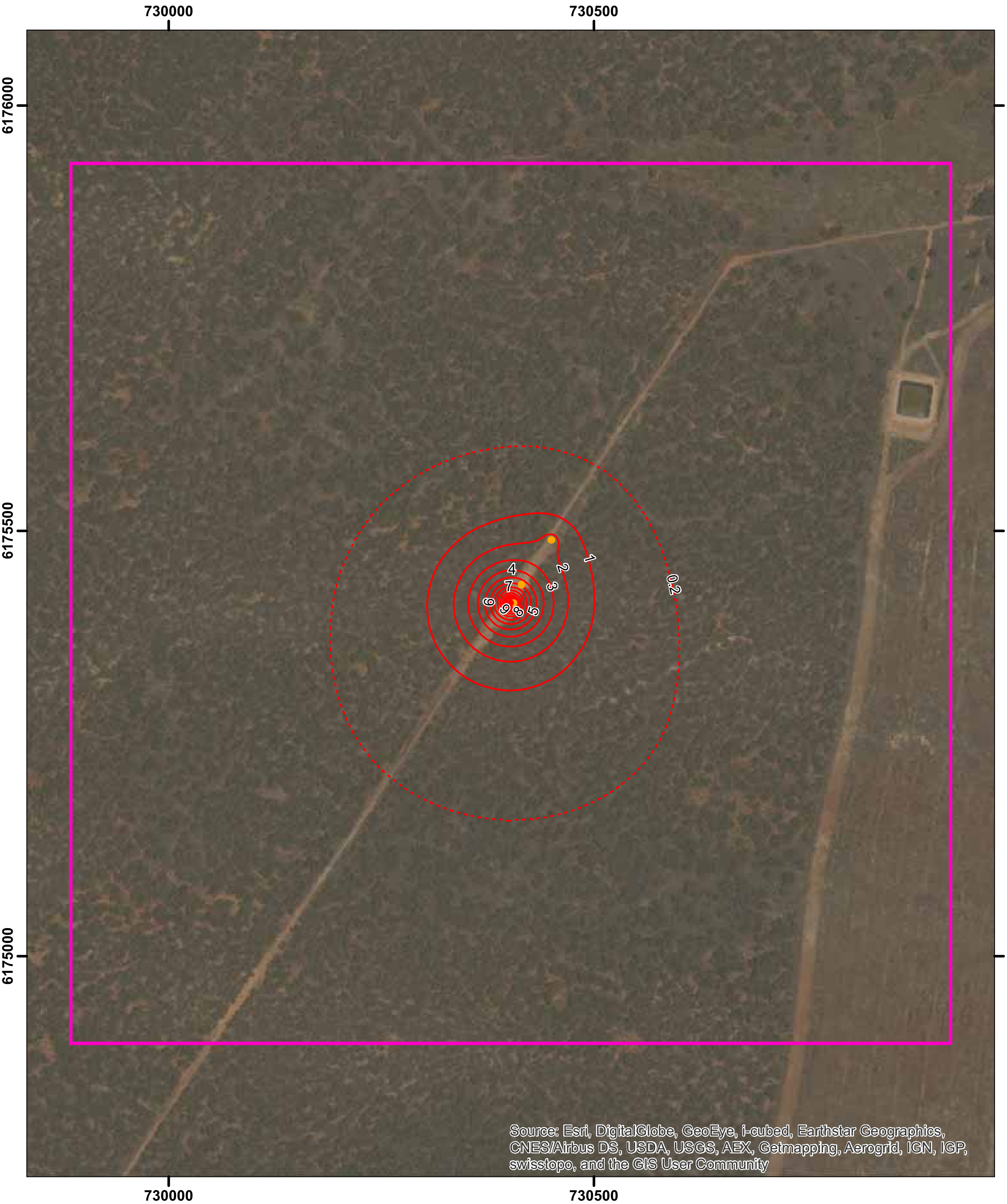


TN1 1.0 model domain
Modelled drawdown (m)
Production
Observation

0 — 0.2 Kilometres

TN1 1.0 modelled drawdown in LPS2 SZ on 21/02/2012

JACOBS



GDA 1994 MGA Zone 54

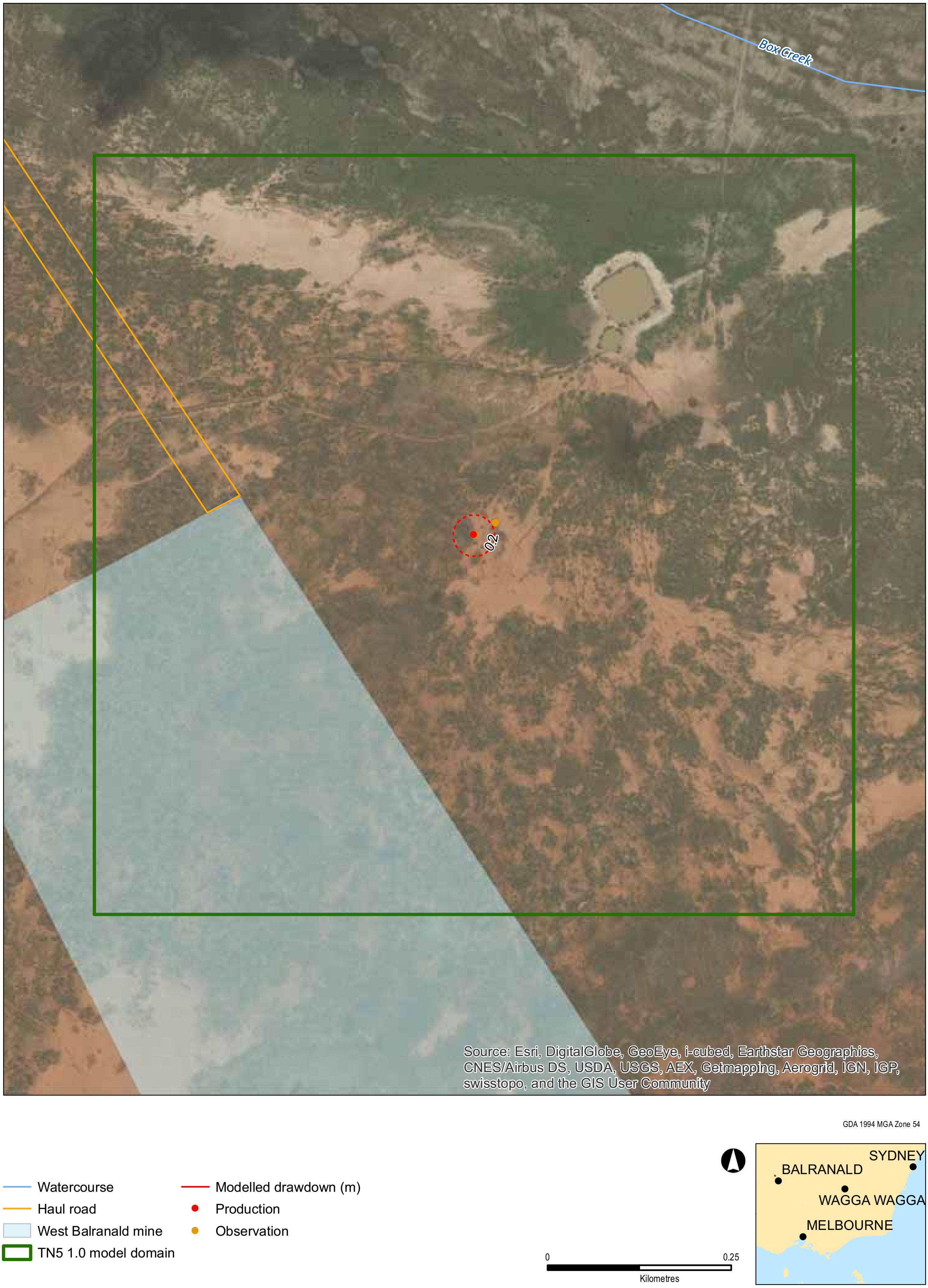
- TN1 1.0 model domain
- Modelled drawdown (m)
- Production
- Observation

0 0.2
Kilometres

TN1 1.0 modelled drawdown in LPS2 LS on 21/02/2012

JACOBS

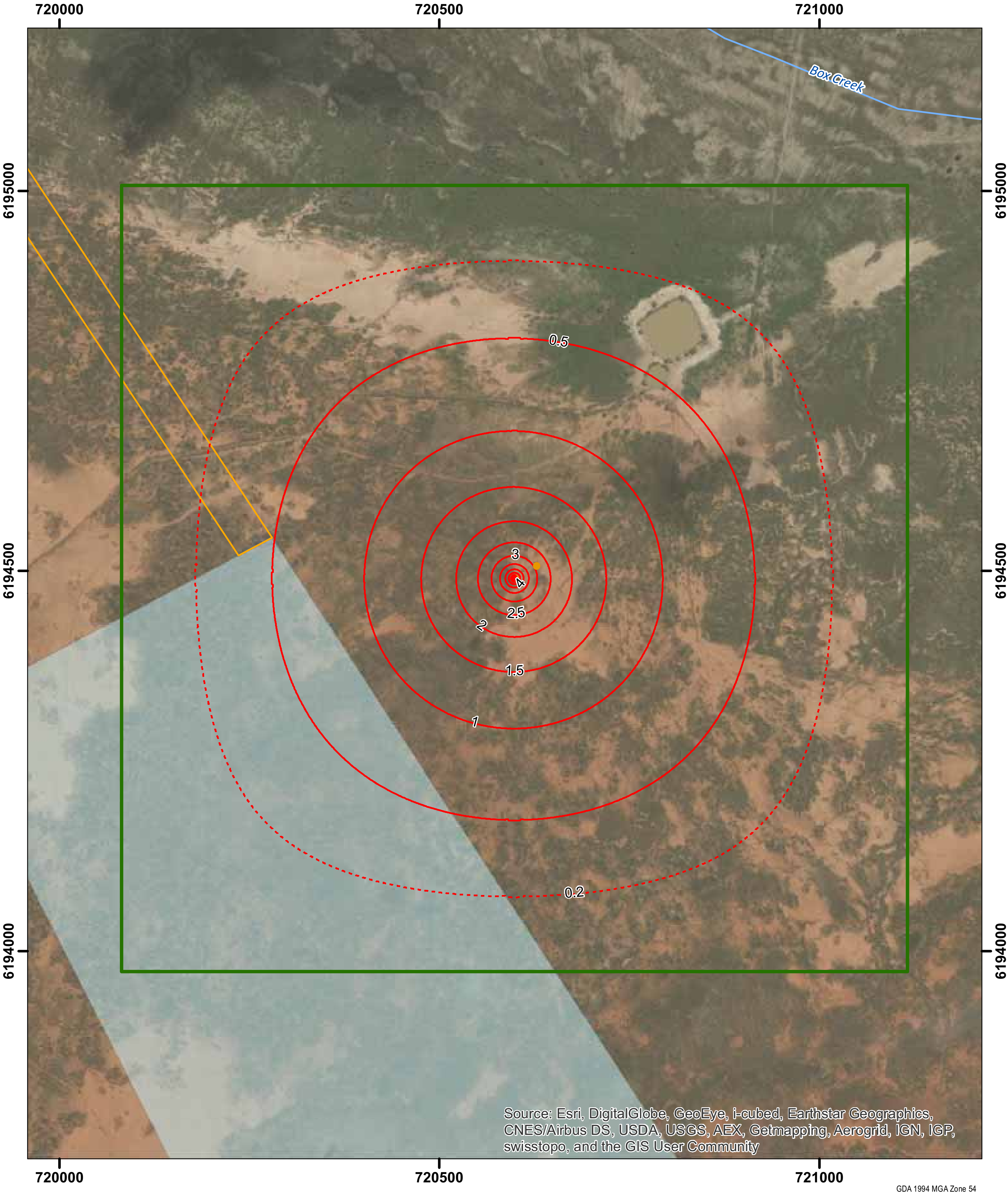
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN1\7 TN1 1.0 Drawdown in the LPS2 LS.mxd



TN5 1.0 modelled drawdown in Shepparton Formation (deep) on 17/10/2011

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN5\2 TN5 Drawdown in the SF.mxd



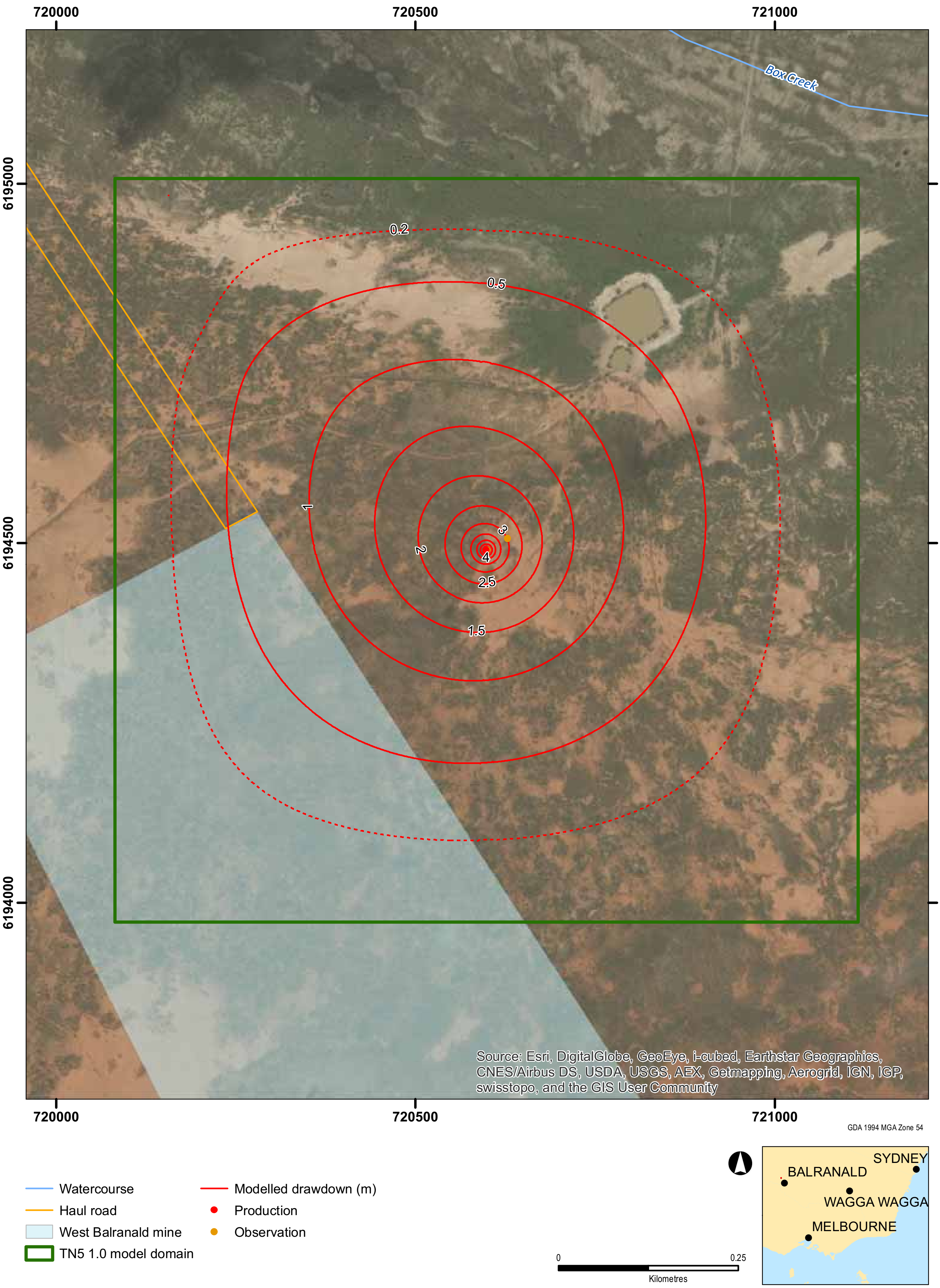
Watercourse
Haul road
West Balranald mine
TN5 1.0 model domain
Modelled drawdown (m)
Production
Observation

0 0.25
Kilometres

JACOBS

TN5 1.0 modelled drawdown in LPS1 FS on 17/10/2011

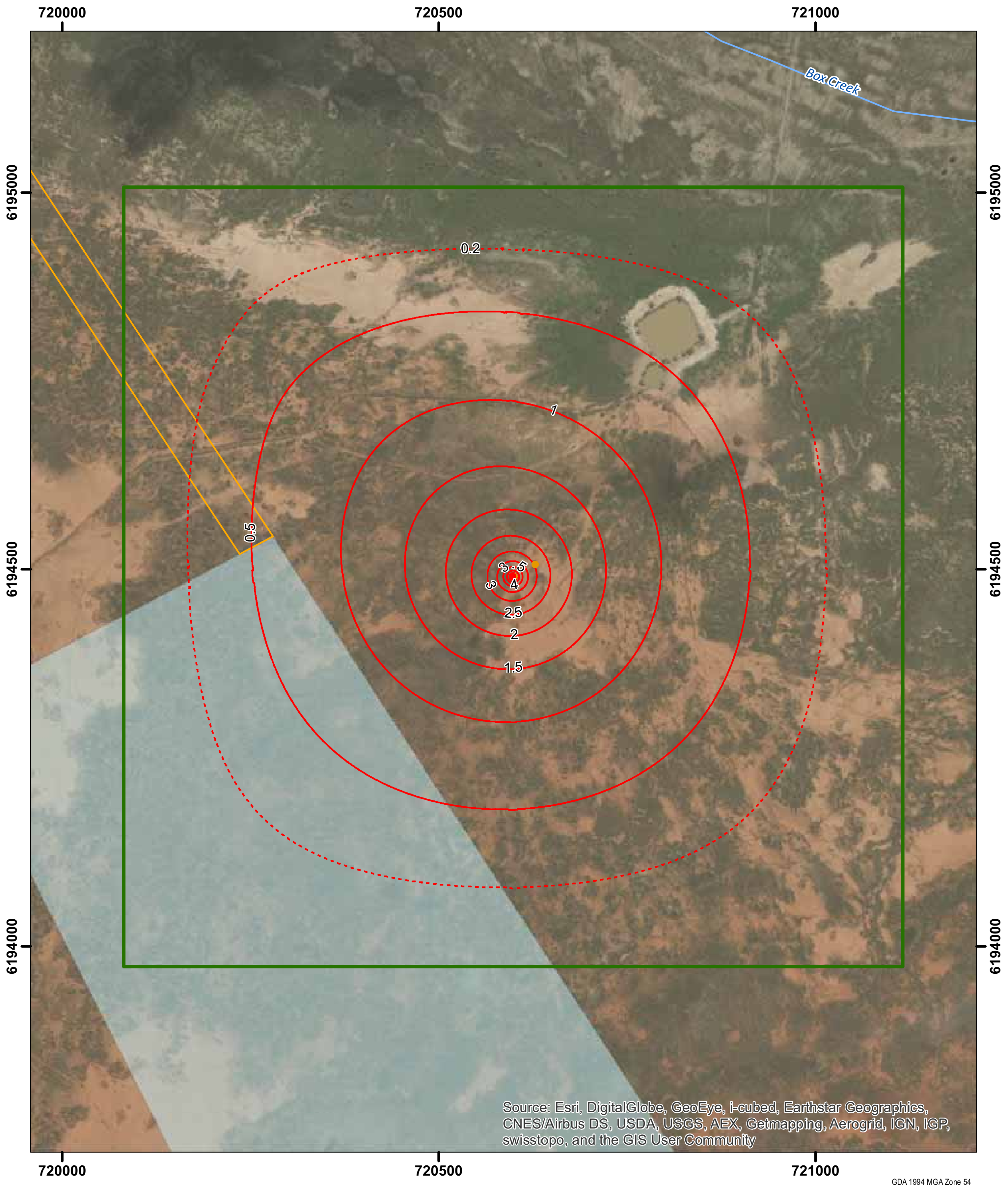
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN5\3 TN5 Drawdown in theLPS1 FS.mxd



JACOBS

TN5 1.0 modelled drawdown in LPS1 SZ on 17/10/2011

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN5\4 TN5 Drawdown in theLPS1 SZ.mxd



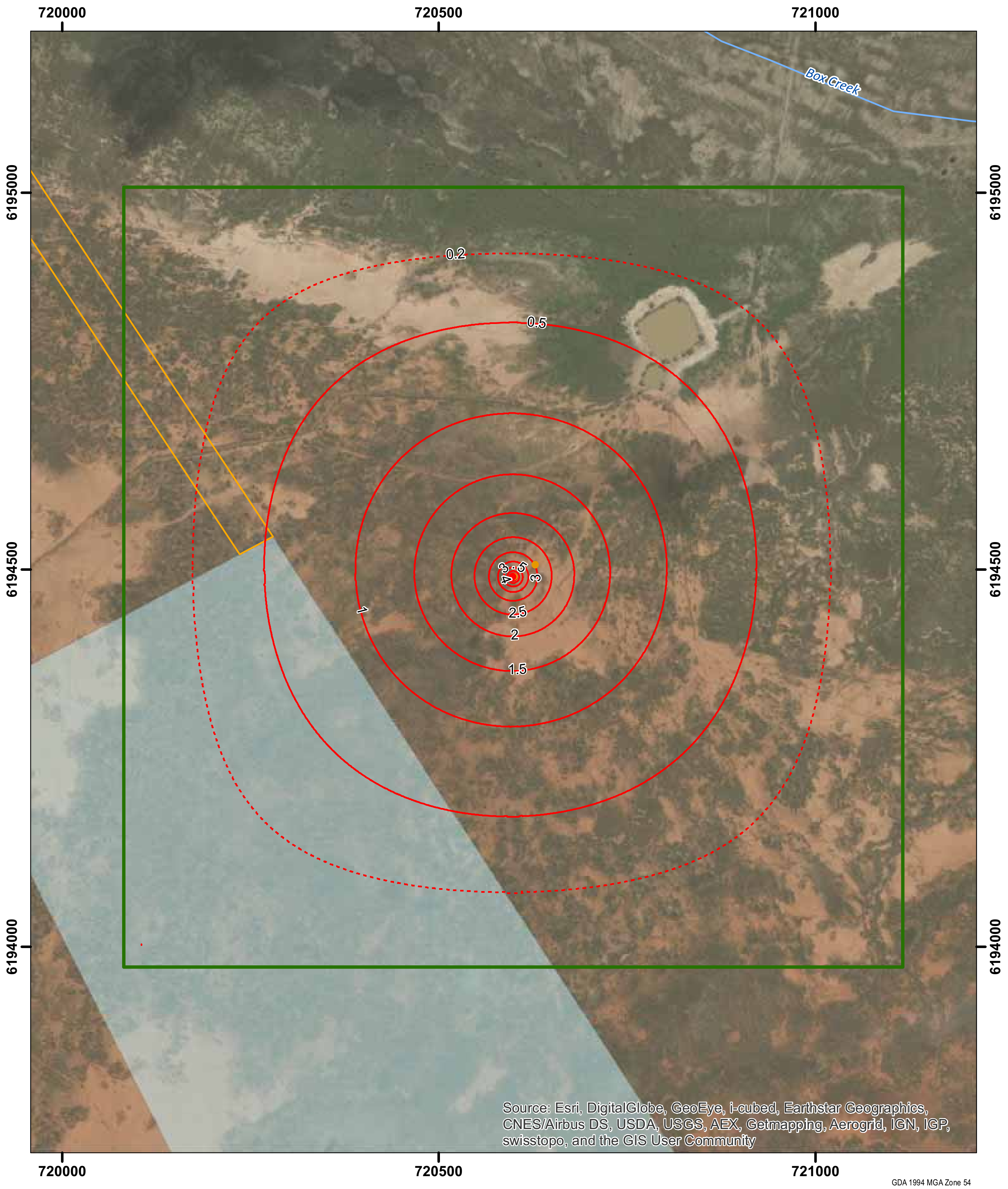
Watercourse
Haul road
West Balranald mine
TN5 1.0 model domain
Modelled drawdown (m)
Production
Observation

0 0.25
Kilometres

TN5 1.0 modelled drawdown in LPS1 LS/LPS2 FS on 17/10/2011

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN5\5 TN5 Drawdown in theLPS1 LS_LPS2 FS.mxd

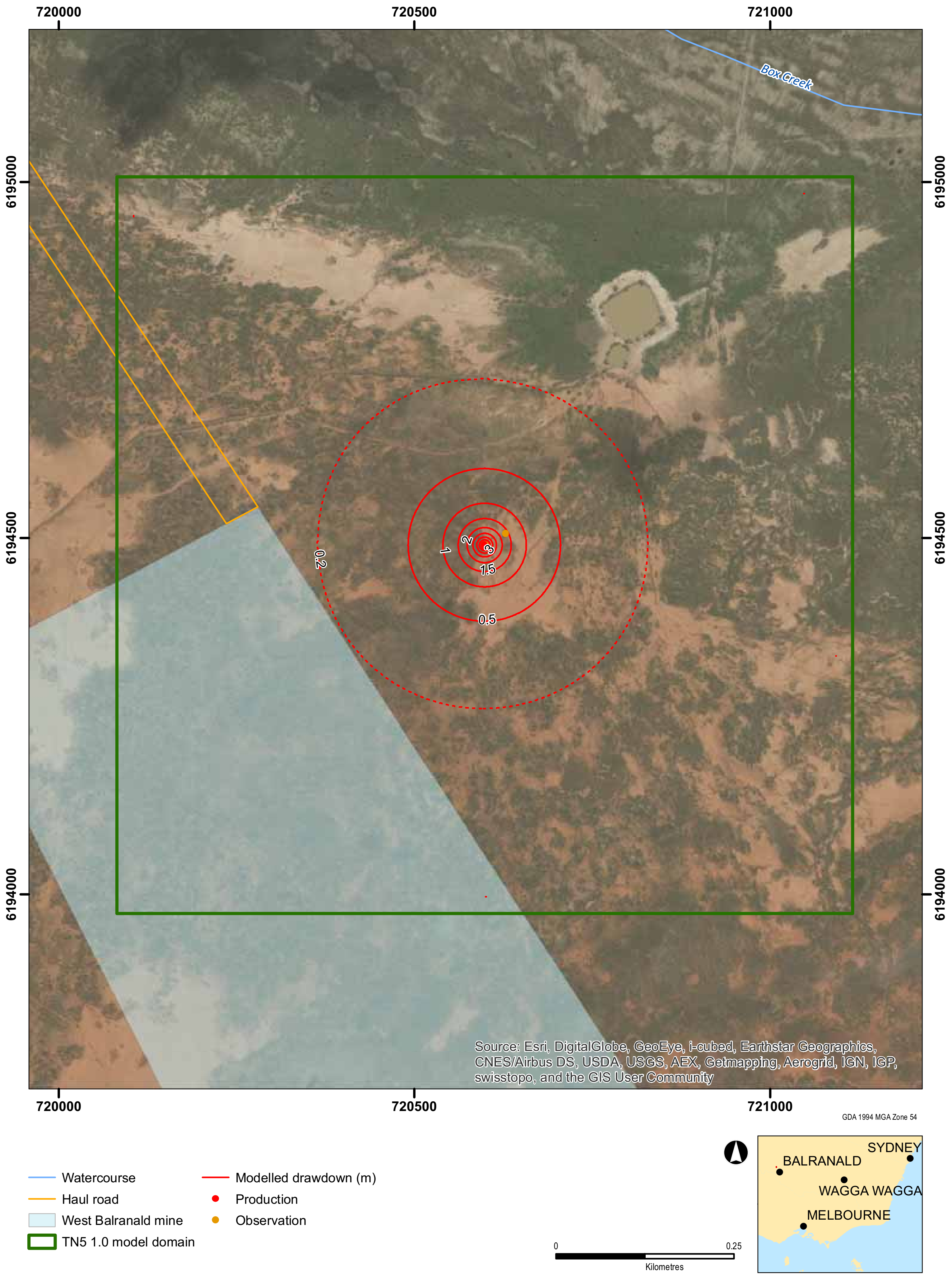


Watercourse
Haul road
West Balranald mine
TN5 1.0 model domain
Modelled drawdown (m)
Production
Observation

0 0.25
Kilometres

JACOBS

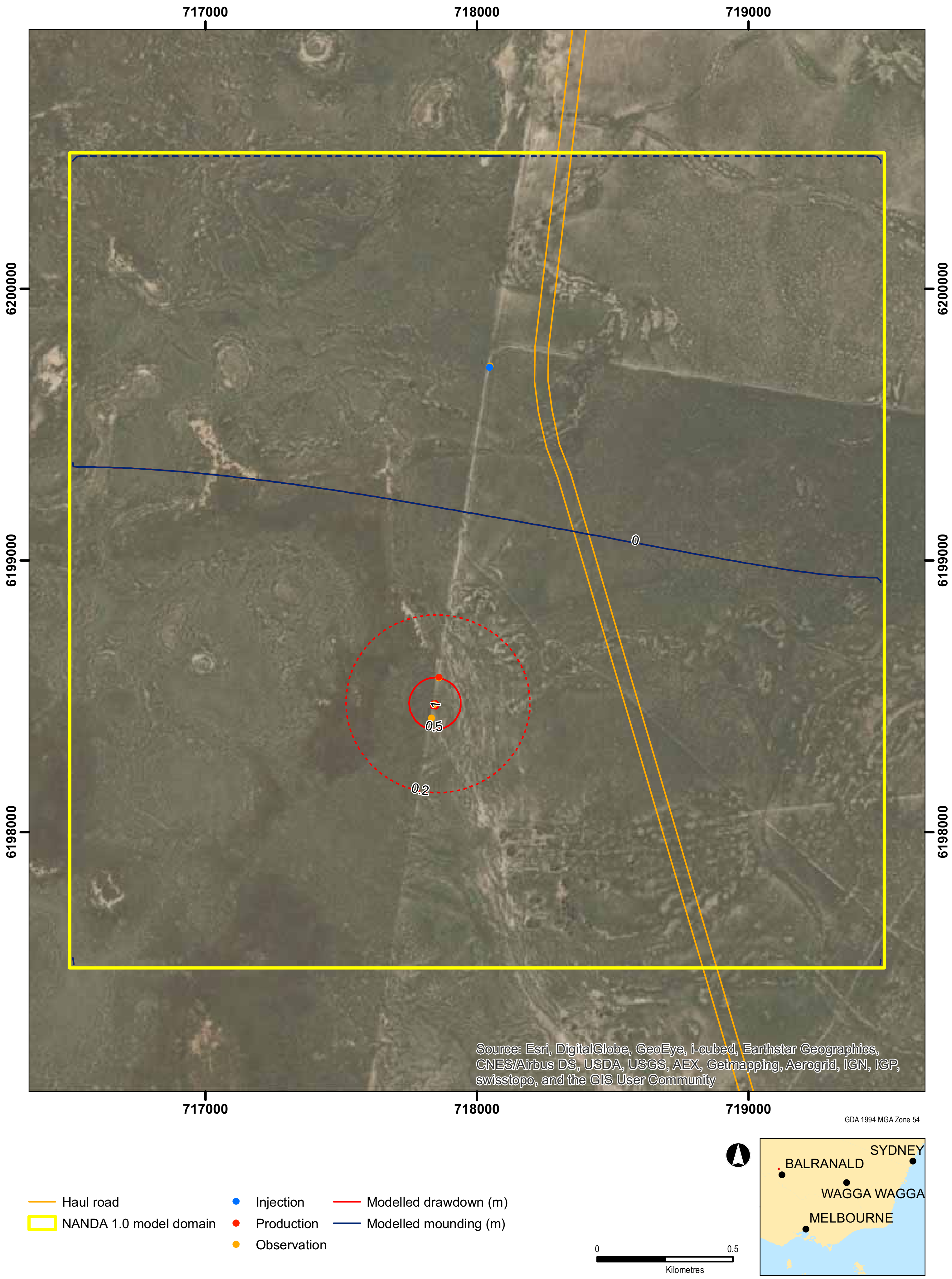
TN5 1.0 modelled drawdown in LPS2 SZ on 17/10/2011



JACOBS

TN5 1.0 modelled drawdown in LPS2 LS on 17/10/2011

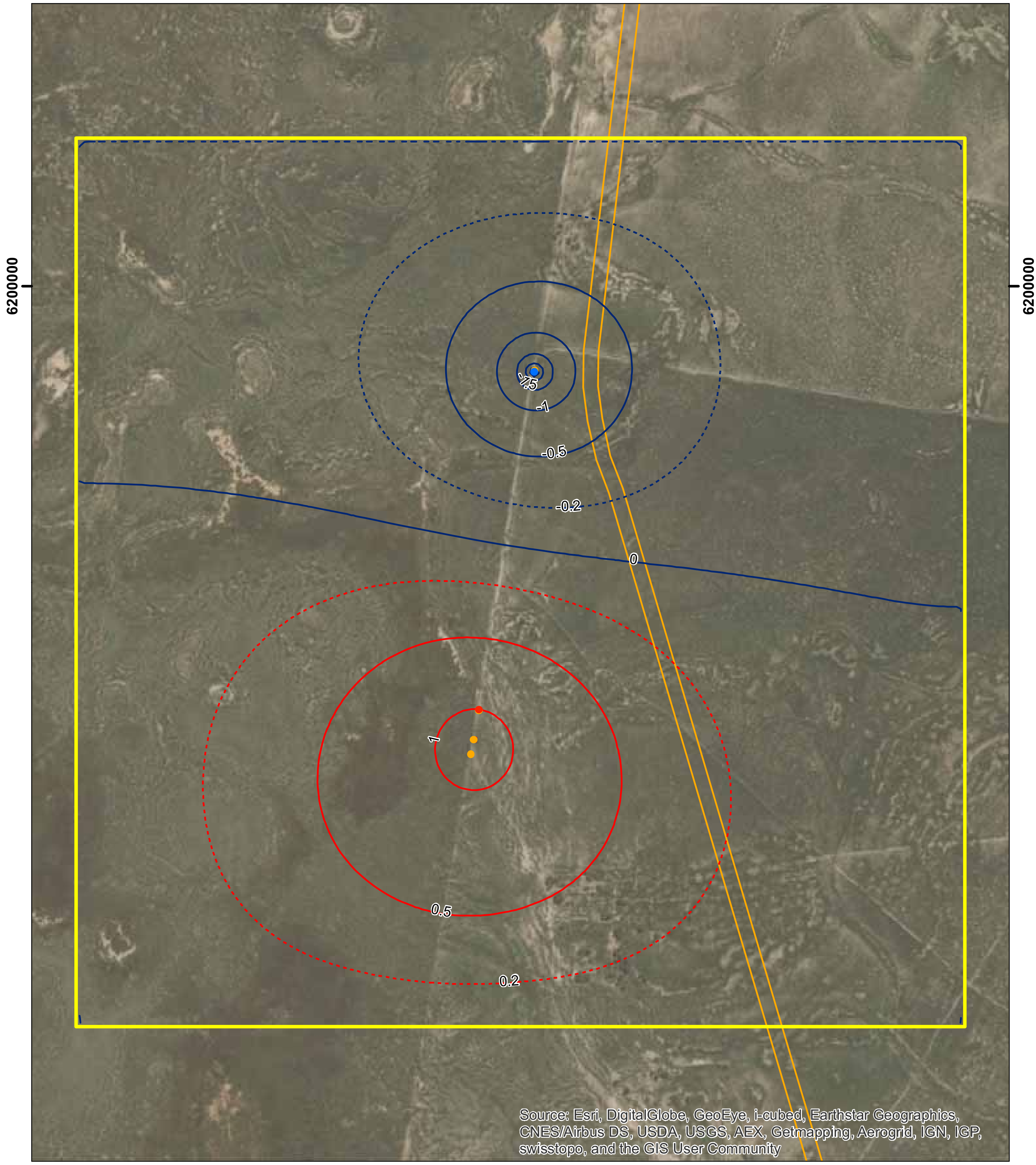
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev2\TN5\7 TN5 Drawdown in the LPS2 LS.mxd



JACOBS

Nanda1.0 modelled drawdown in LPS1 FS on 01/09/2014

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\anda\3 NANDA Drawdown in the LPS1 FS wells_.mxd



GDA 1994 MGA Zone 54

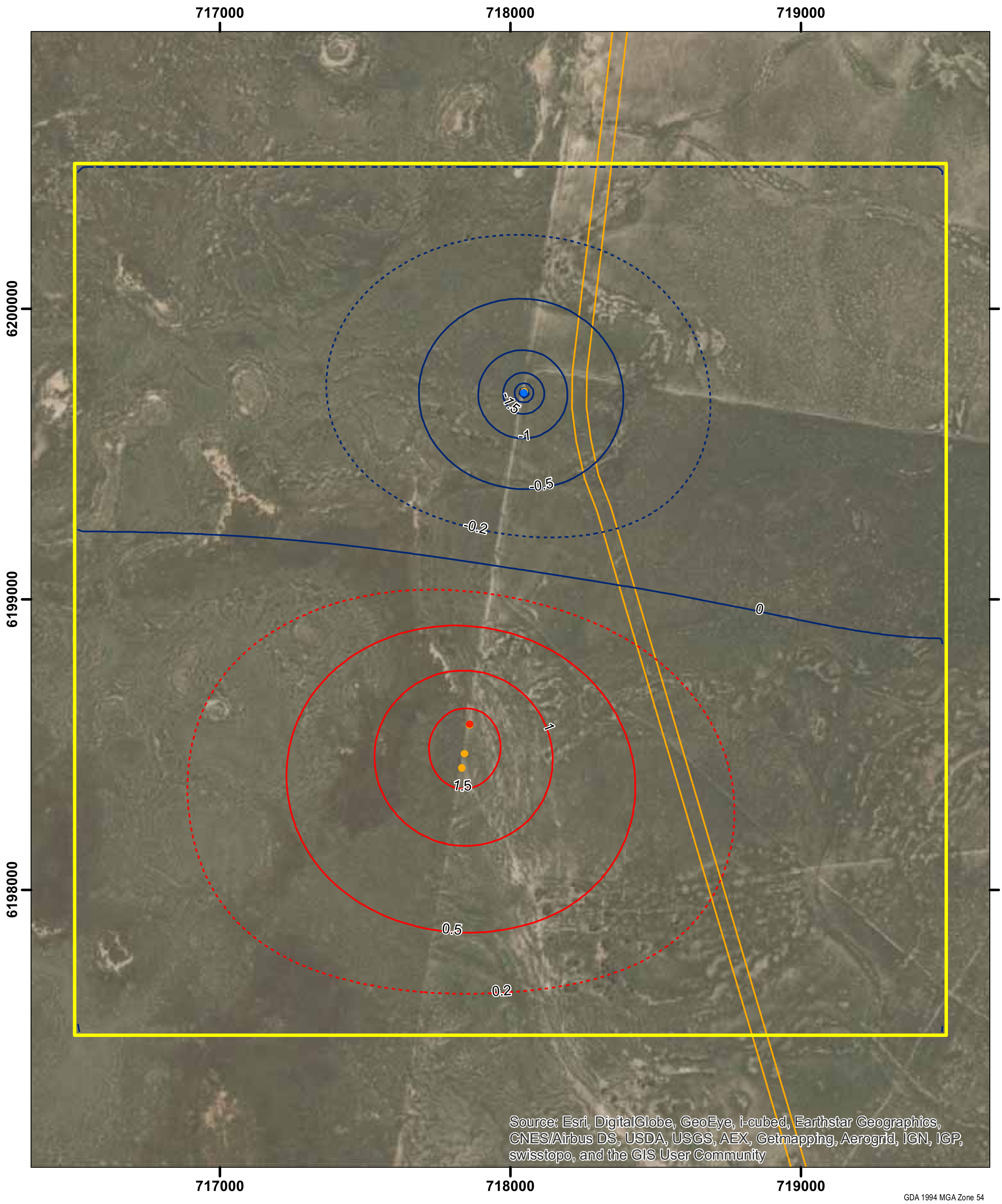
- Haul road
- NANDA 1.0 model domain
- Injection
- Production
- Observation
- Modelled drawdown (m)
- Modelled mounding (m)

0 0.5
Kilometres

JACOBS

Nanda1.0 modelled drawdown in LPS1 SZ on 01/09/2014

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev\Nanda\4 NANDA Drawdown in the LPS1 SZ wells.mxd



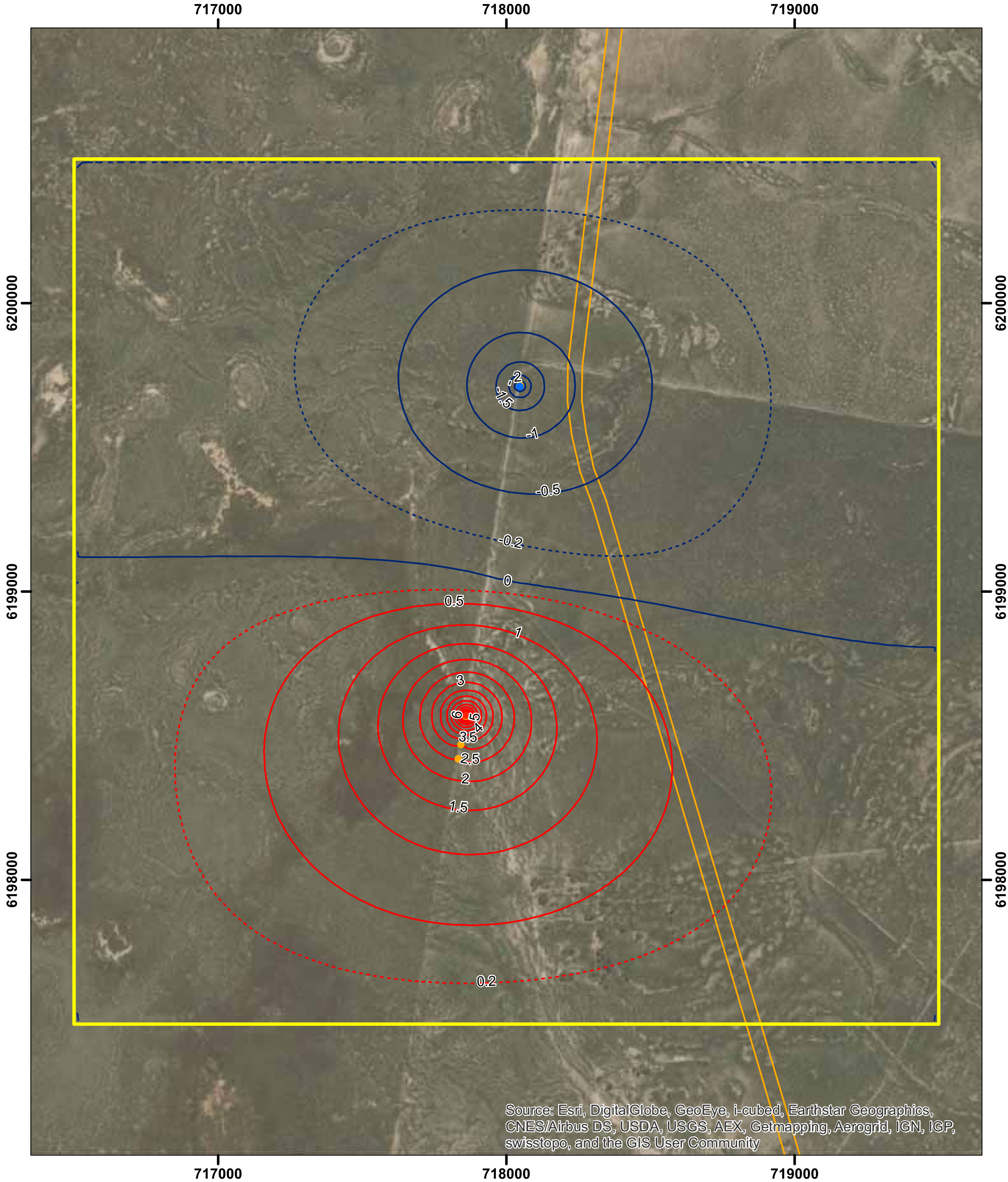
Haul road
NANDA 1.0 model domain
Injection
Production
Observation
Modelled mounding (m)
Modelled drawdown (m)

0 0.5
Kilometres

JACOBS

Nanda1.0 modelled drawdown in LPS1 LS/LPS2 FS on 01/09/2014

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\anda\5 NANDA Drawdown in the LPS1 LS_LPS2 FS wells.mxd



GDA 1994 MGA Zone 54

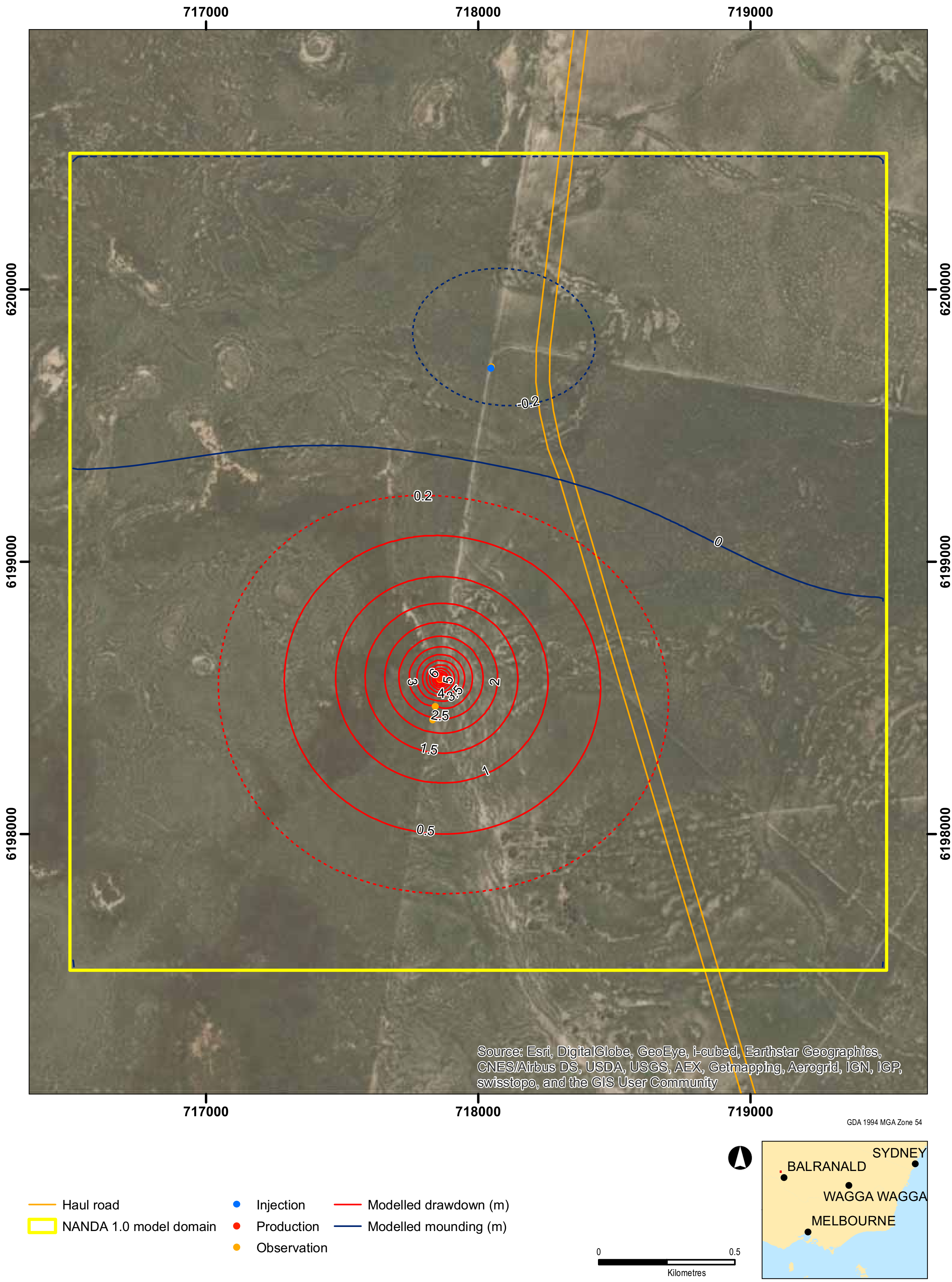
- Haul road
- NANDA 1.0 model domain
- Injection
- Production
- Observation
- Modelled drawdown (m)
- Modelled mounding (m)

0 0.5
Kilometres

JACOBS

Nanda1.0 modelled drawdown in LPS2 SZ on 01/09/2014

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1 anda\6 NANDA Drawdown in the LPS2 SZ.mxd



Nanda1.0 modelled drawdown in LPS2 LS on 01/09/2014

JACOBS

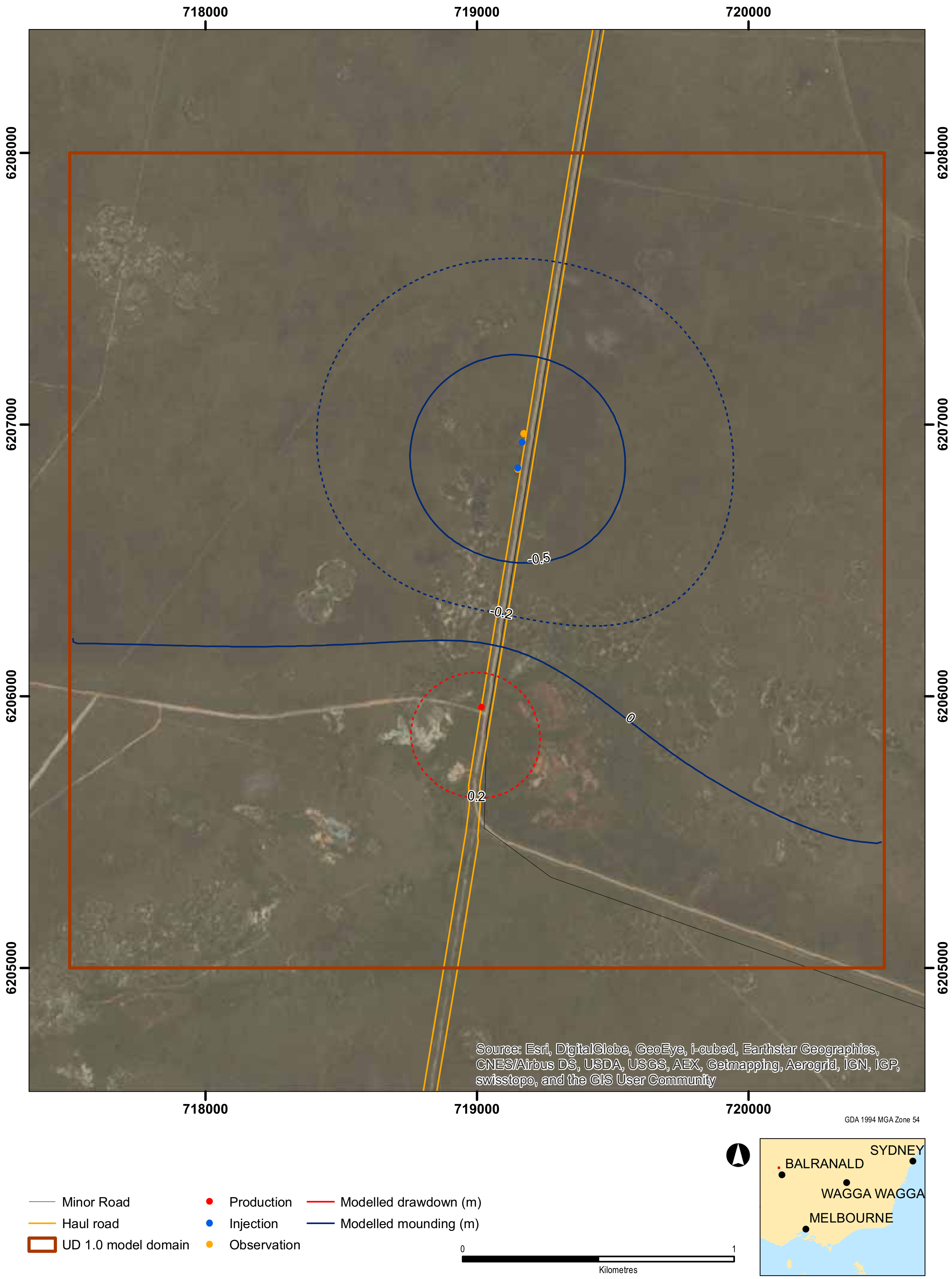
I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\Nanda\7 NANDA Drawdown in the LPS2 LS.mxd

Minor Road
Haul road
UD 1.0 model domain
Production
Injection
Observation
Modelled drawdown (m)
Modelled mounding (m)

0 — 1 Kilometres

UD1.0 modelled drawdown in Shepparton Formation (deep) on 17/09/2014

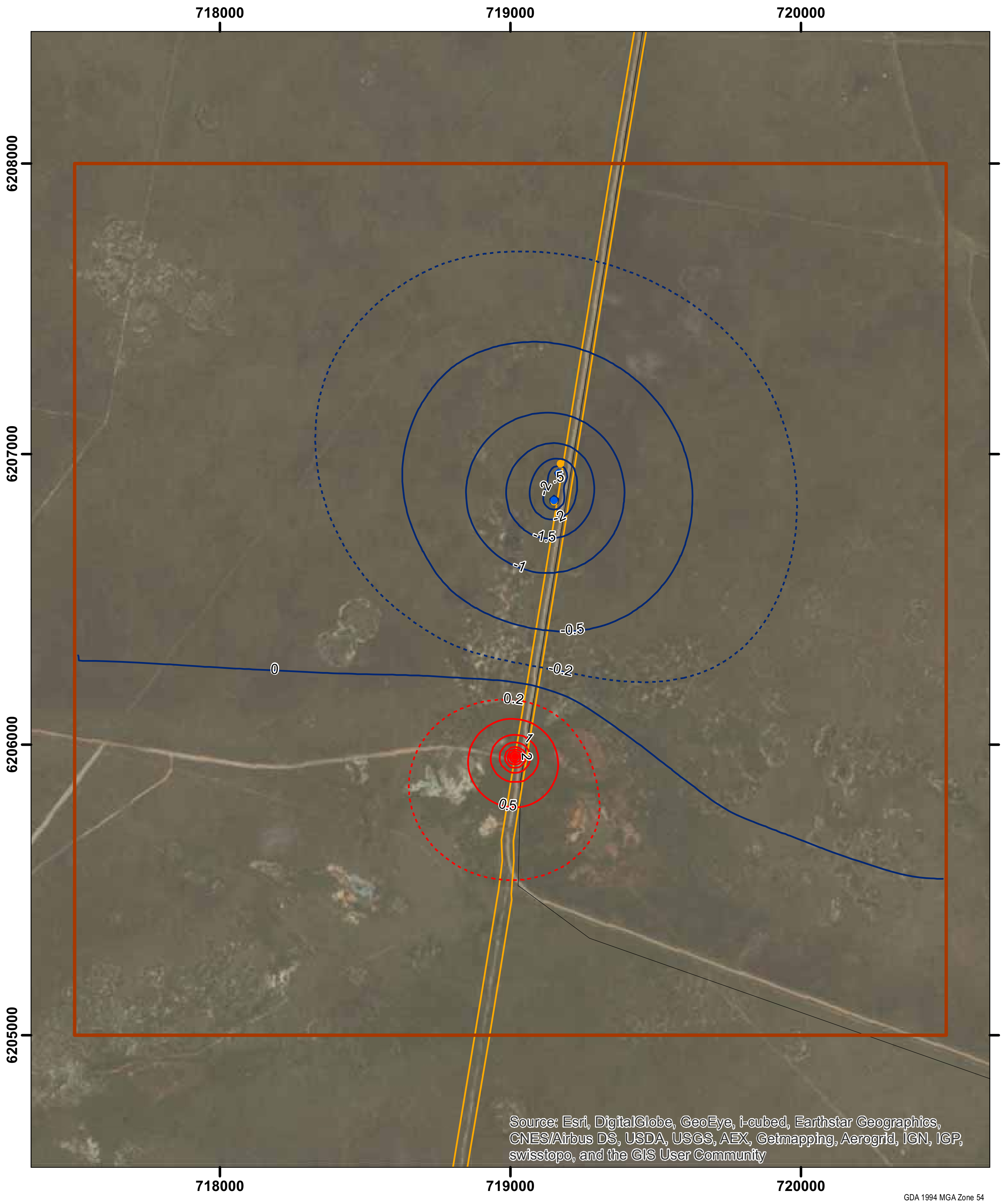
JACOBS



UD1.0 modelled drawdown in LPS1 FS on 17/09/2014

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\UD\3 UD Drawdown in theLPS1 FS.mxd



GDA 1994 MGA Zone 54

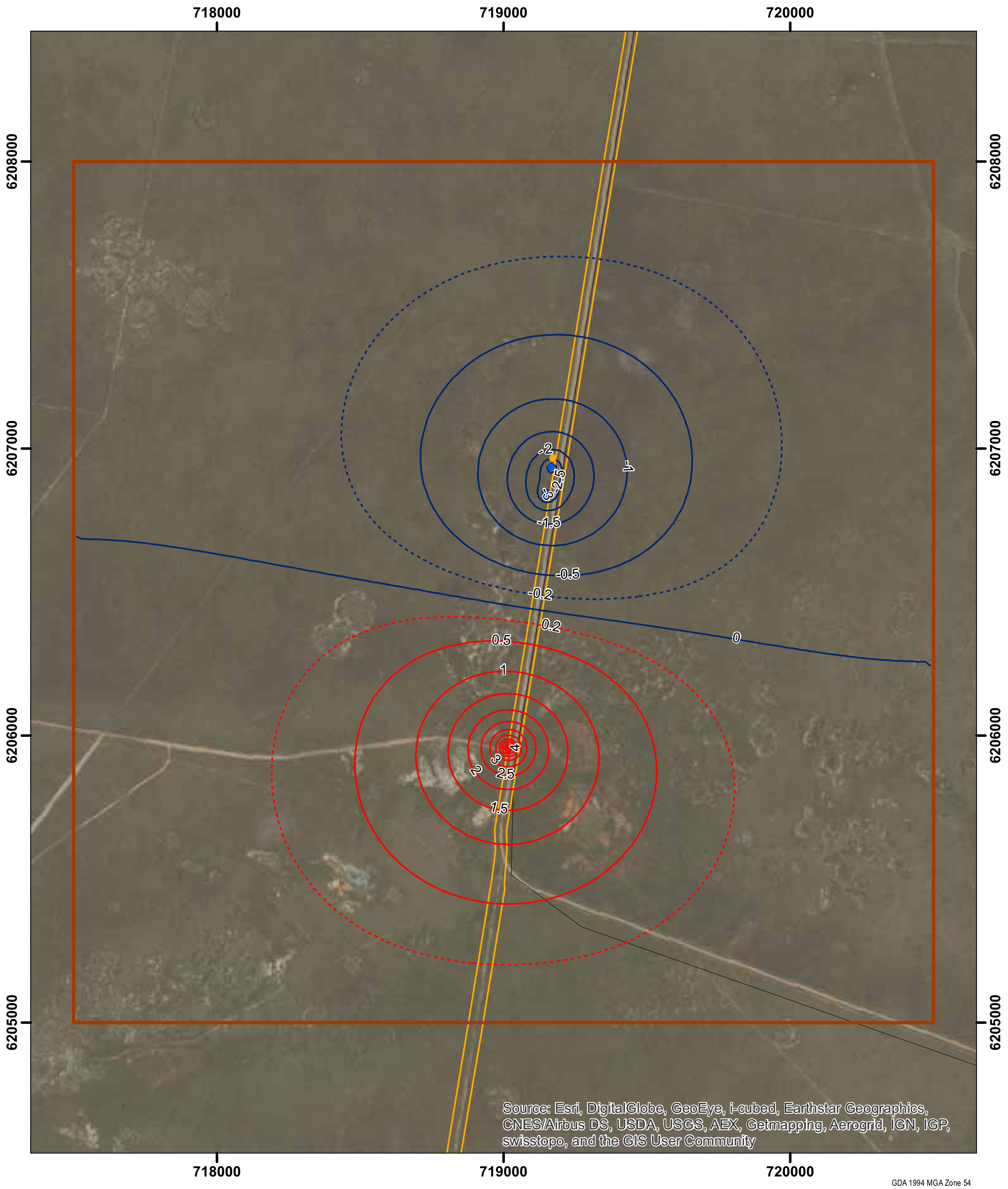
Minor Road
Haul road
UD 1.0 model domain
Production
Injection
Observation
Modelled drawdown (m)
Modelled mounding (m)

0 1
Kilometres

JACOBS

UD1.0 modelled drawdown in LPS1 SZ on 17/09/2014

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\UD\4 UD Drawdown in the LPS1 SZ.mxd



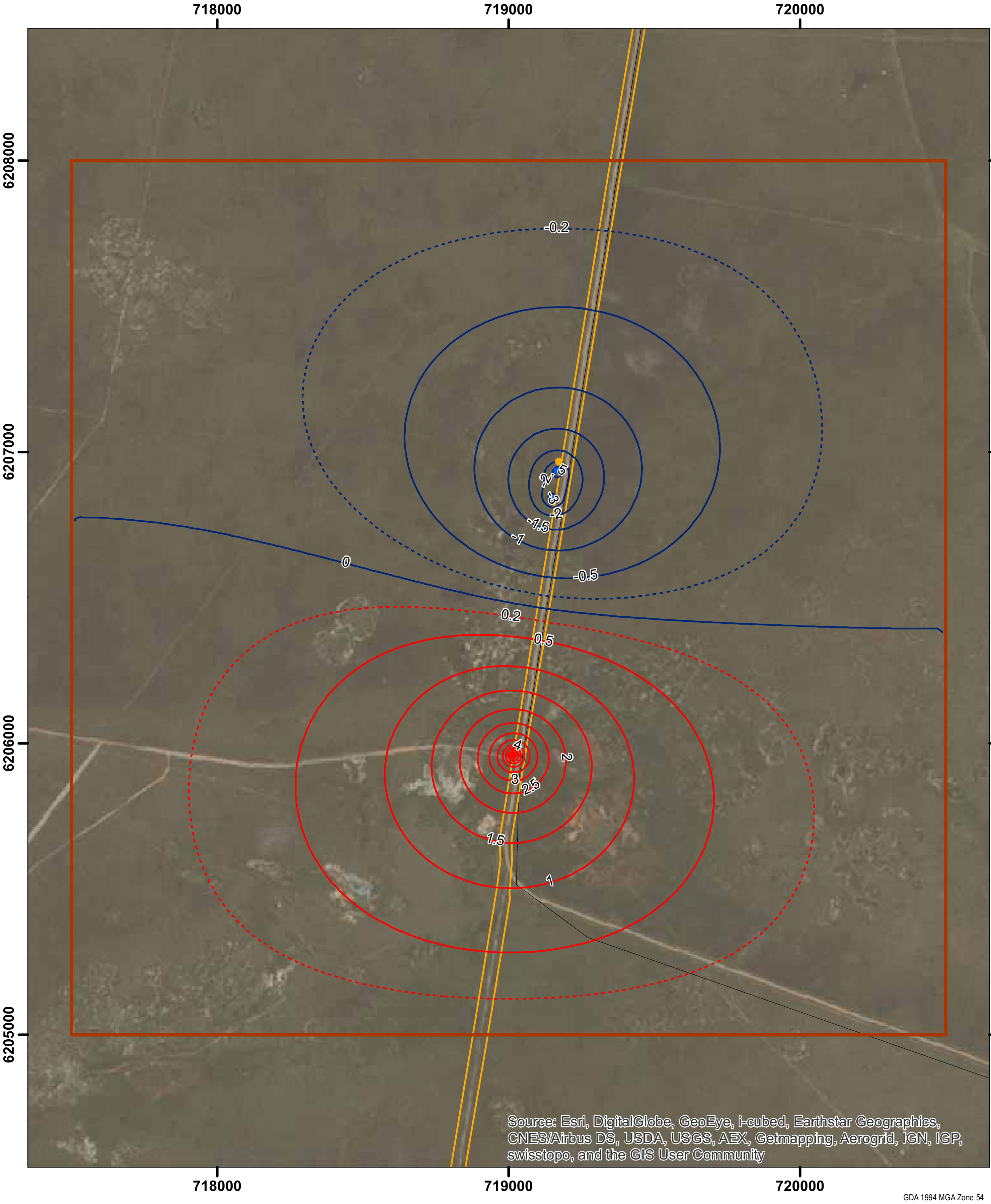
Minor Road
Haul road
UD 1.0 model domain
Production
Injection
Observation
Modelled drawdown (m)
Modelled mounding (m)

0 — 1 Kilometres

UD1.0 modelled drawdown in LPS1 LS/LPS2 FS on 17/09/2014

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\UD\5 UD Drawdown in theLPS1 LS_LPS2 FS.mxd



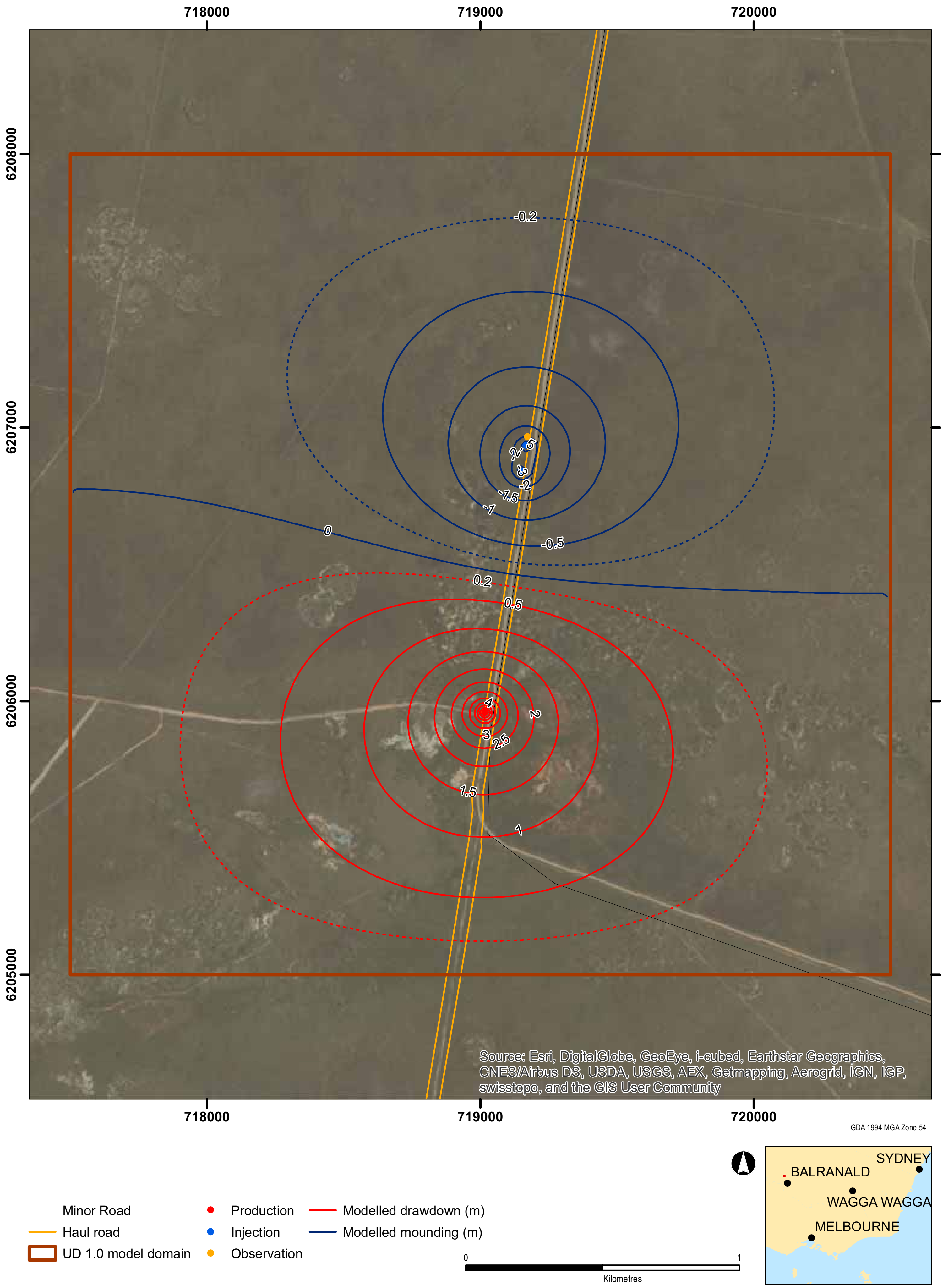
Minor Road	Production	Modelled drawdown (m)
Haul road	Injection	Modelled mounding (m)
UD 1.0 model domain	Observation	

0 — 1 Kilometres

JACOBS

UD1.0 modelled drawdown in LPS2 SZ on 17/09/2014

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\UD\6 UD Drawdown in the LPS2 SZ .mxd



UD1.0 modelled drawdown in LPS2 LS on 17/09/2014

JACOBS

I:\VESA\Projects\VE23875\Technical\Spatial\mxd\Transient Calibration figures\Rev1\UD\7 UD Drawdown in the LPS2 LS.mxd